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Methodology for Comparing Viscoelastic and Poroelastic Properties of GelMA Hydrogels at the Cellular Scale

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19 November 2026

12th European Solid Mechanics Conference
ESMC2025

Lyon 7th to 11th of July 2025



ABSTRACT BOOK

Organised by :

The French Community of Solid Mechanics
The EUROpean society of MECHanics (EUROMECH)

Chaired by :

MatéIS Laboratory INSA Lyon France
Centre des Matériaux, Mines Paris PSL

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EUROPEAN MECHANICS SOCIETY

Welcome note to ESMC2025

Dear Colleagues,

We are delighted to wellcome all attendees of the 12th European Solid Mechanics Conference in Lyon, France, 7th – 1st July, 2025 (ESMC 2025). The conference is being held under the auspices of the European Mechanics Society (EUROMECH, https://euromech.org).

The European Solid Mechanics Conference is the major event for the solid mechanics community, and provides a unique forum for scientists and engineers from Europe and across the world to exchange ideas on the current state-of-the-art in the mechanics of solids, on new concepts and ideas and to identify new research directions.

Solid mechanics is the bedrock of engineering design in areas such as mechanical engineering, civil and structural engineering, and biomedical engineering. It is a critically important element in the design and development of almost all technologies and products in these areas, such as aircraft, automobiles, buildings, bridges, and medical implants and devices. Further, solid mechanics is a key enabler in the development of new technologies that address the major global challenges of our time in sustainability, renewable energy and health.

The first European Solid Mechanics Conference was held in Munich in 1991. This very successful conference initiated a tri-annual series with subsequent conferences held in Genova, Stockholm, Metz, Thessaloniki, Budapest, Lisbon, Graz, Madrid, Bologna, and Galway.

The 12th European Solid Mechanics Conference takes place at the Cité Internationale, in the city of Lyon, France.

We have assembled an outstanding group of invited plenary lecturers for the conference.

The conference is organised in terms of the following eight thopics:

- Mechanics of Materials
- Biomechanics
- Continuum Mechanics
- Experimental Mechanics
- Computational Mechanics
- Dynamics, Waves, and Metamaterials
- Structural Mechanics
- Tribology

There are over fifty Mini-Symposia that cover a range of specialised areas, grouped under each topic.

We warmly welcome you to the wonderful city of Lyon for what promises to be a very exciting and stimulating event.

Yours sincerely,



Eric MAIRE



Samuel FOREST

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Book of abstracts

ESMC, July 6-11, 2025, Lyon, France

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Plenary Lectures

Selected Challenges of Nonlinear Solid Mechanics

Holzapfel Gerhard A.

1 - Graz University of Technology (Austria), 2 - Norwegian University of Science and Technology (Norway)

Speaker: Holzapfel Gerhard A.. **Monday**. Start time: **9:00**. Room: Amphi lumière, Amphi pasteur, Salon pasteur. Link to abstract.

This lecture, presented as part of the EUROMECH Solid Mechanics Prize, addresses aspects of nonlinear solid mechanics with regard to experiments and the modeling of continuum mechanics. It highlights selected current challenges and identifies open problems and future directions.
In particular, the 3D micro- and nanostructure of connective tissue and its reconstruction possibilities, which can be used for corresponding modeling, are briefly discussed (1). The importance of quantifying experimental uncertainties will be highlighted and the need for a framework for their calculation is shown (2). Finally, the cross-linking of the (collagen) fibers will be analyzed. The higher the cross-linking density, the stiffer the mechanical response of the (arterial) tissue. A first attempt to characterize this effect on the elastic behavior is presented and the influence of the crosslink density on the mechanical behavior under uniaxial tensile loading is shown (3). A simple shear test focusing on the sign of the normal stress perpendicular to the shear planes (Poynting effect) is analyzed (4). Experimentally, it was observed that semi-flexible biopolymer gels, in contrast to rubber, tend to approach the top and bottom faces under simple shear (5). This so-called negative Poynting effect and its connection with cross-links as well as the fiber and cross-link dispersion is also investigated.

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Micromechanics: the „strength“ of miniaturized testing

Erica Lilleodden

Fraunhofer-Institut für Mikrostruktur von Werkstoffen und Systemen IMWS

Speaker: Erica Lilleodden. **Tuesday**. Start time: **9:00**. Room: Amphi lumière, Amphi pasteur, Salon pasteur. Link to abstract.

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Eggstreme Mechanics: Shell We Buckle?

Reis Pedro

1 - Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Speaker: Reis Pedro. **Tuesday**. Start time: **13:30**. Room: Amphi lumière, Amphi pasteur, Salon pasteur. Link to abstract.

From birds' eggs to architectural domes and from viral capsids to aerospace vessels, shell structures are ubiquitous across scales in both nature and engineering, primarily due to their exceptional capacities for load-bearing and enclosure. Since the golden era of shell buckling in the 1960s, pioneered by Zoelly, von Kármán, Tsien, Koiter, Budiansky, Hutchinson, and many others, this field has been marked by the fundamental challenge of reconciling theoretical predictions of buckling strength with experimental observations, particularly regarding the dramatic sensitivity to geometric imperfections. The past decade has witnessed a renaissance in shell buckling research, driven by advances in computational methods and fabrication techniques, thereby renewing efforts to move beyond empirical knockdown factors toward more predictive frameworks and rational designs.
In this talk, I will present recent advances in the predictive understanding of the buckling of thin shell structures, with a primary focus on spherical shells, but also presenting some more recent work on cylindrical and negatively curved shells. Empowered by our development of precise fabrication techniques for thin elastic shells of nearly uniform thickness, and combining precision experiments, finite-element simulations, and shell-theory analyses, we have thoroughly investigated how single localized defects and distributed imperfections influence buckling strength. For the probabilistic problem of shells containing multiple defects, we have uncovered that a distribution of defects whose amplitudes are distributed log-normally yields knockdown factor statistics that are well-described by a three-parameter Weibull distribution. This finding reveals shell buckling as an extreme-event statistics problem governed by a finite-size weakest link mechanism, where the most severe imperfection ultimately dictates the buckling strength. Practical applications of this research will also be discussed, including a refreshable braille dot utilizing bistable buckling of magneto-active shells and the design of stiffened shells for aerospace applications.
Even after more than a century of active research, the mechanics of shell buckling continues to raise fundamental questions, reveal surprising phenomena, and remain as practically relevant as ever at the confluence of applied mathematics, mechanics, and engineering. After all, quoting Budiansky and Hutchinson, "Everyone loves a buckling problem"!

Single-image DIC?

Roux Stéphane

1 - LMPS (France)

Speaker: Roux Stéphane. **Wednesday**. Start time: **8:45**. Room: Amphi lumière, Amphi pasteur, Salon pasteur. Link to abstract.

Digital image correlation (DIC) and its many variants, such as multi-view stereo-correlation (S-DIC) or digital volume correlation (DVC), have long since demonstrated their power to resolve very fine details of kinematic fields over time series. As a result, DIC has become an essential metrology tool for experimental mechanics. Moreover, the differences between images, after motion correction, the so-called "residual" field, show very conspicuously evolutions that are not purely kinematic and thus give access to information that is often invaluable, such as the appearance of cracks or changes in temperature. In short, the quantitative exploitation of 2D and 3D images has opened up new avenues for challenging our understanding of the mechanical behavior of materials.
A provocative question is thus: can we go beyond and use DIC to challenge our understanding of materials themselves via their microstructure? The idea is no longer to compare several images of the same object but to confront a single image with our apprehension of what it represents. In other words, starting with one "real" image, the idea is to build its ideal version from what we understand about it and gradually refine our understanding and the subtlety of our description by exploiting and reducing the differences (residuals). The ability of DIC to erase kinematics then emphasizes the preservation of topology, which is often an essential property, difficult to restore from local analyses when hampered by the presence of noise, and which gives greater robustness. The same approach is also a way of promoting long-range order and highlighting finer modulations on a smaller scale. Whereas a reference image was the main focus of classical DIC, one can observe a gradual evolution to install as a key reference a 3D object, the set of its individual components, its CAD or numerical model and finally a collection of (topological) properties.

A few applications of this simple idea will be discussed, such as the segmentation of tomographic images of 3D woven fabrics or MET image analysis of multiferroic multilayers.

Micromechanical modelling of rubbery networks

Brassart Laurence

1 - Department of Engineering Science - University of Oxford (United Kingdom)

Speaker: Brassart Laurence. **Thursday**. Start time: **8:45**. Room: Amphi lumière, Amphi pasteur, Salon pasteur. Link to abstract.

The mechanical properties of soft materials such as elastomers and hydrogels fundamentally depend on the structure of the underlying polymer network and the intrinsic response of the polymer chains. Structural features of interest include the polymer chain length, the density and functionality of the crosslink points, and network inhomogeneities and defects. Understanding structure-property relationships thus requires a modelling approach that addresses the microscale of the polymer network. Conventional constitutive models based on rubber elasticity theory usually fall short in this respect, as they cannot capture the effect of network topology on the chain stretch distribution. On the other hand, molecular simulations remain computationally prohibitive at the network length and time scales, calling for new, complementary modelling strategies.

In this talk, I will present our recent efforts in the development of micromechanical models for rubbery networks, with the objective of linking the behaviour of single polymer chains to the macroscopic behaviour. Discrete Network (DN) models will be introduced as a conceptually simple and cost effective computational approach to investigate the role of network topology on the deformation and failure behaviour, while being firmly grounded in statistical mechanics. DN models can also be used as a guide for the development of advanced continuum constitutive theories. In the second part of the talk, I will present our new model for the force-extension response of a single polymer chain, which accounts for both entropic and energetic effects. The model captures the chain response across all force regimes, while also providing an estimate of the bond stretch, which is critical to predict chain scission. This presentation is primarily based on the works of two PhD students, Lucas Mangas Araujo and Jie Zhu.

New measurement strategies in data-driven mechanics provide fresh physical insights

Deshpande Vikram

1 - Department of Engineering [Cambridge] (Cambridge University, Department of Engineering, Trumpington Street, Cambridge CB2 1PZ, United Kingdom United Kingdom)

Speaker: Deshpande Vikram. **Thursday**. Start time: **13:30**. Room: Amphi lumière, Amphi pasteur, Salon pasteur. Link to abstract.

There has been explosive growth in numerical data-driven mechanics approaches for various problems in the mechanics of materials. These data-driven methods are data-hungry, but traditional measurement protocols are inherently data-poor. Consequently, most studies using these data-driven methods have relied on synthetic data. This dearth of measurement techniques presents opportunities to transform laboratory-based methods, making them more suitable for emerging methodologies in data-driven mechanics. We first present a brief overview of some emerging laboratory techniques to provide observations that were hitherto considered nearly impossible, at least in a laboratory setting. These methods include (i) dynamic tomography to enable 3D visualisation of high-speed deformations and (ii) democratising synchrotron technologies to allow the measurements of local stresses within statically indeterminate specimens to provide fully labelled stress-strain pairs for supervised constitutive model discovery approaches. These and other new laboratory measurement methods provide new observations and large datasets, but are they giving new insights into the mechanics of solids? To address this question, the bulk of the presentation will focus on one of the oldest problems in the mechanics of solids: rubber elasticity. Using innovative X-ray measurements capturing the three-dimensional (3D) spatial volumetric strain fields, we demonstrate the established idea that, under isothermal conditions, stress is (non)linearly related to strain, and no other state variable might need to be revisited. We show that rubbers and many common engineering polymers undergo significant local volume changes, but remarkably, the overall specimen volume remains constant regardless of the imposed loading. This strange behaviour, which also leads to apparent negative local bulk moduli, is due to a mobile phase within these materials. Using a combination of X-ray tomographic observations and high-speed radiography to track the motion of the mobile phase, we propose a revision of the classical thermodynamic frameworks of rubber elasticity.

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Commentary: C. Hartquist, S. Wang and X. Zhao (2024), Local volume changes in deformed elastomers with mobile chains, **Proceedings of the National Academy of Sciences,** 121 (30), e2410811121.

TOPIC: Mechanics of materials

MS1.1 - Mechanics of fibrous materials and textiles

Organisers: Stepan Lomov (KU Leuven), Catalin Picu (Rensselaer Polytechnic Institute, USA), and Dmytro Vasiukov (IMT Nord Europe)

Fluid effects on the fracture toughness of gels

Bassani John (1), Purohit Prashant

1 - University of Pennsylvania (United States)

Speaker: Bassani John. Keynote. **Monday**. Start time: **10:10**. Room: Rhône 1 LVL1. Link to abstract.

The fracture of polymeric gels has been of growing interest in the last two decades, in particular in applications to biological tissue. Well established continuum theories that couple large deformations and fluid diffusion have been applied to gels to determine crack tip fields and the energy release rate. Some studies have combined experiment and calculations to determine the fracture toughness of gels and have shown that fluid effects make a substantial contribution to the toughness. Here we adopt a micro-mechanical view to estimate the fracture toughness of gels, defined as the critical (total) energy release rate, and show how the initiation toughness can be written as a combination of contributions from fiber scission and of fluid-solid demixing at the crack tip. This estimate is based on knowledge of a critical stretch and a volumetric strain when fracture is incipient and reveals dependencies on material properties including the solid volume fraction of gels. There have been no known ways to measure the de-mixing contribution directly from experiment, but the results in this paper provides a methodology. We also show how dissipation due to fluid motion as the crack propagates can contribute to the fracture toughness. Detailed results are presented for fibrin gels, which are the main structural component of blood clots. We find that the contribution of fluid mixing with the fibrin network to the initiation toughness for fibrin gels is significant at moderate critical stretches. We also find that fluid flow around a steadily moving crack leads to a contribution to the toughness that is linear in crack speed and fluid viscosity.

Understanding the moisture transport and swelling in paper by using a multi-phase flow approach

Rojas Vega C.a. (1), Geers M. G. D. (1), Peerlings R.h.j. (1)

1 - Eindhoven University of Technology. Department of Mechanical Engineering P.O. Box 513, 5600 MB Eindhoven (Netherlands)

Speaker: Rojas Vega C.a.. **Monday**. Start time: **10:50**. Room: Rhône 1 LVL1. Link to abstract.

Paper is a natural material mainly composed of fibers and pores. This porous hygrophillic structure is highly sensitive to fluctuations in moisture content because of the swelling of the fibers. In this work, we implement a finite element-based computational model to study moisture transport and swelling in paper. The material is modeled using a multiphase flow approach known as hybrid mixture theory (1). This methodology incorporates some features of mixture theory and averaging procedures. The balance equations are presented at the microscale level and, by an averaging procedure, the corresponding macroscale balances are obtained. By using this methodology we can take into account the moisture transport through the diferent phases and constituents of the material in a thermodinamically consistent framework. An application of this theory to porous cellulose networks can be found in (2). We adapted this model to study the moisture transport and swelling in paper. The novelty of our work is that the constitutive relations are derived from physical principles and assumptions at the microscale level. The moisture transport in pores and fibers is modeled using unsaturated flow theory. To establish the local constitutive relations for moisture transport we assumed that pores are tubular structures with different radii, according to the pore size distribution of our material. Water fills first the smaller pores and then the larger ones. With these assumptions we can derive an expression for the permeability of the porous structure. Furthermore, a simple constitutive relationship is proposed to study moisture transport from the pores into the fibers. By studying a single fiber problem, we find an expression for mass exchange between fibers and pores. Swelling and mechanical deformations are introduced by means of a linear elastic law.

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Water uptake in wood explained by in situ X-ray tomography observation and digital volume correlation

Bordage Romain (1), Orgéas Laurent (1), Rolland Du Roscoat Sabine (2), Nishiyama Yoshiharu (3)

1 - Laboratoire sols, solides, structures - risques [Grenoble] (France), 2 - Laboratoire sols, solides, structures - risques [Grenoble] (France), 3 - Centre de Recherches sur les Macromolécules Végétales (France)

Speaker: Bordage Romain. **Monday**. Start time: **11:10**. Room: Rhône 1 LVL1. Link to abstract.

Wood imbibition by liquids such as aqueous solutions is a relevant processing route to process wood-based products as autoclave or densified woods, *i.e.*, lightweight biosourced materials with optimized functional and structural properties. However, wood imbibition involves complex and coupled mechanisms, *e.g.*, capillary effects, diffusion in wood cell walls, and hygro-expansion of these cell walls, which are not fully understood. Within this context, we performed water imbibition of beech samples at macroscale and at mesoscale with 3D *in situ* observations of samples using X-ray tomography. The acquired 3D images were compared using Digital Volume Correlation (DVC). We obtained simultaneously quantitative information of (i) the impregnation of "free" water in the vessels from the correlation errors, (ii) anisotropic hygro-expansion of wood, from the 3D local strain fields, which gives (iii) the diffusion of bound water inside the wood cell walls. Impregnation induced by capillary effects is faster than diffusion, with an equilibrium state obtained after a few hours for capillary uptake and few weeks for diffusion for a sample size of 5 cm. The kinetics of both phenomena are compared with analytical predictors to extract relevant impregnation and diffusion constitutive parameters.

Mechanochromic sensor for measuring high strain in the healthcare sector

Fierling Ségolène (1) (2), Recoules Loïc (1), Molimard Jérôme (2), Pierrat Baptiste (2), Bonnaire Rébecca (1)

1 - IMT École nationale supérieure des Mines d'Albi-Carmaux (France), 2 - Centre Ingénierie Santé, Saint-Étienne (France)

Speaker: Fierling Ségolène. **Monday**. Start time: **11:30**. Room: Rhône 1 LVL1. Link to abstract.

In health area, measuring high strain for textile medical device wearing by a subject presents high interest.That's why development of small, flexible sensors capable of measuring high strain has gained considerable momentum in recent years. Currently, no sensor technology on the market can meet these needs. The methods used by industries and researchers are optical, requiring expensive equipment, difficult to transport, and technical to set up. The objective of this project was to develop a small, flexible sensor capable of measuring high strain, and compatible with the healthcare sector. This sensor was also design to be stitched directly on textile orthesis such as lumbar belts and used for moving studies. Our goal is to measure 20-30% strain. The sensor developed is a bound sensor based on mechanochromic. Mechanochromy is characterized by an optical and physical-chemical phenomenon that causes a material to change color when subjected to mechanical strain. This phenomenon cannot be observed naturally and does not apply to all materials. It is present in amorphous materials, particularly polymers. To observe this phenomenon, adding a colored additive is essential. This colorant must have some criteria: it must be compatible with the polymer matrix and have photoluminescent optical properties. The most commonly used additives are those from the chromophore family.

In this study, two polymers with the same additive were studied: ethylene-octene (OE) copolymer, better known as POE and polypropylene (PP), and a food colorant as additive, bis(benzoxazolyl)stilbene (BBS). BBS has numerous aromatic rings that interact with each other and the material to form aggregates, also known as excimers. The latter dissociates to form a new metastable molecule called a monomer. Excimers and monomers do not have the same potential energy level. Under UV light excitation, this difference is reflected in the emission of a specific wavelength for excimer (495nm: green) and monomer (430nm: blue). The formation and dissociation of excimers are responsible for the appearance of the mechanochromic phenomenon. To obtain measurement of different strain, we decided to mix both polymers in our sensor. Five blends were created: 80%PP-20%POE; 60%PP-40%POE; 50%PP-50%POE; 40%PP-60%POE, and 20%PP-80%POE.

To test the mechanical properties and the mechanochromy phenoma link to the strain, different sensors were created. Specimens were cuted in 500 μm-thick plates made of the granules using a heated press. The parameters used were: pressure 1.25 bar, temperature 200∘C for two minutes, followed by rapid cooling. BBS additive were included in four different concentrations (0.2%, 0.5%, 0.7%, and 1% BBS by mass) during the pellet manufacturing process. Next, samples were cuted from these plates with a die in the shape of a standardized type 5A tensile test specimen per ISO527-2: 2012. Five tensile tests were performed by polymer types and BBS concentration. These tests were coupled with an optical test rig specifically developed at ICA laboratory for mechanochromy characterization. The optical bench consists of six LEDs and optical fibers that transmit light spectrum to a spectrometer during the test. The spectra are recorded in real-time using a trigger and in-house Python code. The aim was to deform the sensor by up to 50% at a strain rate of 5mm/min and record the light spectrum during the test.

The recorded spectra revealed three peaks at wavelengths characteristic of BBS: 430 nm, 460 nm, and 495 nm. The first is associated with the presence of monomers (blue). The second is linked to the chemical composition of BBS. The last gives information on the presence of excimers (green). Analysis of the spectra focuses solely on the evolution of the intensity ratio between excimer and monomer.

Results show mechanochromy phenomena in all types of polymer when BBS concentration is higher than 0.7%. The sensor changes color from green to blue in UV excitation. The optimum dosage to be used to detect the phenomenon is 1% BBS with an associated strain rate of 20%. Only POE was not suited to our need to measure strain rates in the 20-30% range. Mix polymer is needed to answer our needs. The

60%PP-40%POE mixture is the better compromise between mechanical properties and mechanochromy phenomena. We have therefore obtained convincing results from the use of mechanochromics to measure high strains.
In conclusion, these initial tests are encouraging, as they enable us to imagine the possibility of creating polymer mixtures capable of measuring specific bound values with accuracy. The sensor's properties make it be able to measuring high strain on all types of textile.This sensor could also be easily positioned on medical textiles for movement studies or textile orthesis tightening tests. We can also imagine sensors with several bounds. The use of elastomers could also make it possible to create reversible sensors. This work opens the door to new ideas.

Failure of Network Materials: from Stochastic Damage to Fracture

Picu Catalin (1)

1 - Rensselaer Polytechnic Institute (United States)

Speaker: Picu Catalin. **Monday**. Start time: **13:40**. Room: Rhône 1 LVL1. Link to abstract.

Many materials have a stochastic network of fibers as their main structural component and are referred to collectively as 'network materials.' This includes all biological connective tissue, the extracellular matrix, the cytoskeleton, paper and cellulose networks, nonwoven textiles and various molecular networks. Failure is critical in many applications involving such materials. However, interpreting and quantifying failure is less straightforward than in continua due to the discrete nature of the structure, its intrinsic stochasticity and the coupling of length scales of the fracture process with that of the network. This talk reviews results related to this topic including the relationship between strength and toughness and network parameters, the effect of preferential fiber alignment on stiffness, strength and toughness, the competition between diffuse damage and localized, fracture-like damage. Non-dimensional structural parameters are used to distinguish between types of behavior, leading to a classification of network materials in view of their failure characteristics.

Mechanics of Damage Propagation in Thermally Bonded Non-Wovens

Sen Shashwati (1), Deb Arghya (1)

1 - Indian Institute of Technology Kharagpur (India)

Speaker: Sen Shashwati. **Monday**. Start time: **14:00**. Room: Rhône 1 LVL1. Link to abstract.

Non-woven fabrics find applications in diverse fields such as geotechnical engineering, biomedical engineering, naval and aerospace industries. In this work, we study the dependence of damage initiation and propagation on the bond geometry in a non-woven fabric. In thermally bonded non-wovens, the cross-link/ bond point is artificially introduced by applying heat to the fibres at discrete positions in the random fibre networks. Fibres melt locally, connect and congeal to form cross-links. Therefore, non-wovens with a high network density contain stiff bonded domains that restrict fibre rotations while non-wovens with low network densities result in point cross-links that allow fibres a certain degree of rotational flexibility. The geometry and strength of the bond point plays a crucial role in determining the extent of fibre reorientation and recruitment occurring in the network following damage initiation. Fibres tend to rotate and realign along the direction of the applied tension in order to compensate for the damaged fibres. We aim to highlight the mechanisms by which fibre damage accumulates and propagates in non-wovens with different fibre densities and bonding patterns.

To this end, we introduce **cross-link fraction**, a parameter which is given by the area covered by the cross-link/bond points per unit area of the fabric (assuming that the fabric thickness equals the link thickness). The *cross-link fraction* is proportional to the network density and the area of heat application to achieve the bonding. We consider a stochastic model based on this parameter and study the mechanics of fibre reorientations due to damage of the material.

For our study, we have taken two polypropylene based commercially available non-woven fabrics, one with a high network density and the other with a low network density for validating the developed model. The non-woven fabric structure observed under a microscope was digitized to obtain fibre connectivity and the bond geometries. The constitutive behaviour of a single polypropylene fibre was adopted from the literature. A finite element model of the non-woven is then constructed with fibres modelled as trusses and the cross-links modelled as two-dimensional plane stress elements. The computational model is validated with uniaxial tensile tests upto failure conducted on both fabrics and their responses are compared. The computational model is then employed for a stochastic analysis of the effect of cross-link fraction on damage propagation in non-woven fabrics with varying network densities.

Tunable mechanics of bioinspired adaptive fibrillar materials with transient crosslinking and entanglement

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Speaker: Pensalfini Marco. **Monday**. Start time: **14:20**. Room: Rhône 1 LVL1. Link to abstract.

Animal cells and tissues adapt their mechanical properties by combining cytoskeletal networks with widely different characteristics. Short, crosslinked actin filaments can turn over rapidly and develop active tension, controlling cell mechanics at moderate strains, whereas long, physically entangled intermediate filaments (IFs), which lack motors or long-lived crosslinks, control the large strain behavior (1). Intriguingly, double-network microstructures have also been key to enable realization of hydrogels with remarkable mechanical properties (3).
We have recently shown that entanglement-mediated self-organization provides corralled tangles inspired by epithelial IF networks with extremely non-affine and non-linear mechanics (2). However, in actual cells, the reorganization of IFs is hindered by interactions with the actin cytoskeleton or the nucleus. As a result, depending on the inter-network interactions and their time scale, cells can adapt their emergent mechanics by switching between affinity – mediated by crosslinking – and extreme non-affinity/non-linearity – mediated by entanglement. In this talk, we will discuss the mechanics of epithelial cells under stretch in terms of minimal models of interacting cellular components, identifying the building principles of such living materials and anticipating their translation into artificial adaptive materials.

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Mechanical behaviour of a model random fiber network under harmonic small strain

Markey Grégoire (1) (2) (3), Barthel Etienne (4), Picu Catalin (5)

1 - Saint-Gobain Recherche (France), 2 - Sciences et Ingénierie de la Matière Molle (UMR 7615) (France), 3 - Roberval (France), 4 - Sciences et Ingénierie de la Matière Molle (UMR 7615) (France), 5 - Rensselaer Polytechnic Institute (United States)

Speaker: Markey Grégoire or Barthel Etienne. **Monday**. Start time: **14:40**. Room: Rhône 1 LVL1. Link to abstract.

Fibrous materials, such as mineral wool, are widely used for acoustic insulation in various construction applications, including partitions, ceilings, and more. Mineral wool consists of a random network of glass fibers that are partially bound by polymeric bonds. However, the relationship between its microstructure and its acoustic behavior remains poorly understood. Historically, studies of macroscopic acoustic parameters have assumed that the fiber network behaves as a rigid skeleton. This assumption, though convenient, proves inadequate for modeling applications like floating floors or ceilings, where the displacement of the material's structure plays a significant role. Consequently, the primary objective of this research is to investigate the dynamic behavior of mineral wool and establish connections between its microstructure and its macroscopic mechanical properties.
To achieve this, a series of 54 model specimens were created to systematically examine how various microstructural parameters influence the material's behavior. Macroscopic measurements, focusing on quasi-static quantities such as stiffness and loss factor under small strain conditions, were conducted. These measurements revealed that certain microstructural characteristics significantly impact the dynamic performance of the material. Building on these observations, a simplified analytical model was developed based on existing research. This model successfully replicated the trends observed during the measurements and identified the predominant mechanisms of energy dissipation in the material.

However, the analytical model demonstrated limitations, particularly for specimens with a higher volume fraction of polymer binder. To better understand this discrepancy, confocal microscopy was employed to examine the material's microstructure. The images revealed that the polymer binder is distributed very irregularly throughout the material. Moreover, the structural complexity of the material was found to be far greater than initially assumed. Additional mesoscopic observations and preliminary experiments highlighted a critical property of the material: it exhibits significant anisotropy, even at small scales. Specifically, the compressive stiffness across the material's thickness is relatively low, while distinct fiber sheets are observed in the transverse direction. This anisotropic structure raises important questions about its influence on the material's overall behavior, particularly in light of the experimental findings, and these considerations are explored in depth.
Finally, the study outlines several promising avenues for further research, which build on the insights gained from this work.

Accurate frictional contact algorithms for the numerical exploration of the mechanics of fibrous assemblies

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1 - Inria Grenoble Rhône-Alpes, INRIA Greoble-Rhône Alpes, Univ. Grenoble-Alpes, Laboratoire Jean Kuntzman, 2 - Department of Mechanical Engineering, Keio University, Yokohama, Japan

Speaker: Hohnadel Emile. **Monday**. Start time: **15:00**. Room: Rhône 1 LVL1. Link to abstract.

The goal of this work is to explore novel algorithms to enhance the predictability of fibre assembly simulators, without sacrificing the complexity of the target scenarios. Our work relies on the super-helix curvature-based discrete model for Kirchhoff elastic rods (1), coupled with the non-smooth so-bogus (2) solver for frictional contact resolution. While previously validated at the geometrical level in both 2D and 3D configurations (3), the contact forces produced by the simulations can exhibit spurious jumps, inconsistent with smoothly sliding configurations. Starting from a detailed analysis of a simulation of the three point bending test, we show that these jumps are not specific to our model, but result from the use of low order contact detection methods. We propose new algorithms to achieve efficient and accurate high-order contact detection (4), thereby retrieving artefact-free forces, as expected from our high-order discretisation.

In the 2D case, an analytic solution exists for our specific discretisation and is simple to implement in our current framework. There is however no general solution in 3D, where the problem becomes non convex. Instead we propose a branch-and-bound approach to find pairs of closest points between two curves. Our algorithm applies to a wider range of curves than the analytic approach used in 2D. The only requirement is to have a bound on the norm of the second derivative of the curve. Our method proves on par with low order schemes in terms of computational cost, while possessing much better scaling in terms of accuracy.

As an application in the 2D case, we investigate the mechanical response of a random stack of bidimensional flexible open rings subject to compression cycles (5). Our approach is first validated against theoretical predictions for the snap-fit of a single ring onto a cylinder, which also serves as a calibration protocol to determine the physical parameters. We then carefully compare simulations and experiments of random assemblies of 30 rings under compression-decompression cycles, and demonstrate an excellent agreement between computed and measured forces. This allows us to rely on the numerical models to further investigate the role of the friction and the geometry of the rings on the overall behaviour of the material.

The 3D case proves richer and more complex. Our preliminary results show the wide impact the spurious jumps have on the overall force on the scenario of combing hair of various natural curvatures.

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Basket Weaving Provides Remarkable Stiffness and Resilience for Functional Structures

Tu Guowei (wayne) (1), Filipov Evgueni (1)

1 - University of Michigan [Ann Arbor] (United States)

Speaker: Filipov Evgueni. **Monday**. Start time: **15:20**. Room: Rhône 1 LVL1. Link to abstract.

The craft of basket weaving has been used since antiquity to interweave thin fibers into sophisticated 3D geometries that retain their shape to serve as storage containers or other functional structures. In this talk, we explore the unusually high stiffness and resilience that results from planar-weaving of ribbons into corner topologies. Through experiments and numerical simulations we show that woven structures have a stiffness that can be comparable to a continuous non-woven counterpart made with the same amount of material. The woven baskets have a high stiffness because axial compressive loads are carried with all ribbons engaged similar to a continuous sheet. However, under large loads with global buckling, crushing, and wrinkling deformations, the woven baskets are much more resilient than their continuous counterparts. While the continuous sheets experience localized stress concentrations with plastic deformations, woven composites remain elastic and fully recover to their initial configurations. This high resilience is possible because the discontinuities between ribbons allow for segmented elastic buckling which deconcentrates stresses. We generalize the planar-woven basket corners to a family of corner geometries and assemble these to create functional robotic systems and stiffness-tailored metamaterials. The proposed concepts in basket weaving can be applied to create packaging, consumer products, furniture, automobile components, metamaterials, and other structural systems, where high stiffness and resilience to damage are desired.

Full sample fiber network models of nonwoven textiles

Tkachuk Anton (1), Tkachuk Mykola (1) (2)

1 - Karlstad University [Sweden] (Sweden), 2 - National Technical University "Kharkiv Polytechnic Institute" (Ukraine)

Speaker: Tkachuk Anton. **Monday**. Start time: **16:00**. Room: Rhône 1 LVL1. Link to abstract.

Network models are frequently used for the computational analysis of various fibrous materials. The resolution of single fibers is often viewed as a descend to the microscopic level opposed to the macroscopic level of deformations of the apparently continuous material. This two-level approach gives the ground to the constitutive modeling of the fibrous material via a representative volume element (RVE) that resolves the discrete fiber network microstructure. Uniform strains are imposed on the RVE through some boundary conditions and the averaged stresses are returned as the superposition of the equilibrium forces in the fibers (2). However, the assumed scale separation does not hold for many fibrous materials. Nonwoven textiles are made of long fibers that match the dimensions of the macroscopic sample. Thus a single microscopic cell can not properly represent the inhomogeneous deformations within the materials and the response of the fiber network beyond the simulation window no matter how large is the size.
As an alternative, one can model the entire random fiber network within the macroscopic sample. This requires an effective numerical method for the equilibrium of the system. We have recently developed a new fiber network model describing irreversible deformations of needlepunched nonwoven materials (3). Fibers are considered to be inextensible cables that can only be loaded in tension. They respond to the applied loads by relative sliding in the entanglements introduced by the needle-punching process. The frictional forces in the knots need to be overcome in order to initiate this mechanism of deformation. The rate-independent loading of such network structure is constituted within the theory of standard dissipative systems. A minimum principle for incremental potential is formulated with respect to the displacement-based variables: nodal coordinates, segment end-to-end vectors, segment lengths and incremental fiber slidings. It takes the form of second-order cone programming (SOCP) similarly to the case of elastic cable networks (4). A pure complementary energy principle is derived as the dual formulation in terms of stress-like variables: nodal reactions, fiber force vectors, axial forces and friction forces. Both SOCP problems can be solved numerically by interior-point methods.

This makes feasible the simulation of the entire domain of the macroscopic sample with hundreds of thousands of segments and sliding systems. We show that the model captures qualitatively the response of the needle-punched materials (5). The analysis relates the internal structure of the fiber network: the orientation of fibers, their curl as well as the pattern of the bonding sites introduced through the needlepunching to the strength and toughness of this type of materials.

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Local mechanical characterization of soft fibrous materials

Cameron Paula (1), Guan Haishuo (2), Junker Havar (1), Paccagnan Giacomo (2), Hopf Raoul (1), Zambelli Tomaso (2), Mazza Edoardo (1) (3)

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Speaker: Cameron Paula. **Monday**. Start time: **16:20**. Room: Rhône 1 LVL1. Link to abstract.

Soft collagenous tissues are highly heterogeneous at cell length scale. Local deformation mechanisms determine their mechanical properties and influence the behaviour of resident cells. Therefore, improved understanding of tissue biomechanics and mechanobiology requires mechanical characterization at the micrometer scale. Collagen is the most abundant protein found in the human body and represents the mechanically dominant components of soft tissues, such as skin. Better understanding the mechanical behaviour of collagen fibers and their interplay with the surrounding matrix would provide insights into various diseases related to collagen. In particular, it would allow us to better characterize the conditions of the extracellular matrix leading to the onset and progression of fibrotic diseases.
Current assessment of local mechanics of soft fibrous materials is based on micro- or nanoindentation. Atomic force microscopy (AFM) is a form of scanning probe microscopy that has found many applications in the mechanobiology field since its invention in the late 1980's. This tool, among its many functionalities, permits measurements of mechanical properties of biological tissues at the length scale of cells. However, depending on the tissue of interest, AFM indentation may not be sufficient for tissue characterization. In our previous study, two collagen hydrogels with different concentrations of collagen were measured with AFM-based nanoindentation (1). The results demonstrated that despite a 14-fold increase in collagen concentration, the apparent Young's modulus of the two collagen hydrogels were not significantly different (1). On the other hand, cells cultured within the two hydrogels behaved very differently in terms of their proliferative state (1). These results can be rationalized using a model which represents the collagen hydrogels in two parts: a discrete network model to exhibit the properties of the collagen fibers and a continuum solid to represent the matrix part of the hydrogel. The model confirms that the collagen fiber network is not activated by AFM-based nanoindentation (1).

In this contribution, we will present a novel approach for characterization of the local properties of soft fibrous materials. Our aim is to develop an experimental protocol which could activate fibers on this length scale. It is commonly understood that collagen fibers behave differently in compression and in tension and this led to the idea of comparing the mechanical response of collagen hydrogels when subjecting them to nanoindentation versus a nanoscale pulling force. Fluid force microscopy (FluidFM) has emerged as an advancement to AFM technology that incorporates nanofluidic channels into the AFM probes thereby allowing the suction or dispensation of fluids (2).

In our experiments, FluidFM-based suction is applied to collagen hydrogels of different compositions, and their response is compared against their nanoindentation behaviour. Using pulling forces instead of indentation was shown to distinguish between the two collagen hydrogels with different collagen concentrations. This approach provides insights into how collagen fibers respond to forces within their tissues and how these forces are transmitted and shared with other material components. Alongside this experimental work, we aim to rationalize these observations through computational modelling. A biphasic model represents the matrix part of the hydrogels, with a solid and liquid phase, and is combined with a discrete network model representation of the collagen fiber network. The improved protocols and models will be applied to skin samples, with the aim to contribute to the development of mechano-therapeutics for fibrotic diseases, such as systemic sclerosis, impaired wound healing, hypertrophic scarring or for the optimization of skin tissue-engineering.

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Development of a Biaxial Loading Device for Advanced Fibrous Materials (Identifying the Thermomechanical Behavior Laws of Viscoelastic-Plastic Materials with Complex Structures)

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Speaker: Hussein Mahmoud. **Monday**. Start time: **16:40**. Room: Rhône 1 LVL1. Link to abstract.

This study introduces the development of an advanced biaxial testing device designed to characterize and model the thermomechanical behavior of complex fibrous materials, specifically those exhibiting viscoelastic-plastic properties under dynamic and cyclic loading. Given the expanding application of fiber-based composites across industries like aerospace, automotive, defense, and energy, understanding their fatigue and hysteretic behaviors is essential for predicting performance and longevity. The designed testing system aims to address this need by providing a controlled, high-precision environment to simulate and analyze the behavior of fibrous materials under biaxial stress conditions, an approach that replicates real-world operational scenarios more accurately than traditional uniaxial tests.
The core of the system is a biaxial thermomechanical testing setup that combines dual-axis loading with high-frequency modulation. Each axis operates independently and can apply up to 4000 daN in modulation at frequencies of up to 20 Hz, supporting high-stress applications. The testing device is equipped with an array of sensors, including four strain gauges per axis, allowing for continuous monitoring of the mechanical response of the sample. This system generates up to 36 parameters per cycle, enabling detailed real-time data collection on stress, strain, and force distribution. Such precise measurement is critical in capturing the nonlinear and anisotropic responses of fibrous structures and in determining their mechanical and thermal behavior under cyclic loads.

In addition to mechanical measurements, the device integrates a synchronized 2D optical correlation system and an infrared (IR) thermography setup to capture both deformation fields and thermal variations. The 2D optical correlation system provides high-resolution surface displacement data, enabling tracking of in-plane and out-of-plane deformations across the sample. IR thermography captures temperature changes induced by stress variations, leveraging the thermomechanical coupling principle to map local heat generation-a key indicator of material fatigue and microstructural transformation under stress. By correlating thermal and deformation data, this setup allows for a comprehensive understanding of the spatial and temporal evolution of mechanical behavior across fibrous structures.
This research also develops a computational framework to analyze and interpret the acquired data. The data are synthesized to establish predictive behavior models for these materials, focusing on their viscoelastic and viscoelastic responses. This modeling supports the identification of fatigue parameters and mechanical degradation pathways, crucial for estimating service life in applications such as hydrogen transport systems, where weight optimization and durability are critical.

A multi-scale modelling-experimental framework for predicting the chemo-mechanical degradation of paper

Parsa Sadr Amir Maraghechi Siavash Suiker Akke Bosco Emanuela (1)

1 - Eindhoven University of Technology, Department of the Built Environment, Eindhoven (Netherlands)

Speaker: Bosco Emanuela. **Monday**. Start time: **17:00**. Room: Rhône 1 LVL1. Link to abstract.

This contribution presents a multi-scale modelling-experimental framework for predicting the chemo-mechanical degradation of paper (1). Paper is modelled as a two-dimensional periodic repetition of a fibrous network unit cell, where the fibres are characterized by a moisture-dependent chemo-hygro-elastic constitutive behaviour. Paper degradation occurs primarily due to the hydrolysis of cellulose, which causes a reduction of the degree of polymerization and a consequent decrease of the effective mechanical properties. This may ultimately lead to embrittlement and loss of material integrity. The proposed model accounts for the interplay between the acidity of the paper, the ambient environmental conditions, and degradation behaviour by first determining the coupled time evolution of the degree of polymerization, acidity, and moisture content. A time-dependent evolution law for the tensile strength of the paper depending on these parameters is proposed and calibrated from dedicated micro-tensile experiments (2,3). A change in moisture content induces internal stresses in the fibrous network, potentially leading to brittle damage once the fibre tensile strength is reached. The effective hygro-mechanical properties of the degrading fibrous network are calculated as a function of time using asymptotic homogenization. Numerical simulations highlight the impact of the time-evolving moisture content, acidity of the paper, and microstructural features on the degradation process. The results of this work may be valuable for conservators of cultural heritage institutions to determine optimal environmental conditions to limit the time-dependent degradation of historical paper artefacts.

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An elasto-plastic material model for paper and paperboard at finite deformations.

Ochoa Ontiveros Lilian Aurora (1), Kopic-osmanovic Nadir (2), Prume Erik (3), Felder Sebastian (4), Kloppenburg Greta (1), Simon Jaan-willem (2)

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Speaker: Ochoa Ontiveros Lilian Aurora. **Monday**. Start time: **17:20**. Room: Rhône 1 LVL1. Link to abstract.

Paper and paperboard are materials commonly used in the packing industry. Due to their high sustainable nature, they are preferred to less eco-friendly options. However, their complex behavior has postponed their wider usage. In order to achieve a clearer insight on the material's performance, it is necessary to address phenomena like the anisotropic elasto-plasticity, temperature- and moisture sensitivity, damage occurrence and wrinkling, to mention some.
During the manufacturing process, the paper and paperboard endure considerable elasto-plastic deformations. The conventional yield criteria by Hill, does not capture in an adequate way the material response. The evolution of plasticity leads to the alteration of elastic properties and in conjunction with the anisotropic plastic hardening, the material's behavior advances in complexity.

Therefore, a novel material model was developed. The fundamental framework was derived consistent with the thermodynamic principles ensuring its applicability to finite deformations. The anisotropy of the material was introduced via the concept of structural tensors. Accounting for the densification effect, the elastic domain was made dependent on the plastic deformation via the strain energy function formulation. Additionally, a distinguished yield criterion was modified to be in concordance with the principles of finite-elastoplasticity. Furthermore, inconsistencies regarding the initial yield stresses and plastic strain ratios were considered. Lastly, a set of internal plastic hardening variables were defined to consider the present anisotropic plastic hardening.
A comparison between the presented formulation and Hill's yield criterion is demonstrated for the creasing and folding examples.

Fracture mechanics of paper using cellulose from cow dung

Harrison Thomas (1) (2), Thakur Vijay Kumar (1), Alam Parvez (2)

1 - Scotlandś Rural College (United Kingdom), 2 - School of Engineering [Edinburgh] (United Kingdom)

Speaker: Harrison Thomas. **Monday**. Start time: **17:40**. Room: Rhône 1 LVL1. Link to abstract.

Waste streams provide an attractive alternative to virgin sources of biomass in the pulp and paper industry due to their lower economic and environmental costs. In most of Europe, livestock manure has been largely overlooked as a potential feedstock on an industrial scale. Furthermore, engaging with green technologies may enable farmers to offset their carbon footprint. A process was developed to extract purified cellulose fibres from bovine faecal matter. A method for producing (hand-crafted) paper was developed and the potential for supplementing standard wood-based pulp with the manure-derived cellulose pulps was explored. Various mechanical test were used to assess the mechanical suitability at supplementation ratios of 0-100%, including tear resistance, tensile strength and creep recovery. Tensor mechanics were used to mathematically approximate uniaxial tension of a strain-hardening, elastic material. This model was found to fit the data well, meaning stress-strain responses could be reliably generated from a few key empirical parameters. Significant differences were observed between wood-based and manure-derived pulps in terms of the fracture mechanics. The data suggests that manure-derived cellulose may be suitable as a partial replacement for traditional wood-based pulps.

Dynamic Behavior of Parachute Canopy Fabrics and Seams

Amirkhizi Alireza (1), Seyhani Fatemeh (1), Drane Patrick (1), Sherwood James (1), Witkowski Al (2)

1 - University of Massachusetts [Lowell] (United States), 2 - Katabasis Aerospace (United States)

Speaker: Amirkhizi Alireza. Keynote. **Tuesday**. Start time: **10:00**. Room: Rhône 1 LVL1. Link to abstract.

Parachute canopy fabrics and seams are designed and qualified under loading conditions that are far from what they undergo during the deployment. The current design paradigm for parachutes generally rely only on ultimate strength measured in uniaxial stress conditions, and ignore anisotropy, nonlinearity, temperature sensitivity, stress bi-axiality, and visco-plastic behavior of fabrics. Furthermore, the effect of seams and other stress concentrators are usually only considered through knock down factors not thoroughly studied. While a parachute failure is critical and should be avoided at all costs, it is also not desirable to use high safety factors given the significant cost of adding unnecessary mass in aerospace systems. With the significant expansion of the capabilities of fluid-structure interaction (FSI), development of accurate constitutive models of textiles under deployment conditions has become increasingly necessary. In this work two methods of dynamic extension of fabrics at intermediate rates, comparable with those occurring during deployment, are presented. A drop tower apparatus and a modified gas-gun driven direct impact setup were employed to simulate the rapid deployment of a parachute, closely mimicking the high-amplitude impulse forces encountered during actual parachute deployment. These tests provide critical insights into the fabric's tensile properties. Additionally, large-scale biaxial testing was employed to simulate realistic loading conditions on fabrics by pulling them along the warp and weft directions at the same time. The biaxial machine enables testing of larger fabric samples, thereby reducing boundary effects and providing more accurate data compared to previous work focusing on small swatch-scale biaxial tests. Both biaxial and fast-rate tests aim to emulate the conditions the fabric experiences during deployment. The combined results from these tests provide a better understanding of parachute fabric behavior, contributing to the development of more reliable and safer parachutes. Finally, seam tests were conducted to evaluate the integrity and performance of the French fell seam method, commonly used to connect gores in parachutes. It indicated significant additional compliances normal to the seam, but minimal loss of strength, at least in quasi-static testing. Dynamic testing is planned and expected to also include the localization of strain due to additional mass. This study underscores the necessity of multi-faceted testing approaches to ensure the optimal performance and safety of parachute fabrics in diverse environmental conditions.

Bias-extension test of woven fabrics: an advanced analysis through X-ray microtomography and Digital Volume Correlation

Stamati Olga (1), Orgéas Laurent (2), Rolland Du Roscoat Sabine (3), Lhuissier Pierre (4), Dumont Pierre (5), Martoïa Florian (6)

1 - 3SR laboratory (France), 2 - 3SR laboratory (France), 3 - 3SR laboratory (France), 4 - SIMAP (France), 5 - LaMCoS (France), 6 - LaMCoS (France)

Speaker: Dumont Pierre. **Tuesday**. Start time: **10:40**. Room: Rhône 1 LVL1. Link to abstract.

Thanks to both their good specific mechanical properties and deformability, woven fabrics are widely used in fiber-reinforced composites and have attracted increasing attention in several industrial domains, including aeronautics, automotive, and sport. The processing routes of woven fabric-reinforced composites usually involve a draping stage during which woven fabrics are subjected to severe deformation mechanisms. Therefore, understanding the deformation of woven fabrics has been the subject of numerous studies. Within this context, the bias-extension test has been commonly used to characterize the mechanical response of woven fabrics (1), and more particularly their in-plane shear deformation response which is the predominant deformation mode. Usually, the in-plane shear response of fabrics is quantified in the central zone of stretched rectangular samples. However, because of their multiscale architectures, woven fabrics also exhibit complex macroscale deformation phenomena with shear strain localization with finite band-width between the central zones and its adjacent regions. Modelling these effects has led to the development of enriched theories such as second gradients theories (2). In addition, other important deformation mechanisms that occur during bias-extension tests, such as in-plane surface changes and out-of-plane deformations have been rarely studied.
Therefore, to better analyze the in-plane and out-of-plane deformation mechanisms of woven fabrics, a specially-designed setup was installed in a laboratory X-ray microtomograph (3) to perform a bias extension test on a twill sample made of basalt yarns. The obtained time series of 3D images were analyzed with a dedicated Digital Volume Correlation (DVC) procedure, enabling 3D kinematic fields to be obtained (4-5), as well as the measurements of relevant strain invariants (6) during the test. The results obtained in this study highlighted that the studied twill exhibited an important 3D consolidation that involved a coupling between a significant out-of-plane auxetic deformation which was compensated by a higher in-plane surface densification. In addition, smooth transition zones were observed between the central sheared zone and its adjacent regions. The width of the latter extended to 2-3 period lengths of the twill, highlighting the role of its mesostructure. By extracting some interesting gradients of the strain invariants from the 3D strain fields, this study also demonstrated that the combination of X-ray tomography and DVC could be an interesting experimental investigation method to build and validate macroscopic models with enriched kinematic fields.

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Multiscale study of ballistic fabric mechanical properties over a wide strain rate range

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Speaker: Begaud Marie-Amélie. **Tuesday**. Start time: **11:00**. Room: Rhône 1 LVL1. Link to abstract.

Due to their high impact resistance, aramid fibres have been widely used to withstand high-velocity impacts in the form of flexible, lightweight yet hard-to-break garments. However, proper validation of such protection still involves expensive experimental ballistic testing. Therefore, numerical simulations are commonly used to reduce costly processes and to provide insightful information during impact. Numerical models require the introduction of material data relevant to the ballistic application. It has been widely demonstrated that the coefficient of friction, Young's modulus, failure stress and strain have an effect on ballistic performance. However, these observations haven't yet been coupled and compared on the same material with dynamic loading tests, weaving effect on weft and warp yarns, to assess the extent to which key parameters are critical for protection against projectile impact.
Moreover, proper validation of such protections still consists in expensive experimental ballistic tests. Therefore, in order to reduce costly processes and to have some insightful information during impact, numerical simulations are commonly used. This work is focused on a single fabric layer and examines the mechanical behaviour of two woven fabrics, a plain weave and a twill 2x2, respectively made with 215 and 1264 dtex of Kevlar multifilament yarns and with 13.4 and 6.7 weft and warp yarns/cm respectively (Figure 1). For this purpose, friction and tensile tests are conducted at different scales: fibre and yarn, for tensile behaviour investigation quasi-static tests are carried out by means of a universal press, intermediate regime of strain velocity is achieved via a drop tower and dynamic range is covered by split Hopkinson tensile bars. In addition, inter-fibres and inter-yarns friction coefficient are measured. Low velocity impacts are performed as preliminary impact tests to assess the energy absorbed by the two woven structures. Two kinds of indenters were used: a hemispheric and FSP so as to vary the stress state. The aim of those experiments is to understand the influence of the weave architecture on stress distribution and to identify the damage mechanisms induced by the round and sharp edge nose projectiles. The post-mortem specimens are observed to investigate the different profiles of yarn failure.
From this very rich experimental data set, an Abaqus Explicit numerical model is developed. An analysis of the influence of the woven fabric structure, strain rates and stress states on the impact performances of the fabrics is proposed either from an experimental and numerical point of view

TEXTILE-ELASTOMER COMPOSITES: IN-DEPTH COMPARISON OF EXPERIMENTAL RESULTS AND FIBER SCALE SIMULATIONS

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Speaker: Auteri Gianluca. **Tuesday**. Start time: **11:20**. Room: Rhône 1 LVL1. Link to abstract.

Textile cords are widely used to reinforce elastomers. Their dimension and the complexity of their architecture, though, often limit to the macro-scale the information that can be extracted experimentally. Finite element analysis allows access to filament-scale quantities, revealing the mechanisms behind the filament's response, deeply linked to the architecture, when the composite is loaded.
Textile cords are constituted by many filaments which are entangled in a hierarchical organization and subjected to large deformations. All these reasons call for dedicated algorithms for an efficient solving. In this work, the in-house code *Multifil* (1) is used. Each filament is modeled with a 1D kinematically enriched finite strain beam model, frictional-contact interactions are modeled with ad-hoc strategies for efficient contact detections and an implicit solver is used to solve the global non-linear problem, under quasi-static assumptions.

The successive twistings of the cord are closely reproduced in numerical simulation, this is crucial to represent the complexity of the entanglement between filaments. The main steps of the numerical manufacturing are: *a)* Single ply twisting, fundamental to reproduce the migration phenomena (2) *b)* Two-ply cord twisting, to create a balanced cord *c)* Glueing process, to model the glue network on the outer contour of the cord *d)* Calendaring, coupling of the filaments with the composite matrix.

Once the composite sample has been numerically generated, it can be subjected to various loads to analyze the filament response. Particular attention is given to the dialogue between experiments and simulations. The latter being able to reproduce experimental results for standard testing (traction until rupture, compression, flexion response, etc.) and for peculiar phenomena (e.g. buckling instabilities), only observable at the micro-scale using x-ray tomography.

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Deformation mechanisms and spinning conditions controlling the mechanical response of spider silk fibers

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1 - Technion - Israel Institute of Technology [Haifa] (Israel), 2 - Department of Materials Science and Engineering, Technion - Israel Institute of Technology [Haifa] (Israel)

Speaker: Olivé Renata or Cohen Noy. **Tuesday**. Start time: **14:15**. Room: Rhône 1 LVL1. Link to abstract.

Spider silk is a fibrous protein material with a unique microstructure that leads to exceptional mechanical properties such as high stiffness and toughness. The behavior of the silk depends on the microstructure, which is determined through the spinning process (i.e. fibers can be naturally spun or forcibly silked). The microstructure can also be controlled via post-processing. Yet, the relations between the microstructure and the macroscopic response is not fully understood.
In this talk, we present an energy-based multi-scale model that sheds light on the influence of microstructure on the overall response. Specifically, the model accounts for the spinning conditions, the composition and alignment of the chains, and the density of intermolecular bonds. The model is validated through comparison to a wide range of experimental results.

Our findings provide a comprehensive framework that enables one to tailor the mechanical response of silk fibers and offers insights that can be used for the design of advanced bio-inspired materials with superior mechanical performance.

Olive, R.; Cohen, N. Deformation and failure mechanisms in spider silk fibers. *J. Mech. Phys. Solids* **2024**, *182*, 105480.
Olive, R; Cohen, N. Employing spinning conditions to control the mechanical response of spider silk fibers. **2024**, Under review.

Development of an Analytical Mechanical Model of Staple Fibre Yarns from fibre tensile and friction properties

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Speaker: Balestier Nathan. **Tuesday**. Start time: **14:35**. Room: Rhône 1 LVL1. Link to abstract.

Fiber-based materials are ubiquitous in both daily life and industry, appearing in applications such as clothing, insulation, civil engineering, and composite materials. The study and modeling of the mechanical behavior of yarns-structured assemblies of fibers or filaments-has been a foundational research area in the textile field since the pioneering work on staple fiber yarn by Gégauff in 1907 (1). Between 1940 and 1980, extensive theoretical research established a mathematical formalism and analytical models to describe structural characteristics that influence yarn behavior. Mechanical studies of staple fiber yarns provide insights into the deformation and rupture phenomena of yarns composed of synthetic or natural fibers, aiding in the determination of manufacturing process parameters. Several models exist to predict the rupture forces of yarns with high twist (2-3); however, the mechanical behavior of intermediate and low twist yarns is more complex, as it requires understanding the frictional interactions between fibers within a yarn. The proposed model addresses these interactions using the Euler-Eytelwein model, with lateral force transmission through the yarn based on Love's theory of elasticity for a rod bent into a helical form (4).
An experimental study is conducted on synthetic fibers and yarns, selected for their clean and uniform structure that aligns well with the model's geometrical assumptions-ideal for an initial experimental approach. Tensile properties are obtained by using the Automatic Single-Fibre Test System FAVIMAT+ to measure the linear density of individual aramid fibers and capture their complete stress-strain profiles during tensile testing. Friction characteristics are obtained from a specific method (5). Pertinent tensile and friction criteria are chosen supplying essential mechanical parameters for model input. Yarn samples are tested using an Instron tensile testing machine with specialized clamps to impose and measure specific twist levels, ensuring controlled torsional conditions throughout testing. Tensile tests on yarns across varying twist levels are conducted to facilitate direct comparison with the model, assessing its accuracy in predicting the mechanical response of the yarn under different torsion conditions. Following this initial study with synthetic fibers, future work will compare results with natural fibers, such as flax. Although the model may require adjustments to account for the variability of natural fiber properties, this step will enable a broader validation of the model across different fiber types.

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Exploring dry and lubricated sliding friction behaviour of carbon fibre tows: Discrete Element Method simulations and mixed lubrication model

Smerdova Olga (1), Brunetiere Noël (1)

1 - Institut Pprime (France)

Speaker: Smerdova Olga. **Tuesday**. Start time: **14:55**. Room: Rhône 1 LVL1. Link to abstract.

Understanding the sliding behaviour of fibrous materials presents a significant challenge that must be addressed to improve the manufacturing processes of fibrous composite materials and reduce defects in composite parts. In many processes, friction plays a crucial role: it can help keep fibres in place to prevent unwanted sliding, which may lead to the formation of matrix-rich zones in a composite. Conversely, friction can also promote sliding between tows, facilitating shear deformation of a fabric and helping to avoid out-of-plane defects in dry preforms. Moreover, the friction between fabric and tool is an inevitable aspect of all manufacturing processes. However, the sliding behaviour of fibres, tows and fabrics remains poorly understood due to the multiscale nature of these materials, which consist of numerous individual fibres with varying degrees of mobility.
This aim of our research is to contribute to the understanding of the sliding friction of fabrics through a detailed study of the sliding behaviour at a scale of a single tow in both dry and lubricated by liquid resin states. Two distinct approaches, both combining numerical models and experiments, have been employed in this work. A tow consisting of 12,000 carbon fibres (ref. T700SC-12k-60E) with a nominal width of approximately 10 mm and a fibre diameter of around 7 μm, was used for the sliding experiments. In all experiments, the tow was clamped at both ends and slid against a smooth glass plate in a direction transverse to the fibre orientation. To investigate lubrication, a liquid epoxy resin without hardener was introduced into the contact area between a tow wound onto an aluminium cylinder and the rotating glass disk. For the dry friction study, the glass plate was slid over the flat tow. The axial tension of the tow was controlled in both experiments by suspending weights.

To explain the results of the lubricated sliding experiment, a numerical lubrication model for a rough, tow-like elastic surface was developed (1). The model considers the tow as an elastic foundation under sliding with and without lubrication by a non-Newtonian liquid. The lubrication behaviour of this surface was investigated by varying the normal load and sliding speed. In the mixed lubrication regime, it was found that friction depends on the local arrangement of the fibers. This dependence disappears in the hydrodynamic regime; however, this regime is only achieved at high sliding speeds (several meters per second). Therefore, the mixed lubrication regime is the most probable scenario during common composite forming processes.

In the sliding friction experiments conducted on a dry flat tow, the friction force, displacement and transverse strain of the tow were continuously measured during sliding. Several repetitions of this experiment on different pieces of tow cut from the same spool revealed considerable variability in these three parameters. To understand the origins of this behaviour, a two-dimensional Discrete Element model representing the tow's cross-section was developed. The advantage of this method is that is allows for rapid numerical analysis of large movements involving a high number of particles (3,000 in our model), while considering frictional contact between all particles. The bending and torsional stiffness of the fibres were represented by linear and rotational springs attached to each fibre. The model was used to explore the effects of compression load, the number of fibres in a tow, and the local friction coefficients between the fibres and between the fibres and the glass plate. A simulation of repeated cyclic sliding was also performed to study the accommodation of sliding. This parametric study revealed the crucial significance of the bending and torsional stiffness of the fibres on the overall sliding behaviour of the tow. These parameters, in turn, depend on the axial tension in each fibre, which can vary among the thousands of fibres in a tow.

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Impact of fiber pre-opening and number of passes on the properties of recycled carbon fibers from carded webs

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1 - Génie des Matériaux Textiles - ULR 2461 (France)

Speaker: Ivars Jean. **Tuesday**. Start time: **15:15**. Room: Rhône 1 LVL1. Link to abstract.

The reuse of recycled carbon fibers (rCF) addresses environmental concerns in the composites industry by offering a sustainable alternative to virgin carbon fibers. Recycling and reusing carbon fibers reduces waste at the end of the life cycle of composite materials and decreases dependency on virgin raw materials. While recycling methods effectively recover carbon fibers from end-of-life composite products, these processes often yield shorter fibers, complicating their reintegration into high-performance applications. Challenges such as achieving fiber alignment and improving processability are further exacerbated by the brittle nature of rCF and the absence of sizing, which typically enhances fiber-matrix bonding and handling.

Carding, a technique traditionally used in the textile industry to disentangle and give continuity to short fibers, has shown promise in addressing these challenges for recycled carbon fibers. Previous studies conducted on laboratory-scale carding machines demonstrated that blending rCF with crimped thermoplastic fibers, such as polypropylene (PP), during carding reduces fiber breakage and does not degrade the mechanical properties of rCF. Statistical analysis of tensile data from carded webs also indicated an improvement in the uniformity of tensile modulus values with increasing amounts of crimped thermoplastic fibers.

In this study, the focus extends beyond blend ratios to investigate additional parameters of the carding process, such as the number of passes through the carding machine and the opening of the fibers. Tensile properties, including stress at break, modulus, and elongation at break, are evaluated to understand the influence of these parameters on the quality and mechanical performance of the fibers in the resulting carded webs. A statistical approach is employed in order to further understand the impact of those parameters, especially on the scattering in tensile data.

MS1.2 - Mechanics of composite materials

Organisers: Frédéric Laurin (ONERA) and François Guillet (CEA)

An Experimental Investigation on Flexural and Interlaminar Shear Behavior of Glass Fiber Reinforced Polymer Composites under Extreme Environments

Tudu Suplal (1), Ramachandran Velmurugan (1)

1 - Indian Institute of Technology Madras (India)

Speaker: Tudu Suplal or Ramachandran Velmurugan. **Monday**. Start time: **10:10**. Room: Rhône 3B LVL1. Link to abstract.

This paper studies the flexural and interlaminar shear properties of glass fibre-reinforced polymer (GFRP) composites under extreme environments. The aerospace industry utilizes polymer-based composites (GFRP, CFRP) abundantly in primary and secondary applications in various satellite and spacecraft structural designs for space exploration because of their attractive thermo-mechanical properties, high strength-to-weight ratio, and corrosion resistance. Commercial flight operates in the temperature range from +50◦C to -50◦C (1). The supersonic aircraft's Mach number is more than 2, and its skin temperature often increases by 120◦C.In this work, GFRP composites were fabricated by hand land-up method, and for the curing process, an Autoclave moulding machine was used with curing parameters of 80◦C for 30 mins and 6 bar pressure for 3 hours (2).GFRP composites have improved mechanical and thermal properties over other traditional materials (metals). Despite their advantages over conventional materials, composites are not entirely used in spacecraft and satellites because of limited knowledge of materials' behaviour under extreme temperatures. A three-point bending and short-beam shear test were done in UTM at temperatures ranging from -75◦C to 100◦C to determine the flexural strength and interlaminar shear strength, which are essential for proving their structural integrity in demanding applications. The findings showed significant effects of temperature on stiffness and strength. The flexural strength of GFRP at -50◦C increased by 41.8% and decreased by 80% at 100◦C when compared to room temperature (30◦C). Interlaminar shear strength of GFRP at -50◦C increased by 44% and decreased by 86% at 80◦C when compared to 30◦C. At ultra-low temperatures, polymer chains of matrix material (Epoxy resin) are more rigid, and the fibre-matrix interface gets a strong bond, which leads to increased stiffness and strength. In contrast, at higher temperatures beyond Tg, the epoxy resin softens, and the interfacial bond weakens, resulting in lower mechanical properties. Dynamic mechanical analysis (DMA) testing was done to determine the glass transition temperature(Tg), storage modulus (E'), loss modulus (E") and damping factor(tand), which are used to study the thermo-mechanical characterization of the materials (3). The Tg and E' values of GFRP were around 87◦C and 26.47 GPa, respectively. Scanning Electron Microscope (SEM) images were used to study the fractography behaviour of damaged specimens. At -50◦C, delamination, matrix cracks, fibre/matrix rupture and fracture were shown, and at elevated temperatures, delamination occurred in the SEM images.

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Analysis of the compression process of an angle made of flax fibers in a PLA resin matrix

Gawryluk Jarosław (1), Santiuste Carlos (2), Wawerski Bartłomiej Wiśnios Dominika

1 - Politechnika Lubelska [Polska] = Lublin University of Technology [Poland] (Poland), 2 - Université Carlos III de Madrid (Avenida de la Universidad, 30 Spain)

Speaker: Gawryluk Jarosław. **Monday**. Start time: **10:30**. Room: Rhône 3B LVL1. Link to abstract.

The ongoing development of technology worldwide is creating increasing opportunities for engineers to design structures that are both durable and environmentally safe. The significance of not only the material's strength but also its origin, and the possibilities for recycling or disposal, is becoming more prominent. An informed society pays more attention to what it purchases and whether it has the option of choosing elements or structures that are more environmentally friendly. Consequently, materials that can be widely used to produce strong and durable components while maintaining a lower carbon footprint compared to conventional materials are the subject of intensive research worldwide.

In the case of fiber-reinforced composites, natural materials that can replace synthetic fibers (e.g., carbon and glass) include flax, hemp, sisal, and jute. The production of one kilogram of flax fiber consumes 4 MJ (1.1 kWh) of electrical energy, which is 99% less than that of carbon fiber (900 MJ – 250 kWh). Furthermore, the production of flax fibers results in lower CO2 emissions into the atmosphere (1.65 kg per 1 kg of fiber) compared to carbon fiber (24 kg per 1 kg of fiber), representing a 93% improvement in air quality.

Given these benefits of using flax, it was decided to conduct research on the failure of a simple structural element (an angle) due to axial compression. Studies were carried out using both numerical and experimental methods. In the experimental study, failure occurred for five samples made from natural composite materials (flax fibers with a polylactic acid (PLA) matrix). Compression tests were conducted on a testing machine to determine the performance characteristics of the laminates. A non-contact measurement system, Aramis, was used to monitor the geometry. Additionally, an acoustic emission system was implemented to register sound signals generated during the tests, which allowed for the identification of when fiber or matrix damage occurred.

A numerical analysis was performed on an ideal model rounded to correspond with the real object. The Abaqus software was used, employing the finite element method (FEM). The critical force for the first mode of buckling was determined. An initiation damage analysis was conducted using maximum stress criteria, Tsai-Wu, Tsai-Hill, and Azzi-Tsai-Hill criteria. The Hashin criteria were used to determine the mechanism leading to material failure. A stability loss analysis was performed based on the Hashin parameters, and equilibrium paths were established along with the value at which load-bearing capacity is lost.

Further research on biocomposite materials will increase the potential for their effective use across various industrial sectors, which could contribute to reducing negative environmental impacts.

Characterizing Adhesion and Failure in Overmolded T-Joint Composites with Novel Isostatic Fixtures

Daghia Federica (1), Song Xiaofei (1), Elie Yannick (2), Cluzel Christophe (1) (3)

1 - Laboratoire de Mécanique Paris-Saclay (France), 2 - cetim (France), 3 - IUT d'Évry (France)

Speaker: Daghia Federica. **Monday**. Start time: **10:50**. Room: Rhône 3B LVL1. Link to abstract.

Overmolding, a widely used technique across industries, involves molding a material, usually a thermoplastic, over an existing base. A key design challenge in overmolding is the risk of failure at the interface between the base laminate and the overmolded part. Research has focused on understanding the adhesion between composite laminates and overmolding materials, addressing various material pairings, such as thermoplastic overmolding on thermoplastic and metal substrates (1)(2)(3)(4).
As discussed in the literature, there is currently no normalized test to directly measure the maximum stress at the laminate/overmold interface. Tensile testing of overmolded T-joints is widely used to assess their mechanical behavior (1)(2)(4). Yet, during these tests, the base laminate can experience unintended bending, which often results from inaccuracies in the boundary conditions (5). Additionally, misalignments in load application can lead to considerably lower failure loads. Previous studies, which involved numerical simulations by means of a cohesive zone model (6), show that bending of the base laminate, as well as load misalignment, can lead to a non-uniform stress distribution along the interface, where failure is controlled by the maximum stress for crack initiation and by the energy required for crack propagation. A fine control of the loading conditions during a T-joint tensile test would enable us to impose different types of stress distributions along the interface, from (nearly) uniform distributions adapted for direct identification of the maximum stress to high stress gradients which could be encountered in real-life loading conditions.

This work aims to bridge this gap by designing novel isostatic test fixtures. The fixture with double ball joints allows to control the loading axis while not adding extra moment inadvertently. The distance between the two bending supports can be adjusted between 6 and 17 mm to modulate the bending of the base laminate. To eliminate bending and reach a more uniform stress distribution at the interface, a thick metal support can be glued on the back face of the base laminate. Finally, the loading axis and the T-joint axis can be misaligned by 5 mm maximum, adding a controlled moment on the T-joint. The different testing configurations enable us to identify and validate the numerical model.

To understand the influence of the geometry of the overmolded part, the tests were carried out on two different T-joint shapes: a straight T-joint and a T-joint with an additional chamfer. Both joint shapes were tested with different boundary conditions, described above.

During tests involving the glued metal support, a uniform stress distribution was able to be achieved, yet not maintained until ultimate failure. Indeed, the load transfer goes primarily through the interface, leading to various cracks forming within the base laminate, thus changing the boundary conditions seen by the laminate/overmold interface. The direct identification of the maximum stress is thus not feasible; however it can still be determined through inverse identification by correlating experimental and simulation results. During tests involving bending of the base laminate or load misalignment, the tendencies of the maximum load as a function of the boundary conditions predicted numerically were confirmed experimentally. Different cracking locations were observed and links with the simulations were able to be established. Therefore, the numerical approach was validated by the tests. The remained scatter in the results highlighted the need of stabilization of the manufacturing process.

Acknowledgements

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Linear viscoelasticity of anisotropic carbon fibers reinforced thermoplastics: from micromechanics to dynamic torsion experiments

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Speaker: Diani Julie. **Monday**. Start time: **11:10**. Room: Rhône 3B LVL1. Link to abstract.

Focusing on tanks applications, like H2 tank, the creep behavior of structures is a concern. In order to predict it, one needs to know the composite viscoelastic behavior. In this study, we have tried to answer to two questions: 1) Is it possible to simply characterize the transversely isotropic linear viscoelastic of a unidirectional (UD) composite in the lab? 2) Can we predict it using homogeneization?
For that purpose, dynamic torsion tests were conducted at 1 Hz over a wide temperature range, from the glassy to the rubbery states of the polymeric matrix, on both the pure matrix and the composite, for various cutting angles relative to the fibers. A two-step modeling procedure in the frequency domain is presented to predict and validate the effective behavior of the composite. The first step involves FFT-based homogenization, which maps the microstructure and constituent behaviors to effective transversely isotropic viscoelastic properties. The second step consists of finite element simulations using the effective behavior calculated from homogenization as input to replicate the experiments. A comparison between experimental results and model predictions across the entire temperature range is performed. The modeling predictions show good accuracy at low temperatures, where the matrix is in the glassy state. At high temperatures, where the matrix is in the rubbery state, the predicted behavior becomes too soft. As the phase contrast increases and the ratio of matrix bulk modulus to shear modulus rises significantly, the impact of fiber arrangement on the effective properties becomes more pronounced.

Evaluation of the strain gradient effect on compressive failure of CRFP composites

Bianchi Tobias (1) (2), Bouvet Christophe Serra Joël (3), Ratsifandrihana Léon (4)

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Speaker: Bianchi Tobias. **Monday**. Start time: **11:30**. Room: Rhône 3B LVL1. Link to abstract.

A pin-ended buckling test, inspired by Wisnom (M. Wisnom, 1992), was designed to examine the influence of strain gradients on the compressive failure strain of composite laminates. The study focused on unidirectional (UD) carbon/epoxy AS4/8552, with strain measurements obtained via digital image correlation. Cross-ply stacking sequences-$((0/90)_2)$s, $((0/90)_4)$s, $((0/90)_8)$s-as well as unidirectional configurations $(0)_8$ and $(0)_{16}$ were tested to explore the impact of specimen thickness on compressive failure strain. Most specimens failed on the tension side, driven by the high compressive strength induced by the strain gradient, while the tensile failure strain remained unaffected. To provoke failure on the compression side, an innovative approach was employed by adding an aluminum 2024 ply to the top tension side of bi-material specimens, resulting in all specimens failing on the compression side. The findings revealed a non-linear relationship between compressive failure strain and the strain gradient, contrasting with Wisnom's linear trend. Furthermore, we've obtained for the thinner specimens, values that go up to -33000 micro strains, which is more than 2.5 times the compressive failure of -12500 micro strains.

Wisnom, M. 1992. " On the High Compressive Strains Achieved in Bending Tests on Unidirectional Carbon-Fibre/Epoxy ". *Composites Science and Technology* 43 (3): 229-35. https://doi.org/10.1016/0266-3538(92)90093-I.

Experimental characterization and numerical simulations of fracture of interfaces in mode I and II for printed circuit boards application

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Speaker: Ziouani Charaf-Eddine. **Monday**. Start time: **11:50**. Room: Rhône 3B LVL1. Link to abstract.

The ongoing trend towards miniaturization in electronic devices leads to the developement of a new generation of printed circuit boards with embedded active components. This trend is motivated by the e-mobility and power electronics. During their lifetime, PCBs experience thermal stresses due to heat generated by active components or the surrounding environment. PCBs are complex assemblies composed of various materials. Each constituent has distinct thermo-mechanical properties. In particular, the heterogeneities of thermal expansion coefficients are the main cause of thermal stresses that can lead to layer delamination, occurring between insulating substrates or between copper and the insulating substrates.
Historically, the prevalent technique for quantifying the interfacial energy within PCBs has been the peel test, providing an estimation of the interface energy based on the IPC standard (1). However, during peeling, copper tends to experience large plasticity. Consequently, the analysis of peel tests with plasticity developement in the film has been extensively explored in the literature (2). More recently, in (3) and (4), focusing on the elasticplastic response of copper, the peel test has been analysed to identify the cohesive behavior of the substrate/copper interface. Nevertheless, it has been observed that this approach is challenging when seeking a precise evaluation of the mechanical response of the interface.
To address this challenge, we propose to adapt the Double Cantilever Beam (DCB) and End Notched Flexure (ENF) (5) tests, initially developed for thick composites, to the PCB domain where the layer thickness is very limited (copper thickness is around 17 to 35 μm). The experimental configuration has been validated by FE simulations prior to tests. It is shown by FE simulations that the plastic dissipation for the DCB and ENF configurations is very limited compared to one occuring during peel test. Moreover, an interesting feature of the two tests is the controlled mode fracture while in the peel test, the fracture process taking place is under a mixed mode (I and II). The main outcome of this dialogue between FEA and experimental tests is the estimation of the critical strain energy release rate in mode I and mode II (GIc and GIIc) and the associated critical stress. The shape of the traction-separation law will also be discussed.

Development of a technological test for an aircraft braking application: Study of a carbon/carbon composite and metal structure assembly

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Speaker: Bouillon Florent. **Monday**. Start time: **13:40**. Room: Rhône 3B LVL1. Link to abstract.

Carbon-carbon composites have become the reference material for aircraft braking since the late 1980s (1). The ability of carbon/carbon brakes to provide reliable and consistent braking performance under intense temperature conditions improves aviation safety, particularly during emergency landings where maximum braking efficiency is critical.
These composites are obtained by assembling a carbon fibre preform and a carbon matrix called pyrocarbon, which in our case is obtained by chemical vapour infiltration. The materials obtained in this way offer high thermal capacities combined with temperature stable mechanical and tribological properties, giving them a major advantage over metallic materials (2). What's more, the low density of these materials is a major advantage for aerospace applications.
A heat sink consists of an assembly of brake discs, some of which are static, called the stator, and are connected to the fixed structure of the brake, while the others, called the rotors, are driven by the wheel. The aircraft's kinetic energy is dissipated by friction at the interface between the various discs. In addition to their tribological function, the discs must be able to transmit the braking torque. To achieve this, metal parts are riveted to the disc to ensure that the braking torque is transmitted throughout the life of the disc, even under extreme braking conditions.
The behaviour of this assembly remains complex and the justification of these structures requires technological testing. The traditional approach is based on full-scale tests to take into account all the complexity of the structure and the mechanical and thermal loads. Although indispensable and irreplaceable, full-scale tests have their drawbacks. In addition to cost and time, these tests are difficult to instrument. As part of the ongoing optimisation of the heat sinks, we need a more detailed understanding of how our brake discs work.
The work presented consists of the development of a specific test to study and justify the behaviour of the assembly under different loading conditions, both static and fatigued. The test procedure is based on multi-instrumentation. The aim is to create an intermediate test in the test pyramid (3) between the full-scale heatsink tests and the material characterisation tests. To achieve this, specific instrumentation has been developed for this test using Digital Image Correlation (DIC) and Acoustic Emission.
Digital Image Correlation was used in several areas. Firstly, to analyse the overall behaviour to determine the boundary conditions required to model the test. In addition, a detailed analysis of the behaviour of the rivets under different loads was carried out. Finally, image correlation was used for fatigue testing to improve the reliability of crack detection.
Acoustic emission has also been used to detect and analyse damage in C/C composites (5). This technique is particularly well suited to ceramic matrix composites in general and carbon-carbon composites in particular. It has the advantage of providing information that are very complementary to image correlation. In the context of our work, acoustic emission has enabled us to detect the initial damage to carbon-carbon composites and also to obtain information on the damage kinetics.
The combined analysis of the elements obtained by image correlation, acoustic emission and post-mortem analysis using X-ray tomography provides a detailed understanding of the behaviour of our assemblies.

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ment by using advanced signal processing techniques. Part I: Acoustic emission monitoring and damage mechanisms evolution, Composites Science and Technology (2009)

Comparative study on the residual flexural behavior of woven-ply reinforced thermoplastic or thermosetting laminates exposed to a hydrogen/oxygen flame

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Speaker: Vacandare Julie. **Monday**. Start time: **14:00**. Room: Rhône 3B LVL1. Link to abstract.

The current environmental crisis (CO2 emissions and energy demand) reveals that two of the main issues in aeronautics are the light-weighting design (1) and the development of hydrogen combustion aircrafts (2). To respond to the light-weighting concern, the integration of polymer matrix composites in structural parts is increasing. However, their behavior depends significantly on their working conditions due to their polymer matrix. In particular, the fire issue is a primary concern for aircraft manufacturers. Therefore, understanding and characterizing the thermomechanical properties of composite under critical conditions (fire) is essential (3). Previous works have investigated the (residual) mechanical properties in tension and compression of composite materials after exposure to a kerosene flame (flame at 1100∘C and heat flux of 116kW/m^2) (4), (5). Regarding the mechanical consequences of an exposure to a hydrogen/oxygen flame, very few analyses have been presented so far (6) and different questions remain open, besides the differences in input energy that a hydrogen/oxygen flame can provide (200 to 800kW/m^2, versus 116kW/m^2 with kerosene), the thermal transfers and the involved physics depend on the nature of the fuel. Both, a hydrogen/oxygen flame and a kerosene flame result in the formation of a carbonaceous char layer. However, a hydrogen combustion produces about 2.6 times more water vapor than a kerosene one (7), which is suspected to affect char formation. In ref. (6), the residual tensile behavior of CG/PEEK was investigated after a 5 minutes exposure to a hydrogen/oxygen flame (flame at 2000∘C and heat flux between 200kW/m^2 and 800kW/m^2). The mechanical properties in tension were correlated with the applied heat flux: the axial strength and stiffness were equal to 0 for the highest heat flux (600kW/m^2 and 800kW/m^2), whereas the decrease was moderate after an exposure to 200kW/m^2 heat flux (-35% for strength and -60% for stiffness). These reductions in tensile properties could be explained by the delamination of the specimens, which affects their structural integrity. For the highest applied heat flux, X-ray tomography showed a severe delamination of the plies near the back surface. During the tensile tests, the transverse compressive load applied by the grips of the tensile machine resulted in the bucking of these plies and the loss of the structural integrity of specimens before even starting the tensile test. The impact of thermal degradation (interply delamination) on the residual mechanical properties would be more critical for a different loading such as a bending test where the interfaces between the plies play a major role.
This study investigates the thermomechanical behavior of three polymer matrix composites that differ only in the nature of the polymer: 5-harness satin weave carbon fiber fabric for all, polyetheretherketone (PEEK), polyphenylene sulfide (PPS) or epoxy for the matrix. Rectangular plates of 100x150mm^2 were exposed to a hydrogen/oxygen flame at the temperature of 2000∘C and with a heat flux of 400kW/m^2 for different durations from 1 to 15 minutes.

The first step consists in the characterization of the thermally induced damage. The kinetics of decomposition were analyzed according to the duration of exposure and the nature of the matrix. Actually, thermoplastic matrices first melt with temperature and then decompose, whereas a thermosetting matrix decomposes directly. The decomposition of the matrix leads to the formation of cavities. Microscopic observations of the two faces (exposed and back) reveal the degree of matrix degradation (melt matrix, porosities, carbonaceous char layer). X-ray tomography enables to inspect the interply delamination and the porosity network.

In a second time, the residual flexural properties were examined. From the exposed plates, 10 specimens were extracted, corresponding to different degrees of degradation, in relation to their positions. The three-point bending tests were performed according to the European standard EN 2562 (8). The

flexural properties were then characterized according to the duration of exposure, the position of the specimen in the plate and the nature of the matrix. The main purpose is to evaluate the criticality of flame exposure on interface damage state, which is a key factor ruling the load bearing capabilities of the materials.

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Design and analysis of helical vertical axis offshore wind turbine

Fereidoonnezhad Mohammad (1) (2), Leen Seán (1), Nash Stephen (1), Kenedy Ciaran (1), Mannion Brian (3), Kelly Conor (2), Burke Darragh (3), Jiang Yadong (1), Mee Joseph (1), Finnegan William (1), Flanagan Tomas (2) (3), Mcgarry Patrick (1)

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Speaker: Fereidoonnezhad Mohammad. **Monday**. Start time: **14:20**. Room: Rhône 3B LVL1. Link to abstract.

Helical-bladed vertical axis wind turbines offer distinct advantages over straight-bladed designs, particularly in reducing torque fluctuations on the blades (1, 2). This study presents the design and optimization of a medium-scale helical-bladed turbine for offshore environments. One of the key challenges in composite applications is the design of bolted joints, which are critical for structural stability and strength (3). As part of this study, we firstly design a bespoke connection system to attach helical blades to composite struts using a system of T-bolts. Extensive finite element analyses are performed to optimize the connection design to ensure its ability to transmit the high aerodynamic and centrifugal blade forces generated during operational conditions. Potential failure modes, including bearing failure, net-tension failure, shear-out failure, fastener pull-through, and bolt failure, were systematically evaluated using cohesive zone modelling. The design was optimized to achieve a high degree of safety and reliability.
A modal analysis was conducted to identify the turbine's natural frequencies, which, along with other considerations such as weight and deflection, informed decisions on geometry and number of struts. Due to the dominance of centrifugal forces over aerodynamic loads under operating conditions (4), various strut designs were explored to reduce radial deflection. Parametric finite element studies were used to identify optimal design parameters (blade and strut dimensions and composite lay-up configurations) based on competition between weight reduction and deflection reduction.
To validate computational findings, two experimental tests were performed. Firstly, a prototype of the strut-blade connection was fabricated and tested to failure. The measured failure load under radial and circumferential loading was compared to finite element predictions, and experimentally observed mechanisms of failure were compared to finite element predictions of composite delamination and crack propagation. Secondly, a full-scale blade was tested under the application of two-point loading that was computed to approximately replicate operating conditions. Measured blade deflections and blade and strut strain tensors were compared to finite element predictions, further validating the efficacy of the turbine design.
In summary, this research addresses the challenge of developing efficient helical-bladed turbines through the development of finite element models and experimental testing systems for bespoke bolted joint design, and optimization of blade and strut geometry and composite material configuration.

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Accelerating innovations in building envelope materials using orchestrated multiscale material modelling workflows

Mercier David (1)

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Speaker: Mercier David. **Monday**. Start time: **14:40**. Room: Rhône 3B LVL1. Link to abstract.

It is well established that nearly 70% of product innovation relates back to the development of new materials or to the combination of existing materials in a new fashion (1). In specific use cases multiscale materials modelling has proved to be able to significantly speed up this process. However, despite the great promises and early successes, its widespread adoption within industry remains constrained. Recent analyses pinpoint data management, interoperability, the integration of experimental and modelling data across various time and length scales, and the automation of workflows as pivotal enabling technologies for unleashing the full potential of multiscale material design (2, 3). In the context of the EU-funded project Iclimabuilt, we present an approach that seamlessly integrates a materials information management system (Granta MI) with a robust simulation orchestration platform (OptiSLang) to facilitate, to automate and to orchestrate multiscale materials modelling alongside multiple simulation tools (4, 5).

In this presentation, we explain first how experimental materials data are captured from pilot lines and harmonized in a single repository (iDMS for Iclimabuilt data management system), before to be used as inputs for multiscale simulations. Then, through an advanced end-to-end multiscale workflow (from atomistic to building scale), we showcase framework's key concepts and features, illustrating its efficacy in estimating architectured composite material behavior from micro- to macro-scale, in the case of an insulation panel design test case made of innovative concrete development. Finally, we discuss how such multiscale workflow can be implemented as a reference template into a use-friendly ICME software framework (5).

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Energy Efficient Morphogenic Manufacturing of Composite Materials in Space and on Earth

Tawfick Sameh (1), Hmeidat Nadim Zakoworotny Michael Kim Yun Seong Zhu Matthew Hossain M. Tanver Sottos Nancy Ewoldt Randy Geubelle Philippe

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Speaker: Tawfick Sameh. **Monday**. Start time: **15:00**. Room: Rhône 3B LVL1. Link to abstract.

Bio-inspired manufacturing research aims at providing economic benefits and energy savings of structural materials with minimal environmental impacts. In this talk, I will present our efforts using frontal polymerization (FP) for space and terrestrial morphogenic manufacturing of carbon fiber reinforced composites. FP uses poly-dicyclopentadiene (pDCPD), a stiff and tough thermosetting polymer capable of energy-efficient "self-propagation and self-curing".
In space, I will describe our progress towards "Mission Illinois": the first on-orbit carbon fiber composite manufacturing space experiment planned for launch in 2026. This mission will enable the manufacturing of extremely large, mass-efficient, and precise structures on-orbit. We introduce reactive extrusion of CFRP (RE-CFRP), where two rollers provide localized heat and pressure to sustain the curing reaction and the consolidation of a continuous carbon fiber tow pre-impregnated with DCPD. We study the effect of the extrusion speed, temperature, and compaction force on the properties of the produced CFRP. Mechanical testing confirms that the resulting fiber volume fraction and the elastic modulus are similar to bulk cured tows. A homogenized thermo-chemical model is developed to study the effect of the process parameters on the polymerization reaction. The process produces hollow woven composite tubes directly via extrusion and in situ curing. Overall, this process offers advantages in curing, tooling, speed, and energy.
Next, I will describe growth printing, an additive manufacturing (AM) process harnessing this spatially propagating FP reaction to produce 3D polymer parts 1000 times faster and twice as energy efficient than the faster stereolithography. In contrast with existing 3D printing, this morphogenic process is inspired by biological "growth and form" due to the self-directed propagation of the polymerization reaction. Growth printing is triggered when a heated initiator contacts the uncured liquid resin in an open container. The initiator nucleates the frontal polymerization reaction and the radial propagation of the growth front. During the front propagation, the initiator is simultaneously moved up across the free surface of the resin, pulling the cured object out of the uncured resin. The vertical motion of the initiator with respect to the free resin surface controls the growth morphology of the 3D part. We developed an inverse design algorithm to produce 3D part geometries by modeling the reaction-diffusion-driven solidification process. Various bio-inspired geometries achieved using this process demonstrate substantial energy and data savings and high printing speeds. I will describe experiments and modeling to enable the potential use of this disruptive technology.

Novel Methodology for Monitoring Skin-Stringer Delamination Growth In Thermoplastic Composite Panels

Pereira Andres (1), Kassapoglou Christos (1), Turteltaub Sergio (1)

1 - Delft University of Technology (Netherlands)

Speaker: Turteltaub Sergio. **Monday**. Start time: **15:20**. Room: Rhône 3B LVL1. Link to abstract.

Thermoplastic composite specimens, representative of fuselage panels, are tested under quasi-static compressive load to investigate a novel methodology for continuously monitoring stable skin-stringer delamination growth in the post-buckling regime. The experiment is designed using finite element analysis with the objective of maximizing stable delamination growth during post-bucking. The panel has an initial delamination parallel to the stringer that exhibits stable growth until a critical load is reached that triggers the final collapse (unstable final failure).
To monitor the stable growth of the delamination during the test, a novel methodology is developed that estimates the position of the crack front based on strain concentrations on the outer mould side of the panel. These strain concentrations on the surface are measured through a multi-scale Digital Image Correlation (DIC) technique that provides a local high spatial resolution in the surroundings of the skin-stringer delamination front (1). This local 3D-DIC is complemented by a global 3D-DIC that captures displacements across the entire panel. The crack front monitoring method involves two aspects, namely (i) determining the spatial resolution required to properly capture the superficial strain concentration at the delamination fronts and (ii) the strategy for estimating the actual location of the fronts based on the measured strain data.
The accuracy of the damage characterization based on digital image correlation measurements is evaluated by comparing results with ultrasonic scans. To this end, tests are interrupted during loading, and specimens are unloaded to enable detailed characterization of damage through the thickness via ultrasonic inspection. Novel information on damage morphology such as area, location, and depth is obtained at different instances of the stable crack growth process using a portable C-Scan system. In addition to enabling validation of the DIC-based crack front monitoring method, the C-Scan data provides valuable information on damage area as a function of load, which itself is useful for calibrating and validating numerical models of crack growth.
Retrieving this experimental data is essential not only for understanding the failure behaviour of thermoplastic composites but also for calibrating and validating simulations of damage evolution in stiffened panels under post-buckling conditions.

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Scale and stacking e ects of laminated composite plates with geometric singularities : A critical numerical/experimental comparison

Ha Minh Cuong (1)

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Speaker: Ha Minh Cuong. **Monday**. Start time: **16:00**. Room: Rhône 3B LVL1. Link to abstract.

This paper presents a comprehensive numerical/experimental comparison to analyze both the scale and stacking e ects of laminated composite containing geometric singularities. The numerical simulation was carried out with the new mesomodel-based approach presented in the previous work. Numerical results demonstrate the robustness of this approach, showing a very good correlation with experimental data for both typical singular cases in the aeronautic indus try : holed and V-notched laminates. The complex subcritical damage process is accurately reproduced by the new split approach modeling, including the sud den appearance of local instabilities and nal rupture for all dimensional e ects in the plane, stacking sequences (including e ects due to an increased number of plies), and ply thickness. The physical nature of these e ects has been identi ed. They inevitably inuence the propagation of splits, which is the origin of stress relaxation around singularities and the orientation of delamination along adja cent interfaces, thus signi cantly impacting the complex evolution of subcritical damage.

WIRE-MATRIX DEBONDING UNDER TRANSVERSE LOAD: Inverse identification of a cohesive zone model for the interface

Fradet Adrien (1) (2) (3), Estevez Rafael (1), Rey Thierry (2), Tchoufag Joël (2)

1 - SIMaP (France), 2 - Michelin (France), 3 - DGA (France)

Speaker: Fradet Adrien. **Monday**. Start time: **16:20**. Room: Rhône 3B LVL1. Link to abstract.

Numerous single-fiber tests have been developed in the last decades to study interfacial debonding between fibers and matrices in composites. The most commonly used are the pull-out, push-out and fragmentation tests, but these tests focus solely on interfacial shear strength. In addition, these tests do not allow crack length measurement for a non-transparent matrix. The transverse test (1), in which the fiber is embedded perpendicularly to the loading direction, allows surface observation of debonding while under mixed-mode loading (2)(3).
In this work, the debonding of a steel wire in an epoxy matrix under transverse tensile loading is investigated. A simple method for identifying the cohesive model parameters for the wire-matrix interface is proposed, based on a so-called through-light measurement of the debonding extent. The length of the crack is optically monitored during a monotonic loading. Crack initiation occurs abruptly at the wire poles where the stress concentrates. Once initiated, crack grows progressively, which is also recorded. An inverse identification of the cohesive parameters is carried out based on these observations. A 2D plane strain finite element analysis is used with cohesive elements along the interface. The influence of mode mixity on the critical energy release rate is considered as in Hutchinson and Suo (4). The non-linear mechanical behavior response of the epoxy is also accounted for.
A restricted set of interface fracture properties is first determined using the initiation phase (remote stress and debonding angle at crack initiation). These are further refined for capturing the stable crack growth stage. The agreement between experimental data and simulations is very good, especially at crack initiation. This identification is compared with an approach using the coupled criterion (5) and the influence of cohesive zone length is discussed.

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Carbon Fiber-Reinforced Polymer Composites: Enhanced Properties through Nanoparticle and Thin Film Integration

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1 - Materials Science and Testing of Polymers, Montanuniversitaet Leoben (Austria), 2 - Institute of Physics, Montanuniversitaet Leoben (Austria)

Speaker: Haiden Lukas. **Monday**. Start time: **16:40**. Room: Rhône 3B LVL1. Link to abstract.

Carbon fiber-reinforced polymer composites (CFRPs) are widely utilized across industries such as aerospace, automotive, sports, and construction due to their exceptional mechanical properties and long-term durability. These composites, consisting of carbon fibers embedded in a polymer matrix, form a robust laminate structure ideal for demanding structural applications. The incorporation of nanoparticles or thin films onto the surface of carbon fibers has been shown to significantly enhance their mechanical properties and durability. These modifications improve the interfacial bonding between the fibers and the resin, resulting in increased interfacial shear strength, as demonstrated in numerous studies (1,2).
Enhancements in the surface morphology at the nano- and microscale levels also play a critical role in determining optical and UV reflectivity properties. Materials like Vantablack®, composed of aligned carbon nanotubes (CNTs), exhibit a remarkable absorption rate of 99.96% (3). CNTs grown on surface-activated aluminum (CNT/sa-Al) have achieved an even higher absorption of 99.995% (4). In contrast, natural surfaces like fresh snow demonstrate a high reflectivity of up to 90% for incident radiation due to multiple scattering within its porous crystalline structure (5). These insights underscore the potential for advanced surface modifications to enhance both mechanical and optical properties.
This study investigates two distinct approaches for modifying the interface between carbon fibers and the polymer matrix to enhance mechanical and optical performance. The first method employs electrophoretic deposition (EPD) to deposit silica and silver nanoparticles onto the fibers. In this process, a suspension of nanoparticles is subjected to an electric field, causing the particles to adhere to the carbon fibers. The deposition is controlled by parameters such as voltage and duration, which influence the uniformity and distribution of the nanoparticles.
The second method utilizes physical vapor deposition (PVD) to apply thin films of SiOx and Ag on the fiber surfaces. PVD involves vaporizing the target material in an ionized gas environment, which is then deposited onto the fibers. This process is optimized using magnetron sputtering, which enhances the ionization rate of the gas to improve the deposition efficiency. Critical parameters such as current, deposition time, and gas flow rate are carefully adjusted to achieve thin films with the desired properties.
The adhesion performance of the nanoparticles and thin films was assessed using lateral force microscopy (LFM), which measures the binding forces required to detach particles or scratch films from the fiber surfaces. These measurements provide quantitative insights into the strength of the interface modifications (6). Additionally, changes in the mechanical properties of the carbon fiber surfaces, including hardness and Young's modulus, were evaluated using atomic force microscopy-based nanoindentation. Preliminary findings suggest that the adhesion quality and mechanical performance are strongly influenced by the deposition parameters, including the voltage and time in the EPD process and the film thickness in the PVD process.
The optical properties of the modified carbon fibers, incorporated into polymer composites, were analyzed using UV/VIS spectroscopy. The results revealed significant differences in reflectivity depending on the type of coating and the deposition parameters. EPD-modified fibers exhibited enhanced UV reflectivity, while composites with PVD-modified fibers showed a modest increase in reflectivity across the entire spectrum.
This study demonstrates the potential of surface modification techniques, such as EPD and PVD, to improve the mechanical and optical properties of carbon fiber-reinforced composites. By optimizing deposition parameters, significant enhancements in interfacial bonding, durability, and optical performance can be achieved. These findings provide valuable insights for advancing the development of high-performance composite materials for industrial applications.

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Experimental study using interfacial inserts to create bridging to improve delamination response in composites

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Speaker: Daghia Federica . **Monday**. Start time: **17:00**. Room: Rhône 3B LVL1. Link to abstract.

Composite materials have grown rapidly due to their ability to provide high stiffness at low weight, resulting in increased use in aerospace and automotive applications, among others. However, interlaminar adhesion is a problem with these materials, as cracks can form between the laminaes, leading to delamination and subsequent structural collapse. This work analyzes different strategies to improve the delamination response of carbon fiber-reinforced composites, focusing on delaying and stabilizing crack propagation, a critical challenge for performance and reliability in advanced industrial applications. The main proposal in this work is to modify the interface by adding heterogeneities with two different materials to create bridging. This will reduce crack propagation and help maintain stability in the load-displacement curve.
The material studied was unidirectional carbon fiber (HexPly M79), fabricating specimens by prepreg at 120 ∘C for 1 hour and at a pressure of 5 bar, with a stacking. To create the bridging ligaments, two types of materials were incorporated as interlaminar inserts: mat-type fiberglass (E-glass) and TPU 92-A patterns 3D printed on a Stratasys 270 printer. Two different patterns were designed, consisting of squares with equal dimension, having different orientations with respect to the crack propagation direction. They are defined as "diamond" and "square" patterns in the following.

Two types of experimental tests were performed to study crack propagation: the Double Cantilever Beam (DCB) test in mode I, according to ASTM-D5528, and the Climbing Drum Peel (CDP) test in mixed mode, according to ASTM-D1781, which is usually used to evaluate adhesion in sandwich panels. The aim was to investigate the robustness of the improved performance depending on the mode mixity and type of test. For the DCB test, the inserted materials (mat and TPU) were placed in the midplane, while for the CDP, they were inserted between plies 2 and 3. Both tests were performed at a 1 mm/min test speed on a Zwick-Roell Z100 electromechanical machine with a maximum capacity of 100 kN.
DCB experimental results showed that the inserts generated fiber bridges, creating long process zones that slow down crack propagation compared to the baseline case. The mat and the TPU diamond inserts displayed similar behaviors, while the TPU square introduced some instability in the crack propagation. In the case of the CDP test, the inserts did not have the same behavior. Few or no bridging ligaments were observed in all cases, as the crack tended to deviate towards the peel arm side of the insert. Due to its brittleness, no effective bridges were formed for the mat material, and its behavior was like that of the baseline case. In contrast, the two types of TPU did increase the delamination energy, although they also caused instabilities in crack advancement.

A compact model for the micro- to macro-scopic deformation behavior of natural short-fibre reinforced semi-crystalline polymer composites

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Speaker: Holopainen Sami. **Monday**. Start time: **17:20**. Room: Rhône 3B LVL1. Link to abstract.

Despite the popularity of biopolymers nowadays, ranging from their applications in the aerospace and automotive industry to food packaging, the research and modeling of their mechanical resistance have been considerably limited to date. In this research, a micromechanically based constitutive model is proposed to investigate the elastic-viscoplastic micro- to macro-scopic deformation resistance of the biocomposites consisting of a semi-crystalline polymer matrix and short biofibers. The uniaxial tension of the high-strength Polylactic acid (PLA) polymer-hemp fiber composite was taken as a case study. Due to sufficiently high fiber content and strong bonding between the fibers and the two phases of the polymer, that is, amorphous and crystalline, influence of the lattice crystalline structure was suppressed. This enabled a compact model to be developed and the predictions of the elastic-viscoplastic macroscopic deformation behavior.

A mesoscopic constitutive model for simulating rate-dependent plasticity and creep in unidirectional polymer composites

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Speaker: Hofman Pieter. **Monday**. Start time: **17:40**. Room: Rhône 3B LVL1. Link to abstract.

Although modeling the rate-dependent plastic response of polymers has seen significant advances in recent years, accounting for the complex combined behavior of fibers and polymer matrix in a composite material is still subject to ongoing research. In this work, we present a mesoscopic constitutive model for simulating rate-dependent plasticity and creep in continuous fiber reinforced polymer composites. The model is an extension of an isotropic viscoplastic constitutive model for neat polymers, based on the Eyring flow theory. The direction dependence of the composite is taken into account through a set of transversely isotropic invariants. For obtaining an accurate response under finite deformations, the re-orientation of the transversely isotropic plane under plastic deformations is properly taken into account in the constitutive equations. Furthermore, the model requires only a few parameters for the direction, rate and pressure dependence of the composite. The performance of the mesoscopic constitutive model is assessed by comparing the response with that from a recently developed micromodel for Carbon/PEEK with fibers and matrix explicitly described. The micromodel is first used to identify the elasticity and rate-dependent plasticity parameters of the mesomodel through numerical homogenization. It is then demonstrated that the mesoscopic constitutive model gives a similar response as the micromodel subjected to off-axis uniaxial tension and compression under various strain rates. The strong anisotropy of the composite, which is hyperelastic in fiber direction, and rate-dependent plastic in transverse direction, is well captured. Furthermore, the constitutive model can simulate creep deformations under constant stress, which enables the model to be used for simulating plastic deformations in unidirectional composites under short- and long-term loading.

Mechanical properties of titanium matrix composites produced by Electro-Sinter Forging

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Speaker: Denis Gaëtan. **Tuesday**. Start time: **10:00**. Room: Rhône 3B LVL1. Link to abstract.

A novel field assisted sintering process called Electro-sinter-forging (ESF), developed by EPoS Technologies SA, produces unique metal matrix composite structures. It is an ultrafast sintering process, combining a mechanical pulse and an electromagnetical pulse. This technology ensures a sintering at full density, in a sample obtained in a few seconds. We explore ESF process capabilities for the production of titanium matrix composites. This comprises the design and production of new materials, the in-depth study of their microstructural development, and their characterization for mechanical behaviour. General goals of the project are to design novel, high-performance titanium metal matrix composites for structural applications, and to contribute to our understanding of the links between composition and process parameters on one hand, and resulting microstructures and mechanical properties on the other hand, of metal matrix composite materials produced by the electro-sinter-forging process. This presentation will focus on in-situ Ti/TiC composites and their mechanical properties including their tensile behavior and elastic properties.

Behavior and damage study of Oxide/Oxide CMCs using in-situ Micro-CT test and Digital Volume Correlation

Thomas Drouin (1), Laurin Frédéric (2), Couégnat Guillaume (3), Guillet Francois (1)

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Speaker: Thomas Drouin. **Tuesday**. Start time: **10:20**. Room: Rhône 3B LVL1. Link to abstract.

Ceramic Matrix Composites (CMCs) are lightweight materials with excellent mechanical properties at elevated temperature, making them promising candidates for various advanced applications. Oxyde/Oxyde (Ox/Ox) laminates are particularly relevant for moderate thermo-mechanical loadings due to their favourable balance between mechanical properties and cost. However, these materials experience damage even at low load levels, resulting in an highly non-linear behaviour (1). The determination of a constitutive law requires a precise understanding of their mechanical behaviour, including at the ply level, as well as rigorous observation and measurement of their damage mechanisms.
X-Ray Computed Tomography (CT) is a widely recognised imaging method allowing access to a material structure in 3D provided local absorption coefficients provide enough contrast in the resulting 3D image. In the same way that the observation of a surface speckle pattern can be used to compute a displacement field during a mechanical test (2), the material structure may provide a natural pattern that can be used to compute a 3D displacement field through Digital Volume Correlation (DVC). In addition to the 3D determination of the displacement field, the advantage of CT is that temperature has no effect whatsoever on X-Ray absorption and material contrast. Thus temperature measurements are no different than room temperature measurements if the X-Ray absorption of the furnace windows is put aside. This allows to overcome experimental issues related to measuring strain fields at elevated temperatures (strain gauges, high-temperature speckles for 2D Digital Image Correaltion (DIC)...) and it is one of the most important industrial advantage of this application.
Our study aims to elucidate the damage scenario in Ox/Ox through in-situ micro-computed tomography (μCT) tests. To achieve this, tensile/compression and bending using compression with pivot device are conducted on a 2D woven Ox/Ox with different lay-ups (0/90, 45/-45 and a quasi-isotropic) both at room temperature and up to 700∘C. To address issues arising from too small sample sizes, as highlighted by (3),the samples used in this study will present a minimum size larger than 1.5 times the Representative Elementary Volume of the ply (REV). The maximum volume obtained by backprojection of is 4000x4000x4000 pixels, which, at a maximum resolution of 15μm/voxel, allows us to study approximately a 50x50x50 mm area if the Region Of Interest (ROI) at the centre of the sample.
There are two possible approaches to conduct digital images correlation : global or local, which mainly differ in how the displacement field is computed. In the local approach, the studied zone Ω is subdivided into small zones of interest Ω i . For each of these small zones, the average mechanical transformation is estimated between the reference state and the deformed state. This approach has the advantage of being easier to implement and can be easily parallelized, and this is the reason why it is currently the most used correlation method, particularly in commercial software. However, although the results can be interpolated over the entire reference zone Ω, the continuity of the displacement field between subvolumes is not. In contrast to local methods, global methods rely on defining a continuous kinematic field u(x) over the entire region of interest examined.The formalism of this method is thoroughly described in (4). The main advantage of this approach lies in ensuring the continuity and regularity of u(x) on Ω, thanks to local support from finite elements. This aspect is moreover interesting in the determination of constitutive equations, because the same finite elements framework can be used for DVC and numerical computations. In this study, we will consider a global DVC method using and a tetrahedral mesh created with the software "GMSH", which will serve as local support for finite elements. The global DVC software used is "Kintsugi" (5), which is mechanically regularized (6). In a nutshell, a rigid registration of rigid body motions is performed beforehand to estimate rigid translations and compute an initial solution for the DVC algorithm. The DVC is then conducted in a pyramidal manner to help the system to gradually converge from the largest to the smallest regularization length, starting sometines from binned volumes to full volume for example.
Thus, the mechanical and thermo-mechanical tests mentioned previously are analysed using mechanically-regularized global Digital Volume Correlation (DVC) to access global and local displacements and strains,

towards a DVC-based identification of constitutive parameters for a damage model at the ply level (7). In order to guarantee the relevance of the displacement field measurements, for a relatively short scan time to be able to conduct mechanical tests with multiples points (34' per scan). A full signal/noise ratio analysis was performed with formulae suggest by (8) and made it possible to optimize and obtain a standard deviation of 0.05 voxel of the displacement field. This also included a reduction in the effects of beam hardening and noise during scanning, while optimizing local contrasts which are very useful for the displacement field calculation by DVC.
Finally, to integrate these tests into a test/calculation dialogue methodology, nonlinear finite-element simulations will be performed. The comparison between these numerical results and the experimental observations will be presented also the identification with FEMU methods of the ODM constitutive law parameters. This case includes the search and integration of the boundary conditions of the mechanical tests, based on the results obtained by DVC. To understand damage scenarios, especially delamination, a study based on DVC calculation residual is in progress, and is focussed for example, on crack apparition and propagation on (+45◦/-45◦)s lay-up , due to mechanical edges effects in laminated composites.

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Experimental characterization and modeling of concrete behavior under highly confined compression loading

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Speaker: Calmels Théo. **Tuesday**. Start time: **10:40**. Room: Rhône 3B LVL1. Link to abstract.

Concrete is characterized by a complex mechanical behavior that shows a strong dependence on the loading path, particularly on the hydrostatic pressure to which it is subjected. Indeed, even under relatively modest confinement pressures, the strength of concrete is much higher than in unconfined (uniaxial) compression loading... Moreover, a brittle behavior is observed under low confinement, whereas it becomes ductile under high confinement. The modeling of the behavior of concrete under ballistic impact that induces significant variations in pressure requires experimental data obtained over a wide range of pressures. Quasioedometric compression (QOC) tests provide the means to characterize the deviatoric and hydrostatic responses of geomaterials over an extended pressure range in a single test. In the present study, dynamic QOC tests were performed using a large-diameter (D80mm) Hopkinson bar apparatus, following the protocol established by (Forquin et al. 2010). Two concrete formulations of different porosity states were considered. Additionally, specific attention was paid to the hygrometric condition of the tested samples to investigate the influence of the saturation state on its dynamic volumetric and deviatoric behavior. The results enable the identification of parameters of the KST (Krieg-Sewenson-Taylor) model for use in numerical simulation codes. Micro-tomographic analysis conducted before and after QOC tests allows the damage evolution induced by such loading conditions to be characterized.

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Gradient damage model for simulating thermo-mechanical coupling: application to composite material degradation

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Speaker: Abdoussalam Mhadji. **Tuesday**. Start time: **11:00**. Room: Rhône 3B LVL1. Link to abstract.

Keywords: composite material, damage, thermal degradation, gradient-based model, crack, coupling, microstructure, interface, pyrolysis, heterogeneity, phase field

The use of composite materials is widespread in structures where weight reduction is essential while maintaining high stiffness and strength properties. However, these materials are flammable, increasing fire risks. It is generally observed that heat flux transforms sound composite material into char, leading to the degradation of mechanical properties and a modification of initial thermal properties. Nevertheless, the influence of microstructural heterogeneity on thermal degradation, as well as the coupling between thermal degradation and mechanical damage, remains underexplored in the literature.
The objective of this study is to investigate the influence of mechanical and thermal degradation mechanisms on physical phenomena such as heat transfer, thermal decomposition, and cracking. The study aims to simulate the interaction between different degradation modes and their kinetics to assess their mutual impact on the material's behavior at the microstructural scale. To achieve this, a rigorous thermodynamic approach is adopted, introducing internal variables corresponding to each physical phenomenon, as well as their gradients.
This modeling approach combines two methods: on the one hand, a phase-field gradient model is employed to describe thermal degradation, which evolves according to an Arrhenius law. This method is suitable for simulating phase transition phenomena and interface motion in a non-homogeneous material. This approach introduces a degradation gradient term to characterize the interface energy between degraded and sound regions, allowing the influence of microstructural fluctuations to be considered.
On the other hand, a gradient damage model based on the principle of virtual powers distinguishes the thermodynamic forces associated with the reversible process, derived from free energy, from those associated with the irreversible process, derived from the dissipation potential. This modeling choice avoids issues related to damage localization and mesh dependency. By coupling these two approaches, it becomes possible to simulate the interaction between mechanical damage and thermal degradation of the material.
The results show that, on the one hand, charred regions become areas where damage and cracking are easily initiated due to the degradation of mechanical properties. On the other hand, damaged or cracked zones act as thermal barriers, delaying heat propagation. Indeed, the presence of cracks reduces thermal conductivity in these regions, thereby limiting the advancement of the thermal front.

Effect of the viscoelastic behavior of the composite substrates on the thermomechanical modeling of a printed circuit board

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Speaker: Girard Gautier. **Tuesday**. Start time: **11:20**. Room: Rhône 3B LVL1. Link to abstract.

Printed circuit boards (PCBs) are complex assemblies of materials with very different thermomechanical behaviors. Under thermal loads (environmental or self-heating), the differences in coefficients of thermal expansion induce mechanical stresses that can lead the structure to failure (1).
In order to predict their service life or understand the origin of failures, it is interesting to model these structures in operation, including their manufacturing process. The characterization of the thermomechanical behavior of the materials that constitute PCBs is hence necessary.
Insulating substrates are composite materials made of a glass fabric and a thermosetting resin. The behavior of glass is very little dependent on temperature on the given range of interest (approximatively -50∘C to 200∘C). It is well described by an elastic model. The behavior of the resin is, however, very influenced by temperature, in particular when approaching its glass transition temperature (Tg). The resin response is also time dependent and a thermo-viscoelastic model is required to rationalize its behavior (2). This time and temperature dependence is inherited at the composite level, with an additional complexity: the reinforcement (woven glass fibers) leads to anisotropic behavior.
In multilayer PCBs, burried holes are often encountered to transmit electrical information between inner layers. In the present work, a buried hole structure is modeled under cyclic environmental loadings by integrating the thermo-viscoelastic behavior of the identified composite (3). The main outcome of the work is tha it is essential to take into account the effects of temperature on the behavior of materials if predictive simulations are to be performed. Viscous effects become significant at temperatures close to the Tg, but can be neglected if the maximum temperature excursion remains more than 30∘C below the Tg.

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Failure Analysis of a Thick Composite Tidal Turbine Blade

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Speaker: Valdivia-Camacho Miguel A.. **Tuesday**. Start time: **14:15**. Room: Rhône 3B LVL1. Link to abstract.

This study is concerned with the failure analysis of a 5.25-metre composite tidal turbine blade under controlled static loading. Understanding the structural behaviour of these blades is critical for improving the performance and reliability of tidal turbines in an emerging energy sector still progressing towards full commercial deployment. While tidal turbine blades share many characteristics with wind turbine blades, their failure mechanisms differ due to a higher thickness-to-length ratio. In this work, we researched the primary factors contributing to blade failure, correlating both experimental and numerical analyses using strain data from sensors and digital image correlation (DIC). Static testing revealed that delamination was the predominant mode of failure, highlighting the importance of interlaminar stresses in thick composite structures. A 3D finite element model was developed to further analyse the failure mechanics of the blade, employing cohesive zone modelling to represent interlaminar failure and an element deletion framework to simulate the evolution of intralaminar failure. Well-established 2D modelling methods are computationally efficient, relying on plane stress conditions and thin structure assumptions, but neglect interlaminar stresses and out-of-plane failure modes. Building on this limitation, this research also evaluates the accuracy and computational efficiency of 3D modelling for composite materials, introducing an open-source tool that provides a high-performance framework for the finite element development stage.

Post-fire fracture behavior of hybrid PEEK thermoplastic composite laminates under one-sided kerosene flame aggression: Experimental and numerical analysis

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Speaker: Lin Lanhui. **Tuesday**. Start time: **14:35**. Room: Rhône 3B LVL1. Link to abstract.

With regard to the stringent fire safety regulations for thermoplastic-based (TP) composites in aeronautics field (1), it is a critical issue to understand and quantify the fracture mechanisms of degraded laminates, whose behavior is highly heterogeneous and anisotropic (2). Most of the attention has been given to unidirectional (UD) thermosetting laminates (3). Therefore, this study aims at investigating the influence of different kerosene flame exposure time on both the thermally-induced damages and the post-fire fracture behavior of hybrid woven-ply carbon/glass fibers reinforced PolyEther Ether Ketone (CG/PEEK) laminates.
In the present work, the pyrolysis behavior of CG/PEEK composites subjected to one-sided fire exposure is explored by experimenting on a burner bench (4). The Compact Tension (CT) specimens are exposed to kerosene flame (116 kW/m2 and 1150°C) with exposure time ranging from 5 min to 15 min. The mechanical tests are then conducted to evaluate the residual fracture toughness of laminates at room temperature. Fractographic analysis has been carried out by means of microscopic and tomographic observations using a numerical optical microscope Keyence VHX-5000 and RX Solutions EasyTOM-150 respectively to visualize, classify and quantify the thermally-induced damages along with the translaminar fracture under mechanical loading (5). Using a Digital Image Correlation (DIC) system combined with a binarization algorithm (6), the crack tip is located via the discontinuity of the strain field resulting from the crack propagation within material during loading. Here, the ASTM-399 test standard (7) is applied to determine the value of the critical strain energy release rate (SERR), from the application of the compliance method to the force-displacement data during crack propagation.

Under flame exposure, the microstructure observations show a heterogeneous distribution of damages associated with a significant temperature gradient within the laminates. Depending on the pyrolysis degree of each ply, the load bearing capabilities of the plies gradually deteriorate from the exposed to the opposed side. The two regions (named char and decomposition regions) characterized by different thermally-induced damage states do not take up the mechanical loading the same way, the most tensile loading being born by region with less damage. The critical fracture toughness (FT) values shows a decreasing trend (as a function of fire exposure time) with increasing ply number of the charred region through the thickness. FT tends to slightly increase during crack propagation in each case, which is attributed to fiber bridging occurring in the char region (characterized by a weak interface), and secondary cracks occurring within the char region that may prevent the compliance method to be relevantly applied.

The correlation between post-fire residual mechanical properties and thermally degraded regions is further investigated, with the implementation of an analytical model (8) based on the porosity content ratio of each region, to better account for the coupling between fracture behavior and critical service conditions (under fire). A numerical model implemented in the FE code Abaqus/Explicit is used to simulate the translaminar fracture and the damage propagation resulting from fiber breakage in CG/PEEK laminates. Based on CT testing data, the model accounts for the translaminar fracture in opening mode (mode I) due to fiber breakage. Ultimately, the proposed model enables a better understanding of the role played by the mechanical response of each ply along with the PEEK matrix pyrolysis on the tensile translaminar fracture behavior of woven-ply laminates after kerosene flame exposure.

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Identification method of the resin shrinkage: Application to woven composite used in Power Electronics

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Speaker: Leicht Mickaël. **Tuesday**. Start time: **14:55**. Room: Rhône 3B LVL1. Link to abstract.

Abstract:
Printed circuit boards (PCB) are a fundamental part of any electronical device. PCBs are essentially made of copper (conductive material) and woven glass fibers embedded in a polymeric resin (structural and dielectric material). One of the PCB manufacturing step is hot pressing to ensure the adhesion between the copper and pre-impregnated composite by curing the resin within the composite (leading to a shrinkage). Unfortunately, the resin and its thermo-mechanical properties are not available which make difficult the development of a predictive FE model (1,2).

Therefore, a two step method was developed to determine the effective shrinkage associated to the woven composite (3,4). First, hot pressing and curing composite layers on top of already cured layers result in a bent plate due to difference in strain history. Second, identification is carried out based on the plate curvatures acquired by Digital Image Correlation. Note that effective shrinkage is a homogenized property, resulting from the real chemical shrinkage of the resin, interacting with the glass fibers (which do not shrink).

Clearly, the effective shrinkage depends on the thickness (or more precisely on the local volume of constituents), whereas the plate thickness was assumed uniform in previous studies (3,4). Therefore in this work, thickness measurement and cross-sectional optical observations were carried out and actually revealed a difference in the thickness distribution and fiber/resin volume fraction. Thermo-mechanical properties are significantly different between the center and borders of the plate due to a heterogeneous resin flow during the hot pressing stage.

From the thickness and volume content measurements, a numerical model has been developed using Abaqus™ FEM Software (5). In the present simulation, the bent plate is modeled using shell elements. The local thermo-mechanical properties are obtained following the work of Girard et al. (6). A better restitution of the experimental measurements is given by the model, demonstrating the added value to the existing method. Finally, a precise value of the chemical shrinkage of the resin is given.

Key-words: Resin shrinkage, Woven Composite, Numerical identification method, Multiscale homogenization, Printed Circuit Board.

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Design of bio-inspired glass-sponge lightweight cellular structures and manufacture via 3D printing continuous flax fiber biobased composite for energy absorption application

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Speaker: Caillault Thomas. **Tuesday**. Start time: **15:15**. Room: Rhône 3B LVL1. Link to abstract.

In the context of reducing CO2 emissions, various industries, including construction, automotive, aerospace and biomedical sectors are actively seeking for innovative lightweight and environmentally friendly materials and structures.
Nature has severely outpaced humans in developing optimized structures regarding to environmental stresses. Euplectella Aspergillum sponge (glass-sponge) has a complex multiscale architectured lattice structure. That organisation permits to withstand hydrodynamic forces due to deep depths (from 150 to 5000m), uneven loads because of dynamics currents and fend off marine predator attacks. Therefore, the sea sponge assures a high mechanical properties in bending and torsion, while maintaining toughness and lightness (1). The present work aims to study the bio-inspired glass-sponge design for energy absorption applications.
3D printing, particularly Fused Filament Fabrication (FFF), enables the creation of complex structures. The incorporation of continuous natural fiber into composite cellular structure offers the potential for significant weight reduction while maintaining high mechanical strength. The continuous flax fiber reinforced PLA composite will be used due to its lower environmental impact, lightweight nature and comparable specific properties when contrasted with synthetic fiber reinforced composite (2)(3). Our approach leverages in-nozzle impregnation to achieve precise orientation and placement of continuous flax fibers, drawing inspiration form sea sponge design to develop optimized composite structures (4).
To attempt the objective, three designs are proposed: **Design A**, a simple square structure; **Design B**, a Design A coupled to a cross distributed in checkerboard pattern; **Design C**, a bio-inspired structure made up of a Design A coupled to a double diagonal distributed in checkerboard pattern. The study employs Digital Image Correlation (DIC) to investigate the impact of structural density on deformation modes (in-plane and out-plane) and energy absorption under uniaxial compression loading. Ultimately, this research aims to establish the link correlating structural design and relative density with mechanical performance, advancing the development of sustainable, high-performance composite materials.

Keywords
Lattice composite structures, Bio-inspiration, Glass-sponge, Fused filament fabrication, Compressive test

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Analytical modeling for ballistic impact behavior of multi-layer composite structure

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Speaker: Xiao Liping. **Tuesday**. Start time: **15:35**. Room: Rhône 3B LVL1. Link to abstract.

Cosmic dust is submillimeter debris scattered throughout the solar system. These particles hold valuable geological data from various celestial bodies, piquing the interest of researchers to collect and analyze them (1). Dozens of dust detector instruments have been flown on space missions. To characterize the captured particles, the detector needs to measure key properties of them, such as size, composition, density and porosity. Previous studies reveal a strong correlation between colliding particles and impact tracks (2). Quantifying the correlation between shape parameters of the impact tracks and projectile parameters has been a hot scientific enquiry. For example, quantitative models of penetration tracks or impact craters were investigated by many researchers (3-5). In this work, a new form of passive dust detector is proposed based on the porous silica aerogel and laminated composite structure. Owing to this combination, the multi-layer composite structure can not only capture tiny particles but also resist the impact of projectiles with large kinetic energy. As shown in Fig. 1, the aerogel is arranged at the front of the multi-layer composite structure, followed by a composite laminate.
Compared with composite laminate (6), the formation of penetration tracks in silica aerogel is not fully understood up to now, hindering the establishment of theoretical model. To advance a first-order understanding about the interaction process between cosmic dust and silica aerogel, similitude impact tests covering a wide range of impact velocities (10^(-5)_~10^3 m/s) are conducted firstly. Within the impact velocity in tests, the induced penetration tracks exhibit obliquely forward branching trajectories, as shown in Fig. 2(a). Such cone-in-cone penetration tracks are observed in both ground experiments and returned aerogel samples, while poorly understood. Here, the formation mechanism of the cone crack is determined from the perspective of low-velocity impact. It's revealed that the cone crack is initiated by the contact between projectile and aerogel, and expanded resulting from the forward aerogel pushed by projectile. Driven by the clarified formation mechanism, a theoretical model is developed based on contact mechanics and energy methods. The conical shape of tracks is explained by Hertz contact, as shown in Fig. 2(b). The stress fields within aerogel during impact is given by (7):

$$\sigma_i = f(p_m, \nu, a, r, z) \quad (1)$$

where σ_i are contact stresses expressed in cylindrical coordinate; p_m is the mean contact pressure during impact; ν is the Poisson's ratio of the specimen; a is the radius of the contact area between the sphere and the flat surface; r and z are coordinates. Then the principal stresses within the rz plane and the cone crack path which is orthogonal to the direction of the maximum tensile stress σ_1 can be determined. The stress distribution is visualized in Fig. 2(b) and the angle α between the crack path and specimen surface is calculated as 33°. Furthermore, the energy absorption mechanism during impact is analyzed. As the formation of cone cracks is driven by compaction, it's seemed that the kinetic energy of a projectile is spent by overcoming the strength and elasticity of the aerogel material. In this way, possible energy absorbing mechanisms include motion, deformation, fracture and crushing of the aerogel:

$$E_KP0 = E_KPi + E_KSi + E_(FS(i-1)) + E_(SS(i-1)) + E_(CS(i-1)) \quad (2)$$

where E_KP0 is the initial kinetic energy of the projectile; E_KPi and E_KSi are the kinetic energies of the projectile and the moving cone region of silica aerogel at the ith time interval; $E_(FS(i-1))$ is the energy dissipated by the fracture until the $(i-1)$th instant of time; $E_(SS(i-1))$ and $E_(CS(i-1))$ are energies absorbed by the compression and crushing of the aerogel. With the determined energy conversion at each time interval, the velocity of the projectile can be calculated furthermore. An iterative computational framework is developed based on the theoretical model. The results are output until the projectile velocity is diminishing to zero or the target is penetrated. The accuracy of the analytical model is validated through experimental data and results are given in Fig. 2(c).

In conclusion, we propose a multi-layer dust detector combining silica aerogel and composite laminate.

The ballistic behavior of silica aerogel is investigated by similitude impact tests. It's found that the cone cracks are typically formed in hypervelocity impact events with relatively low impact velocities (< 3 km/s), and there is a strong correlation between the impactor parameters and crack morphologies. This work firstly reveals how cone cracks form in penetration tracks within silica aerogel. The proposed analytical model contributes to the design of aerogel collector and improve the interpretation of characteristic parameters (initial size, pristine compositions, velocity distribution, astrophysical source) of cosmic dust from penetration tracks. Moreover, the model may facilitate in excavating invaluable information on initial planetary building materials, as well as the formation and evolution of the solar system.

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Thermal-mechanical-chemical coupled model and three-dimensional damage evaluation based on computed tomography for high-energy laser-ablated CFRP

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Speaker: Zhao Zeang. **Tuesday**. Start time: **15:55**. Room: Rhône 3B LVL1. Link to abstract.

High-energy laser is widely used for machining carbon fiber reinforced polymer (CFRP) composites because of their high precision and fine quality. However, the mechanism by which CFRPs are damaged by high-energy laser in processing is unclear. In this research, the coupled mechanism of laser-ablated CFRPs is investigated experimentally and theoretically. The three-dimensional morphology of laser-damaged CFRPs is captured by computed tomography (CT), which quantitatively characterizes the degree of charring and internal delamination. Accordingly, a thermal-mechanical-chemical coupled model is established considering the matrix pyrolysis, pyrolysis gases flow, sublimation of the charring layer and mechanical failure. The progressive loss of solid media and the inhomogeneous deformation of CFRPs are incorporated into the traditional ablation kinetic model, making it possible to describe the damage to CFRPs caused by both chemical reactions and thermal stress. The predicted damage morphology is consistent with the experimental results, revealing the generation of internal defects due to the synergistic effects of interlaminar tensile stress and matrix pyrolysis. Additionally, the effects of charring layer sublimation, laser power density and process time on damage responses are analyzed, and the real-time evolution of damage degree is investigated.

Influence of the fiber length distribution on the modeling procedure of short fiber-reinforced composites by cross-correlated non-Gaussian random fields

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Speaker: Widera Ilona Małgorzata. **Tuesday**. Start time: **16:35**. Room: Rhône 3B LVL1. Link to abstract.

Short fiber-reinforced composites are highly suitable for lightweight structures due to their high specific strength and stiffness. One major advantage is that components made from short fiber-reinforced composites can be manufactured rapidly and cost-effectively in large quantities by mold injection. However, modeling such components accurately presents challenges due to the resulting heterogeneous nature of the material on the microstructural level, where fibers are not only distributed randomly but also show stochastic characteristics. These characteristics comprise the fiber length, diameter, and orientation and hence play a critical role in determining the overall mechanical properties of the composite.
Following this, research focuses on developing methods to model components made from short fiber-reinforced composites to capture their random nature accurately. Among these efforts, approaches utilizing random fields have emerged as a promising strategy to address this complexity.
This work aims to develop a method to represent the spatial distribution of local mechanical properties at the component level using cross-correlated non-Gaussian random fields. Thereby, the focus is to investigate the influence of the fiber length distribution on the micro- and macrostructural behavior. To achieve this, microstructures with two various fiber length distributions are generated. The remaining geometrical information regarding diameter and orientation are in both cases the same.From these microstructures, statistical volume elements are extracted and analyzed using the moving window method. The resulting probability distributions and correlation structures of the stiffness tensor elements are identified and compared.
For the subsequent analysis at the component level, this data is employed to generate non-Gaussian, cross-correlated random fields using the expansion optimal linear estimation in combination with the Nataf transformation. These non-Gaussian random fields are then utilized in FEM-based numerical simulations of tensile tests on the component level. For both fiber length distributions, the statistical properties of the obtained Young's modulus are analyzed considering different correlation lengths. This allows to establish a relationship between the mean value and standard deviation both as a function of the correlation lengths.
Finally, the statistical behavior of the longitudinal Young's modulus obtained from numerical simulations using non-Gaussian random fields is compared to experimental results. This analysis reveals the influence of the fiber length distribution on Young's modulus at the component level.

Microstructure-sensitive modelling of solid explosives under mechanical impulse

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Speaker: Ushasi Roy Dr.. **Tuesday**. Start time: **16:55**. Room: Rhône 3B LVL1. Link to abstract.

Designing solid explosives for insensitive munitions is an essential exercise to reduce the wastage of human and material resources due to catastrophic accidents involving unexpected explosions. Some standard tests and protocol exist to test the insensitivity of the solid explosives towards sudden mechanical and thermal impulse. The novel materials must qualify tests, specifically, the bullet/fragment impact test for structural integrity. However, performing such tests with explosives is not only expensive, at times, almost impossible in terms of hazards and threats it offers. This shows the necessity of a predictive computational model that could replicate these insensitive munitions tests reliably and thereby reduce the number of experiments needed to qualify a novel material for insensitive munitions. The hydrocodes currently available to predict the detonation behavior of explosives do not take into account the microstructural details of the solid explosives and therefore cannot be appropriately used for novel materials' design purposes. To design next generation solid explosives as insensitive munitions, it is customary to establish the relation between microstructural features and the detonation behavior at the macro-scale. The macro-scale characteristics of solid explosives are largely influenced by the equations of states before and after chemical reaction initiates. These constitutive laws are still not known as a function of the composite's microstructure. Therefore, in this work, we develop a microstructure-sensitive Finite Element based model that predicts the constitutive laws at the macroscale as a function of the microstructure. A solid explosive is primarily made up of energetic particles embedded in polymer matrix. We use a simple HTPB-estane type polymer bonded explosive (PBX) for our study. However, the model is capable of accounting for any other phases that may be present in PBX like Ammonium Perchlorate and so on. Statistically similar microstructures are generated to account for stochasticity in performance of these composites. Different distributions of energetic grains are studied to delineate the influence of microstructures on the deformation behavior of these composites under high strain rate loading. These digitally generated microstructures are then subjected to high strain rate periodic boundary conditions to study their deformation behavior. Cohesive elements are employed to allow fracture during loading to happen at arbitrary locations. Different constitutive laws are defined for each of the constituents of the microstructure, as well as the cohesive surfaces. The overall stress-strain responses of the microstructures are recorded along with their local heterogeneous response. Master curves are drawn to obtain the equations of state at the macro-scale as a function of their microstructure. Temperature evolution is also studied during this high strain rate loading. Heating throughout this adiabatic loading is effected through inelastic dissipation and frictional dissipation at the cracked surfaces. This leads to generation of hotspots. The hotspot maps under different loading conditions are also extracted to facilitate identification of the initiation of chemical reaction in these composites. Our simulation stops before the chemical reaction initiates. This thermo-mechanical model helps in delineating the effects of microstructure on the macro-scale equations of state of the unreacted solid explosive and on the probability of ignition initiation. The model has the capability to aid in novel composites design for insensitive munitions.

Closed-form estimates of the homogenized elastic properties for bio-inspired staggered composites

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Speaker: Gaziano Pierfrancesco. **Tuesday**. Start time: **17:15**. Room: Rhône 3B LVL1. Link to abstract.

Several biological materials, such as nacre, spider silk and bone, have evolved their nano- and micro-structure in order to optimize their load-bearing capabilities in response to various external stimuli. In many cases, exceptional mechanical properties are achieved, combining strength, stiffness, and toughness in a way that often exceeds those of most commonly used engineering materials. This remarkable performance can be attributed to their highly organized microscale structure, characterized by a staggered arrangement of platelet-like elements embedded within a compliant matrix.
Inspired by these highly performing natural materials, bio-mimetic staggered composites have recently attracted significant attention, with early manufacturing attempts made possible by advancements in multi-material 3D printing technologies. Moreover, the growing interest in staggered composites has driven the development of various analytical formulations that attempt to describe the mechanical behavior of these class of materials. However, the majority of the existing formulations focus primarily on determining the stiffness along the staggering direction, leaving the other equivalent elastic properties underexplored. Moreover, notable discrepancies often arise when comparing the available analytical estimates with established numerical results or experimental measurements.
This work tries to overcome these limitations by proposing simple yet effective closed-form expressions for the complete set of equivalent elastic constants characterizing the mechanical response of staggered composites. A micromechanical variational formulation is used, considering six independent loading scenarios: three axial tests along the mutually orthogonal axes of orthotropy, and three shear tests in the planes orthogonal to these directions. By imposing stationary conditions of the (microscale) total potential energy over a class of quasi-compatible strain fields describing the dominant microscale kinematics, a consistent approximation of the equilibrium solution at the representative volume element (RVE) level is established. The overall equivalent constitutive response naturally follows from the Hill-Mandel homogenization conditions. The soundness and accuracy of the proposed formulation is assessed through comparisons between the theoretical estimates of the equivalent elastic constants and their counterparts obtained via a computational homogenization procedure.

2D+ multi-scale method for industrial design of multi-layered bending plates

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Speaker: Triclot Julie. **Tuesday**. Start time: **17:35**. Room: Rhône 3B LVL1. Link to abstract.

Structures with a multi-layered plate morphology, such as composite laminates, are of great interest to industry due to their high stiffness to density ratio. However, their design phase is long, expensive and requires many experimental tests in order to fulfill the requirements for the uptake of new products. High fidelity simulations are seen as a valuable tool to accelerate these processes but face the challenge of providing accurate and efficient solutions. It Is worth highlighting that the complexity of such materials is found precisely in the thickness dimension, this being remarkably lower that the in-plane ones. This is the reason why full 3Dcomputations are prohibitive since typical discretisations are extremely thin in order to overcome pathologies derived from high element aspect ratios.
In this view, the multiscale methodology presented in (1) (the 2D+ multiscale approach) is adopted in this contribution. The idea is to take advantage of a dimensional reduction of the multi-scale problem at both macro and meso-scales to render extremely competitive computation times while preserving the heterogeneous description through-the-thickness. The strategy is based on the computational homogenization formalism employing a 2D plate with degenerated kinematics at the macro-scale and a 1D RVE (Representative Volume Element) through-the-thickness at the meso-scale. This methodology is not invasive and has been implemented in the commercial software Abaqus as a dedicated user element.
The application of this method to different bending-dominated scenarios results in exceptionally accurate results compared to fine-meshed 3D calculations. Stress distributions are accurately captured both in-plane and through the thickness. A huge reduction in computation time compared to 3D analyses is achieved, reaching speed-up factors of three orders of magnitude. The 2D+ truly accomplishes the goal of being as accurate as the 3D at a cost close to the 2D one. The presented method is an interesting alternative to existing numerical procedures to handle multi-layered bending plates. Furthermore, it provides a solid basis to account for failure modes arising within these materials (e.g. delamination in laminated composites).

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On the computational methods for the analysis of transversely flexible sandwich beams

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Speaker: Balestro Tiago. **Tuesday**. Start time: **17:55**. Room: Rhône 3B LVL1. Link to abstract.

Sandwich structures are already well known in fields like aerospace due to their high stiffness-to-weight efficiency. However, by adding a flexible core, new interesting properties arise. In comparison with a single layer structure or a rigid sandwich, the configuration of flexible sandwich structures enables more complex deformation mechanisms, specifically, a transversely flexible core allows the face sheets to deform semi-independently, enhancing flexibility and allowing a tunable shape. When combined with magnetorheological materials, for instance, these structures can have important applications in fields like adaptive structures, soft robotics, and morphable wings.
The foundational high-order theory of transversely flexible sandwich beams, introduced by Frostig *et al.* (1992), provides a closed-form solution, enabling analysis of vertical normal stress, in-plane shear stress, and displacement fields. The last allows researchers to predict structural deformation in advance by solving the governing equations and updating the displacement field equations.
Even so, the solution of the original model governing equations is not straightforward. In particular, Swanson *et al.* (1999) expanded the topic further by introducing a work on implementing the theory. Moreover, further studies have emerged over the years, suggesting the solution in a different way, based on the Fourier series (Phan *et al.*, 2012), (Lashkari *et al.*, 2016).
The governing equations of the theory constitute a set of five coupled linear ordinary differential equations of fourth order. Its complete solution provides the shear stress, as well as the longitudinal and vertical displacements of both the upper and lower faces. Such solutions are fundamental to a complete analysis of the sandwich, creating a displacement field of the core and evaluating stresses on the structure.

In this context, the present work discusses the solutions procedure further and analyses alternative methods: direct numerical solution, nondimensional equation simplification and solution by means of commercial Differential Equations Solvers. The computational algorithms are employed using Mathematica software, allowing easy mathematical implementation. The study also seeks to produce accurate graphical representation of the core deformation, an aspect that has not been extensively explored in prior research, yet crucial for predicting beam behaviour.
It was observed that although Fourier analysis can be powerful, expressing certain load conditions in Fourier terms can be challenging, restricting practical applications. The direct numeric approach, which is simpler to implement at first, faced challenges due to ill-conditioned systems resulting from coefficients of widely varying magnitudes. The plot of the theoretical core deformation was simple to implement in Mathematica and produced excellent graphical results of the nonlinear deformation pattern, a high-order effect.
In the current stage, some methods are still being tested. The performance of all will be compared to the original solutions, even though these require extra computation as well, as outlined in Swanson. Furthermore, once the ODE system is solved, the computational model will be validated through bending tests on real transversely flexible sandwich structures. Especially for flexible structures, where displacements are significant, comparing the real displacement field to that predicted by the theory is important. Finally, special care will be taken with the performance of the computational model, since it aims to be used alongside structural optimization routines.
With the proposed studies concluded, it is expected to find a computational model that is both robust and user-friendly, enabling the simulation of transversely flexible sandwich beams under diverse static load conditions.

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From Microstructure to Mechanical Integrity: SiC/Al IPCs for Demanding Industrial Applications

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Speaker: Kharbatli Abdul-Rahman. **Wednesday**. Start time: **10:00**. Room: Rhône 3B LVL1. Link to abstract.

Interpenetrating Phase Composites (IPCs) represent an innovative class of materials that combine the advantages of ceramics and metals by offering high-temperature stability, wear resistance, and enhanced ductility and toughness. The unique interlinked microstructure of IPCs, which is formed by integrating two or more continuous phases, develops properties that surpass those of conventional composites, thus making IPCs suitable for high-performance applications in fields such as medical tools, grinding instruments, defense, aerospace, and components exposed to extreme environments. In this study, silicon carbide (SiC) IPCs were fabricated through the infiltration of aluminum alloy to further enhance their mechanical performance. A pressureless infiltration method was utilized in an atmospheric furnace, with aluminum blocks introduced into SiC foams (10 ppi and 20 ppi) placed in graphite molds. The furnace was filled with N2 gas and heated gradually to 1100 ∘C over four hours, then maintained at this temperature for an additional three hours, and subsequently allowed to cool. Optical microscopy of the fabricated Al-SiC IPC samples revealed a well-connected structure, free of voids or cracks, indicating a robust metal-ceramic bond. SEM/EDS analyses and mechanical assessments of the developed SiC-Al IPCs have shown promising results that demonstrate the material structural integrity and potential for implementation in extreme environments and demanding applications. Subsequently, further in-depth SEM/EBSD analyses and impact testing are planned to comprehensively evaluate the microstructural cohesion and mechanical robustness of the IPCs. These investigations will validate the suitability of SiC-Al IPCs for applications involving high wear, stress, and thermal fluctuations, thus emphasizing their role as high-performance materials for challenging operational conditions.

Thermal Barrier Coating for Carbon Fiber-Reinforced Plastic Composites

Lee Min Wook (1)

1 - Korea Institute of Science and Technology (South Korea)

Speaker: Lee Min Wook. **Wednesday**. Start time: **10:20**. Room: Rhône 3B LVL1. Link to abstract.

In order to use CFRP composites in a high-temperature environment, a coating that can effectively block external heat is required. TBC (Thermal barrier coating) has generally been studied for the purpose of mechanical and corrosion protection of metal materials at high temperatures. Recently, research has been conducted to effectively reduce thermal conductivity by controlling the pores of the TBC layer. This study aims to introduce a non-combustible TBC layer on a CFRP substrate to protect it from high temperatures. A bilayer composed of yttria-stabilized zirconia (YSZ) - polyetheretherketone (PEEK) was fabricated using a flame spray technique, and its high-temperature characteristics were investigated. The thermal property analysis results show that the thermal conductivity of the entire coating layer can be controlled by controlling the porosity. In particular, the decrease in thermal conductivity becomes much more pronounced as the PEEK feed rate increases because of the presence of many pores. These pores effectively reduce the overall thermal conductivity of the porous TBC layer through convective heat transfer, especially when there is a temperature gradient between the interior and the surface of the TBC. Through the thermal shock test, the surface temperature of the CFRP heated to 500∘C exceeded 300∘C in 300s and started to ignite. In contrast, the surface temperature of the TBC-coated CFRP specimen was maintained at 230 ∘C for 10 min, and no spontaneous ignition or combustion was observed.

Optimization of impact properties and weaving patterns of woven composites

Zheng Shaoqiu (1), Li Zhiqiang (1), Wang Han (1)

1 - Taiyuan University of Technology (China)

Speaker: Zheng Shaoqiu. **Wednesday**. Start time: **10:40**. Room: Rhône 3B LVL1. Link to abstract.

Fibre Reinforced Polymer (FRP) laminates are used extensively in automotive and aerospace components because to their reduced weight, increased design freedom, increased durability, and reduced susceptibility to corrosion. Several possible weave architectures (combinations of weave patterns and material choices) present a challenging question about how they could influence the physical and mechanical properties of woven fabrics and reinforced structures. Predictions of elastic and impact properties of patterns in woven fabric composites are proposed based on unit cells. This study addresses the optimization of the impact properties within woven fabric composite unit cells with multiple designs based on periodic boundary conditions and evolutionary algorithms. Furthermore, the study permits a reliable prediction of mechanical behavior of woven fabric composites unit cells in which the weave patterns are the variables. The models are treated as a single-ply for each weave pattern embedded in a matrix pocket. The analyzed weave patterns are created by TexGen, the simulation is done with ABAQUS. At the unit cell level, effective elastic properties of the yarn were estimated from Finite Element (FE) simulations using periodic boundary conditions. Then the energy absorption capacity of the laminates was analyzed on a macroscopic scale. An evolutionary algorithm is adopted in optimizing the energy absorption capacity of woven fabric composites with recombination and mutation operators. We present a parameter study to investigate the effect of various geometric parameters. Those parameters include the gap length, the shape of the yarn section, the yarn thickness, the constituent materials, the fiber volume fraction and the elastic properties. By examining this optimized model through the pre-determined parameters as mentioned above, an optimal parameter set for composite's performance can be properly selected.

Discrete Element Method (DEM): A numerical technique to insight on the role of microcracks on the sustainability of refractory materials

Ranganathan Harikeshava André Damien Mouiya Mossaab Huger Marc (1), Soth Ratana Wohrmeyer Christoph

1 - IRCER - Axe 4 : céramiques sous contraintes environnementales (France)

Speaker: Huger Marc. **Wednesday**. Start time: **11:00**. Room: Rhône 3B LVL1. Link to abstract.

Andalusite and Aluminum titanate are utilized in various industries due to their superior intrinsic properties for thermal shock applications. At the microstructural scale, these materials are identified by their grain crystallinity, such as aluminum titanate, a polycrystalline material with orthorhombic crystals at the microstructure scale. In addition, Aluminum titanate exhibits anisotropic thermal expansion behavior at the microscopic scale. Therefore, these materials exhibit spontaneous microcracking at high temperatures during operational conditions due to CTE mismatch. Moreover, microcracks in the refractory microstructure have led the material to depict a quasi-brittle (non-linear mechanical) behavior under tensile loading. The experimental experts claim that the non-linear macroscopic response of refractory material signifies the toughening of the material. The betterment of the material's fracture toughness contributes to the improvement of its thermal shock resistance. Therefore, simulation of cracking phenomena, including microcracking, branching, or fragmentation, that occurs in brittle or quasi-brittle media has become a topic of research interest. So, the authors propose a simplified and pure polycrystalline model microstructure using the Discrete Element Method (DEM), with Aluminum titanate as a reference material. The study is focused on understanding the role of anisotropy of the grains in a polycrystalline material in promoting debonding or microcracking because of the Coefficient of Thermal Expansion (CTE) mismatch between the grains of the polycrystalline material. In addition, this model involves thermomechanical coupling, crack-closure, and Periodic Boundary Conditions (PBC) to perform thermomechanical simulations such as to predict the dilatometry results, tensile test results, and the fracture mechanism at the microstructural scale of a polycrystalline material. The obtained results are validated using the experimental results regarding mesoscopic thermomechanical quantities (such as CTE, Young's modulus, stress-strain law, etc). In conclusion, the potential advantages of using microcracks engineering for commercial refractory products could be highlighted.

Numerical analysis of regularly arranged brick structures inspiring nacre tissue

Arai Masayuki (1), Fujita Hayato (2)

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Speaker: Arai Masayuki. **Wednesday**. Start time: **14:30**. Room: Rhône 3B LVL1. Link to abstract.

Nacre is a composite material composed of calcium and organic matter, which is known to have excellent fracture strength and toughness. Recently, the development of composite materials that mimic the microscopic structure of such organisms has been actively promoted. In this paper, we developed a finite element model in which the calcium layers of nacre are periodically arranged in a group of bricks, replacing the organic layers with a cohesive model, and exampled about the deformation and crack propagation process. The obtained result shows that as the aspect ratio of each brick (defined as the ratio of width to height) increases, the bricks slip together and deform along the cohesive layer, and cracks propagate with large deflections along the interfaces between the bricks, resulting in high fracture ductility and high fracture energy. On the other hand, it is found that if the aspect is chosen too large, the cracks propagate in a straight line, and the expected properties are not be obtained. Therefore, we will claim that by optimizing the crack orientation plane and the aspect ratio of the brick geometries an extremely excellent biomimetic composite material can be obtained.

Steady State Thermal Non-linear Stability Analysis of Bi-directional Nanotube based Functional Graded Composite Plate

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1 - Indian Institute of Technology [Dhanbad] (India), 2 - Westlake University [Zhejiang] (China)

Speaker: Dey Tanish. **Wednesday**. Start time: **14:50**. Room: Rhône 3B LVL1. Link to abstract.

The study of steady state thermal non-linear stability in bi-directional nanotube-based functionally graded composite plates (FGCPs) is crucial for modern engineering applications involving advanced materials. This research investigates the thermal stability behavior of FGCPs reinforced with bi-directionally aligned carbon nanotubes (CNTs), focusing on their response to steady state thermal loads. The composite plates are modeled with spatially varying material properties, engineered through functionally graded distributions of CNTs to achieve optimal thermal and mechanical performance. A non-linear thermal stability analysis is conducted using a combination of higher-order shear deformation theory and von Kármán-type geometric nonlinearity. The governing equations are derived through the Hamilton's variational principle and solved numerically to capture the non-linear thermal deflection and post-buckling behavior under various boundary conditions. Results highlight the influence of bi-directional CNT reinforcement, grading profiles, and temperature distributions on the thermal stability and structural resilience of the composite plates. The study provides insights into optimizing the design of nanotube-reinforced FGCPs for applications requiring high thermal stability and mechanical robustness, such as aerospace and high-performance structural components.

Composite materials and structures reinforced with bamboo fibers: A comparative study on the influence of species and age on the fiber physical and mechanical properties

Noubiap Japhet (1), Lecompte Thibaut Ngohe-ekam Paul Salomon Neba Nfornkah Barnabas Kervoelen Antoine Nzegang Frantz Dunant Mbouyap Chengoue Anatole Messi Jacques Materne Noubissi Noumfo Romeo Szczepaniak Robert

1 - University of Yaoundé1 (Cameroon)

Speaker: Noubiap Japhet. **Wednesday**. Start time: **15:10**. Room: Rhône 3B LVL1. Link to abstract.

With over 1,500 botanical species of bamboo worldwide, the remarkable rise in the utilization of natural fibers has spurred extensive research into bamboo's potential across various engineering fields. The aim of this study is to examine the influence of bamboo age and species on the physical and mechanical characteristics of the fibers. Three species of bamboo, representing three distinct age groups, were meticulously selected in Cameroon, namely *Bambusa Vulgaris*, *Yushania Alpina* and *Phyllostachys Aureus*. The fibers derived from the three-bamboo species, spanning three distinct age groups, underwent a chemical treatment with a 1% NaOH solution. Subsequently, the fibers were subjected to four comprehensive analyses: tensile testing, thermogravimetric analysis (TGA), Fourier-transform infrared spectroscopy (FTIR), and density measurement. A comparative analysis of the tensile test results reveals that the Young's modulus varies significantly depending on both the age and the species of the bamboo. In contrast, the thermogravimetric analysis (TGA) curves exhibit a striking similarity, regardless of the bamboo's age. The findings of this study will provide designers of innovative materials and engineers with the ability to effortlessly select the appropriate bamboo species and age, tailored to the specific requirements of various applications.

A study on the defects in the lay-up process of prepreg-based carbon fiber composites

Hooshmand-ahoor Zahra (1), Jose Kevin (1), Huang Tiancheng (1), Deshpande Vikram (1)

1 - Department of Engineering, Cambridge University (United Kingdom)

Speaker: Hooshmand-Ahoor Zahra. **Wednesday**. Start time: **15:30**. Room: Rhône 3B LVL1. Link to abstract.

Carbon fiber reinforced polymer (CFRP) composites are widely used in aerospace, automotive, and marine industries due to their high strength-to-weight ratio, fatigue resistance, and corrosion tolerance. Prepreg materials, with carbon fibers pre-impregnated with partially cured resin, enable precise control over fiber alignment and resin content, enhancing mechanical performance. However, the manufacturing process of prepreg-based composites presents several challenges, including the formation of voids, wrinkles, and other interlaminar imperfections. These defects can significantly undermine the structural integrity and performance of the final composite, particularly under high-stress conditions. This study examines the impact of defects in the lay-up process of partially cured prepegs. The materials selected for this investigation are commonly used in advanced applications, particularly in aerospace. IM7 carbon fibers and 8552 epoxy resin have been chosen as the primary components of the CFRP composite. X-ray computed tomography (XCT) is employed to analyze the microstructure and identify defects, such as shear strains between layers caused by voids. The results aim to provide insights into optimizing the lay-up process and understanding how defects affect the mechanical properties of laminates, particularly when shaped into complex geometries.

MS1.3 - Architected and additively manufactured materials (metals, polymers, ceramics)

Organisers: Emily D. Sanders (Georgia Tech), François Barthelat (CU Boulder), Eric Charkaluk (LMS Paris) and Dennis Kochmann (ETH Zurich)

Effect of thermal history on defects in brittle Fe-6.5wt%Si soft magnetic alloy produced by Laser Powder Bed Fusion

Van Roy Simon (1) (2), Dehez Bruno (2), Poncelet Olivier (1), Reuter David (3), Kairet Thomas (3), Hernandez Hector (4), François Arnaud (4), Kuci Erin (4), Simar Aude (1)

1 - Institute of Mechanics, Materials and Civil Engineering (iMMC), Materials and process Engineering (IMAP), UCLouvain (Belgium), 2 - Institute of Mechanics, Materials and Civil Engineering (iMMC), Mechatronic, Electrical Energy, and Dynamic System (MEED), UClouvain (Belgium), 3 - Sirris (Belgium), 4 - Cenaero (Belgium)

Speaker: Van Roy Simon. **Monday**. Start time: **10:10**. Room: Audi Pasteur LVL1. Link to abstract.

Optimization of radial flux machines with punched laminated sheets of electrical steel is well covered in the literature. Additive manufacturing, and in particular Laser Powder Bed Fusion (L-PBF), of soft magnetic should enable a less restrictive design of electrical machines, particularly for axial flux machines whose flux path is fundamentally 3D. Fe-6.5wt%Si is a good candidate in terms of magnetic and electrical properties as well as material cost. As a first step towards designing such complex parts, this alloy needs to be well characterized both mechanically, electrically and magnetically. However, this material tends to exhibit cracking, due to its brittleness, and pores during LPBF manufacturing. First, a detailed comparison of process parameters is carried out to understand the appearance of cracks and pores. Different parameters, laser scanning strategies as well as support structures are compared. Secondly, a thermal dynamic finite element method (FEM) simulation of L-PBF process is developed. It is validated using in-situ thermal measurements by a thermal camera. Subsequently, both mechanical and magnetic properties are measured on the best samples and compared based on their thermal history.

Enhancing Mechanical Properties through Graded Materials in Multi-Layer Friction Surfacing of Aluminum Alloys

Yideg Wubit Ashagre (1) (2), B. Lezaack Matthieu (1), Khodabakhshi Farzad (1) (2), Simar Aude (1) (2)

1 - Institute of Mechanics, Materials and Civil Engineering [Louvain] (Belgium), 2 - WEL Research Institute (Belgium)

Speaker: Yideg Wubit Ashagre. **Monday**. Start time: **10:30**. Room: Audi Pasteur LVL1. Link to abstract.

Multi-Layer Friction Surfacing (MLFS) has emerged as a promising additive manufacturing technology due to its ability to minimize energy consumption, reduce material waste, and enhance material properties. The mechanical properties of MLFS components can be further improved by incorporating material grading. Graded materials are characterized by a gradual variation in composition and structure, enable tailoring of local material properties. Applying graded microstructures through MLFS enhances the mechanical performance of 7075 aluminum alloys. A significant grading in grain size can be achieved by adjusting deposition parameters between layers and also subsequent post annealing treatment. This work addresses the effect this grading has on fatigue crack propagation favoring crack deviation due to the multi-layer grading.

Keywords: Multi-layer friction surfacing, Graded materials, Microstructure, Mechanical properties, Fatigue crack propagation

Experimental analysis of hardening mechanisms in an aluminum alloy manufactured by the L-PBF process

Toualbi Louise (1), Le Bouar Yann Fossard Frédéric Merot Jean Sébastien Stricot Pauline (2) (3), Fritz Simon (4) (5), Grevin Eric Bachelier-locq Agnès Horezan Nicolas (6), Barres Quentin (7), Renollet Yves (8)

1 - DMAS, ONERA, Université Paris Saclay [Châtillon] (France), 2 - DMAS, ONERA, Université Paris Saclay [Châtillon] (France), 3 - Mines Paris - PSL (École nationale supérieure des mines de Paris) (France), 4 - Ingénierie des Matériaux Polymères (17, Av. Jean Capelle 69621 Villeurbanne Cedex France), 5 - Matériaux, ingénierie et science [Villeurbanne] (Bâtiment Blaise Pascal 7, avenue Jean Capelle 69621 VILLEURBANNE CEDEX France), 6 - ONERA (France), 7 - DMAS, ONERA, Université Paris Saclay (France), 8 - DMAS, ONERA, Université Paris Saclay [Châtillon] (France)

Speaker: Toualbi Louise. **Monday**. Start time: **10:50**. Room: Audi Pasteur LVL1. Link to abstract.

The development of Additive Manufacturing (AM) processes in recent years has enabled the production of complex geometry parts that are challenging to produce using conventional manufacturing methods. However, AM results in microstructures and metallurgical states that differ from those achieved with traditional processes. The aerospace industry is currently focusing on the use of traditional aerospace materials and applying post-processing homogenization heat treatments to ensure that the mechanical properties are comparable to those obtained through conventional methods. However, the development of new alloy grades specifically for AM can exploit the unique characteristics of these manufacturing processes.
In the case of the Al-Fe binary system, Laser-Powder Bed Fusion manufacturing induces the precipitation of strengthening phases and the formation of dislocations due to thermal hardening. Indeed, L-PBF process involves successive melting of layers of powder material via a laser, which induces very short interactions between the raw powder and the laser, resulting in rapid solidification and cooling rates. As a result, the as-built material exhibits remarkable hardening, which raises questions about the thermal stability of this as-built microstructure, especially when considering the potential for using these new alloy grades for applications such as repairing components using AM processes.

Aim is to improve understanding of metallurgic and thermal mechanisms related to rapid solidification and cooling rates that are characteristic of L-PBF production and lead to structural strengthening of alloy in service. To achieve this, samples produced using different manufacturing parameters were subjected to detailed characterisation using Transmission and Scanning Electron Microscopy and X-Ray Diffraction. The results showed that the as-built microstructure produced is characterised by a remarkable hardening, which can be modulated by adjusting the manufacturing parameters (essentially the laser scanning speed and the temperature of the manufacturing plate). The impact of the manufacturing parameters on the microstructure is highlighted, particularly on the size of the solidification cells which largely controls the mechanical behaviour. The results also reveal the correlation between the Fe distribution in the microstructure and the local hardness of the material.

The differences in mechanical behavior related to microstructural organization are highlighted by conducting in-situ SEM tensile tests, allowing for visualization of more ductile zones along the edges of the melt pools. Additionally, microstructural characterizations carried out using Atom Probe Tomography (at GPM UMR 6634, Rouen, as part of a METSA grand) and Transmission Electron Microscopy have revealed a significant amount of Fe in solid solution, which could potentially further harden the material in the form of nanometric precipitates. This finding underscores the value of exploring the application of a post-fabrication heat treatment, both to fully harness the available hardening potential in the alloy and to reduce the local behavior gradient in the as-built microstructure.
The results demonstrate the impact of heat treatments on material hardening in terms of microstructural evolution, changes in local micro-hardness levels, and focus particularly on describing hardening mechanisms at the scale of solidification cells.

In-Situ X-Ray Compression Testing with DVC and FEA Analysis of Zr-Modified Al7075 TPMS Gyroid Lattice Structures Processed by LPBF and HIP

Farag Mohammed (1), Pyka Grzegorz (1), Nothomb Nicolas (1), Attallah Moataz (2), Remacle Jean-françois (1), Simar Aude (1)

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Speaker: Farag Mohammed. **Monday**. Start time: **11:10**. Room: Audi Pasteur LVL1. Link to abstract.

Additive manufacturing has revolutionized the design of architected materials, offering the ability to create complex structures with tailored mechanical properties. This study focuses on Zr-modified Al7075 alloy lattice structures based on Triply Periodic Minimal Surfaces (TPMS) with a Gyroid structure, produced at a volume fraction of 10-15%. These structures are designed for use as architected materials or Metal Matrix Composites, providing exceptional performance in lightweight and load-bearing applications.

The specimens used were manufactured in a cylindrical form in accordance with ISO compression testing standards. To extensively investigate deformation and failure processes, in-situ X-ray compression experiments were conducted to capture real-time interior structural changes. Micro-scale strain fields were mapped using Digital Volume Correlation (DVC), offering key insights into structural response under load. Finite element analysis (FEA) models allow to predict strain distributions and validate experimental results.

We further investigate the improvement of these lattice structures using Hot Isostatic Pressing (HIP) to minimize porosity and promote material densification. This is followed by a solution heat treatment that refines the microstructure and improves mechanical properties. Our findings suggest valuable connection between lattice structure, material behavior, and load-bearing efficiency, underlining the potential of Zr-modified Al7075 Gyroid structures as strong and lightweight structure for use in Metal Matrix Composites for advanced engineering applications.

Influence of additive manufacturing process parameters on cemented carbides : microstructural and mechanical behavior with Weibull analysis of sintered parts

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Speaker: Marciano Erwan. **Monday**. Start time: **11:30**. Room: Audi Pasteur LVL1. Link to abstract.

Cemented carbides, primarily composed of tungsten carbide and cobalt, are traditionally manufactured through powder metallurgy processes that require full densification. However, in response to the growing demand for more sustainable manufacturing methods, additive manufacturing (AM), particularly Metal Binder Jetting (MBJ), is emerging as a promising alternative. Despite its potential, significant challenges remain in understanding the relationship between AM process parameters, powder physicochemical properties, microstructure evolution, and the mechanical performance of sintered parts.
In this study, we address two key aspects of cemented carbide manufacturing via MBJ. First, we investigate the effect of printing parameters on green parts, highlighting how defects induced during the printing process affect the quality and mechanical properties of the non-sintered parts. Specifically, we focus on the impact of printing parameters on properties such as relative density and porosity.
Second, we apply Weibull statistical analysis to evaluate the mechanical reliability of sintered parts. This analysis quantifies the variability in the mechanical performance of sintered parts, accounting for residual defects introduced by the printing process. We also explore the relationship between microstructural characteristics, such as grain size and homogeneity, and the mechanical properties of sintered parts, considering both commercially available powders and in-house produced powders.
A series of mechanical tests, including 3-point bending, 4-point bending, and biaxial flexure, are conducted to assess mechanical performance under various loading conditions. Hardness, fracture toughness, and bending tests are complemented by microstructural observations using SEM and EDS techniques, providing a comprehensive analysis of the material's properties.
The findings highlight the importance of printing parameters in determining the mechanical behavior of green parts and demonstrate, through Weibull analysis, how these parameters influence the reliability of sintered parts. This study contributes to a deeper understanding of the relationship between manufacturing processes, microstructure, and mechanical performance in additive-manufactured cemented carbides.

Mechanical behaviors at 77K of Zr-modified Al 7075 alloy printed by L-PBF

Tiphéne Gabrielle (1), Nothomb Nicolas (1), Simar Aude (1)

1 - Université catholique de Louvain, Institute of Mechanics, Materials and Civil Engineering, IMAP (Belgium)

Speaker: Tiphéne Gabrielle. **Monday**. Start time: **13:40**. Room: Audi Pasteur LVL1. Link to abstract.

Decreasing the mass of structure is the main goal of aeronautic and aerospace industries. One solution to do so is to remove all unnecessary parts when designing them. However, classical fabrication methods do not allow such new designs to be easily implemented. The recent development of additive manufacturing technologies has opened the path towards huge mass reduction in those industries. Optimization of printing strategies for different alloys has been of great importance in recent research (1–3).
Recent works of our team focuses on the development of printing strategies for Al 7075 series (4–6), a high-strength aluminum alloy, widely used in aerospace industries. As printing strategies are now better understood, it becomes important to determine the mechanical properties of such alloys at their working temperature. Using a home-made tensile device working at cryogenic temperatures, the mechanical characterization of Zr-modified Al7075 alloys has been carried out. The results are promising when compared to classical Al7075-T6. The as-built samples have a yield stress of 415 MPa at RT and 476 MPa at 77K with correct elongation values ($>$ 14% at both temperatures) while T6 samples presents values of 550MPa and 650MPa at those temperature respectively. However, through optimized thermal treatment, we achieve stress levels of 526MPa and 668MPa at both RT and cryogenic temperatures for the printed samples. X-ray tomography analysis and Scanning Electron Microscopy characterization have been carried out to understand the deformation mechanisms taking place at cryogenic temperature compared to room temperature for this material.

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Multiaxial high cycle fatigue (HCF) behavior of IN718 thin wall structures obtained by laser powder bed fusion (LPBF)

Bouzid Souihli Badr (1) (2), Saintier Nicolas (3), Chemisky Yves (4), Ciobanu Oana Alexandra (2)

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Speaker: Bouzid Souihli Badr. **Monday**. Start time: **14:00**. Room: Audi Pasteur LVL1. Link to abstract.

In order to achieve the 2050 challenging goal of zero carbon emissions, the aeronautical industry research focus on the latest fabrication processes to produce new materials and reduced weight parts. Our aim is to show that metallic, LPBF manufactured, triply periodic minimal surface structures (TPMS) can be used to reduce the weight of critical mechanical aeronautical components and optimize their performance, achieving a better weight-to-resistance ratio. We present our results on HCF multiaxial behavior of IN718 thin-wall structures, the first step to master complex, TPMS behavior.
TPMS structures, made of thin walls are essential for achieving low densities, but have complex microstructures with few grains across their thickness. The LPBF process can add additional complexity, like porosities, lack of fusion, and oriented microstructures. The resulting complex geometry generates stress gradients under mechanical loading and influences surface topology, which is a key factor when considering fatigue strength.
Our study describes the microstructure and mechanical behavior of thin walls, down to 200 microns of width. Tubular thin-wall fatigue specimens, fabricated with different thicknesses and orientations to map the behavior at various locations within the TPMS geometry are thoroughly investigated.

Microstructural analysis aligns with findings reported in literature (Sanchez-Camargo et al., 2003). Columnar grains along the building direction are observed even after heat treatment. EBSD maps reveal elongated grains and a significant degree of texture. We show that surface topology in the as-built state is heavily dependent on the building orientation and remains a primary factor influencing fatigue life. Moreover, adhered powder on surfaces can create small notches in material and serves as potential crack initiation sites.
Given that surface topology is a critical factor for fatigue behavior, optical and tomographic measurements were used to characterize it, before performing axial, torsional and combined cyclic loading. Furthermore, we show how factors like width, high-stress concentrations, coupled with adhered powder notches and gaseous process lead to a decrease in fatigue life.

Multiscale mechanical testing of hybrid additively manufactured 420 stainless steel

Avegnon Kossi Loic (1) (2), Henry Ronan (1), Sealy Michael (2), Keller Clément (3), Barbe Fabrice (1), Vieille Benoit (1)

1 - Institut national des sciences appliquées Rouen Normandie (France), 2 - School of mechanical engineering, Purdue Unviersity (United States), 3 - Laboratoire Génie de Production (France)

Speaker: Avegnon Kossi Loic. **Monday**. Start time: **14:20**. Room: Audi Pasteur LVL1. Link to abstract.

While additive manufacturing (AM) generally involves building components layer by layer, the term 'hybrid AM' refers to a process that combines printing with a secondary process such as machining or surface treatments. This approach enables the manufacturing of parts with complex geometries, tailored microstructures, and enhanced mechanical properties that are difficult to achieve with AM alone. In this context, printing was combined with interlayer laser peening of individual layers. Laser peening is a cold working surface treatment technique known for improving fatigue life through strain hardening and microstructure refinement. The hybridization of AM through interlayer laser peening is an effective approach to control grain size from printing, which enhances material properties by impeding dislocation motion at grain boundaries (1) or by a local strain hardening. By selectively incorporating laser-peened layers, it becomes possible to create architected materials with tailored mechanical properties. Despite this potential, the interplay between macroscopic and micro/nano properties remains unexplored. In addition, the alternation between printing and peening introduces complex thermal effects and microstructural variations in each layer, which are not yet well understood. The aim of this study is to understand the link between macro-, micro-, and nanoscale properties of interlayer peened 420 stainless steel. The resulting changes from cyclical printing and peening were characterized across multiple length scales, using macroscopic compression tests to assess overall mechanical properties, and locally via micropillars to evaluate small-scale behavior. It was revealed that though as-printed samples were tougher, interlayer laser peening increased ductility at the macroscopic level, with local gradients in mechanical properties observed across the build height. Knowledge of the texture created from interlayer peening will be further evaluated by examining the role of peened layers on the fracture behaviour of hybrid specimens, building on previous research conducted on as-printed samples (2). Understanding the structural architecture created by interlayer peening constitute a first step towards establishing a model linking manufacturing parameters to mechanical properties and optimizing peened layer placement in hybrid AM.

Optimizing Lightweight Stainless Steel 316L Structures via Material Extrusion Additive Manufacturing (MEAM)

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1 - Laboratoire de Mécanique, Multiphysique, Multiéchelle - UMR 9013 (France), 2 - Centrale Lille (France), 3 - Laboratoire de Mécanique, Multiphysique, Multiéchelle - UMR 9013 (France), 4 - Centrale Lille (France), 5 - École polytechnique universitaire de Lille (France), 6 - CRITT Matériaux Innovation (France)

Speaker: Badin Sophie or Witz Jean-François. **Monday**. Start time: **14:40**. Room: Audi Pasteur LVL1. Link to abstract.

While extensive studies in Material Extrusion Additive Manufacturing (MEAM) primarily focus on the fabrication and optimization of dense parts, research on lightweight structures remains limited. This is despite the significant potential of additive manufacturing (AM) to revolutionize the design and production of optimized, weight-efficient components, which are crucial for applications in industries such as aerospace, automotive, and biomedical engineering.
This study investigates the mechanical performance of lightweight 316L stainless steel structures fabricated using a MEAM process, leveraging a cost-effective and accessible approach to metal additive manufacturing. A single infill pattern "grid" was selected, with two key variations: (i) changing the infill density while using a single wall and (ii) varying the number of walls while fixing the infill density. The primary objective was to assess whether, for parts of equivalent mass, prioritizing wall count or infill density yields superior mechanical performance, offering insights into the structural optimization of lightweight components. Unlike topology optimization, which requires redesigning parts from scratch, this approach offers the advantage of leveraging existing industrial part libraries without requiring complete reconceptualization.
Mechanical testing was conducted using three-point bending tests, providing macro-scale analysis of force-displacement curves to evaluate stiffness, strength, and failure behavior. At the meso-scale, detailed deformation analysis was performed using digital image correlation (DIC) with the DISFlow algorithm, capturing localized strain.
The results indicate that, for components of equivalent mass, increasing the wall count consistently results in superior mechanical properties compared to increasing the infill density. These findings emphasize the importance of wall-dominated designs for lightweight structures where bending loads are significant. The DIC results also highlighted the limitations of existing modeling approaches for lattice structures, underscoring the need for the development of new, efficient computational models capable of rapidly and accurately predicting the mechanical behavior of additively manufactured architectures. Finally, a significant finding of this study was the establishment of a link between the local second moment of area and crack initiation, demonstrating how local geometric parameters influence mechanical performance and failure mechanisms in lattice structures.

Properties of 7075 aluminium chips deposition produced by multi-layer friction surfacing

Jadot Matthieu (1), Lezaack Matthieu (1), Simar Aude (1)

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Speaker: Jadot Matthieu. **Monday**. Start time: **15:00**. Room: Audi Pasteur LVL1. Link to abstract.

The solid-state additive manufacturing process of multi-layer friction surfacing is ideal for building three-dimensional parts from high-strength precipitation-hardened 7075 Aluminium chips. This process can be efficient for aluminum recycling, bypassing the resource-hungry recycling fusion process and maintaining material properties despite the use of chips as raw material. The current study shows that the fully softened chips provide high deposition density. The microstructure retains the elements as the original 7075 aluminium alloy. Thanks to the knowledge already acquired with dense rods, hardening precipitation can be restored with post-T6 heat treatment. This implies a significant improvement in microhardness, effects on microstructure and mechanical properties.

Compensating for distortions in architected microstructures 3D printed by two-photon polymerization

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1 - Laboratoire de Mécanique des Solides (LMS) (France)

Speaker: Bodelot Laurence. Keynote. **Monday**. Start time: **16:00**. Room: Audi Pasteur LVL1. Link to abstract.

Two-photon polymerization (2PP) is an additive manufacturing technique exploiting two-photon-absorption-induced photo-polymerization to fabricate three-dimensional complex geometries at the micrometric scale. Applications span various fields from photonics to bio-scaffolds to microrobotics. Unfortunately, even when using ultra-low-shrinkage polymeric resins, distortions occur, which compromises the dimensional fidelity and expected performance of the printed structures. In nano-mechanics, this lack of fidelity results in discrepancies between experimental results and numerical simulations and, so far, the most widely adopted workaround entails consideration of the distorted geometry rather than the intended one as an input for simulation. This work aims at compensating for such distortions so that the printed objects match the initially intended geometries. Hence, the physical sources of the distortions arising in 2PP 3D-printed structures are carefully examined. A primary distortion (due to a refractive index mismatch between the immersion medium of the objective and the polymeric resin) causes an overall stretching, whereas a secondary distortion (related to a saturating voxel growth during hatching and slicing) leads to an additional thickness on individual features within a structure. Two prints are thus devised to evaluate the stretching factor and saturated voxel height, and a straightforward technique is proposed to pre-compensate for distortions in the initial design of a structure. Finally, this methodology is shown to successfully eliminate all distortions in complex structures such as lattices and triply periodic minimal surfaces (TPMS).

Dynamic compression of additively manufactured architected materials

Lavigne Lea (1), Ramakrishnan Karthik Ram (2)

1 - Polytech Montpellier (France), 2 - Bristol Composites Institute (United Kingdom)

Speaker: Ramakrishnan Karthik Ram. **Monday**. Start time: **16:40**. Room: Audi Pasteur LVL1. Link to abstract.

Architected materials produced through additive manufacturing offer unparalleled advantages. This technique enables intricate designs and customizable structures, optimizing material distribution for enhanced strength, weight reduction, and functionality. By precisely layering materials, it allows for geometric complexities that traditional manufacturing methods cannot achieve. One of the family of structures that were previously unachievable through traditional machining but realised by AM, is lattice structures. This category of structure including gyroid, octet truss, re-entrant honeycomb are classified based on their geometry, material, and intended functionality. Each lattice type showcases unique characteristics like energy absorption, compression, and shear resistance in applications ranging from lightweight components to impact-absorbing structures. The Gyroid lattice features interconnected, curved lines, offering optimal strength and minimal material usage. Diamond lattice presents a balanced combination of strength and space efficiency, ideal for load-bearing applications. This study focuses on two different lattice structures made with a thermoplastic polyurethane: the triply periodic minimal surface (TPMS) called Schwarz "D" or more commonly diamond and the re-entrant structure. Re-entrant honeycomb are auxetic cellular structures that exhibit negative Poisson's ratio so that, unlike regular cellular structures, they show lateral shrinkage upon axial compression. This project used a combined experimental and numerical approach to study the mechanical behaviour of two lattice structures fabricated using Additive Manufacturing. The material chosen is Thermoplastic Polyurethane (TPU) (EOS TPU 1301) manufactured using Selective Laser Sintering. TPU is commonly used in 3D printing and injection molding, and finds applications in automotive components for impact absorption, medical devices due to biocompatibility, footwear, flexible seals and gaskets, protective cases for electronics, and sportswear for stretchable and resilient fabric. TPU's unique blend of mechanical properties and processability makes it indispensable in various industries seeking robust yet flexible materials for their energy absorption capacity. Quasistatic and dynamic compression tests were conducted using a universal tester and drop tower respectively. Full field imaging techniques were used to to analyse the kinetics of the deformation. MatchID 2D software was used to quantify displacements and strains in materials thanks to the digital image correlation technique. The quasistatic testing was conducted in a universal testing machine (Shimadzu autograph AGS-X). Both structures were first tested under a 10 kN maximum load capacity but as the maximum force measured during the first test for the re-entrant structure is under 1 kN, the setup was changed for this structure under a 1 kN maximum load. The image acquisition frame rate for these experiments is set at 1 frame per second while the tests usually lasts about 5 minutes. The dynamic testing was conducted in a drop weight impact testing machine (Instron 9450). The setup for this experiment included a high speed camera and a set of two leds in order to get the highest resolution possible for DIC. The tests duration are both about half a second so the high speed camera frame rate set is 20,000 frames per second. The DIC analysis allows the discussion of the folding happening for the diamond or the collapse of the struts for the re-entrant for instance but it can also measure the strain within each structure. In quasi-static compression, the deformation rate being very slow, the structure has time to respond to the load and to dissipate energy progressively. This leads to a more uniform deformation process. Dynamic compression is characterized by extremely rapid deformation rates. The energy does not have enough time to be dissipated in the structure, hence a less predictable deformation organized in layers. When the drop tower impacts the structure, kinetic energy is transferred to the structure and converted into other forms of energy such as deformation energy or vibration and resonance. Another part of the impact energy could also be reflected and may cause the impacting object to bounce off the structure with a portion of the original energy. To determine which structure would exhibit better absorption capabilities, displacement alone is not sufficient. It is essential to compare force-displacement curves, since the energy absorption (EA) corresponds to the surface below the force-displacement curve, in other words, its integral. Finite element models were created using Abaqus software and a stochastic model was created using Python scripting to account for the variability in material properties introduced by additive manufacturing. TPU behaviour is considered hyperelastic. Hyperelastic materials exhibit

only a non-linear elastic behaviour, meaning that the material returns to its initial shape when the stress is removed. They have the ability to experience a large deformation without considerable permanent deformation after load is removed. This type of behaviour can be characterised by the strain energy potential and can be modelled with many different forms (polynomial, Ogden, Arruda-Boyce etc..). The model retrieved for the TPU from is a polynomial form called Mooney-Rivlin. The Python code takes the input file from Abaqus and different arguments. The code takes the information for the material that needs to be modified and writes copies partly modified. For this present work as a first intention, only the Young's modulus is altered but it can be easily be modified to be the yield strength as it is intended to work on elasto-plastic materials. From the arguments information, the name of the part concerned allows to get the number of elements and to distribute them normally and randomly into elements sets that are each assigned a section with a unique material defined before. The results show that the introduction of material uncertainty with the stochastic model reduced the properties of the lattice structures. For the same mean Young's modulus, the stochastic model's response is definitely different and the resulting reaction force is below for the whole displacement. This behaviour is what was expected in the first place when seeing the weakened behaviour of AM structures. However as it is a random distribution, it would be more accurate to run several stochastic models with the same distribution parameters in order to get a mean response and not an isolated one. The validation of the numerical model by comparison with experimental data shows that there is still significant work required to have a good correspondence. By integrating advanced material models based on intricate geometries and microstructures, simulations can replicate the intricate stress distribution, deformation, and failure mechanisms. This enables a deeper understanding of how architected materials respond under various conditions, guiding design optimization and performance prediction. With refined material models, engineers can fine-tune the composition and arrangement of structures to match real-world behaviour.

Compression and shear performance of pyramidal lattice structures with I-beam struts

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Speaker: Schiffer Andreas. **Monday**. Start time: **17:00**. Room: Audi Pasteur LVL1. Link to abstract.

Pyramidal lattice (PL) structures are widely regarded as excellent choices for core materials in sandwich structures due to their low density, high weight-specific shear strength, and the ability to absorb kinetic energy in the event of an impact or blast. However, their response is generally bend-dominated, which greatly limits their strength and stiffness under compression and shear loading, particularly at low relative densities. Since the flexural stiffness and strength of a strut in the PL depends on the size and shape of the strut cross-section, it is anticipated that modifications in the shape of the strut cross-section alone could lead to a significant improvement in mechanical performance.

To investigate potential performance enhancements resulting from the incorporation of rationally designed strut cross-sections in bend-dominated lattices, this study investigates the quasi-static mechanical response of PL sandwich cores with I-beam cross-sections. These novel PL structures are 3D printed using the Digital Light Processing (DLP) technique, allowing for precise geometrical adjustments at the sub-mm scale. The elastic modulus, strength and energy absorption of the tailored PL structures are evaluated under out-of-plane compression and shear loading and are compared to the results obtained for non-tailored PL structures with square strut cross-sections. Additionally, detailed finite element (FE) calculations are performed to examine underlying collapse mechanisms and explore the vast design space offered by the cross-sectional tailoring scheme. The experimental and numerical results reveal that the tailored PL structures with I-beam struts exhibit superior performance under both compression and shear loading compared to their non-tailored counterparts of equal relative density. In compression, the integration of I-beam struts leads to considerable enhancements in elastic modulus, strength and energy absorption of 24%, 21% and 68%, respectively. Specifically, the improvements in the collapse strength are attributed to the occurrence of an unusual lateral buckling mode, causing the I-beam struts to bend sideways and thus delaying the onset of structural collapse. It is also demonstrated numerically that specific cross-sectional designs can achieve improvements in compressive strength and energy absorption of up to 93% and 161%, respectively, as compared to a conventional pyramidal lattice with equal relative density. Under shear loading, the enhancements in modulus, strength and energy absorption are less pronounced, reporting 13%, 11% and 24%, respectively. This is because shear loading causes the PL struts to undergo unsymmetric bending which requires cross-sections with high resistance against bending in all directions. Additionally, a simple analytical model is developed to predict the stress distribution in the lattice struts under shear loading and the onset of brittle fracture, accurately capturing the shear strength enhancements predicted by the FE models.

The findings of this study demonstrate the effectiveness of cross-sectional tailoring in enhancing the mechanical properties of truss lattices. Notably, these insights hold significance for the design of lightweight lattice-cored sandwich structures for advanced applications within the aerospace and defense sectors.

A new process for designing wooden structural elements using additive manufacturing

Mingondza Sarah (1), Audonnet Fabrice (2), Charlet Karine (2), Pambou Nziengui Claude Feldman (1), De Baynast Hélène (2), Buissiere Pierre-olivier (2), Moutou Pitti Rostand (3) (4) (5)

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Speaker: Moutou Pitti Rostand. **Monday**. Start time: **17:20**. Room: Audi Pasteur LVL1. Link to abstract.

As a part of CAP 2025 Emergence program, this exploratory study develops an innovative process for creating wood-based raw materials with enhanced mechanical properties for additive manufacturing applications in construction and mobility devices. The materials, composed of high wood-content pellets or filaments, are derived from temperate softwoods (white fir) and hardwoods (beech), including hybrid mixtures, bonded using a patented wood-sourced and/or biodegradable resin developed in the laboratory. Commercial PLA serves as a benchmark for comparison.
Structural elements are fabricated and tested under various mechanical conditions, including four-point bending, shear, and crack propagation under mixed-mode loading using Compact Tension Shear (CTS) and Mixed Mode Crack Growth (MMCG) specimens. Using these advanced test setups, key mechanical properties such as flexural modulus, shear modulus, fracture stress, and critical energy release rates are calculated and compared. A specially designed extruder enables the homogenization of these bio-sourced compounds into filaments or pellets suitable for 3D printing. Thermal analyses (DSC, TGA) complement these mechanical tests by providing insights into the material's processing behavior and its influence on mechanical performance.
This work demonstrates the mechanical performance potential of eco-friendly materials for structural applications in construction and mobility, setting the stage for sustainable and innovative engineering solutions.

A PINN-based domain decomposition method for the optimal design of additively manufactured lattice structures

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Speaker: Cadart Thomas. **Monday**. Start time: **17:40**. Room: Audi Pasteur LVL1. Link to abstract.

While the rise of additive manufacturing techniques has made it easier to produce complex lattice structures, optimizing their designs for specific applications remains challenging, and requires advanced numerical simulations. Homogenization-based multiscale methods struggle with insufficient scale separation, while directly applying standard numerical methods to the full fine-scale problem is often computationally intensive. Design optimization exacerbates the computational challenge, as it involves numerous successive simulations to enhance the structures effectively. Recent research aims to address this challenge by employing multiscale topology optimization, although the persistent issue of scale separation still limits its effectiveness. Alternatively, a new class of approaches has emerged which combine domain decomposition methods together with pre-train models.

In this context, we develop a Physics-Informed Neural Network (PINN) based domain decomposition method. We straightforwardly decompose the lattice into unit cells and employ a primal domain decomposition approach which consists in solving interface problems where only the displacements at the cell connections are involved: a technique known as Balanced Domain Decomposition (BDD). To efficiently handle the local sub-problems to be solved, we constructed a PINN that learned the relationship between boundary displacements and reaction forces of shape-parameterized unit cells. By leveraging the pre-trained PINN within our domain decomposition framework, we not only obtain a fast solver, but also a fast optimization procedure as the relationships between the unit cell geometry and its mechanical behavior have been explicitly discovered during the training phase.
During the talk, we will illustrate how this approach facilitates the optimal design of additively manufactured lattice structures for specific applications.

Impact of structural disorder on the micromechanical behavior of shell-based micro-architected metamaterials

Groetsch Alexander (1) (2), Ainger Kate (1), Valdevit Lorenzo (1)

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Speaker: Groetsch Alexander. **Tuesday**. Start time: **10:00**. Room: Audi Pasteur LVL1. Link to abstract.

Architected (meta)materials allow unique structure-mechanical properties that surpass classical engineering materials. Such metamaterials encompass a myriad of material classes and properties that can be tailored to dedicated engineering applications yielding new opportunities in various technological fields. With the aim to create bio-inspired metamaterials, recent efforts target to harness characteristic features omnipresent in nature: heterogeneity, randomness and disorder. Objectives include stress delocalization, defect insensitivity and increased ductility. Advances in additive manufacturing now enable us to synthesize micro-architectures with nanoscale features necessary to replicate the internal structural complexity in such bio-inspired architected materials. In this study, we outline how we can control the degree of disorder in micro-architected metamaterials ranging from periodic to random topologies with the aim to tailor their microscale elasto-plastic behavior. We use shell-based topologies due to their superiority regarding energy absorption, strength and stiffness at a low weight. Arrays of polymeric micro-architectures featuring 11 different degrees of randomness were 3D-printed using two-photon lithography (Photonic Professional GT2, Nanoscribe, Germany). For a selection of these architectures, we also varied the relative density. *Pre-* and *post*-test imaging was done with a high-resolution SEM (Tescan, CZ) and the effect of disorder on the micromechanical behavior quantified by *in situ* experiments using a portable nano-indenter (FemtoTools, CH) integrated into an SEM. Uniaxial micro-compression tests were performed displacement-controlled and at a quasi-static strain rate (10-3 s-1) up to an engineering strain of 50%. Mechanical properties such as Young's modulus, yield strength and energy absorption were extracted using a custom-written Python code. Results show that transitioning from periodic to random architectures leads to a reduced yield strength but a highly homogeneous deformation, characterized by a lack of softening, a prolonged plastic plateau and stress-delocalization. For the micromechanical behavior and all mechanical properties, including energy absorption, we observe two clusters of data with distinct differences. Our data also suggest that the effect of disorder is disguised at higher relative densities. Using nanoscale resolution 3D printing while controlling the degree of disorder of micro-architectures creates new opportunities for highly multifunctional (meta-)materials.

Mechanical characterization of architected materials with tunable disorder

Di Brizzi Diego (1), Marino Tommaso (2), Micoli Laura Loredana (1), Pugliese Raffaele (3), Graziosi Serena (1)

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Speaker: Di Brizzi Diego. **Tuesday**. Start time: **10:20**. Room: Audi Pasteur LVL1. Link to abstract.

Because of the relative simplicity of their design, ordered and periodic arrangements have been widely used for years to generate architected materials. However, the design space of metamaterials is virtually infinite and can go well beyond the standard non-stochastic arrangement. To allow designers to explore such a design space, its complexity must be mastered, and relations concerning how to correlate the material arrangement with its properties must be identified. Structures based on the periodic repetition of a single unit cell constitute the maximum level of complexity reduction, as the architected material's overall properties depend on the features of the single building block used to generate it (1). Throughout the years, the possibilities offered by a plethora of different unit cells have been explored, generating many design possibilities, all characterized by different parametrizations of the building blocks they are based on. Each has then been correlated with the set of properties that could be obtained by tuning their design parameters (2).

Despite the many possibilities offered by such an approach, in recent years, interest has been witnessed in developing architected materials whose design could go beyond the conventional repetition of a unit cell. Recent advances in generative Machine Learning (ML) technologies and computational design have provided powerful tools that can be coupled with designers' intuitions for obtaining unprecedented levels of accuracy in the correlation between geometrically complex design spaces and their relative properties (3). ML algorithms can manage structures whose intricacy goes well beyond that of ordered ones, which in nature only constitute a set of limited cases. ML algorithms can then be used to generate and study the properties of architected materials whose geometry is closer to those available in nature (4).

Recent studies in the field of irregular disordered geometries have highlighted the superior behavior exhibited by structures characterized by heterogeneous topologies. Similarly to naturally formed structures (such as trabecular bones, bird beaks, or turtle shells), irregularly architected materials exhibit isotropic behaviors and especially high resistance to the presence of local defects. These two properties are rarely witnessed with conventionally ordered metamaterials because of the strong correlation between the unit cell (and the direction of its periodic repetition) and the overall properties of the structures. It is then deemed fundamental that newer properties, closer or surpassing that of natural materials, are added to the repertoire of behaviors that can be obtained with metamaterials (5,6).

Among the many design solutions for disordered architected materials developed throughout the years, one of the most used approaches is based on the employment of the Voronoi tessellations to generate truss-based structures. Studies on irregular Voronoi-based structures have shown that they can exhibit isotropic behaviors and that the impact of local defects on their mechanical responses is hindered by the irregularity of their geometry. This is why Voronoi tessellations were used to build an architected materials generation framework that could include both ordered and disordered designs to push the boundaries of the set of obtainable properties to include the largest amount of behaviors possible (5,7,8).

To obtain such a defined design space, the parametrization was based on controlling the degree of disorder of the structures. Starting from a perfectly ordered periodic distribution of the Voronoi tessellation seeds, a controlled and parametrized perturbation to the seeds' positions can be applied to generate irregular structures. Consequently, the perturbation level applied to the structures could be used as a parameter to allow continuous shifting from ordered to disordered designs. Other parameters are included in such a design framework. Control over other geometric features of the structures was also included to extend the number of tunable properties. Specifically, the possibility of replacing trusses with nonlinear beams was added to the framework. The pre-perturbation seeds' distribution was tuned with a geometric parameter. This way, the presence of non-convex cells was ensured, and the variability of generated geometries was broadened.

To assess the properties of the generated design space, the compressive behavior of a set of structures created using this approach was explored through finite element simulations and experimental tests per-

formed first on 2.5 D structures. A direct correlation between the degree of disorder and the mechanical properties, such as stiffness and Poisson ratio, was obtained. As could be expected because of their similarity with natural structures, disordered ones also exhibit enhanced failure resistance under compression, mainly because of the deformation mechanism on irregular and non-convex cells. The shape and the connectivity of the cells proved to be highly relevant aspects that influence the failure of the structure.
The presentation will start by introducing the proposed design framework and will continue detailing the numerical and experimental results obtained on the 2.5 D structures. Finally, it will discuss the preliminary considerations performed on how this framework could be extended to allow the generation of 3D disordered structures.

Keywords Disordered structures, Mechanical metamaterials, 2.5D structures, Poisson's ratio

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Defect sensitivity of architected random cellular materials produced by LPBF

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Speaker: Leonardi Selma. **Tuesday**. Start time: **10:40**. Room: Audi Pasteur LVL1. Link to abstract.

Metallic cellular materials with heterogeneous pore features are used in many branches of technology, from lightweight structures to biomedical implants and electrodes. These materials derive their properties from their internal architecture, which can now be precisely-controlled via advanced mfabrication techniques such as additive manufacturing.
Despite the geometrical complexity enabled by additive manufacturing, the produced cellular mesostructures often deviate from their nominal design, and may contain a variety of manufacturing defects within the matrix. Defects, in turn, affect the resulting properties, which differ significantly from the targeted ones. This issue is common to a large number of architected materials and is exacerbated in metallic lattices, which may exhibit variations in strut geometry, size and waviness alongside density defects.
Here, we study the defect sensitivity of architected cellular materials with random pore distributions. Specifically, the materials of this work contain cylindrical pores randomly dispersed into an AlSi10Mg matrix and are fabricated by Laser Powder Bed Fusion (LPBF). Their porous architecture is generated numerically by a Random Sequential Absorption (RSA) algorithm prior to fabrication.
Using Digital Image Correlation (DIC) combined with extensive microstructural analyses, we investigate how defects affect the elasto-plastic response of these materials in compression. Notably, we quantify the influence of a random arrangement of pores, combined with density defects, on the mechanisms of strain localization, and show that the latter ones differ remarkably from those observed in periodic metallic lattices.

Investigation of lattice TPMS structures between low and high-speed rate compression

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Speaker: Mondelin Pierre. **Tuesday**. Start time: **11:00**. Room: Audi Pasteur LVL1. Link to abstract.

The aerospace industry has been interested in metal architected structures for many decades. Starting with metal foam (aperiodic pattern) in the 60's and honeycomb (2D pattern, extruded), metal additive manufacturing (AM) pushes the limit further with 3D periodic structures, often called lattices.
Characterized by their lightweight yet strong composition, periodic lattices are made up three different parameters: pattern nature, density and cells size. According to Yin et al (1), lattice patterns are divided into two families (2D pattern and 3D pattern) with 4 categories include in the 3D one (truss-based, plate-based, shell-based and hierarchical). These lattices are mainly studied for their mechanical properties and energy absorption.
In the literature, mainly since a decade, different types of lattices are tested in quasi-static compression for different materials (polymers, metals and mostly 316L). Al-Ketan et al (2) shows (on metal lattices) that shell-based lattices have a higher plateau stress than any other 3D categories (in quasi-static compression). The TPMS (Triple Periodic Minimal Surface) subcategory of 3D shell-based appears to be a better candidate for energy absorption due to a further densification point.
The literature also point out the role of the density and the cell size on the energy absorption capacity (see for example Mishra et al (3) and Yin et al (4)).
The vast majority of the experimental results previously discussed have been obtained for quasi-static loading rates. Only few studies deal with the response of such structures at high loading rates.
Therefore, this study will focus on dynamic loading rates effects on TPMS lattices. Three TPMS are studied: Primitive, Gyroid and Diamond. The samples are printed using Additive Manufacturing (LPBF technology) and Inconel 718 powder.
Each sample has a cell size of 5mm, with a repetition of 3x3x6 cells and a 25% density for a good printed thickness.
In this communication, quasi-static and dynamic effects for TPMS structures loading will be experimentally compared. The strain localization process is analysed with stereo-graphic imaging and local stereo digital correlation in order to detect dynamic inertia as Singh et al (5) pointed out from numerical results.
Our first experiment was with three different TPMS on quasi-static's loading rate. A comparison of stress plateau heights shows that the Gyroid and the Diamond dominate. Calculating the energy absorption from the experimental curves shows that the Gyroid at 93 J.m-3 outperforms the Diamond at 92 J.m-3.
The corresponding non-linear Finite Element numerical model is under progress in order to compare their prevision with the experimental results.

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(4) Hanfeng Yin, Crushing behavior and optimization of sheet-based 3D periodic cellular structures, 2020
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Rate-dependent compressive properties of 3D printed copper microarchitectures with tunable microstructure

Ding Kuan (1), Kang Sung-gyu (2), Bhaskar Lalith Kumar (1), Schürch Patrik (3), Koelmans Wabe (3), Dehm Gerhard (1), Ramachandramoorthy Rajaprakash (1)

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Speaker: Ding Kuan. **Tuesday**. Start time: **11:20**. Room: Audi Pasteur LVL1. Link to abstract.

3D printed metallic microarchitectures have the potential to be applied in lightweight packaging to protect sensitive components for micro-/nanoelectromechanical systems or microelectronics. The recently developed localized electrodeposition in liquid (LEL) technique enables printing copper microarchitectures with high precision and 3D geometrical freedom. The LEL technique utilizes a silicon based hollow microcantilever with an orifice to deliver metal ions under controlled pressure into an electrochemical cell. The metal ions are locally reduced and microscale metal dvoxels are deposited with high spatial resolution on a conductive substrate. Complex metal geometries such as micropillars, microlattices, and microsprings have been successfully fabricated using this technique. Here, we present the effect of printing parameters (pressure and voltage) on the microstructure of 3D printed metal microarchitectures. The microstructure characterization by electron backscatter diffraction (EBSD) unveils the correlation between grain size and the printing parameters. The key focus of the presentation will be on the mechanical performance of metallic microarchitectures and their dependence on both the architecture and microstructure. The micromechanical properties of the microarchitectures were analyzed using *in situ* compression testing inside a scanning electron microscope (SEM). Copper micropillars printed using LEL with microcrystalline and ultrafine-grained (UFG) microstructure exhibit significant differences in strength and deformation mechanism (1). Specifically, the UFG copper micropillars show a strain rate sensitivity that's three times higher than the microcrystalline counterparts and show a unique saturation in yield stress beyond a strain rate of 0.1/s. More complex copper microlattices with octet and honeycomb architectures with UFG microstructure show excellent energy absorption properties under compression at a wide range of strain rates (0.001/s till 100/s) and temperatures (-150 ∘C till 25 ∘C) (2). Finally, the impact of our current study on utilizing metallic microarchitectures as highly localized lightweight packaging for protecting sensitive micro/nanocomponents will also be discussed.

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Automated discovery of reprogrammable nonlinear dynamic metamaterials

Bertoldi Katia (1), Bordiga Giovanni Vincent Tournat

1 - Harvard John A. Paulson School of Engineering and Applied Sciences (United States)

Speaker: Bertoldi Katia. Keynote. **Tuesday**. Start time: **14:15**. Room: Audi Pasteur LVL1. Link to abstract.

Harnessing the rich nonlinear dynamics of highly deformable materials has the potential to unlock the next generation of functional smart materials and devices. However, unlocking such potential requires effective strategies to spatially engineer material architectures within the nonlinear dynamic regime. Here we present an inverse-design framework to discover flexible mechanical metamaterials with a target nonlinear dynamic response. The desired dynamic task is encoded via optimal tuning of the full-scale metamaterial geometry through an inverse-design approach powered by a fully differentiable simulation environment. By deploying such a strategy, mechanical metamaterials are tailored for energy focusing, energy splitting, dynamic protection and nonlinear motion conversion. Furthermore, our design framework can be expanded to automatically discover reprogrammable architectures capable of switching between different dynamic tasks. For instance, we encode two strongly competing tasks- energy focusing and dynamic protection-within a single architecture, using static precompression to switch between these behaviours. The discovered designs are physically realized and experimentally tested, demonstrating the robustness of the engineered tasks. Our approach opens an untapped avenue towards designer materials with tailored robotic-like reprogrammable functionalities.

Inverse designing three-dimensional metamaterials with programmable nonlinear responses in graph space

Maurizi Marco (1), Zheng Xiaoyu (rayne) (1)

1 - University of California [Berkeley] (United States)

Speaker: Maurizi Marco. **Tuesday**. Start time: **14:55**. Room: Audi Pasteur LVL1. Link to abstract.

The rapid development of additive manufacturing technologies has enabled the fabrication of truss metamaterials, i.e., a novel class of lightweight-yet-strong materials with engineered complex hierarchical structures. Manipulating the architecture over chemical composition dramatically expands the achievable materials design space, allowing to largely control the mechanical response of metamaterials. While methods such as topology optimization and machine learning have demonstrated to be powerful tools to discover structures with desired material properties, designing three-dimensional (3D) complex truss metamaterials with programmable mechanical behaviors is still a challenge. Here we propose a paradigm, based on graph neural networks (GNNs) and deep reinforcement learning, to design 3D truss metamaterials with programmable nonlinear quasi-static and dynamic responses. By combining the ability of our GNN-based model to accurately predict the mechanical response across multiple orders of magnitude and the explorative power of deep reinforcement learning, together with numerical simulations and mechanical testing, we inverse design truss metamaterials for compressive loading up to 30 % of strain and dynamic transmissibility with desired band gaps. Our method not only demonstrates a pathway to design mechanical metamaterials with desired mechanical behaviors but also provides a flexible framework that can be applied to tailor the response of 3D photonic or robotic metamaterials.

Image-based tracking of the crack propagation within regular and irregular architected materials

Lingua Alessandra (1), Sanner Antoine (1), Hild François (2), Kammer David (1)

1 - Institute for Building Materials, ETH Zürich (Switzerland), 2 - Ecole Normale Supérieure Paris-Saclay (France)

Speaker: Lingua Alessandra. **Tuesday**. Start time: **15:15**. Room: Audi Pasteur LVL1. Link to abstract.

Architected materials offer disruptive opportunities to combine low density with high toughness or strength. Tuning their architecture allows for further unlocking of features not intrinsic to the base material, such as negative Poisson's ratio, local toughening, and ultra-stiffness. Due to the reduced slenderness of lattice struts, it is challenging to characterize and predict how engineering the topology of lattice materials alters the local stress state and modifies their macroscopic failure. We propose an approach based on digital image correlation (DIC) to unravel the damage nucleation and propagation mechanisms of 2D lattices under mode I loading. To identify the dominant strut failure modes, we 3D-printed compact tension specimens with stretching and bending-dominated topology (triangular, hexagonal, and Kagome). Using FE-based DIC, we measured the nodal displacements of the joints and extracted the strain distribution within the struts by sub-lattice scale meshing. Based on the gray level residuals, we determined failure criteria for the strut in terms of strain thresholding, and we tracked the crack propagation. By using integrated DIC, the fracture toughness and energy release rates were obtained by a priori knowledge of the detected crack path. Leveraging these local measurements, we assessed the influence of heterogeneities on the lattice strain distribution and thus damage nucleation and propagation mechanisms, resulting in increased work to failure. Ultimately, we highlight how image-based characterization approaches enlighten the effects of the topology and its alterations on the local fracture behavior of lattice materials and provide realistic failure criteria for numerical damage modeling. This insight is essential to design architected materials with engineered properties and customized fracture behavior for real-world applications.

AI-driven optimization of heterogeneous structures in LPBF-fabricated Al-Cu-Mg aluminum alloys for enhanced mechanical performance

Zhou Changshan (1), Kang Nan (2), El Mansori Mohamed (3)

1 - Mechanics surfaces and materials processing (France), 2 - Mechanics surfaces and materials processing (Centre Arts et Métiers ParisTech 2 cours des Arts et Métiers 13 617 Aix en Provence France), 3 - Mechanics surfaces and materials processing (Centre Arts et Métiers ParisTech 2 cours des Arts et Métiers 13 617 Aix en Provence Centre Arts et Métiers ParisTech Rue Saint Dominique B.P 508 51 006 Châlons-en-Champagne Centre Arts et Métiers ParisTech 8 boulevard Louis XIV 59 046 Lille Cedex France)

Speaker: Zhou Changshan. **Tuesday**. Start time: **15:35**. Room: Audi Pasteur LVL1. Link to abstract.

The use of artificial intelligence (AI) to regulate the heterogeneous structure of materials in order to enhance mechanical properties has become a critical area of research in materials science and engineering. By integrating machine learning (ML) and deep learning (DL) techniques, a quantitative relationship can be effectively established between manufacturing process parameters, heterogeneous microstructural features, and mechanical properties. This study proposes a method based on a conditional generative adversarial network (cGAN) to regulate the heterogeneous structure of a new high-strength aluminum alloy, Al-Cu-Mg, using laser powder bed fusion (LPBF) process parameters. The method generates the desired microstructure and further optimizes the mechanical properties, thereby demonstrating the potential of AI in additive manufacturing. This study provides a foundational framework for systematically linking additive manufacturing parameters with microstructure and mechanical properties through AI-driven models. This work not only promotes process optimization and material design but also lays the groundwork for precise microstructure control in a wide range of metal additive manufacturing applications.

Experiment-Informed Finite-Strain Inverse Design of Spinodal Metamaterials

Thakolkaran Prakash (1), Espinal Michael (2), Dhulipala Somayajulu (2), M. Portela Carlos (2), Kumar Siddhant (1)

1 - Delft University of Technology, Department of Materials Science and Engineering (Netherlands), 2 - Massachusetts Institute of Technology, Department of Mechanical Engineering (United States)

Speaker: Thakolkaran Prakash. **Tuesday**. Start time: **15:55**. Room: Audi Pasteur LVL1. Link to abstract.

Spinodal metamaterials, with architectures inspired by natural phase-separation processes, have presented a significant alternative to periodic and symmetric morphologies when designing mechanical metamaterials with extreme performance. While their elastic mechanical properties have been systematically determined, their large-deformation, nonlinear responses have been challenging to predict and design, in part due to limited data sets and the need for complex nonlinear simulations. This work presents a novel physics-enhanced machine learning (ML) and optimization framework tailored to address the challenges of designing intricate spinodal metamaterials with customized mechanical properties in large-deformation scenarios where computational modeling is restrictive and experimental data is sparse. By utilizing large-deformation experimental data directly, this approach facilitates the inverse design of spinodal structures with precise finite-strain mechanical responses. The framework sheds light on instability-induced pattern formation in spinodal metamaterials—observed experimentally and in selected nonlinear simulations—leveraging physics-based inductive biases in the form of nonconvex energetic potentials. Altogether, this combined ML, experimental, and computational effort provides a route for efficient and accurate design of complex spinodal metamaterials for large-deformation scenarios where energy absorption and prediction of nonlinear failure mechanisms is essential.

Language-based deep learning for design of shellular metamaterials

Zheng Li (1), Kochmann Dennis (1), Kumar Siddhant (2)

1 - ETH Zurich (Switzerland), 2 - TU Delft (Netherlands)

Speaker: Kumar Siddhant. Keynote. **Tuesday**. Start time: **16:35**. Room: Audi Pasteur LVL1. Link to abstract.

Shellular lattices are gaining interest in the world of metamaterials, as the absence of sharp intersections in their structural members and the resulting lack of stress concentrations enables superior strength and resilience over the conventional truss- and plate-based lattices. Among shellular lattices, triply periodic minimal surfaces (TPMS) are the go-to designs. They are approximated in closed form via implicit equations containing linear and nonlinear combinations of sinusoidal terms. However, only a handful of ad-hoc TPMS lattices exist (e.g., Gyroid, Schwarz' P Surface, Schwarz' D Surface, etc.). To this end, we broaden the design space by considering all sinusoidal-based implicit surfaces, hence relaxing the minimal surface restriction. This results in a tremendously richer design space. However, the implicit equations defining these surfaces involve varying number of sinusoidal terms and exhibit permutation invariance under addition and multiplication, making finite-dimensional, vector-based parameterization and automated inverse design strategies challenging. Inspired by large language models (LLMs), we introduce a language-based conditional denoising diffusion model for the inverse design of shellular metamaterials with targeted nonlinear stress-strain responses. In this framework, trigonometric terms (e.g., sin x, cos y) and mathematical operations (+, –, *) are tokenized, and each design is represented as a string of tokens (akin to words). The conditional denoising diffusion model is trained to map a given target stress-strain curve to a tokenized string that represents a metamaterial design with the corresponding mechanical properties. Our model achieves high accuracy in inverse design tasks and generalizes well to target properties beyond the training dataset. While this study focuses on the design of shellular metamaterials, such language-based approaches open the possibility of ChatGPT–esque foundational and automated design frameworks for a wide range of metamaterials and functional properties.

Multi-objective shape optimization of architected materials

Bosi Federico (1) (2), Azam Farooq I (1), Tan Pj (1)

1 - University College, London (United Kingdom), 2 - University of Applied Sciences and Arts of Southern Switzerland (Switzerland)

Speaker: Bosi Federico. **Tuesday**. Start time: **17:15**. Room: Audi Pasteur LVL1. Link to abstract.

Architected lattices are a type of metamaterial with distinctive mechanical properties that conventional materials cannot achieve. These properties arise from a carefully designed geometry and/or the combination of different materials. Recent advancements in lattice materials have been supported by the development of small-scale additive manufacturing techniques. These methods allow for precise manipulation of geometric features at the micro and nanoscale, offering greater control over macroscopic properties and enabling the creation of lattices with exceptional mechanical performance. Architected materials, known for their enhanced mechanical and functional properties, are widely used in high-strength lightweight materials, energy storage, and other fields. While traditional periodic lattices usually consist of unit cells with struts (or walls) of uniform cross-section, strategically redistributing material along the length of the struts shows promise in improving the lattice's mechanical behavior, especially in bending-dominated architectures (1).
In this study, we present analytical and machine-learning-assisted approaches for the parametric shape optimization of two- and three-dimensional lattices, aiming to improve stiffness while increasing the plastic and buckling strengths by rationally redistributing the material of regular lattices along the cell walls. First, an analytical multi-objective shape optimization is shown for a two-dimensional bending-dominated hexagonal honeycomb and compared to a finite element-based Bayesian optimization that allows exploration of a wider design space (2). This numerical method is then extended to plate and shell lattices, where a Genetic Algorithm is used to optimize the shape of representative three-dimensional unit cells, highlighting the influence of the bending- and stretching-dominated response on the effectiveness of the material redistribution strategy. Experiments conducted on additively manufactured polymeric and metallic microlattices validate the theoretical predictions and showcase the improvement in mechanical properties achievable through the redistribution of solid material (3).

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Towards the Design of Re-Entrant Auxetic Structures with Magnetoactive Mechanical Behavior: A Hierarchical Experimental and Numerical Investigation

Bharadwaj Prajwal (1), Saidy Kaitlyn (1), Kocharyan Hrachya (2), Yuan Zhangxian (1), Karanjgaokar Nikhil (1)

1 - Worcester Polytechnic Institute (United States), 2 - American University of Armenia (Armenia)

Speaker: Kocharyan Hrachya. **Tuesday**. Start time: **17:35**. Room: Audi Pasteur LVL1. Link to abstract.

Auxetic metamaterials are a class of periodic metamaterials characterized by spatial arrangements of topologically interlinked unit cells capable of counterintuitive lateral deformation under the action of external loads. With the advent of additive manufacturing technology, it is now possible to realize auxetic metamaterials with complex and intricate unit cell designs and to construct architectures composed of combinations of multiple materials with varying mechanical behavior. This fact has been utilized to create adaptive metamaterials that are sensitive to changes in external stimuli such as temperature, pressure, and electromagnetic fields. The parametric nature of the geometric auxetic unit cell leads to the formation of an expansive structure-property design space, which can be exploited to realize auxetic metamaterials with bespoke mechanical behavior. Although several field-driven adaptive metamaterials have been experimentally demonstrated, parametric studies elucidating the effect of the external field on the expansion of the structure-property design space of an adaptive metamaterial are limited. These investigations are crucial in uncovering novel adaptive metamaterial configurations that could be utilized in various engineering fields. In this work, we address this shortcoming through experimental and numerical experiments of a vascular reentrant honeycomb auxetic metamaterial that is composed of magnetorheological fluids. Custom test fixtures are developed to characterize the behavior of these auxetic structures under compressive loading and varying magnetic field strengths. Beginning with the composite struts that constitute the auxetic metamaterial, we develop a simplified analytical model that accounts for the influence of the external magnetic field on the mechanical response of the adaptive auxetic metamaterial. We perform a suite of numerical simulations to explore the expanded field-structure-property design space to uncover the influence of various geometric parameters on the mechanical response of the metamaterial. The presented class of adaptive auxetic metamaterials can find application in energy absorption technologies such as protective armor.

Inverse designing surface curvatures by deep learning

Guo Yaqi (1), Sharma Saurav (1), Kumar Siddhant (2)

1 - Delft University of Technology (Netherlands), 2 - Delft Univeristy of Technology (Netherlands)

Speaker: Guo Yaqi. **Tuesday**. Start time: **17:55**. Room: Audi Pasteur LVL1. Link to abstract.

Smooth and curved microstructural topologies found in nature – from soap films to trabecular bone – have inspired several mimetic design spaces for architected metamaterials and bio-scaffolds. However, the design approaches so far have been ad hoc, raising the challenge: how to systematically and efficiently inverse design such artificial microstructures with targeted topological features? Here, we explore surface curvature as a design modality and present a deep learning framework to produce topologies with as-desired curvature profiles. The inverse design framework can generalize to diverse topological features such as tubular, membranous, and particulate features. Moreover, we demonstrate successful generalization beyond both the design and data space by inverse designing topologies that mimic the curvature profile of trabecular bone, spinodoid topologies, and periodic nodal surfaces for application in bio-scaffolds and implants. Lastly, curvature and mechanics are bridged by showing how topological curvature can be designed to promote mechanically beneficial stretching-dominated deformation over bending-dominated deformation.

Wave guiding in spatially graded on-chip metamaterials

Kochmann Dennis (1), Kannan Vignesh (2), Dorn Charles (3)

1 - ETH Zurich (Switzerland), 2 - Institut Polytechnique de Paris (France), 3 - University of Washington (United States)

Speaker: Kochmann Dennis. **Wednesday**. Start time: **10:00**. Room: Audi Pasteur LVL1. Link to abstract.

We present a new paradigm for microscale wave guidance in metamaterials containing hundreds of thousands of spatially graded unit cells, enabled by recent advances in computational ray tracing and wafer-scale fabrication. Periodic and spatially graded metamaterials have emerged as powerful tools for controlling or suppressing elastic waves by careful engineering of the unit cell to optimize the elastic dispersion relations. However, scalability limits in fabrication have so far unfortunately restricted their realization to small structures, which severely hampers the exploitation of the theoretically available design space. Here, we discuss recent progress on three fronts – a micro-fabrication route for wafer-scale 2D metamaterials, an experimental characterization framework based on interferometry, and optimization of spatially graded structures by computational ray tracing – which jointly enable what was not possible before: the careful design of spatially graded metamaterials with hundreds of thousands to millions of unit cells for the successful guidance of waves along arbitrary paths. We restrict our attention to 2D beam-based metamaterials excited in out-of-plane bending, for which ray tracing allows us to spatially vary a predefined unit cell such as to purposefully adjust the local dispersion relations. The generated computational designs are fabricated from silicon-on-insulator wafers using a process involving photoresist deposition, patterning by exposure to ultraviolet light through a mask, followed by deep reactive ion etching and removal of the buried oxide layer, thereby generating free-standing unit cells in the device layer. The thus-fabricated samples are excited mechanically in out-of-plane bending mode by pulsed-laser excitation, and the resulting out-of-plane displacements are captured by interferometry. We demonstrate that this approach successfully admits the design and fabrication of metamaterials that steer elastic waves along complex paths in 2D. Moreover, we show that the wave guidance capability of those spatially-graded metamaterials is surprisingly broadband, enabling the successful wave guidance across broad frequency ranges.

Fabrication and characterization of Si-based micro-architected metamaterials for elastic wave guiding

Kannan Vignesh (1) (2), Dorn Charles (2) (3), Kochmann Dennis (2)

1 - Ecole Polytechnique (France), 2 - ETH Zurich (Switzerland), 3 - University of Washinton (United States)

Speaker: Kannan Vignesh. **Wednesday**. Start time: **10:20**. Room: Audi Pasteur LVL1. Link to abstract.

Architected materials present an unprecedented design space to control material functionality across length and time scales. Among the range of functionalities available, the control of elastic wave propagation (or "wave guiding") through an architected material is particularly exciting and challenging. An important measure of wave guiding is "dispersion", i.e., the relationship between frequency and wavenumber of waves propagating in the material. In architected materials, dispersion could be affected either by the architecture (structural), or the constituent material (constitutive law). Despite a significant body of literature on this problem, fundamental experimental studies are complex due to limitations in (1) fabricating materials with large number of unit cells (scale separation), (2) exciting and measuring elastic waves with high spatial and temporal resolution (to sample enough points on the dispersion surface), and (3) separating the structural and material effects on wave dispersion. We overcome these limitations through the fabrication of micro-architected materials on a silicon wafer, and characterizing their dispersion behavior using a home-built photo-acoustic pump-probe experiment. We will first discuss our sample fabrication technique from commercially-procured 100 mm Silicon-On-Insulator (SOI) wafers, to free-standing micro-architected "thick" films with over 500'000 unit cells. The choice of silicon ensures linear elastic material behavior. We will then bring these samples to the lab, to characterize dispersion; the experiment involves a pulsed laser source to excite the acoustic wave, and a home-built heterodyne interferometer to measure particle velocities on the sample surface with tens of nanosecond temporal resolution. The resulting data set is used to generate the full spatio-temporal evolution of elastic waves, which we analyze in Fourier space to compute dispersion. Data from periodically-architected samples show excellent agreement with finite element simulations, and demonstrate the ability of the experiment to probe up to the second dispersion mode. We will end the discussion with experimental realizations of computationally-designed spatially-graded architectures for wave focusing, and the potential of this experiment to generate large, automated and high-throughput data sets - invaluable for rigorous data-driven computational design of elastic wave guides.

Asymmetric and anisotropic elasticity of contact-based architected materials

Yastrebov Vladislav (1), Forest Samuel (2), Kondo Djimédo (3)

1 - Centre des Matériaux, MINES Paris - PSL, CNRS UMR 7633 (France), 2 - Mines Paris - PSL (École nationale supérieure des mines de Paris) (60, boulevard Saint-Michel 75006 Paris France), 3 - Institut Jean Le Rond d'Alembert, Sorbonne Université, CNRS (France)

Speaker: Yastrebov Vladislav. **Wednesday**. Start time: **10:40**. Room: Audi Pasteur LVL1. Link to abstract.

Architected materials with internal contacts (1) represent a relatively novel and still underexplored class of materials. In addition to exhibiting specific dissipative properties and path-dependent behavior, these materials possess a distinctive feature: elastic asymmetry (2), i.e., the dependence of elastic constants on the sign of deformation. The organization and orientation of contact interfaces make these materials not only asymmetric but also anisotropic. This combination of asymmetry and anisotropy poses significant challenges in constructing associated homogenized models. However, understanding their behavior can enable intelligent exploration of such properties at the structural scale. Specifically, the unique properties of anisotropic asymmetric - or asymmetrically anisotropic -materials can be utilized to design structures with tailored stress distributions. Furthermore, constructing accurate constitutive models may lead to advancements in continuum damage mechanics, particularly for materials for which the primary source of damage arises from oriented cracks.
Currently, there is no consensus in the existing constitutive models (3,4) on how to effectively account for this interplay of asymmetry and anisotropy. To address this question, our direct numerical homogenization approach, incorporating accurate modeling of contact interactions, enables a critical analysis of existing constitutive models and facilitates the development of a new thermodynamically consistent framework.
The identified constitutive model will be applied to analyze classical solid mechanics problems in both static and dynamic contexts, including a bar under tension/compression, bending, and torsion, as well as a plate with a hole and a notched plate.

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Predicting the domain of linear elasticity of architected materials – focus on symmetries.

Combescure Christelle (1) (2), François M.l.m. (3), Auffray Nicolas (4)

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Speaker: Combescure Christelle. **Wednesday**. Start time: **11:00**. Room: Audi Pasteur LVL1. Link to abstract.

Introduction

Modern engineering challenges have pushed forward the use of architected materials(9) and called for a new branch of material science to be explored. These special materials exhibit unconventional properties directly linked to their geometry. When composed of slender elements, architected materials can undergo large deformations exhibiting geometric non-linearities through buckling or snapping behaviors of the cell walls(8). Furthermore, as any conventional material, their constitutive material could enter its non-linear domain(6). The combination if these two limits define the *domain of linear elasticity* of the architected material(7). This presentation will expose the domains of linear elasticity of various 2D architected materials and relate the symmetry of the domain to that of the parent material.

Method

The domain of linear elasticity is constructed from the intersection of the non-buckling domain of the architected material and the linear elasticity domain of its constitutive material. It is well-known that buckling in architected materials can happen at different scales, especially when working with periodic architected materials(1)(4). Bloch-wave analysis is the appropriate tool for predicting buckling in such periodic materials(2)(5). This presentation will only consider 2D lattice periodic architected materials composed of beam elements that are modelled with Euler-Bernoulli beam theory. Moreover, the method only accounts for isotropic constitutive material and constant cross-section beams but the latter limitation can be lifted. The method could be extended to architected materials composed of plate or shell elements or to more complex modeling of the beam elements(3).

Results

The method has been validated on the classical examples of regular square, triangular and hexagonal honeycombs. The observed bifurcated patterns presented in the literature both numerically and experimentally are predicted by our method and results on the shape of the non-buckling domain can be retrieved.

More interestingly, it is possible to correlate the shape of the domain of linear elasticity with the symmetry of the parent architected materials. Based on several examples, it is observed that the symmetry group of the architected material is partially transferred to the symmetry group of the domain of linear elasticity, when observed in the deviatoric space. This can be explained by a tensorial representation of that domain.

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Elastic Mechanical Cellular Automata

Ten Wolde Malte (1), Bley Eoinlee (1), Bertoldi Katia (2), Farhadi Davood (1) (2)

1 - Delft University of Technology (Netherlands), 2 - Harvard University (United States)

Speaker: Farhadi Davood. **Wednesday**. Start time: **11:20**. Room: Audi Pasteur LVL1. Link to abstract.

Cellular automata are computational frameworks known for their ability to model complex behaviors through simple, discrete rules. These systems consist of unit-cells, each in an 'on' or 'off' state, with states evolving each input cycle based on local interactions with neighboring cells. Elementary Cellular Automata (ECA), a subclass of one-dimensional arrays, are particularly notable for their simplicity and diverse behavior. Translating these rules into mechanical systems presents a novel approach to physical computation. However, developing a scalable and adaptable mechanical framework for accurately implementing ECA rules, such as rule 110, remains a challenge. Here, we present a general framework for realizing elastic mechanical metamaterials representing ECAs using a unified unit-cell design. Each unit-cell uses a bi-threshold logic gate, achieved through a tri-stable mechanism that governs its 'on' and 'off' states, while nonlinear springs handle the interactions between cells, transmitting forces based on the unit-cell's state and its neighbors. By adjusting the stiffness of these springs, different computational rules from ECA can be executed. Our framework provides design instructions for the ECA rules, and enables scalability by simply adding more unit-cells to increase computational capacity. The ability to dynamically modify spring stiffness in situ offers further flexibility, allowing for real-time changes in computation. By harnessing elastic mechanical structures, these mechanical ECAs open new possibilities for embedding computation into materials, paving the way for innovations in self-regulating rule-based systems.

GROUP-THEORETIC APPROACH FOR NONLINEAR PROBLEMS IN ARCHITECTED MATERIALS AVOIDS USE OF IMPERFECTIONS

Triantafyllidis Nicolas (1) (2) (3)

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Speaker: Triantafyllidis Nicolas. Keynote. **Wednesday**. Start time: **14:30**. Room: Audi Pasteur LVL1. Link to abstract.

Many interesting problems in nonlinear mechanics, from classical to more recent, pertain to applications with high initial symmetry: from the buckling of thin walled structures to the morphing in architected materials – the list is long! A common feature of these problems, in addition to their importance for engineering applications, is their great theoretical interest due to the complex bifurcation mechanisms leading to their failure. Unlike the classical Euler column buckling with the widely separated bifurcation points where the post-bifurcation equilibrium paths can be easily found using imperfections in the shape of the different eigenmodes, using imperfections in these highly symmetric structures with complex bifurcation diagrams is confusing and can often lead to erroneous results. The method proposed here is based on the perfect structure and uses the properties of its initial symmetry group to identify and follow the bifurcated equilibrium paths: primary, secondary, tertiary and so on, and for the case of elastic systems, to study their stability. Two different applications will be presented here: the development of folds and creases in an axially compressed elastic half-space, the pattern formation in biaxially compressed circular honeycomb. Time-permitting some additional applications for the thermo-mechanical martensitic transformations in NiTi crystals might be presented.

Modeling a beam with a lattice structure made of bi-modulus material

Morozov Aleksandr (1), Balobanov Viacheslav (2), Khakalo Sergei (3)

1 - Technical University of Berlin / Technische Universität Berlin (Germany), 2 - VTT Technical Research Centre of Finland (Finland), 3 - Aalto University (Finland)

Speaker: Morozov Aleksandr. **Wednesday**. Start time: **15:10**. Room: Audi Pasteur LVL1. Link to abstract.

Recent developments in additive manufacturing technologies make the mass fabrication of functional materials with substructures (mechanical metamaterials) cheaper and economically feasible. Predicting the mechanical behavior of such materials and structural elements becomes a critical issue for engineering science. For this purpose, we used advanced material models based on the so-called generalized continua theory, in particular a strain gradient elasticity (SGE). According to this theory, the substructure is represented by an additional material constant, namely, the length scale parameter. Though the SGE theory for simple isotropic materials is studied quite broadly, there is a place for its extension. Some materials, such as epoxy resins and nylons, used in the stereolithographic manufacturing of metamaterials, demonstrate different elastic responses in tension and compression. In this work, a material model is introduced in the context of SGE taking into account the bi-modulus nature of the manufacturing materials. The Green-Mkrtichian approach to model a bi-modulus material where the form of strain energy depends on signs of principal strains is utilized. With the developed model, the effect of tension-compression asymmetry in a beam with a 2D substructure is studied numerically.

Scaling laws in the elasticity of additively manufactured woodpile lattice structures

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Speaker: Bhaskar Atul. **Wednesday**. Start time: **15:30**. Room: Audi Pasteur LVL1. Link to abstract.

Porous and cellular solids are known to exhibit modulus-porosity relationships resulting from the dominant mechanism of deformation leading to their apparent elasticity (1). The well-known relationship of cubic and quadratic dependence of the apparent modulus of elasticity on volume fraction, for 2D and 3D lattices and open cell foams, respectively, may not be valid for certain lattice geometries even when the deformation is bending dominated. Here we summarise and report some novel scaling results for bending dominated deformation in woodpile lattices that are not in line with these. We present simple mechanics of woodpile structures where the deformation mechanism is neither bending nor stretch, yet when scaling arguments can be effectively applied. Here we present the mechanics of additively manufactured woodpile lattices to assess their apparent elasticity. Analytical, computational and experimental approaches are employed.

Consider a woodpile lattice with alternate layers stacked in a staggered arrangement (2). When such a lattice is compressed in the stacking direction, the individual members are in flexure. For lattice spacing much larger than the characteristic cross-sectional dimensions, the scenario can be approximated as one of beam bending, leading to a surprisingly high exponent in the fifth power law with respect to volume fraction. This result is validated against numerical and physical experiments on additively manufactured samples, showing excellent agreement with the fifth power law discovered using a simple scaling argument, when the spacing is much larger than the diameter. For dense solids, the departure from the power law scaling in observed in both experiments on 3D printed samples as well as finite element numerical results. This departure is further quantitatively accounted for by including the role of shear correction when the spacing is not very large compared to the diameter of the struts. Following the analysis, computation, and experimentation on woodpile lattices with staggered arrangement, consider the same lattices when the alternate layers are aligned (3). Under compressive loading in the stacking direction for such a lattice, each of the elastic cylinders are diametrically compressed and the deformation mechanism is neither bending nor stretch but one requiring rather complex elasticity solutions. Here we take an alternative approach of using scaling arguments that lead to a quadratic power law when the dominant mechanism of deformation is diametrical compression. Excellent agreement with numerical results as well as laboratory experiments on additively manufactured lattices is reported. Deviations from the power law for high density lattices is explained. The influence of response due to neighbouring lattice sites is quantitatively assessed and shown to be small. Variational approximations based on an exponential ansatz for spatial decay match extremely well with numerical computations.

Finally, results for the apparent elasticity of a hierarchically porous woodpile lattice with hollow cylindrical tubes are presented (4). The result is not a simple power law, yet an analytically tractable elegant expression in terms of the volume fraction and the ratio of thickness to the radius of hollow struts. The influence of deformation at neighbouring sites is quantitatively examined. Simple analyses, computations and laboratory experiments on additively manufactured samples using bespoke nozzles are reconciled and found to be in excellent agreement.

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Symmetries of periodic and quasiperiodic heterogeneous materials: From invariance to indistinguishability

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Speaker: Husert Markus. **Wednesday**. Start time: **15:50**. Room: Audi Pasteur LVL1. Link to abstract.

The effective behavior of heterogeneous materials is governed by the spatial arrangement of the matter on a microscopic scale, in other words by its microstructure.
Microstructures are classically divided into two families, periodic ones and random ones. Each has its own strengths and weaknesses, as well as its own techniques for calculating the resulting effective physical properties. Periodic microstructures are deterministic but often anisotropic, while random microstructures have higher toughness at the cost of high variability between samples. In recent years, these classical boundaries have been blurred since new paradigms of spatial organization have emerged from the introduction of long-range order into random media (hyperuniformity) (1) and local disorder into periodic ones (quasiperiodicity).
The presented works focus on the latter option of quasiperiodic order. These materials are appealing because they allow higher-order rotational symmetries while losing translational invariance. The result is a highly isotropic, deterministic structure with high resistance to crack propagation (2). However, the classic techniques and concepts of periodic homogenization need to be completely revised.
Knowing material spatial symmetries enables us to determine, via Currie's principle, the symmetry class of the effective property (3). This information is useful either for validating a traditional numerical homogenization model or for predicting the number of effective material parameters in a data-driven approach.
However, for quasiperiodic materials, the classical definition of symmetry is meaningless, since the strict criterion of invariance can no longer be satisfied. Hence the first point to revisit is the notion of spatial symmetries.
This generalization amounts to substituting the more general concept of indistinguishability for the concept of invariance. Two media are said to be indistinguishable if their n-point correlation functions are equal at any order n. This criterion, formulated in Fourier space, takes a particularly elegant form (4) which allows for direct numerical evaluation.
Following this path, we propose a numerical method operating on gray scale images that detects the symmetries of both periodic and quasiperiodic microstructures in Fourier space. The designed tool can be applied to less ordered structures, as it gives a meaningful definition of symmetries in an approximate sense.

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Design and mechanics of 3D intertwined helix-based architected materials

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Speaker: Elias Pescialli. **Wednesday**. Start time: **16:10**. Room: Audi Pasteur LVL1. Link to abstract.

Helix-based intertwined architected materials belong to a newly class of metamaterials created from a lattice structure whose trusses are hierarchically made by helices. The generated material is hence composed by a complex network of structured filaments, which suppress stress concentration, giving rise to interesting properties such as high compliance, increased strain at failure, high energy dissipation. One of the novelties of this work relies in the design of such periodic structures, which is tackled first from a topological description of the unit cell, followed by an optimization of the spatial features of the fibres. A thorough study of the topology of the unit cell involving tools from computational combinatorics allows to span the whole range of possible connections amongst intertwined filaments. Then, optimization of the spatial features of the fibres completes the unit cell geometry, resulting in lower density and improved initial and contact-induced stiffness for each given topology. A wide spectrum of the generated intertwined material designs is tested within an in-house finite element variational framework, which includes a novel implementation of frictional contact, being it at the core of the interaction between filaments. This allows to find a clear relation between the topological description and the mechanical response of the material, paving the way to manufacture 3D intertwined structures with tailored properties.

Effect of Unit Cells Networking and Topology on Stiffness and Energy Absorption in Zero Poisson's Ratio Metamaterials

Khodabakhshi Mohammaderfan Khakalo Sergei (1)

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Speaker: Khodabakhshi Mohammaderfan. **Wednesday**. Start time: **16:45**. Room: Audi Pasteur LVL1. Link to abstract.

Stiffness and energy absorption are critical characteristics in mechanical structures, influencing their performance, safety, and durability under diverse loading conditions. While traditional materials derive these properties from their chemical composition, metamaterials – engineered materials with unique internal structures – achieve tailored mechanical properties through geometric design rather than the properties of their base materials. Recent advancements have focused on chiral metamaterials, where chirality-defined as the interaction between tensile/compressive and torsional forces that introduces additional rotational freedom-manifests through twist deformation under uniaxial compression, a property rarely observed in uniform materials. Thus, unlike uniform materials, these metamaterials exhibit a unique behavior: their structure rotates while undergoing compression or tension.

Building on previous work that introduced a novel compression-torsion coupled (CTC) metamaterial unit cell design with six defining geometrical parameters – capable of varying degree of chirality and transitioning from semi-achiral to highly chiral behavior through modifications to the infill ratio – this study shifts focus from individual cell design to the impact of cell networking and arrangement on the overall mechanical properties of metamaterial structures. The unit cell's design supports both clockwise (CW) and counterclockwise (CCW) configurations, offering flexibility in achieving tailored deformation responses.

A key focus of this research is the development of zero Poisson's ratio structures, achieved by combining CW and CCW unit cells in equal proportions. Thirty-two distinct configurations of a 4×4×4 unit cell assembly were analyzed to explore the variability in stiffness and energy absorption resulting from different unit cell arrangements. Finite Element Analysis (FEA) conducted in COMSOL Multiphysics 6.0 was complemented by experimental validation using 3D-printed samples produced via selective laser sintering (SLS) with Nylon 12. The stiffness and energy absorption of each configuration were measured under quasi-static compression by 10% of the sample's initial height.

Results revealed substantial differences in mechanical properties across configurations, despite identical geometrical parameters and unit cell counts. The configuration with an "oxox/oxox/xoxo/oxox" pattern in the XY direction and an "xoxo" pattern in the Z direction exhibited the lowest stiffness and energy absorption, while an "oooo/oooo/xxxx/xxxx" pattern in the XY direction and an "ooxx" pattern in the Z direction demonstrated the highest values. The comparison between these two configurations shows a difference exceeding 40% in both stiffness and absorbed energy. These findings underscore the significant impact of network arrangement on metamaterial properties, enabling the design of structures with a wide range of stiffness and flexibility to meet specific application requirements.

Entangled particles as engineered architectured materials

Sohn Youhan Pezeshki Saeed Barthelat Francois (1)

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Speaker: Barthelat Francois. **Wednesday**. Start time: **17:05**. Room: Audi Pasteur LVL1. Link to abstract.

Typical noncohesive granular materials based on spherical or other convex geometries have relatively low shear strength and no tensile strength. Individual grains can however be designed with non-convex geometries to generate interlocking, entanglement and tensile strength. Interestingly entangled matter is found in nature (Fire ant rafts, burr seeds), and recent studies on staple-like particles have shown unusual and interesting properties. Entangled matter indeed provides intriguing perspectives in terms of deformation mechanisms, mechanical properties, assembly and disassembly. While some of their attributes and mechanisms share some traits with traditional granular materials, few studies have focused on entanglement and strength and there are large gaps in our understanding of the mechanics of these materials.
We have recently developed a simple "pick-up" test to measure the entanglement in staple-like particles with various leg lengths, crown-leg angles, and backbone thickness. Interestingly some of these parameters have a non-monotonic effect on entanglement, with a clear optimum entanglement for certain combinations of crown-leg angles and leg lengths. This suggests that competing mechanisms are play in the entanglement process, and to capture these effects we developed a "throw-bounce-tangle" model based on a 3D geometrical entanglement criterion between two staples, and a Monte Carlo approach to predict the probabilities of entanglement in a bundle of staples. This relatively simple model is computationally efficient, and it predicts an average density of entanglement which is consistent with the entanglement strength measured experimentally. The model confirms that entanglement is very sensitive to the thickness of the backbone of the staples, even in regimes where that thickness is a small fraction (< 0.04) of the other dimensions. We also demonstrate an interesting use for this model to optimize individual staple-like particles for maximum pairwise entanglement.

Collective entanglement mechanisms are however more complex and they occur over multiple length scales. To study these collective effects, we developed tensile tests on staple-like particles, focusing on the effect of adjusting the angle between the legs and the crown in individual staples. Our experiments, combined with discrete element models, confirm the competing mechanisms between entanglement strength and geometric engagement between particles, giving rise to an optimum crown-leg angle that maximizes strength. We also show that tensile forces are transmitted by a small fraction of the staples, which is organized in only 1-3 force chains. The formation and breakage of these chains is highly dynamic: as force chains break, they are replaced by fresh ones which were previously mechanically invisible.
Entangled matter as "granular metamaterials" offer interesting perspectives in terms of materials design, and a vast design space for individual particles. Since their properties can be tuned with the shape of the staple, we interpret these entangled materials are "granular metamaterials" with unusual combination of properties: simultaneous strength and toughness, controlled assembly and disassembly, re-conformability and recyclability.

Exploring In-plane Elastic Properties and Energy Absorption of the Bio-inspired Glass Sponge Structure

Beigi Rizi Hassan (1), Auradou Harold (1), Hattali Lamine (1)

1 - Université Paris-Saclay (France)

Speaker: Beigi Rizi Hassan. **Wednesday**. Start time: **17:25**. Room: Audi Pasteur LVL1. Link to abstract.

The biological systems have evolved a diverse variety of robust skeletal architectures that can be used as lightweight structures to meet environmental requirements. However, the utilization of bio-inspired structures for energy absorption applications remains less common compared to conventional structures due to the novelty of the bionic approach in this field and limited fabrication capabilities. In this study, first we explore numerically and experimentally the in-plane elastic mechanical properties of lattice derived from Euplectella Aspergillum Glass Sponges (EA-sponge). The lattice structure is designed by approximating the architecture of EA-sponge using fused filament fabrication (FFF) process with thermoplastic Polylactic acid (PLA) filaments. The quasi-static compression test and finite element analysis (FEA) were conducted to study the energy absorption behavior of EA-sponge structures which involved open cells and close cells. The unit cell length of 10 mm, improved energy absorption by controlling buckling. Closed cells enhance stability, by increasing shear deformation mechanisms while open cells show increased waviness and unstable deformation mechanisms in EA-Sponge structure.

Failure of stretching dominated architected interfaces with rotation imperfections introduced by the confining structure

Hedvard Michelle (1), Weißgraeber Philipp (1)

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Speaker: Hedvard Michelle. **Wednesday**. Start time: **17:45**. Room: Audi Pasteur LVL1. Link to abstract.

Confined interfaces such as thick bond lines appear in many structural situations. Athanasiadis et al (2021) have proposed to replace such bulk interface materials with architected materials utilizing their superior material properties. This type of interface is referred to as an architected interface. Architected interfaces introduce additional parameters in the form of topology, relative density, and unit cell size of the architected materials. It has been indicated such architected interfaces have the potential to significantly change the failure process, introducing toughening effects (Hedvard, 2014), and altering the plastic fracture process zone (Fulco et al. 2022).
In recent years, multiple works have studied the fracture mechanics of architected materials and their fracture toughness by using concepts of fracture mechanics of continuous materials. Omidi & St-Pierre (2023) evaluated the fracture toughness of architected lattice materials considering compact tension tests while Shenhav & Sherman (2019) evaluated the fracture toughness of brittle open-cell structures under compression loading, showing a failure process controlled by local buckling. For some topologies tension and compression-loaded lattices are both present, leading to two potential failure modes. As shown by Shaikeea et al. 2022, for an octet truss lattice structure with an introduced crack the failure mode can be changed by altering the relative density, biaxial loading ratio, or the unit cell size to crack length ratio. Material properties of interface materials are often evaluated using the double cantilever beam introducing a localized tension and compression zone resulting in multiple failure modes for even simple architected interfaces such as the pillar interface.
In this work, we evaluate the failure of architected interfaces considering a double cantilever beam setup with a stretching-dominated lattice interface. Stretching-dominated lattice materials are known for their high strength-to-weight and stiffness-to-weight ratios making them a suitable material for lightweight structures. In tension, the failure load is determined by the material strength, while buckling determines the failure in compression under the assumption of slender structures. The introduction of small imperfections changes the buckling problem to a deformation problem leading to a reduction of the load-bearing capacity of the structure (Timoshenko & Gere, 1961). Considering the bending of the confining adherend under loading a rotation imperfection is introduced to the elements within the architected interface. An analytical method of evaluating buckling failure with rotation imperfections is derived and implemented in an analysis framework for architected interfaces. The critical failure load and fracture toughness of such architected interfaces are evaluated for various interface properties for both tension and compression failure.

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Fracture toughness and crack propagation of architected orthotropic triangular lattices

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Speaker: Omidi Milad. **Wednesday**. Start time: **18:05**. Room: Audi Pasteur LVL1. Link to abstract.

Lightweight structural materials are crucial to the transport industry as they offer an efficient option to reduce their CO2 emissions. For example, reducing the mass of a Boeing 787 by 20% decreases its fuel consumption by 12% (1). This industrial demand for lightweight materials can be fulfilled by a range of solutions, which among them, lattice materials have become increasingly popular in engineering because their architecture can be tailored to achieve desired properties (2). Lattice materials are made from tessellation of an interconnected unit-cell of struts or cell-walls filling 2D (planar lattices) or 3D (spatial lattices) spaces (3). They are frequently manufactured with polymers, ceramics, or metals providing stiff, strong, tough, and lightweight materials. Albeit the theoretical upper bound for strength and stiffness are reached by conventional planar lattices, there is no limitation in improving toughening behavior (4, 5).

Enhancement in toughness and resistance against crack propagation in lattice mate- rials is crucial because it increases the reliability and lifespan of structures. Triangular lattice is a planar lattice presenting high fracture toughness among conventional lattices (6). However, there is a room to enhance the resistance of triangular lattice against crack propagation (R-curve) by controlling their toughening mechanisms. Since the micro- architecture of lattices can be altered, the concepts of changing the thickness of struts is employed to investigate the possibility of R-curve improvement in triangular lattice.

The crack propagation in lattices was predicted using Finite Element (FE) simulations rely on a boundary layer method introduced by (7, 8). For each tessellation, we used a square domain with a side length of $1600l$, where l is the length of a cell wall. The domain contained an initial crack in the negative x1 direction. The ratio of the thickness of bars aligned in x2 direction to the inclined bars T = t2/t1 was altered so that maintain the constant relative density with that of triangular lattice with uniform thickness. The effect of T on propagation was examined for a brittle and ductile materials.

Results show that increasing amount of T up to 2 could significantly enhance rising of R-curve, especially for ductile materials. For the ratio of T $>$ 2 the orthotropic effect changes the direction of propagation in comparison with that of isotropic triangular lattice. Also, brittle triangular lattice gets mutually tougher and stronger in x2 with increasing T. This study provides insight into tailoring the micro-architecture of conventional lattices to improve their damage-tolerance in industries.

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3D-printable wearable pad for the breast skin treatment: design and printing optimization

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Speaker: Graziosi Serena. **Thursday**. Start time: **10:00**. Room: Audi Pasteur LVL1. Link to abstract.

This study presents the preliminary results obtained to develop a novel biobased and biocompatible wearable pad by exploiting the flexibility and affordability of the Material Extrusion additive manufacturing process, specifically of the Fused Filament Fabrication technology and the unique multifunctional properties of architected materials. The study specifically focuses on identifying and optimizing the key design parameters of the pad, tailored to the unique characteristics of the newly developed composite material used in its fabrication. The primary objective is to develop a wearable patch designed for direct application on the skin, enabling targeted topical treatment over the covered surface area. Therefore, it must be lightweight, breathable, non-invasive, biocompatible, and ergonomically conformable to the human body -specifically the women's breast, the intended area of treatment-ensuring comfort and minimizing any potential inconvenience. It must be manufactured without asperities to avoid skin irritation due to the potential rubbing of the pad surface over the breast, a sensitive region of the woman's body, in particular after surgical intervention or during breastfeeding. Despite the solutions already available in the literature of 3D-printable patches based on architected materials for wound repair (1), there are no examples of solutions targeted for women's breasts, except some limited and valuable studies, such as the one discussed here (2) presenting a wearable and non-invasive ultrasound breast patch for cancer diagnosis.
The development of the pad is grounded on a complementary study conducted to develop a novel 3D-printable biobased composite material conceived for this scope, which has been obtained by blending a low-extrusion temperature thermoplastic and biocompatible matrix, i.e., the Polycaprolactone (PCL), with biobased content by using a lab-scale extrusion system. The PCL was selected to preserve the biobased content characteristics after the printing. That biobased content is propaedeutically for future research focusing on blending that matrix with a biobased material, which is also bioactive to allow the pad to implement its topical treatment, mainly concerning anti-inflammatory and antioxidant activities. Mechanical characterization was conducted on tensile and compressive samples to thoroughly evaluate the properties of the newly developed material. Simultaneously, the study explored optimal printing parameters to ensure the successful fabrication of a lightweight, deformable, and comfortable-to-wear pad. This included addressing critical factors, such as minimizing debris and eliminating stringing within the structure, to achieve a high-quality final product. For the pad design, parametric digital models of auxetic-based configurations have been developed to exploit the synclastic curvature property provided by auxetics. Specifically, preliminary experimental tests have been conducted on a pad exploiting the sinusoidal ligament unit cell because it shows a Poisson Ratio comparable to the skin (3). The final pad design is a sinusoidal "net" conceived to obtain the proper coverage of the breast skin surface that should receive the treatment. Besides, two pad configurations have been designed and printed, one showing a textile-like architecture and a standard planar one. Results show the feasibility of 3D-printing such a lightweight and conformable patch. However, further studies are needed to understand how the pad design and manufacturing parameters influence its mechanical behavior and capability to treat skin properly.

Keywords
Wearable pad, 3D-printing, material extrusion, composite material, mechanical metamaterials

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Triply Periodic Minimal Surfaces (TPMS) for Additive Manufacturing of High-Performance Beams

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Speaker: Schiantella Mattia. **Thursday**. Start time: **10:20**. Room: Audi Pasteur LVL1. Link to abstract.

Triply periodic minimal surfaces (TPMS) are mathematical surfaces characterised by having zero mean curvature in every point (1), favouring optimal material distribution with exceptional mechanical performance (2). These geometries are extensively studied for their applications in biomedical engineering, particularly in prosthetic devices and osseous scaffolds (3). Their porous structures not only mimic the mechanical properties of bone but also promote stress transfer and minimise stress shielding effects, making them ideal for load-bearing applications.
First TPMS were discovered and studied in the second part of the twentieth century, but their realization was impossible until the rise of additive manufacturing.
This study relies on TPMS geometries to design and fabricate beams with enhanced mechanical performance and material efficiency (4). The design is developed using computational models, followed by experimental testing on samples fabricated with additive manufacturing techniques to ensure validation. The realization of beams with superior properties compared to conventional designs is achieved by tuning the density of the TPMS structures throughout the beam or by a gradual transition between different TPMS geometries. Both approaches are dependent on load and boundary conditions. (5)
This study shows how TPMS can revolutionize structural design by combining advanced manufacturing methods with bio-inspired concepts. This work contributes to the development of sustainable and high-performance systems, creating opportunities for future innovations.

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Piezoelectric truss metamaterials: data-driven design and additive manufacturing

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Speaker: Sharma Saurav. **Thursday**. Start time: **10:40**. Room: Audi Pasteur LVL1. Link to abstract.

Mechanical metamaterials enable a variety of tailored physical characteristics such as negative Poisson's ratio, selective energy dissipation, non-reciprocity, shape morphing, and elastic waveguiding. Incorporating the concept of metamaterials with active materials leads to the development of *smart metamaterials,* which opens the possibility of having unique characteristics in multiphysics-coupled phenomena. Though mechanical metamaterials have been designed to achieve tuneable anisotropy of mechanical response through inverse design, there is an unexplored potential for metamaterial design and fabrication for tailored piezoelectricity. Here, we design novel piezoelectric truss metamaterials using machine learning to efficiently harness the full design space of tuneable electromechanical response. An electromechanically coupled computational framework based on the finite element method and deep learning is developed to surrogate the effective elastic, electrical, and electromechanical response of a unit cell. Based on this computational framework, an inverse model is trained to efficiently and systematically reverse engineer the geometry and topology of the metamaterial unit cell with the tailored, effective piezoelectric response of the metamaterial. We explore auxetic piezoelectricity, uni-directional piezoelectricity, and arbitrary ratios of shear and normal piezoelectric coefficients through the architectures designed with the inverse-design framework. As a proof of concept, lattices with exotic properties are additively manufactured, and their piezoelectric response is characterized.

HCP granular crystals with tunable mechanics

Tian Gao (1), Karuriya Navdeep (1), Barthelat Francois (1)

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Speaker: Tian Gao. **Thursday**. Start time: **11:00**. Room: Audi Pasteur LVL1. Link to abstract.

Traditional granular materials, such as sand and rice, consist of discrete, non-cohesive particles that interact through friction, exhibiting complex mechanics like cluster formation, stress transfer, jamming, shear bands, and shear-induced dilatation. However, their random arrangement of spherical or ellipsoidal grains limits packing density and mechanical properties, leading to poor load transfer, inhomogeneous jamming, and strain localization. One effective method to enhance their strength is by inducing crystallization with space-filling solids, improving packing factor and load transfer efficiency. Inspired by hexagonal close-packed (HCP) crystals, I developed a new strategy to transform amorphous granular materials into fully dense, crystallized materials using trapezo-rhombic dodecahedral (TRD) grains. Firstly, 3D printed millimeter-scale TRD grains were crystallized into dense HCP granular crystals through mechanical vibrations. Subsequently, the infiltration of tacky, polyacrylic adhesive at the interfaces between the grains created sustained adhesion, enabling the formation of self-standing granular structures. Compressive tests revealed highly anisotropic properties and diverse deformation mechanisms, including nonlinear deformations, crystal plasticity resembling atomistic mechanisms, cross-slip, shear-induced dilatancy, and micro-buckling. The grains can be recycled without strength loss after mechanical tests. By further modulating the c/a ratio (like in HCP metal crystals) and grain face angle, a wider parameter space is available to control TRD grain shape evolution for tunable mechanical behavior. Once fully understood and utilized, this method has the potential to create 3D architectured materials with unique mechanical performance, offering capabilities for repair, reshaping, on-site adjustments, and efficient recycling of building blocks.

Microstructure and mechanics of crumpled materials

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Speaker: Martoïa Florian. **Thursday**. Start time: **11:20**. Room: Audi Pasteur LVL1. Link to abstract.

Crumpled materials are primarily regarded as model systems by physicists due to their fascinating topology and their related scaling laws close to those observed in many other materials or systems such as for example polymerized membranes, biological cells or plants. More recently, several studies have shown that crumpled materials could also be potentially used in many structural applications (e.g., shock absorbers, core of sandwich panels) due to their low-cost, simple fabrication route and promising mechanical properties. However, the selection and the use of a specific crumpled material for a particular engineering application require a proper control of the process-induced microstructures and a comprehensive understanding of their role on the mechanical behavior. In the last decade, significant effort was made to understand the physics of crumpling phenomena and the microstructures of crumpled sheets. Despite this effort, further studies are still required to fully elucidate the links between the three-dimensional self-locked architectures of these cellular materials and their resulting mechanical properties.
Within this context, several low-density crumpled paper-based materials were fabricated by varying both the volume fraction and the geometry and mechanical properties of initial paper sheets. Their 3D architecture was investigated using X-ray microtomography. Several microstructure descriptors such as the pore size distribution, the mean curvature distribution and the volume fraction of ordered domains were finely analyzed. Their mechanical properties were also assessed using both quasi-static uniaxial compression and dynamic impact tests with a Split-Hopkinson pressure bar. 3D real time and in situ observations during compression experiments were also performed using fast X-ray synchrotron microtomography.
The results gathered in this study highlighted the role played by some key microstructure descriptors of crumpled materials, such as ridges and ordered domains, on their mechanical behavior under quasi-static and dynamic loadings. The evolution of the elastic, plastic and shock-absorption properties were studied as a function of their relative densities and compared with experimental data available in the literature for other cellular materials, showing that crumpled papers are promising renewable alternatives to standard polymer foams for several engineering applications.

Multifunctional Origami Packaging

Almessabi Abdulrahman (1), Jamalimehr Amin (1), Pasini Damiano (1)

1 - McGill University (Canada)

Speaker: Almessabi Abdulrahman. **Thursday**. Start time: **11:40**. Room: Audi Pasteur LVL1. Link to abstract.

Packaging is essential for product distribution and protection but often relies on plastic and single-use monofunctional materials, significantly contributing to environmental waste. In this work, we present a paper-based packaging that leverage origami principles to attain reconfigurability, multifunctionality and reusability. Its hallmarks include adaptive shape conformability, multistable locking, and protective cushioning, all integrated into one multifunctional origami packaging. Multistable snapping of origami panels is proposed to generate a grasping function that can hold a cargo in place without resorting to any additional bracing materials. In addition, a tendon-driven folding mechanism is integrated into strategically selected origami panels to reprogram the force-displacement response under uniaxial quasi-static and impact loads, as well as to adapt to various shapes and sizes of the cargo. Our preliminary findings show that our origami packaging can secure the cargo position, and offer protective cushioning to fragile products during transportation, stacking, and handling, paving the way to the attainment of sustainable multifunctional packaging.

Mechanical performance of architected interpenetrating phase composites: Experimental, numerical and machine learning analysis

Singh Agyapal (1), Song Qinze (1) (2), Jaber Abdulrahman (1) (2), Karathanasopoulos Nikolaos (1) (2)

1 - New York University Abu Dhabi (United Arab Emirates), 2 - New York University (United States)

Speaker: Singh Agyapal. **Thursday**. Start time: **14:15**. Room: Audi Pasteur LVL1. Link to abstract.

Interpenetrating phase composites (IPCs) based on architected media allow for mechanical properties well beyond the bounds of their constituent phases. The arising mechanical response depends on a series of underlying influential design features, which include the material properties of the phases involved, their architectural design, their volume fraction, as well as loading-related parameters, such as the strain-rate of the loading. In the current contribution, extensive numerical and experimental insights on the dependence of the effective composite material performance on the aforementioned design parameters are provided for different IPC materials that include polymer and soft matrix phase composites (1, 2). The data are used as a reference for the development of dedicated tree and deep learning modeling architectures that can not only accurately capture the effective composite performance but also be used as surrogate models for subsequent explainability analysis tasks. In particular, dedicated high-accuracy and low computational cost machine learning models are elaborated and employed to assess the significance of the underlying influential design parameters, as well as their interaction, classifying their importance for different base material combinations and loading scenarios.

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Mechanics of architected interfaces for the design of tough composite-metal joints

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1 - Faculty of Aerospace Engineering - Delft University of Technology (Netherlands), 2 - Instituto de Engenharia Mecânica [Lisboa] (Portugal)

Speaker: Van Innis Charline. **Thursday**. Start time: **14:35**. Room: Audi Pasteur LVL1. Link to abstract.

Thermoplastic (TP) composite materials are increasingly replacing thermoset composites in complex applications, such as in aeronautics, due to their excellent properties. Manufacturing complex structures often involves joining TP composites with other materials, such as metals. Due to the melting behavior of TPs, adhesive bonding can be replaced by co-consolidation or welding (1). However, interfacial failure can occur, necessitating the development of toughening strategies. One common approach is to modify the surface roughness through grit or sandblasting to promote mechanical interlocking (1). Other strategies have also been explored, such as creating grooves, dimples, grids (2), or even complex interlocking microstructures on one or both substrate surfaces (3). Among these, introducing grooves oriented perpendicular to the crack propagation direction has shown the most promising results. However, no consensus has been reached regarding the optimal design. This work aims to find such a consensus and provide design guidelines.
To achieve this, finite element modeling with cohesive elements is employed. A double cantilever beam geometry is modeled, with the two arms made of dissimilar materials and grooves inserted at the interface. It is assumed that without grooves, interfacial failure takes place while in the presence of a groove, the crack can either propagate through the second material or follow the groove pattern. The influence of groove spacing, width, and depth on joint toughness and failure mechanisms is investigated, taking into account the elastic mismatch of both materials as well as the cohesive properties of the materials and the interface.

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Characterization and Modeling of PolyJet Materials for Realistic Anatomical Models

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Speaker: Martin Vincent. **Thursday**. Start time: **14:55**. Room: Audi Pasteur LVL1. Link to abstract.

Additive manufacturing is playing an increasingly important role in healthcare, particularly through its use in the production of anatomical models. These models have become essential tools in various contexts, such as surgical planning, enabling better anticipation of complex procedures, and in training programs for healthcare professionals. They are evaluated not only for their anatomical accuracy-encompassing geometric precision, modeling relevance, and color fidelity-but also for their ability to replicate the structures and mechanical properties of biological tissues.

The PolyJet additive manufacturing process (Stratasys) offers an innovative solution to this challenge, thanks to its capability to print multi-material polymer parts with different mechanical properties. This process allows for the creation of property gradients within a single part or the assignment of specific Shore hardness values to localized areas by modifying the resin mixing ratios. This flexibility unlocks new possibilities for the design of realistic anatomical models by assigning each element mechanical properties that closely resemble those of biological tissues. Moreover, the technical solution under study enables fine control of material selection at the voxel level, providing a degree of realism that meets the demanding standards of modern medicine.

A deep understanding of the mechanical behavior of materials produced through the PolyJet process is critical for improving the quality of anatomical models, particularly their ability to realistically replicate the tactile sensations experienced by healthcare professionals under real-use conditions. In this context, research conducted by the LaMcube laboratory on the modeling of nonlinear hyperelastic behaviors (1), initially focused on silicones and soft biological tissues, provides a robust theoretical framework and advanced characterization tools. These studies extend this knowledge to the complex composite materials manufactured by PolyJet, paving the way for more precise modeling of their mechanical properties. This scientific approach helps optimize the performance of anatomical models, ensuring they meet the high standards required for demanding biomedical applications.

Implementation of an ALE-based FE method for additive manufacturing processes

Chirianni Francesco (1), Vairo Giuseppe (1), Marino Michele (1)

1 - University of Rome Tor Vergata [Rome, Italy] (Italy)

Speaker: Chirianni Francesco. **Thursday**. Start time: **15:15**. Room: Audi Pasteur LVL1. Link to abstract.

Additive manufacturing allows for on-demand production of functional constructs through an accurate layer-by-layer deposition of filaments. These are generally made of polymer-based materials that exhibit shear-thinning and viscoelastic features. The shear-thinning behavior eases the extrusion process inside the nozzle, while viscoelasticity plays a significant role as the material flows outside, where the extrudate-swell phenomen occur. This latter cause a loss in printing resolution since the relaxation of polymer chains.
To accurately describe variations in the extrudate configuration beyond the nozzle outlet, a free-surface problem should be addressed. Modeling viscoelastic flows with moving boundaries is demanding since the intricate interplay between elasticity and capillarity. This complexity can result in localized and significant changes in surface curvature, as well as abrupt alterations in stress distribution within these regions.
In this framework, the aim of the present work is to investigate the extrusion process by means of finite element (FE) formulation. The free-surface problem is addressed by numerically solving the incompressible and isothermal Cauchy equations coupled with viscoelastic differential constitutive models. An Arbitrary Lagrangian-Eulerian (ALE) description is adopted to track moving boundaries alongside the numerical solution. Numerical predictions of this ALE-based FE formulation are presented for various additive manufacturing applications.

Ballistic impact experiments and numerical modelling of additively manufactured and wrought maraging steel

Edwards-mowforth Maisie (1) (2), Costas Miguel (3), Kristoffersen Martin (4) (5), Børvik Tore (4), Teixeira-dias Filipe (1)

1 - School of Engineering, The University of Edinburgh (United Kingdom), 2 - IMPETUS Afea (Norway), 3 - Norwegian University of Science and Technology (Norway), 4 - Norwegian University of Science and Technology (Norway), 5 - Multiconsult AS (Norway)

Speaker: Kristoffersen Martin. **Thursday**. Start time: **15:35**. Room: Audi Pasteur LVL1. Link to abstract.

Additive manufacturing (AM) offers unprecedented opportunities for creating optimised materials and structures tailored for extreme conditions, including high strain rate applications. Maraging steel is a low carbon, high-strength steel, well suited to AM fabrication by laser powder-bed fusion (LPBF). The material takes on ultra high-strength post heat-treatment, making it particularly effective for protective applications. While previous studies have demonstrated promising ballistic performance of AM maraging steel, the tendency for fragmentation following heat treatment raises questions about the influence of AM processing on its ductility.

This work investigates the behaviour of AM maraging steel under high strain rate loading, comparing its performance to that of traditionally wrought counterparts. Both as-printed and heat-treated AM materials were subjected to detailed experimental characterisation, including dynamic tensile testing and ballistic range trials. Despite notable differences in ductility observed in tensile tests, the ballistic limit velocities of AM and wrought maraging steel were found to be comparable across both processing states. Additionally, AM targets often caused greater damage to the projectiles compared to wrought targets, highlighting distinct local responses.

Numerical models were developed in the IMPETUS Solver to simulate the ballistic response of the non-heat-treated material. Using standard material models with some adjustments for AM-specific characteristics, the simulations produced conservative predictions, with ballistic limit velocities agreeing within 10% of experimental results.

This study demonstrates the potential of AM maraging steel for applications requiring high strain rate performance, showcasing its capacity to achieve properties comparable to traditional materials. By additionally leveraging the geometric freedom and customisation enabled by AM technologies, the potential is great for further improvement.

MS1.4 - Multiscale modelling of polycrystalline materials

Organisers: Ivano Benedetti (University Palermo) and Marc Bernacki

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Implementing an energy based dislocation transmission criteria for dislocation-grain boundary interaction using a dislocation transport based crystal plasticity model

Murgas Brayan (1), Hunter Abigail Luscher Darby J.

1 - X Computational Physics Division, Los Alamos National Laboratory (United States)

Speaker: Murgas Brayan. Keynote. **Wednesday**. Start time: **10:00**. Room: Rhône 5 LVL1. Link to abstract.

The interaction between grain boundaries (GBs) and dislocations is a key problem in materials science and mechanics. Pile up of dislocations around GBs gives raise to the Hall-Petch effect; a microstructure with small grains has more GBs that act as barriers causing dislocation pile-up resulting in a higher yield strength compared to a microstructure with bigger grains. However, the Hall-Petch relation does not always hold as GBs have complex interactions with dislocations, such as absorption of dislocations, which can change the GB structure, and is sometimes followed by dislocation emission in adjacent grains producing a change in the properties of the material. Additively manufactured samples and nano-metallic laminates are examples of systems with more complex and denser GB patterns in the material. For this reason, GBs play a more important role, and it is important to account for dislocation-GB interactions when predicting the final properties of materials. The improvement of classic computational methods is necessary to include a treatment of GBs with the aim of being able to predict and engineer GB patterns that enhance the properties
of materials.
In this work, we present a crystal plasticity model with dislocation transport within and across the grains called DiscoFlux (1). DiscoFlux combines continuum dislocation transport and transfer, crystal plasticity and considers stress and deformation fields to simulate material response. Dislocation transport is modeled by solving an advection equation, dislocation transfer is modeled using an interface diffusion transfer model and crystal plasticity is coupled to dislocation transport using Orowan's equation.
While transmission criteria are mainly focused on geometrical factors using the orientation
of the slip systems and grain boundary normal. In this work, we extend the transmission criterion by considering energy terms that describes the energy of the dislocation core and the energy barrier produced by the GBs.

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A grain morphology coupled crystal plasticity finite element model

Chen Jialiang (1), Barrales-mora Luis (1)

1 - George W. Woodruff School of Mechanical Engineering (France)

Speaker: Chen Jialiang. **Wednesday**. Start time: **10:40**. Room: Rhône 5 LVL1. Link to abstract.

Grain refinement is one of the most important strengthening mechanisms in metallic materials. It is described by the Hall-Patch (H-P) relationship as a homogenized single variable function on average grain size. However, in modern additive manufactured (AM) alloys, strong heterogeneous microstructures have been commonly observed. In the modelling of the mechanical properties of materials, usually an average value of grain size determined from the equivalent spherical diameter (ESD) is used. Owing to the complex grain size distribution caused by the temperature gradient, a sole value might not represent complex microstructures of AM materials adequately. In this work, we consider the grain size as a variable for each grain and each slip system based on the input microstructure. This variable is further used in a dislocation density based constitutive law in crystal plasticity finite element model (CPFEM). Thus, the dislocation density accumulation is affected by the directional grain size corresponding to specific slip system. Therefore, the H-P relationship is not directly applied in the constitutive law but embedded in the dislocation strengthening mechanism. The results indicate that the H-P relationship is still valid with this modified model. Furthermore, the results also show that the anisotropy of Young's moduli and yield strength can be well simulated with the same microstructure. Finally, the current model can show a more realistic strain distribution compared to experimental results on complex microstructures.

Cyclic behavior of a Ni-based superalloy: effects of annealing twins and grain size

Ghiglione Flavien (1), Raoult Ida (1), Coudon Florent (1)

1 - Safran Tech (France)

Speaker: Ghiglione Flavien. **Wednesday**. Start time: **11:00**. Room: Rhône 5 LVL1. Link to abstract.

The macroscopic behavior of metallic parts is largely determined by the properties of the constitutive material, which in turn is widely influenced by the microstructure created during the forming process. It is well established that the fatigue lifetime inversely increases with grain size, while the resistance to creep is reduced. Furthermore, for turbine disks, two distinct mechanisms determine the fatigue lifetime:

- Crack initiation at the surface for large load amplitudes.
- Crack initiation in the bulk for low to mid load amplitudes, usually at large grains or inclusions.

The transition between these regions represents a crucial point in the fatigue lifetime of turbine disks, as it corresponds to the loading of critical zones.
Given the incomplete understanding of the interplay between microstructure and macroscopic fatigue behavior, the design rules employed in the aircraft industry frequently fail to consider the influence of microstructure. This leads to the use of excessive design margins, which ultimately results in the production of aeronautical parts with higher mass than necessary. Consequently, it is imperative to explicitly incorporate microstructure into numerical simulations in order to minimize the mass of turbine disks and fuel consumption.
However, due to the size of the problem, it is impossible to directly simulate the behavior of structures at the macroscopic scale based on a detailed representation of microstructural heterogeneities at the microscopic scale. To address this issue, the field of mechanics of heterogeneous materials (a.k.a micromechanics) aims at determining relationships between the microstructure and the macroscopic response of the material, based on volume averages over a sample that is statistically representative.
Based on these premises, Safran Tech aims at developing a fatigue model that accounts for the microstructural features of the material. To this end, full-field simulations are performed on polycrystalline aggregates. Crystal plasticity laws that include other contributions, such as the distance to the grain boundary, are used to capture grain size effects. In addition, the influence of heterogeneities, such as annealing twins, is assessed. Subsequently, fatigue indicator parameters (FIP) are post-processed from the simulation data, thereby inheriting the sensitivity to the grain size and microstructural heterogeneities.

Comparison of Polycrystalline Full-Field and Homogenized Models for Tantalum forming

Thealler Alexandre (1) (2), Flouriot Sylvain (2), De Rancourt Victor (2), Munier Emmanuelle (2), Pilvin Philippe (3), Scherer Jean-michel (1), Forest Samuel (1)

1 - Mines Paris - PSL (École nationale supérieure des mines de Paris) (France), 2 - CEA Valduc (France), 3 - Institut de Recherche Dupuy de Lôme (Rue de Saint Maudé 56321 LORIENT Cedex France)

Speaker: Thealler Alexandre. **Wednesday**. Start time: **11:20**. Room: Rhône 5 LVL1. Link to abstract.

Finite element simulations are invaluable for predicting microstructure evolution during manufacturing processes, which directly impacts the final mechanical properties of a part. In this context, polycrystalline models-whether full-field or homogenized-are particularly effective, as they can simultaneously predict both mechanical behavior and microstructure evolution. This capability is critical for applications such as forming of pure tantalum, a highly ductile metal, which presents significant industrial challenges for CEA.

In this study, crystal plasticity finite element simulations of pure tantalum polycrystals were performed to predict the material's mechanical response and metallurgical evolution. Both full-field (polycrystalline aggregates) and homogenized models, employing a large deformation formalism, were utilized.
A full-field elastoviscoplastic model, based on dislocation density evolution, was adapted within the finite element code Zset. This implementation was built on the model and parameters established by S. Frenois, with particular attention given to the interaction matrix between dislocation slip systems in the isotropic hardening law (1, 2,3). Additionally, a homogenized polycrystal model called β-model (1) was adapted in Zset.
To validate these models, simulations of tantalum single crystals under various loading conditions were conducted and compared to both experimental and numerical results from the literature (3,4). These results were also compared to the Abaqus implementation of the β-model by S. Frenois (1). Subsequently, full-field finite element simulations of polycrystalline aggregates were carried out and compared to results from the homogenized model in Zebulon and the β-model implemented in Abaqus. The full-field simulations successfully captured the evolution of microstructure, including heterogeneous dislocation density fields and crystallographic texture evolution.
The numerical predictions of both mechanical and metallurgical properties were validated against experimental data from previous experiments by S. Frenois and new experiments conducted at CEA Valduc.

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Keywords : Crystal plasticity, tantalum, polycrystal, finite element, homogenization

Coupled crystal plasticity and phase field modelling of intergranular failure of a heat-resistant steel during creep

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1 - Harbin Institute of Technology, School of Science, Shenzhen, China (China), 2 - CGN, Suzhou Nuclear Power Research Institute, Suzhou, China (China)

Speaker: Ling Chao. **Wednesday**. Start time: **11:40**. Room: Rhône 5 LVL1. Link to abstract.

A coupled crystal plasticity and phase field framework has been developed and applied to modelling intergranular failure of a heat-resistant steel during creep. The evolution of the order parameter (damage) was driven by both the elastic energy and a dislocation configuration stored energy that was derived from the crystal plasticity framework. The effect of intergranular carbide precipitates was incorporated by introducing a grain boundary characteristics dependent energy, resulting in a reduction in the local resistance to fracture of the grain boundaries. This approach enabled the prediction of local inelastic deformation fields and the distribution of phase field damage, providing a detailed evaluation of potential crack nucleation sites. The crystal plasticity model is calibrated and validated from the creep tests under various applied stress on an austenitic steel at 665℃. Predictions of creep deformation and creep rupture life are consistent with experimental data. After testing, different degrees of intergranular damage were observed in the specimens by scanning electron microscopy. Detailed grain boundary analyses using EBSD and TEM for the three different service time materials revealed that the primary mechanism responsible for creep damage initiation is the nucleation of microcavities at intergranular carbides. To further understand this mechanism, the contribution of different microstructural features was investigated through the simulations, including Schmid factor, dislocation densities, etc.

Multi-scale and multi-physics modelling of polycrystalline materials by the boundary element method

Benedetti Ivano (1), Gulizzi Vincenzo (1), Campagna Dario (1)

1 - Università degli studi di Palermo - University of Palermo (Italy)

Speaker: Benedetti Ivano. Keynote. **Wednesday**. Start time: **14:30**. Room: Rhône 5 LVL1. Link to abstract.

Polycrystalline materials are widely employed for engineering applications in several sectors, ranging from the civil to the aerospace and biomedical fields. Their macroscopic behavior depends on the morphological and constitutive features of the crystals comprising their microstructure and on the complex mechanisms localized at the intergranular interfaces. Recent developments in microscopy, on the one hand, and in high-performance computing, on the other hand, have allowed the development of complex computational tools able to capture complex non-linear behaviors of such materials, including the nucleation of damage at the micro-scale and its transition to the component level, where it can affect the functionality and, in some cases, the safety of the considered engineering system.
In this context, the present contribution describes the development of a novel computational framework based on boundary elements for the multiscale and multi-physics analysis of polycrystalline materials, capable of representing the initiation, coalescence, evolution of micro-damage and cracking. The formulation underpinning the computational tool is based on the employment of *generalized Voronoi tessellations* as a representation of the material micro-morphology and of *boundary integral equations* for modelling of the fully anisotropic behavior of the individual crystals. The localization of inter-/trans-granular damage and cracking is modelled through *cohesive traction-separation relationships*, which are conveniently coupled with the integral equations modelling the crystals mechanics.
The developed framework has been successfully employed for computational homogenization and microcracking analysis of polycrystalline specimens subject to either quasi-static monotonic loading, low or high cycle fatigue, and in presence of hydrogen embrittlement or thermo-mechanical loads. It has also been used for investigating the inter/trans-granular cracking competition and for analyzing piezoelectric aggregates. Eventually, the development of a two-scale methodology is described and potential future developments are discussed.

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A numerical framework for full scale simulations of polycristalline turbine blades

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Speaker: Bovet Christophe. **Wednesday**. Start time: **15:10**. Room: Rhône 5 LVL1. Link to abstract.

Aircraft and helicopter turbine blades are subjected to severe thermomechanical loads. Often made of a Ni-based superalloy, such as the IN718, the microstructure influences the plastic strain localization and plays an essential role in its creep resistance, oxydation resistance, and fatigue strength. The influence of the microstructure on the mechanical resistance of the blade is usually taken into account by means of extensive experimental campaigns and/or numerical homogenization.
However, these approaches may fail to capture the full complexity of the blade's behavior under operational conditions, necessitating full-scale simulations.
This work proposes a numerical framework to perform full-scale simulations of turbine blades that directly consider their microstructure.
This approach presents several challenges, including the generation of realistic microstructures of the turbine blade; the development of a complex crystal plasticity model accounting for grain size effects; and the resolution of large, highly nonlinear, finite element problems. To tackle these challenges, this work integrates several key advancements:
- Crystal plasticity modeling: a finite strain dislocation density-based model incorporating geometrically necessary dislocations to account for grain size effects.
- High performance mesh generation: a robust and fast mesh intersection process for embedding the microstructure into the blade's finite element mesh.
- High performance solver: multipreconditioned domain decomposition solvers with a specific grain-based partitioning approach for improved efficiency and scalability.

This framework enables the direct study of grain orientation and size effects on plastic strain localization within the turbine blade. What's more, this framework paves the way for the generation of synthetic databases on the blade, which will be used for statistical analysis and reduced order models. As an illustrative application, a graph neural network based machine learning model of the blade will be presented, highlighting the potential of this framework for advanced turbine blade design and analysis.

Multi-scale numerical simulation of the viscoplastic behavior of rock salt

Habib Nour (1)

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Speaker: Habib Nour. **Wednesday**. Start time: **15:30**. Room: Rhône 5 LVL1. Link to abstract.

The global energy landscape is undergoing a significant transformation driven by the urgent need to mitigate climate change and reduce carbon emissions. Hydrogen stands out as a highly promising alternative among the various energy storage methods under investigation, offering the potential to decarbonize multiple sectors-ranging from transportation to industrial processes-and acting as a versatile fuel for energy systems. As a green energy carrier, hydrogen's role in future energy systems could be transformative. However, one of the major hurdles for the widespread deployment of hydrogen-based systems is the challenge of storing hydrogen safely and efficiently. Hydrogen's low density, combined with its high reactivity, presents significant challenges in terms of storage volume and containment safety, necessitating the development of innovative storage solutions.
Underground geological formations, such as depleted oil and gas reservoirs, aquifers, and salt caverns, have been considered for large-scale hydrogen storage. Among these, rock salt formations are especially attractive due to their unique physical and mechanical properties. One of rock salt's most critical properties is its viscoplastic behavior, which allows it to deform slowly under pressure while maintaining structural integrity. This viscoplasticity enables the formation of stable cavities in rock salt, which can accommodate high-pressure conditions over extended periods. Additionally, rock salt possesses a self-healing capability, where cracks generated by stress naturally seal over time, making it highly reliable for containing gases like hydrogen. These self-healing properties, coupled with the absence of permeability, reduce the risk of leakage, thereby enhancing safety. Unlike other geological formations that may require significant engineering interventions to ensure containment, rock salt's inherent characteristics provide a naturally stable and secure environment for hydrogen storage.

The primary objective of this research is to advance the numerical modeling of rock salt's viscoplastic behavior, focusing specifically on its application in hydrogen storage. Previous studies have explored the viscoplastic properties of rock salt, highlighting the importance of crystal slip plasticity observed at the level of individual grains. However, there is a need to go beyond conventional models by incorporating additional deformation mechanisms-namely, inter- and intra-granular cracking. Experimental evidence has shown that the opening and sliding of grain boundaries occur concomitantly with the viscoplastic deformation observed by formation of glide planes on the grain surfaces. These phenomena, often overlooked in traditional models, are significant because grain boundary sliding and opening can account for up to half of the total strain experienced by the rock salt, depending on the size of the grain aggregate. Although crystal slip plasticity remains the dominant deformation mechanism, accurately modeling the behavior of grain boundaries is essential for predicting the overall mechanical response of rock salt.

This research seeks to address the gap in the current understanding of grain boundary behavior by developing a more comprehensive model that integrates these cracking mechanisms. Specifically, the study aims to formulate a thermodynamically consistent relationship between the traction and separation which governs the material behavior at grain boundaries. Additionally, since rock salt exhibits rate-dependent behavior, the model must account for this rate dependency at the grain boundaries by incorporating a rate-dependent traction-separation law. This will allow for a more accurate prediction of how the material behaves under different loading rates, which is key for ensuring long-term stability and safety in hydrogen storage applications. This traction separation law is also tailored for rock salt in both mode I and mode II of fracture, accommodating for the co-dependency of the opening and sliding.

The methodology employed in this research involves the use of multi-scale numerical simulations to capture the complex deformation mechanisms of rock salt. These simulations are performed using finite element analysis within the MOOSE (Multiphysics Object-Oriented Simulation Environment) framework, an open-source platform widely used for modeling complex physical systems. The multi-scale approach allows for the integration of deformation behaviors observed at different length scales, from the microstructural level of individual grains to the macroscopic level of the polycrystalline rock. By capturing

the behavior of cracks at grain boundaries, as well as within the grains themselves, this study aims to provide a more accurate and detailed prediction of the mechanical response of rock salt highlighting the interplay between cracking and the crystal slip plasticity.
By developing a constitutive model that incorporates the experimentally observed deformation mechanisms (the crystal slip plasticity and grain boundary cracking), this study will contribute to more accurate predictions of how rock salt behaves under the conditions imposed by hydrogen storage and will be compared to experimental results conducted at different observation scales within the framework of the ANR RockStoryHy project (Multiscale investigation of ROCKsalt flow for underground STORage of Hydrogen) by other collaborators. The coupling of all these mechanisms, made possible by the MOOSE advanced framework, will allow us to investigate numerically the competition and interaction between intergranular and transgranular deformation mechanisms and fracture. These insights will be invaluable for the operation of underground hydrogen storage facilities, which are critical for the large-scale deployment of hydrogen as a green energy carrier.

Experimental and crystal plasticity investigation of the toughness of W/Cu joints

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Speaker: Ruiz Raúl. **Wednesday**. Start time: **15:50**. Room: Rhône 5 LVL1. Link to abstract.

The context of the work is to contribute to the lifetime assessment of the so-called monoblocks used as plasma facing components in the ITER nuclear fusion reactor based on experiments and numerical modelling. These monoblocks are made of copper-chromium-zirconium (CuCrZr) cooling ducts which are joined to tungsten (W) using a copper (Cu) interlayer. W/Cu joints must ensure efficient heat exhaustion while preserving the component's structural integrity under extreme environmental conditions. The role of plasticity in the crack resistance across these joints is characterized experimentally, using miniaturized CT and DCB specimens. The interpretation of the fracture tests is assisted by fractography analysis combined with nanoindentation. The analysis of plasticity ahead of the crack tip is represented and simulated using crystal plasticity based finite element modelling (CPFEM). The model assessment is under progress. It focuses on the partitioning of the plastic strain field and lattice rotations in the vicinity of the W/Cu joint. The model aims at predicting the response of W/Cu joints under various operational conditions inside the fusion reactor, including cyclic loading and irradiation.

Enhancing the information-richness of Berkovich nanoindentation testing to extract slip systems interaction parameters from residual topographies and crystal lattice rotations on FCC crystal using inverse method

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Speaker: Bourceret Alexandre. **Wednesday**. Start time: **16:10**. Room: Rhône 5 LVL1. Link to abstract.

The single-crystal plasticity framework allows microscale effects to be described from a continuum mechanics point of view, enabling large-scale simulations of great interest in the nuclear and aeronautical fields. Among these parameters, the determination of the coefficients governing the interactions between the slip systems, the core of the plasticity laws, is crucial for reliable simulations applied to industrial fields. However, these parameters are difficult to determine experimentally.
The nanoindentation test seems to be a good choice to improve the identification of the interaction coefficients using the FEMU (Finite Element Model Updating) method. The 10 hardening parameters of the Méric-Cailletaud law of behavior must be identified simultaneously using FEMU to correctly describe the hardening behavior of a material. In order to optimize and improve the identification process, a prior identifiability study is performed to construct an optimal experimental design. The identifiability analysis measures the information richness that could be given to the identification process, leading to better control of the future identification process.

In this study, a numerical study of the information-richness of Berkovich nanoindentation observables will be investigated. The identifiability of crystal plasticity parameters, including interaction coefficients, is investigated using a set of parameters obtained in a previous study, considering crystal lattice rotation, residual topographies, and their combinations. Berkovich nanoindentation simulations and experiments are carried out on single crystal nickel samples. We investigate experimental crystal orientations and the relative orientation between crystal reference frames and the Berkovich tip to simulate the nanoindentation test. The identifiability analysis, allowing the quantification of the information-richness, is based on an I-index, a scalar that transcribe the local convexity of the cost function. It allows comparing the information-richness contained in each experiment and combinations of experiments in order to define an optimal design of experiments.

DIC-Coupled Experimental-Numerical Modeling for Localized Strain Heterogeneity in Polycrystalline Alloys

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Speaker: Kılınç Adil. **Wednesday**. Start time: **16:45**. Room: Rhône 5 LVL1. Link to abstract.

In polycrystals, under the effect of monotonic or cyclic stress, the grains deform in a heterogeneous manner, inducing localizations of plasticity in the microstructure. These localizations of plastic deformation are the origin of material damage (such as slip bands and the initiation and propagation of microcracks) and contribute to the progressive degradation of the material.(1)
Identifying strain heterogeneity at the microstructural scale of polycrystalline alloys remains a significant challenge, particularly when considering contributing factors such as grain size, orientation, twins, and defects. Crystal plasticity models, while useful, are often complex and computationally expensive. Therefore, there is a need for well-structured, simplified models that can effectively explain deformation localizations at a finer scale while being cost- and time-efficient.
This study focuses on developing coupled models and the necessary algorithms to bridge the gap between experimental and numerical tensile testing results of polycrystalline alloys, specifically 316L stainless steel. In the first stage, a digitally representative 2D model is created using optical and electron microscopy images, complemented by digital image correlation (DIC) techniques to capture the strain localization observed in both experiments and numerical simulations.
These algorithms and techniques aim to align experimental and numerical results by employing Ludwik's constitutive law, which facilitates the representation of elasticity and plasticity phenomena at the mesoscale using simplified terms for yielding and hardening coefficients. Several assumptions regarding the transition from macroscale to microscale are also incorporated.
The method built upon detecting elasticity and hardening for each grain from the deformation flow was grounded in the approach well-studied by Hu et al(2) and later study by Kilinç et al(3).
Initial models, simulated at the grain-wise scale using finite element analysis, showed good agreement with experimentally obtained strain fields, particularly in terms of localized deformation zones and statistical data. This finding suggests that it is possible to represent a polycrystalline alloy's microstructure in a 2D model using simplified terms for hardening coefficients and elasticity detection without resorting to complex crystal plasticity models.

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FE modeling of the microscopic strain heterogeneity along grain boundaries inside metallic polycrystalline aggregates

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Speaker: Hanon Guillaume. **Wednesday**. Start time: **17:05**. Room: Rhône 5 LVL1. Link to abstract.

This work investigates the influence of the anisotropy of dislocation glide on the highly heterogeneous strain field across polycrystalline aggregates. The vicinity of grain boundaries and triple junctions is known to host high stresses due to the constrained plasticity (1). It is however debated whether this raises, or rather lowers, the local heterogeneity relative to the macroscopic strain (2). We first address this issue using CPFEM on meshes that conform to the grain boundary geometry. A careful statistical analysis reveals that the amplitude of strain heterogeneity varies depending on the distance to GB and TJ. Based on these results, an alternative approach is then suggested using a simpler voxelized representation, which does not perfectly align with the grain boundaries (3). Every finite element that is intersected by grain boundaries is assigned a bicrystal behavior, by adopting the main hypotheses of the ALAMEL model (4). This original strategy is shown to capture the interactions between neighboring grains along the grain boundaries, resulting in predictions of the macroscopic strain field that closely match those obtained with a conforming FE mesh, while maintaining a low computational cost.

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High temperature solid mechanics: mesoscale continuum describing diffusion, lattice growth and interfaces.

Mesarovic Sinisa (1)

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Speaker: Mesarovic Sinisa. **Wednesday**. Start time: **17:25**. Room: Rhône 5 LVL1. Link to abstract.

At high homologous temperature, deformation of polycrystalline solids is characterized by diffusion within the crystals, as well as lattice growth/disappearance at the grain boundary. This is further complicated by: formation of new phases (either controlled by differential diffusion of components or by phase transformation), diffusion-controlled dislocation climb, and, nucleation and evolution of voids. The typical example in materials service is creep of metals, alloys and ceramics, including creep fracture. In the manufacturing stage, we have sintering, grain growth and recrystallization. To resolve these phenomena on the mesoscale, i.e., withing crystalline grains and on the grain boundaries, a specialized continuum formulation is needed. Here, the general mathematical formulation for such mesoscale continuum is developed, first assuming sharp interfaces between grains, phases and voids, followed by the diffuse interface (phase field) formulation best suited for computational analysis.
In crystalline solids, when diffusion is operational, the mass velocity is different from the lattice velocity, the mass moves with the lattice, and through the lattice. Since most of the traditional (diffusionless) solid mechanics is based on the deformation/motion of the crystal lattice (e.g., elasticity is based on lattice stretching, while dislocation/crystal plasticity is based on the relative translation of lattice parts), it makes little sense to describe solid kinematics using the mass velocity as the primary field. Instead, we identify the *material* with the *lattice*. The lattice density and mass density are easily connected if the concentration of different components is known. The mass velocity will depend on the lattice velocity and on the fluxes of different components.
In the absence of diffusion, the mass and lattice continua are indistinguishable; the traditional elasticity and crystal plasticity are in fact lattice continua, without distinction between mass and lattice. When diffusion is present such distinction is needed. One important consequence bears emphasis. Solid mechanics traditionally relies on Lagrangean (material) frame, where the fundamental tensor field is the deformation gradient. The reference position is typically taken to be the initial position or the position at some reference time – in any case, it corresponds to a specific real configuration. However, when lattice grows and disappears at the boundary, the reference configuration for the newly created lattice cannot be determined by any physical reasoning. Nevertheless, the deformation gradient is needed for description of lattice elasticity, eigenstrains and dislocation plasticity. Therefore, we adopt the Eulerian frame with deformation gradient now treated as a state variable, moving with the lattice, and being function of current coordinates. At the growing boundary, we assume the continuity of the deformation gradient, which determines its value in newly created lattice in the instant of creation, the value in the adjacent old lattice being known.
Much of the sharp interface formulation has been developed in (1, 2, 3). Here, we only summarize the main components as needed for the development of the diffuse interface formulation. Selected computational results are presented.

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Asymmtrical shear responses of grain boundaries

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1 - Nanyang Technological University (Singapore), 2 - Tsinghua University [Beijing] (China)

Speaker: Dang Ruoqi. **Wednesday**. Start time: **17:45**. Room: Rhône 5 LVL1. Link to abstract.

The breaking of symmetry always leads to intriguing physical properties. While extensive research has been conducted on tension-compression asymmetry at the nanoscale in metallic materials, there is a lack of attention on the possibility of shear asymmetry. In this work, we introduce the concept of shear asymmetry in grain boundaries (GBs) and systematically investigated the positive and negative shear responses of 157 symmetric and asymmetric tilt grain boundaries using molecular dynamics (MD) simulations. Our findings reveal that GBs with asymmetric structures have distinct shear responses under opposite shear directions. Furthermore, the extent of shear asymmetry corelates positively with the shear modulus difference across GBs, arising from materials anisotropy. To explain this phenomenon, we proposed a new disconnection-based theoretical model. This discovery of shear asymmetry offers valuable insights into the plastic mechanics of materials and offers potential implications for material design and understanding.

Micromechanical Modeling and Simulations of the Effects of Oxygen in Titanium Alloys

Vernier Patricia (1), Marano Aldo (1), Bornowsky Lucille (1), Kanoute Pascale (1)

1 - ONERA (France)

Speaker: Vernier Patricia. **Wednesday**. Start time: **18:05**. Room: Rhône 5 LVL1. Link to abstract.

Titanium alloys are widely employed for aerospace applications due to their good thermomechanical performances and their lightweight. However, because of their capacity to dissolve oxygen, Titanium alloys may not withstand environments as extreme as temperatures exceeding 600∘C. During the oxidation of the material, oxygen diffuses from the free surface into the depths, where its presence significantly alters the mechanical properties. Particularly, the fatigue life is considerably reduced due to the initiation of cracks at the surface, where the highest oxygen concentrations are found. Therefore, it is crucial to understand the effects of oxygen over the microstructure for accurate predictions of the mechanical behavior of Titanium. Precisely, crystal plasticity models are used to describe the microstructural mechanisms implied in the deformations of such materials. In this work, we propose a methodology to account for the presence of oxygen in crystal plasticity FFT simulations of Ti6242 polycristalline aggregates under cyclic loadings. Our results are then compared to experimental data.

The insertion of oxygen in Titanium results in the increase of elastic anisotropy (3) (4), but also the increase of critic resolved shear moduli (CRSS) (1) (2). Since the oxygen concentration varies in the material with respect to the surface, it is essential to characterize this dependence at the microstructural scale. We thus rely on available nanoindentation experiments data that give indirect estimates of these parameters through the measurement of reduced elastic and hardness moduli. Hence, we can identify and quantify the dependence of the elastic moduli to oxygen concentration by following (4). The identification procedure of these authors is based on a model developed in (5), which provides a relationship between the reduced elastic modulus and the elastic moduli through the displacement of the indent. Similarly, we consider that the CRSS values are related to the measures of hardness. The variation of the material parameters with respect to the oxygen content can then be implemented in the setup of numerical simulations.

Finally, we perform crystal plasticity full-field simulations of Titanium alloys using the massively parallel FFT-based solver AMITEX_FFTP, on both reference and oxidized material. The morphology and texture of the Representative Volume Element are generated from EBSD analyses. We first identify the global behavior of our model by comparison with experimental tensile tests. Next, we focus on the effects of free surfaces under cyclic loadings, which is essential for understanding the deformation mechanisms that lead to crack initiations. The analysis of local fields obtained numerically, in conjunction with experimental observations of surface fractures, provide a deeper insight into the microstructural mechanisms underlying reduction of fatigue life.

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Coupled diffusion-mechanics modeling of titanium alloys under high temperature oxidizing conditions

Marano Aldo (1), Gheno Thomas (1), Fer Benoit (1)

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Speaker: Marano Aldo. **Thursday**. Start time: **10:00**. Room: Rhône 5 LVL1. Link to abstract.

High temperature oxidation of titanium alloys induces substantial oxygen diffusion beneath the oxide scale, forming an oxygen-affected layer (OAL). The stiffness and hardness of alpha-titanium strongly increase with increasing oxygen concentration. The increase in stiffness is known to be strongly dependent on crystal orientation (1), as well as the swelling deformation induced by oxygen intake (2). Compared to the bulk, the OAL is thus characterized by a strong alteration of mechanical properties, that is strongly microstructure dependent. Pre-oxidation has been shown to significantly influence the alloy mechanical response, that evolves towards an embrittlement associated with the evolution of deformation and damage mechanisms at the microstructure scale, particularly in the OAL. Finally, recent results show that oxygen diffusion in the alloy may be affected by a mechanical stress imposed during oxidation (3). Due to these strong interactions, it is necessary to account for the influence of oxygen diffusion when analyzing mechanical tests conducted with in-situ oxidation of the alloy. These encompass, for instance, creep and low-frequency fatigue tests at high temperatures.
To gain new insights into these phenomena, this study presents a novel model coupling diffusion and mechanics to simulate the behavior of quasi-alpha titanium alloys. The model accounts for the effects of pressure and of the pressure gradient on oxygen transport. An eigenstrain is included to account for swelling deformation effects caused by oxygen intake. The material's mechanical behavior is described using a crystal plasticity framework. The elastic and plastic properties evolve as a function of the local oxygen concentration, in order to describe stiffening, hardening, and the evolution of elastic and plastic anisotropy in the OAL. This comprehensive coupling of diffusion and mechanics provides a robust foundation for understanding the complex interactions between oxygen ingress, microstructure, and deformation mechanisms. The model is solved by coupling a finite-difference scheme for the diffusion-transport equation, to a non-linear FFT-based mechanical solver. It has been implemented within the massively parallel spectral solver AMITEX_FFTP to enable the simulation of large and complex microstructures with high computational efficiency.

This framework is applied to study the behavior of the Ti6242s alloy in an oxidizing environment at 600∘C. The simulation of creep tests with in-situ oxidation preceded or not by a pre-oxidation phase is studied. In particular, the influence of the various model features and parameters on mechanical properties and deformation heterogeneities is examined. Finally, in the light of comparison with recent experimental findings, their suitability is discussed to pave the way for an improved understanding of the material's mechanical response during oxidation.

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Coupling Phase-Field Crystal and Field Dislocation Mechanics in Dislocation Modeling

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Speaker: Graini Aymane. **Thursday**. Start time: **10:20**. Room: Rhône 5 LVL1. Link to abstract.

Dislocations are crystalline defects that serve as primary carriers of plastic deformation. Dislocation-based mechanisms are typically modeled via molecular dynamics or discrete dislocation dynamics models; the latter relies on a large set of interaction rules, and both are severely limited in temporal and spatial scales. In this work, we introduce a novel approach to model dislocation dynamics with an atomic resolution and at diffusive time scales by coupling the Phase Field Crystal (PFC) and Field Dislocation Mechanics (FDM) models. PFC had shown great potential in capturing the evolution of topological defects in crystalline materials, but it fails to correctly capture elastic distortions and dynamics. In contrast, FDM captures the latter, but it is unable to keep dislocation cores compact due to its PDE based construct. This work addresses different coupling strategies between PFC and FDM to extract the best of both models. The resulting framework opens pathways for modeling dislocation motion and interactions at diffusive time scales with atomic-level resolution.

On the importance of 3D microstructure for the prediction of microstructural evolution

Stricot Pauline (1) (2), Ask Anna (3), Toualbi Louise (4), Barres Quentin (5), Renollet Yves (6), Proudhon Henry (2), Forest Samuel (7)

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Speaker: Stricot Pauline. **Thursday**. Start time: **10:40**. Room: Rhône 5 LVL1. Link to abstract.

Conventional metallurgy is based on thermomechanical processes. During these processes, strain and temperature induce microstructural evolution including grain boundary migration, recovery and recrystallization mechanisms. Although these mechanisms have been observed and studied for a long time, they are yet to be fully understood. Therefore, it is of particular interest to have a numerical model that can predict the final microstructure of a given material under specific stress and temperature conditions. To achieve this, it is necessary to couple two models: one that predicts microstructure evolution caused by deformation and another that predicts evolution induced by temperature.
The models are used in a decoupled way which allow to study microstructural evolutions during strain followed by annealing. Special care should be given to the simulation data transfer between the two models. To give quantitative prediction of microstructural evolutions, such a numerical procedure should be finely calibrated against experimental data.
This study focuses on the microstructural evolution of pure aluminium (99.999 %) during deformation followed by annealing. The experimental data acquired during the deformation step is used to calibrate a numerical routine of crystal plasticity finite element method (CPFEM) simulations. Then the experimental data acquired during the annealing step is used to calibrate a phase field model.
The main focus of this study is to determine which experimental data is necessary to input to the model and how the transfer of data can be done most efficiently. A major question is if a 2D description of the microstructure is sufficient or if it is necessary to describe the full 3D microstructure.
For the experimental part of the study, an *in situ* scanning electron microscope (SEM) tensile test coupled with Electron Backscattered Diffraction (EBSD) analysis is firstly conducted at room temperature. Lithography is performed on the sample do define a region of interest and create a speckle on the surface which is used for digital image correlation (DIC). The tensile test is performed by imposing the crosshead displacement. This displacement is periodically interrupted to acquire secondary electron images for the DIC. Less frequently, the crosshead displacement is stopped and the sample is deloaded in order to perform EBSD analysis without being impacted by relaxation. The sample is previously characterized by laboratory-based diffraction contrast tomography (LabDCT). This provides a spatially resolved 3D orientation map, which can be used to numerically reconstruct the real microstructure.
The same sample is then submitted to an *in situ* SEM annealing test coupled with EBSD analysis. The sample is heated to the desired temperature and then cooled to 50∘C to prevent microstructural evolution during the EBSD scan. This can be done as many times as desired.
The comparison between the numerical and experimental microstructural evolutions during strain enables fine calibration of the CPFEM simulations and verification of the model's ability to accurately reproduce lattice reorientation and energy accumulation resulting from plastic deformation. Similarly, the comparison between the numerical and experimental microstructural evolutions during annealing enables fine calibration of the phase field model and verification of the model's ability to accurately reproduce grain boundary migration and eventually recrystallization.
Comparison between numerical results performed only using 2D microstructure from EBSD and 3D microstructure from LabDCT is performed to asses whether full microstructural characterization is needed in order to achieve satisfying results.

The Role of Plastic Strain on Microstructural Evolution in Bainitic Steel During Uniaxial Hot Compression Test: Experiment and Finite Element Simulation

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Speaker: Karamabian Mahdi. **Thursday**. Start time: **11:00**. Room: Rhône 5 LVL1. Link to abstract.

The consequence of plastic strain on the hot deformation behaviour and grain size evolution in bainitic steel was investigated using Gleeble thermo-mechanical physical simulation and finite element simulation. The model was validated by comparing the predictions with the experimentally measured true stress-strain curves. The model allowed quantification of the heterogeneity of plastic strain within the uniaxial hot compression test specimens under the investigated conditions. The results reveal that increasing plastic strain enhances dislocation density, promoting the nucleation of recrystallized grains. The recrystallized grain size decreases with higher strain due to enhanced grain boundary migration and subdivision of grains, reaching a saturation grain size at large plastic strains. This behaviour is modelled using an Avrami-type equation, which incorporates the fraction of recrystallized grains. The maximum plastic strain was mainly observed at the centre of the sample and the minimum occurred in the so-called dead zones close to the platen. The inhomogeneous distributions of plastic strain resulted in an inhomogeneous final microstructure, *i.e.,* inhomogeneous distribution of recrystallization, constituent fraction, and average grain size.

Towards real-time exploration of grain boundary effects on diffusion in solid electrolytes

Scholz Lena (1), Ou Yongliang (1), Bauer Ruben (1), Grabowski Blazej (1), Fritzen Felix (1)

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Speaker: Scholz Lena. **Thursday**. Start time: **11:20**. Room: Rhône 5 LVL1. Link to abstract.

Major progress in battery technology is a key to the decarbonization of industry and everyday life. In All-Solid State Lithium Ion Batteries (ASSLIBs) the liquid electrolyte of conventional Lithium ion batteries is replaced by a polycrystalline solid-state electrolyte, promising increased capacity, operational safety, and charging performance. Therefore, an in-depth understanding of the multiphysical multiscale effects within the solid-state electrolyte is the subject of research across various disciplines.
The diffusion behavior of Li ions in the solid-state electrolyte is crucial for the battery's overall performance. Studies on the atomistic scale indicate that grain boundary effects and grain size significantly impact overall diffusivity. Recent advances in active learning methods have enabled large-scale, long-time, and high-accuracy simulations of complex atomic structures using ab initio-based machine-learning interatomic potentials. Despite their promising insights, these approaches still go along with massive computational demands, thereby leaving a significant gap between atomistic and application length scales of interest. In simulations on a larger scale, however, the details of the polycrystalline structure are often neglected or only considered under strong assumptions such as isotropy.

Our approach considers the fully resolved crystalline structure with a parametrization that aligns with the atomistic perspective to find a microscopic description that accounts for diffusion along as well as across grain boundaries. This is embedded into a finite element simulation by introducing a novel collapsed interface element. The results are governed by different and potentially anisotropic diffusion coefficients in bulk and grain boundary domains gained from calculations on the atomistic scale. By means of homogenization, an effective model on the mesoscale is derived based on a periodic reference volume element (RVE). Using the hybrid bulk-interface diffusion model, the contribution of the grain boundary to the overall diffusivity can be studied quantitatively.
Furthermore, the affine structure of the problem is exploited to derive a reduced-order model that offers massive performance improvements at little sacrifice in accuracy: The availability of just a few full simulations enables highly accurate real-time estimates for the effective diffusion coefficients across the parameter space. Moreover, the reduced-order model allows for an in-depth analysis of the material and structural features that govern the effective diffusion behavior. For instance, it enables the investigation of preferred diffusion paths. Interactive parameter space exploration supports bridging the gap between the concepts on different scales as well as computational and experimental results. This will facilitate in silico exploration of microstructures and their implications on larger scales, which, at a later stage, will be used to design improved materials and batteries.

MS1.5 - Mechanics of ceramics

Organisers: Sylvain Meille (MATEIS) and Emilio Jimenez-Piqué (UPC Barcelona)

Understanding the fracture behaviour of tough alumina-based ceramic inspired by nacre.

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Speaker: Bouville Florian. Keynote. **Monday**. Start time: **10:10**. Room: Roseraie 1 LVL3. Link to abstract.

Millions of years of evolution have gifted natural materials with sophisticated hierarchical structures that enable them to resist fracture despite being primarily composed of brittle ceramics. Nacre stands out as having one of the simplest natural microstructures, resembling a brick-and-mortar wall, yet exhibiting many toughening mechanisms leading to a pseudo-ductile behaviour in tension. Today's nacre-like composites exhibit higher values of fracture toughness and improved crack-resistance curves compared to bulk ceramics. However, characterizing fracture in such materials remains a challenge, and understanding the link between the microstructure and the crack resistance is necessary to improve these materials further. We worked on characterizing fracture in nacre-like ceramics composed of alumina bricks with various ceramic interface, with the aim of determining the role of microstructure and composition on the mechanical response. We have developed analytical tools validated by finite element analysis to measure crack resistance curves of highly deflected and branched cracks. Supported by in-situ synchrotron tomography fracture testing and wedge splitting, we assessed the stress intensity mode-mixity at the crack tip and quantified the damage evolution in 3D. This analysis reveals important lessons on the effect of the microstructure and mortar properties to guide the improvement of these materials.

Review and perspectives in characterizing anisotropic fracture of nacre-like alumina

Bert Benjamin (1), Doitrand Aurélien (2), Meille Sylvain (3), Duminy Thomas Henry Ronan (4)

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Speaker: Bert Benjamin. **Monday**. Start time: **10:50**. Room: Roseraie 1 LVL3. Link to abstract.

In recent decades, researchers have been developing composite materials that mimic the microstructure of natural nacre ("brick-and-mortar" assembly), incorporating components with superior mechanical properties compared to those found in the nature. Among these, Nacre-Like Aluminas (NLA), composed of alumina platelets separated by a glassy phase, have garnered the most attention due to their good tradeoff between strength (470 MPa) and toughness (5.8 MPa.m1/2) achieved within a fully dense ceramic structure **(1)**. The primary reinforcement mechanism that can be found in these composites involves crack deflection at the platelet interfaces, the weakest regions of the material. This deflection increases the surface area over which the crack must propagate, thereby dissipating more energy and significantly enhancing the material toughness. Beyond crack deviation, additional mechanisms, though less dominant, also enhance crack resistance, including platelet interlocking, mineral bridging between platelets, and even crack branching, all of which contribute to the overall improvement in resistance to crack propagation **(2)**.
The unique properties of NLAs are closely tied to their microstructure inducing several reinforcing mechanisms, so they should be associated with their overall anisotropy. This anisotropy is defined by three principal directions of stress application in NLA, referred to as *Across*, *Along*, and *Between* **(3)**, which describe the orientation of crack propagation relative to the microstructure. However, almost all of the studies have been focusing on the "*Across* notched " configuration because it is the strongest and toughest one when it is just as important or even more so to understand the weakest configuration, the one most likely to be responsible for the fracture of the material under mechanical loading. Nevertheless, only few studies studied NLA anisotropy **(4, 5, 6, 7)**. Therefore, to fully understand NLA anisotropy, detailed characterization of the material properties and interfacial behavior in each of its principal directions under different loading conditions has to be done. This approach is essential for controlling fracture behavior in order to optimizing the material strength and toughness and adapting its performance to specific applications.

To characterize this anisotropy, bending testing was conducted in each NLA orientation, using both plain and notched samples to evaluate both strength and toughness. A comprehensive characterization was achieved by employing additional techniques to bridge multiple scales-from examining crack characteristics (shape, length, surface, path, and initiation) to performing qualitative and quantitative analyses of microstructural defects (size, type, and location). Further insights were gained through μ-beam flexural tests to estimate interfacial properties and numerical simulations to model and replicate the material's behavior. In summary, this approach offers a more thorough methodology for characterizing the anisotropy of NLAs.

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The fracture of Nacre-like graphite

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Speaker: Li Ao. **Monday**. Start time: **11:10**. Room: Roseraie 1 LVL3. Link to abstract.

Due to its unique bond configuration with weakly bonded graphene layers, graphite is a lightweight material that exhibits excellent and highly anisotropic thermal and electrical conductivities and unique mechanical properties combined with good thermal and chemical stability. For these reasons, graphite is a material of interest for many advanced applications from thermal management to nuclear fusion. In this work, a novel highly aligned nacre-like graphite/ceramic composite was synthesized via pressure assisted sintering. In these composites, single crystal graphite platelets, with dimensions ranging from 10 to 20 μm, act as bricks bonded with a refractory ceramic mortar. We have analysed the strength and fracture resistance of the resultant composites using a combination of ex-situ and in-situ testing in the scanning electron microscope. The materials retain bending strengths ranging from 30 to 100 MPa and their nacre-like structure results in a unique fracture behaviour in which crack propagation is accompanied by the bending and exfoliation of graphite platelets. As a result, the composites exhibit a characteristic raising R-curve with toughness reaching values above 3 MPam1/2. The in-situ experiments allow us to identify the toughening mechanisms and relate them to the materials microstructure. The behaviour is compared to micromechanical tests performed in single graphite platelets. This work will help us to design improved graphite-based composites combining structural and functional capabilities.

In-situ characterization of local fields in alumina using Raman and luminescence piezospectroscopy

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Speaker: Chalony Julie. **Monday**. Start time: **11:30**. Room: Roseraie 1 LVL3. Link to abstract.

Raman and luminescence spectroscopy can provide insights into the local stress or strain field within materials by tracking frequency shifts in their characteristic peaks. Raman scattering is sensitive to changes in lattice vibrations due to an applied strain, while luminescence is responsive to alterations in the electronic environment of specific atoms, providing information on interatomic distances and, consequently, applied strain. A key advantage of these techniques is their high spatial resolution, down to the micrometer scale, enabling precise mapping of local fields during in-situ micromechanical testing. It also appears as an alternative to Digital Image Correlation for materials deforming at small strain levels, such as ceramics. However, the main challenge lies in converting the measured peak shifts into meaningful stress or strain components.

Since the 1960s, both luminescence and Raman peak shifts have been studied in parallel for the corundum structure of α-alumina. Raman spectroscopy, in this context, generates seven independent peaks (1), which is particularly useful for determining the six independent components of the strain tensor. Despite this potential, Raman spectroscopy on alumina is challenging, and variability in peak shifts with strain has limited its widespread use for local field measurements. In contrast, luminescence spectroscopy offers rapid, reliable, and easily accessible peak shifts with respect to strain (2). However, with only two peaks available, luminescence provides less information about the local stress or strain tensor that have 6 components. Therefore, combining both techniques can leverage their respective strengths.

This work aims to compare various models from the literature that link luminescence (3) and Raman peak shifts (4) (5) to stress or strain, and to evaluate which models are most suitable for different use cases. Additionally, we explore how these models can be combined to maximize their effectiveness. These characterization techniques are then applied to fracture mechanics experiments to obtain accurate and localized stress field measurements. Specifically, a simulation-experimental approach is used to extract local stress fields from indirect in-situ measurements via peak shifts.

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Domain evolution mechanisms of ferroelectric ceramics elucidated by a novel EBSD indexing method

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Speaker: Griesbach Claire. **Monday**. Start time: **11:50**. Room: Roseraie 1 LVL3. Link to abstract.

Ferroelectric ceramics are widely used within actuators, sensors, transistors, and solar cells due to their coupled thermo-electro-mechanical properties. Despite their widespread use, the domain nucleation and switching mechanisms within ferroelectric ceramics are not well understood due to the complexities in characterizing a polycrystalline microstructure containing intragranular nanodomains and defects such as pores and precipitates. Domain nucleation and switching mechanisms are hypothetically influenced by both structural features-including the grain orientation, misorientation to neighboring grains, proximity to defects, and the initial domain structure, and the loading configuration-including the boundary conditions, stress applied, and the electric field loading rate. To understand such effects, we have developed an in-house electrical testing setup capable of capturing the bulk ferroelectric response. To connect the bulk polarization hysteresis to the micro-scale evolution of domains, the microstructure is characterized both before and after electrical loading using electron backscatter diffraction (EBSD). We have developed a novel reindexing approach that accurately identifies domain variants in tetragonal ferroelectrics. Minute intensity differences produced by dynamical diffraction within a non-centrosymmetric crystal structure cannot be identified through traditional Hough-indexing, but they can be identified through weighted correlations to simulated patterns of all pseudosymmetric variants. This novel method provides a wealth of microstructural data, giving insight into condition-specific ferroelectric switching mechanisms. The new mechanistic understanding that our research provides will guide microstructural design strategies to yield a target bulk ferroelectric response.

Mechanics-based Tailoring of Room-temperature Dislocations in Ceramics

Fang Xufei (1)

1 - Karlsruhe Institute of Technology (Germany)

Speaker: Fang Xufei. Keynote. **Monday**. Start time: **13:40**. Room: Roseraie 1 LVL3. Link to abstract.

Dislocations are one-dimensional or line defects that carry plasticity in crystalline solids. In the conventional picture, ceramics are considered brittle and exhibit little or no plasticity at room temperature. However, recent research on dislocations in ceramics suggests that dislocations may have been much under-appreciated. Demonstrated promising proofs-of-concept for dislocation-tuned functional properties suggest that dislocations may hold great technological potential in advanced ceramics (1). As the prerequisite to harvest dislocation-tuned properties, engineering dislocations into ceramics without brittle fracture has thus become a pressing bottleneck. To tackle this challenge, we adopt the mechanics-based approach to separately examine the dislocation behavior including dislocation nucleation, multiplication, and motion, enabling us to tailor dislocations in ceramic oxides such as SrTiO3 at room temperature (2). We can now achieve a dislocation density ranging from _~10^11/m^2 to _~10^15/m^2 with a plastic zone size of up to milli-/centimetres using a mechanical deformation toolbox, which further equips us to extend the material toolbox by discovering and reporting more room-temperature plastically deformable ceramics (3). These combined deformation and material toolboxes offer a new platform for studying the dislocation-tuned functional properties and the mechanical properties (such as plasticity, toughness, and damage tolerance) over a wide range of length scales.

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TRIP effect in Zirconia: atomistic simulations and in-situ experiments

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Speaker: Rodney David. **Monday**. Start time: **14:20**. Room: Roseraie 1 LVL3. Link to abstract.

Like steels, zirconia ceramics exhibit transformation-induced plasticity (TRIP) due to a transformation between a tetragonal and a monoclinic phase. This unique feature allows zirconia ceramics to undergo substantial plastic deformation, reaching a remarkable 7% plastic strain. However, this effect is far from fully understood, hindering the development of ceramics with macroscopic deformability exceeding 1%. Additionally, the lack of interatomic potentials capable of accurately describing zirconia complex polymorphism and phase transformations makes understanding the TRIP effect at the atomic scale difficult.

In this work, we combine in-situ Laue diffraction on micropillars and atomic-scale simulations to obtain microscopic information on transformation conditions. Specifically, we explore how compression direction influences the transformation. The simulations required the development of a neural network-based interatomic potential to accurately describe zirconia polymorphism. We characterize the deformation processes, critical stress-strain states, and phase transformations both experimentally and numerically across various compression directions, spanning the entire standard triangle.

Our simulations challenge the prevailing notion that a limited number of variants govern the TRIP in zirconia. Furthermore, we observe through simulations a complex interplay between competing stable and metastable phases, some of which have not been documented experimentally. An interesting question, which remains to be explored, is why these phases have not been reported experimentally so far: an effect of size, temperature, or strain rate, a lack of realism of the NNP, or have these phases been overlooked experimentally in the past?

Dislocation mechanics in KTaO3: room-temperature plastic deformation across the length scales

Frisch Alexander (1), Zhang Jiawen Preuß Oliver Okafor Chukwudalu Setvin Martin Fang Xufei (2)

1 - Karlsruhe Institute of Technology (Germany), 2 - Karlsruhe Institute of Technology (Germany)

Speaker: Frisch Alexander. **Monday**. Start time: **14:40**. Room: Roseraie 1 LVL3. Link to abstract.

Oxides are normally believed to be brittle at room temperature due to the lack of dislocation (line defects in crystalline solids) activities. However, following the observations of dislocation-mediated bulk plastic deformation of SrTiO3 in 2001 (1) and KNbO3 in 2016 (2), there has been an ongoing quest on discovering more ductile perovskite oxides. In this work, we present our discovery of KTaO3 being the 3rd perovskite oxide to exhibit such behavior (3). This has been achieved by understanding the dislocation-based competition between plasticity and cracking. The mechanical response was investigated using bulk uniaxial compression, cyclic Brinell indentation and scratching at mesoscale, as well as the nanoindentation tests at micro-/nanoscale , revealing the material's plastic deformation behavior across multiple length scales. TEM (transmission electron microscopy) characterization reveals the activated slip systems and the tunability of dislocation densities, providing insights into the underlying plasticity mechanisms. These findings underscore the potential of mechanics-based engineering of dislocations in KTaO3, which is an emerging electronic oxide for versatile functional and mechanical properties.

Keywords: dislocations; KTaO3; plasticity; bulk deformation; cyclic deformation

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Strains, stresses and microcracks in pure zirconia polycrystals

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Speaker: Castelnau Olivier. **Monday**. Start time: **15:00**. Room: Roseraie 1 LVL3. Link to abstract.

In pure dense zirconia-based materials, cooling induces a martensitic phase transition associated with a large variation of the ZrO2 molecular volume and anisotropic thermal expansion, both leading to very high level of internal stresses and the formation of large multiscale microcrack networks. We investigate the relationships between the main crystal planes or directions and the orientation of the microcracks using specimens that have undergone only one thermal cooling from the liquid state to room temperature. Two crack orientations have been identified. The first one occurs on the {001}m planes of monoclinic crystals. The second one is on the {110}c planes of the parent cubic phase. We propose to explain these observations through the calculation of stresses and strains induced by phase transitions all along the cooling process, using a micromechanical approach. The experimental observations of crack orientations are in good agreement with the strain model based on a phenomenological approach of the martensitic transformation. Accordingly, strain accommodation mechanisms during this transition seem to be a decisive factor in crack or twin boundary formations between individual monoclinic crystals. *Keywords:* Pure zirconia, martensitic phase transformation, micromechanical modelling, microcracks, EBSD

Donor doping affects dislocation plasticity across the length scale in SrTiO3

Okafor Chukwudalu (1), Takahara Kohei (2), Korneychuk Svetlana (1), Huck Isabel (3), Li Yan (2), Bruns Sebastian (3), Durst Karsten (3), Nakamura Atsutomo (2), Fang Xufei (1)

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Speaker: Okafor Chukwudalu. **Monday**. Start time: **15:20**. Room: Roseraie 1 LVL3. Link to abstract.

Donor doping is widely utilized to tune the physical properties of functional oxides, but its influence on mechanical behavior, particularly dislocation plasticity and fracture, remains largely unexplored. This study investigates dislocation mechanics and fracture of Nb-doped single-crystal SrTiO3 across the length scale, using bulk uniaxial compression (macroscale), Brinell cyclic indentation (mesoscale), and nanoindentation (nano-/microscale). We find that 0.5 wt.% Nb-doped samples exhibit significantly higher yield stress (_~ 50%) and reduced fracture strain at bulk scale, compared to the reference sample. Brinell indentation test (2.5 mm indenter diameter) reveals a discrete density of slip traces (evidence of dislocation activity) on 0.5 wt.% Nb-doped samples indicating a hindered dislocation mobility and multiplication analogous to macroscale deformation. In addition, 0.5 wt.% Nb-doped sample exhibits higher nanoindentation pop-in load and lower indentation creep rates than the reference sample, suggesting less favored dislocation nucleation and mobility. This combinatorial approach consistently shows suppressed dislocation-based plasticity while promoting cracking across the length scale in 0.5 wt.% Nb-doped samples. These findings provide new insight into the impact of defect chemistry on the mechanical plasticity and cracking of doped SrTiO3, with the potential to be extended to other oxides. Keywords: Dislocations; oxides: plasticity; fracture; chemical doping

Effect of testing geometries and notch milling processes on micro-scale fracture energy measurements in ceramics

Li Zhuoqi Lucas (1), Wang Siyang (1), Douglas James O. (1), Li Ao (1), Gavalda-diaz Oriol (1), Marquardt Katharina (1) (2), Giuliani Finn (1)

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Speaker: Li Zhuoqi Lucas. **Monday**. Start time: **16:00**. Room: Roseraie 1 LVL3. Link to abstract.

The single cantilever beam (SCB) with a straight-through notch is widely used for testing the fracture properties of brittle materials at the microscale due to its flexibility in accommodating various materials and the straightforward calculation of fracture toughness, requiring only the peak load and cantilever geometry. However, during the final notching process, ion implantation from the focused ion beam (FIB) induces residual stresses that may resist crack nucleation, resulting in a toughening effect and inflated fracture toughness values. This experimental study investigates the effect of different notching methods on the measured fracture energy of the prismatic plane in 6H-SiC with straight-through notched SCBs, focusing on reducing or eliminating FIB damage through cryo-FIB milling or post-mortem annealing. First, double cantilever beam (DCB) splitting experiments are conducted to establish baseline fracture energy values, as the stable crack growth in this geometry allows calculation of fracture energy away from the notch, mitigating potential inaccuracies in measurements near the notch surface caused by FIB damage. Results from room-temperature Ga-FIB notched SCBs showed systematic inconsistencies with the results from DCB tests. In this talk, we discuss the effectiveness of using cryo-FIB for the final notching and post-notching annealing of reducing the systematic errors in fracture energy calculation with SCB testing geometry. The findings contribute to more accurate measurements of microscale fracture properties using the widely applicable SCB geometry.

New Method Combining Nanoindentation and Finite Element Modeling (FEM) for Estimating Helium Ion Irradiation-Induced Eigenstrain/ Residual Stress in SiC

Bensalem Mohamed (1), Daghbouj Nabil (1), Polcar Tomas (1)

1 - Czech Technical University in Prague (Czech Republic)

Speaker: Bensalem Mohamed. **Monday**. Start time: **16:20**. Room: Roseraie 1 LVL3. Link to abstract.

The advancement of next-generation reactors, focusing on improved safety and reduced waste production, relies on the development of innovative materials. Understanding the degradation of materials used as structural components in reactor cores is a critical aspect of this process. However, studying irradiation effects through test reactors is often constrained by limited access, high costs, and the risks associated with radioactivity. To address these challenges, research frequently employs ion beam irradiation as a safer and more accessible alternative to investigate the impact of radiation on material properties (1).
The ion irradiation process induces microstructural changes, including defect generation and accumulation, leading to mechanical deformation in a material leading to residual stresses (RS) field. Residual stress has a significant impact on the mechanical behavior and service life of materials under extreme conditions. Silicon carbide (SiC), a key candidate for advanced nuclear reactors, experiences a changes in its mechanical properties due to helium ion irradiation. Accurate quantification of these irradiation-induced residual stresses is essential for predicting the material's performance and failure mechanisms.

Experimentally estimating the irradiation-induced eigenstrain profile presents significant challenges, requiring the use of coupled advanced technological setups such as focused ion beam (FIB) techniques and transmission electron microscopy (TEM). However, this destructive approach, which involves slicing the sample, can induce relaxation of residual stresses within the material, potentially leading to underestimated measurements. This limitation highlights the need for developing alternative approaches.
This study proposes an innovative methodology for estimating residual stress in helium-irradiated SiC. The approach relies on minimizing the error between force-displacement curves obtained from experimental nanoindentation tests and corresponding simulations conducted using the finite element method (FEM) in Abaqus. The methodology provides an accurate assessment of the compressive residual stress. This novel technique offers a robust alternative for characterizing irradiation-induced stresses, contributing to the design and evaluation of advanced reactor materials.

Phase Field Modelling of Ni oxidation and YSZ cracking in Solid Oxide Cells

Fournier Sylvain (1), Hubert Maxime (1), Molnár Gergely (2), Doitrand Aurélien (3), Meille Sylvain (3), Laurencin Jérôme (1)

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Speaker: Fournier Sylvain. **Monday**. Start time: **16:40**. Room: Roseraie 1 LVL3. Link to abstract.

Solid Oxide Cells (SOCs) are promising high temperature (700∘C-850∘C) energy conversion devices that present a high efficiency in both fuel cell and electrolysis modes and can be used in a wide range of technological applications. However, their widespread development is currently hindered by durability and reliability problems including various mechanical damage in the cell components such as electrodes and electrolyte (1).
The conventional 'hydrogen' electrode is a cermet of Nickel and Yttria Stabilized Zirconia (Ni-YSZ combining Ni electronic conductivity with YSZ ionic conductivity. Failure in the system (such as air reintroduction during the system shutdown, gas leakage or fuel overutilization due to a problem of gas feeding) leads to the Ni re-oxidation. The transformation from Ni to NiO results causes volumetric expansion within the pores and induces mechanical strain on the YSZ backbone, compromising its structural integrity and electrode functionality. Therefore, the robustness of the cell components still needs to be improved, especially for the cermet. However, the threshold in terms of Ni re-oxidation triggering the fracture in the cermet is not precisely known.
To better understand the involved mechanisms, a modelling approach is proposed to calculate the nucleation and the propagation of the micro-cracks in YSZ during Ni re-oxidation. We developed a phase field model (PFM) to simulate the Ni oxidation and the development of cracks in the YSZ backbone.
Regarding the Ni oxidation, the model takes into account the evolution of the Ni, NiO and porosity phases over time. Particular attention was given to integrate the specificities of the Ni oxidation mechanism, like the stress induced in the NiO layer as previously explored by Lin *et al.* (2). Unlike the majority of PFM oxidation models, our approach simultaneously tracks the evolution of two interfaces (Ni-NiO and NiO-porosity), following the framework established by Zaeem *et al.* (3), but applied to a complex 2D microstructure.
A previously developed (4) phase field model for YSZ backbone fracture is applied to microstructures at different oxidation times to evaluate the probability of their local cracking. For the model calibration and its validation, we compared the simulations with microscopy images of cermet subjected to varying Ni/NiO oxidation states. The results showed that the oxidation model i) reasonably captures the expansion and kinetics of oxidation, despite oversimplifying certain characteristics of the NiO film and ii) satisfactorily reproduces localized cracking of the structure during oxidation.
This study demonstrates the potential of phase-field modelling to provide insights into SOC degradation mechanisms, paving the way for improved microstructure designs or identification of materials that allows mitigating the degradation.

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Novel Water-Loaded Rig for Characterising Materials in Future Fusion Reactor Windows

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Speaker: Colin Christian. **Monday**. Start time: **17:00**. Room: Roseraie 1 LVL3. Link to abstract.

The development of fusion energy is a critical step towards sustainable and clean energy production. One of the key components in fusion reactors, such as ITER, is the vacuum vessel window, which is part of the first safety wall and experiences extreme mechanical and thermal loads over extended periods under radiation. The failure of these windows due to subcritical crack growth (SCCG) can be life-limiting, and understanding this behavior is crucial for the design and operation of future fusion reactors. This paper presents a novel water-loaded test rig for characterizing the SCCG of materials, specifically focusing on silica, a candidate material for vacuum vessel windows. In this study, we conducted tests on silica at two different loading rates to better understand its behavior under varying conditions. Additionally, we developed a Python code to interpret the test data using the Weibull approach.

Introduction
Fusion energy holds promise as a clean and virtually limitless source of power. However, the realization of this technology depends on overcoming numerous engineering challenges, including the design and durability of vacuum vessel windows. These windows, part of the safety wall, must withstand high temperatures, radiation, and mechanical stresses over extended lifetimes. Previous studies have shown that SCCG can be a significant failure mechanism in fields such as dental ceramics and that radiation can impact the SCCG rate in alumina. However, the combined effects of radiation, high temperatures, and long durations on SCCG in materials like silica remain unclear. Understanding the behavior of materials under these conditions is essential for designing windows that can withstand the harsh environment of a fusion reactor.

The Jules Horowitz Reactor (JHR)
The Jules Horowitz Reactor (JHR) is a new research Material Testing Reactor (MTR) under construction in Cadarache, France. It is designed to provide high-intensity neutron flux for a wide range of experimental campaigns, including material and fuel experimental irradiation studies. The JHR will be equipped with a variety of irradiation devices. These devices are designed to simulate the conditions experienced by materials in fission or fusion reactors, including high neutron fluency, irradiation temperature, and mechanical loadings.
The FUSERO project, a collaboration between UKAEA (Oxford, UK) and CEA (Cadarache, France), aims to develop test devices and associated sample holders dedicated to investigating material irradiations more suited to the "fusion community." In addition to "cook and look" irradiation type, the project is divided into three main components: FUSERO A, FUSERO B, and FUSERO C, irradiation devices with in-situ measurements. FUSERO A focuses on the current challenges for ITER and future fusion reactor diagnostic windows, particularly addressing structural issues and investigating further Sub-Critical Crack Growth (SCCG). Given the brittle nature of ceramics, these materials can suffer from premature failure when stressed due to surface cracks and imperfections. FUSERO B and FUSERO C expand on this work by exploring additional materials and conditions, respectively at very low temperatures and under thermomechanical fatigue under radiation environments, to better understand the long-term behavior of materials in fusion reactor conditions.

Methodology, Materials, and Testing
In the framework of FUSERO development, a novel water-loaded test rig used in this study enables cost-effective testing at scale with acceptable measurement accuracy. These rigs are designed to simulate the conditions experienced by vacuum vessel windows in fusion reactors. By changing the pump speed, the

rigs can gather fracture data at various stressing rates, bringing the dataset closer to the requirements of standard BS EN 843-3. In this study, we focused on testing silica (SiO2) at room temperature under two different loading rates to better understand its behavior under varying conditions. Silica is a candidate material for vacuum vessel windows due to its high strength, low thermal expansion coefficient, and excellent resistance to radiation damage. However, the behavior of silica under subcritical crack growth conditions is not well understood. The tests were conducted on silica specimens with dimensions of 50 mm x 10 mm x 5 mm. The specimens were subjected to a constant load at two different loading rates: 100 N/s and 1000 N/s.

Weibull Analysis
The Weibull distribution is a widely used statistical model for describing the strength of materials. It is particularly useful for analyzing the strength of brittle materials, such as ceramics, which exhibit a high degree of variability in their strength. The Weibull distribution is defined by two parameters: the shape parameter (m) and the characteristic strength ($\sigma 0$). The shape parameter (m) describes the variability in the strength of the material. A low value of m indicates a high degree of variability, while a high value of m indicates a low degree of variability. The characteristic strength ($\sigma 0$) is the strength at which 63.2% of the specimens fail. The Weibull parameters were estimated using the maximum likelihood estimator (MLE) method. The MLE method involves finding the values of $\sigma 0$ and m that maximize the likelihood function, which is the probability of observing the given data.

Results and Discussion
The results indicate that the characteristic strength between datasets varies by approximately 10%, with the uncertainty around individual measurements being around 4-5%. This suggests that the increase in strength observed between the datasets is mostly due to the change in loading rates, highlighting SCCG phenomena. The water-loaded test rigs have proven to be a valuable tool for gathering data under conditions relevant to fusion reactors.
Additionally, we developed a Python code to interpret the test data using the Weibull approach. The Python code for Weibull analysis was developed using the SciPy library, which provides a suite of mathematical and statistical functions. The code takes the strength data as input and returns the estimated Weibull parameters ($\sigma 0$ and m) and their uncertainties. The code first calculates the natural logarithm of the likelihood function and then uses the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm to find the values of $\sigma 0$ and m that maximize the likelihood function. The more specimens used to estimate the fit, the more accurate the fit parameters are likely to be. The estimated parameter calculated directly from a finite number of observations is referred to as 'biased'. It needs to be 'unbiased' by multiplying with an unbiasing factor (UF). This brings the expected (or mean) parameter value for a finite sample size closer to the 'true' parameter of the entire population. For the Weibull distribution, the tabulated unbiasing factors from the standard ASTM C1239-13 were applied. In the data analysis of this study, no adjustment was made for the characteristic strength, because it is generally negligibly impacted by bias. This code allows for the fitting of a Weibull formalism and a parameters convergence approach.
The sensitivity analysis shows that the height of the sample is the most important contributor to the combined uncertainty of stress, followed by the tolerance on the span between the inner supports. A coverage factor of k=2 (equivalent to 2 standard deviations) was selected to produce an uncertainty interval with a confidence of approximately 95%.

Conclusion
The findings from this study justify and inform future designs of subcritical crack growth (SCCG) tests for ceramics in irradiated conditions. The novel water-loaded rigs provide a cost-effective and accurate method for testing materials under conditions similar to those experienced by vacuum vessel windows in fusion reactors. Additionally, the development of a Python code to interpret the test data using the Weibull approach enhances the accuracy and reliability of the results. This work is a significant step towards understanding the long-term behavior of materials in future fusion reactors and ensuring their safe and reliable operation. The future work will include a testing program to include irradiation experiments, in JHR as an example, which will allow for the study of the effects of radiation on the SCCG behavior of materials. The Python code for Weibull analysis will also be further developed to include additional features, such as the ability to handle censored data and to perform statistical tests for comparing the Weibull parameters of different datasets. This work will enable a more comprehensive analysis of the test data and a better understanding of the factors that influence the SCCG behavior of irradiated, and under irradiation, materials.

Acknowledgements
This work was performed at the Laboratoire de Mécanique et d'Acoustique (LMA) in CNRS Marseille with funding and personnel from the Commissariat à l'Energie Atomique (CEA), Réacteur Jules Horowitz (JHR) and UK Atomic Energy Authority (UKAEA). Thank you to the teams at LMA and CEA for welcoming the secondees from the UK and supporting their experimental work.

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Keywords: Fusion energy, vacuum vessel windows, subcritical crack growth, silica, water-loaded test rigs, mechanical testing, Weibull analysis, Python code.

Influence of crystallite size of alumina aggregates on the thermomechanical behaviour of refractories

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1 - Université de Limoges, IRCER (France), 2 - Imerys Technology Center (France)

Speaker: Boateng Kwasi Addo. **Monday**. Start time: **17:20**. Room: Roseraie 1 LVL3. Link to abstract.

Alumina is a popular mineral widely used in the ceramic industry providing good mechanical properties and high temperature resistance. Refractories based on alumina are however complex, ceramic materials that need to be designed based on specific applications. Placed in the working lining of steel ladles, these alumina-based refractories undergo cycles of thermal shock during service conditions which eventually leads to their failure, needing repairs or replacements. Tabular and white fused alumina are two polycrystalline grains used in alumina refractories with the former of quite small crystal sizes and the latter of rather large crystal sizes. Other differences in the alumina aggregates lies in their crystallography and porosities due to their different processing routes.
This work conducted as part of the European CESAREF (Concerted European Action on Sustainable Applications of REFractories) consortium, aims to study the influence of crystallite sizes on thermomechanical behaviour of the alumina refractories. High temperature ultrasonic technique measuring the Young's modulus is applied to investigate the microstructural changes during heat treatments. Acoustic emissions during cooling will also be monitored. The acoustic emissions will provide information on microcracks formed in the microstructure during thermal cycling. The above-mentioned techniques will help design the microstructures of alumina-based castables with improved non-linear thermomechanical behaviour suitable for thermal shock applications.

Keywords: Alumina aggregates, Crystal size, Thermomechanical behaviour, Young's modulus, Microcracks

Thin films hardness: comparaison of models

Lakhlioui Zineb (1)

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Speaker: Lakhlioui Zineb. **Monday**. Start time: **17:40**. Room: Roseraie 1 LVL3. Link to abstract.

The characterization of thin films plays a crucial role in advancing micro-technologies, where material performance at micro and nano scales dictates the reliability of devices. This study aims to identify the most robust predictive model for mechanical properties of thin films, while defining its optimal conditions of application and understanding its limitations. By employing a combination of experimental nanoindentation and theoretical modeling, the study evaluates the predictive accuracy of widely used models, including those of Jönsson & Hogmark, Chicot & Lesage, Korsunsky, Puchi-Cabrera, and Burnett & Rickerby. Common point of these models is their linear function.
The objective is to determine the conditions under which these models yield reliable predictions, considering key parameters such as film thickness, residual stresses, and depth-to-thickness ratios (h/t). Limitations of conventional models under varying experimental conditions are explored, leading to some modifications across the majority of the studied models.
Additionally, a comparative analysis of thin films ranging from 1 to 1.7 μm, fabricated using PECVD (Low Pressure Chemical Vapor deposition) and LPCVD (Plasma Enhanced) techniques reveals differences in mechanical behavior due to variations in deposition methods, material composition, and structural uniformity. These findings emphasize the importance of integrating experimental data with theoretical models to refine the design and application of thin films for demanding environments. By defining the optimal application conditions and addressing model limitations, this study advances the development of thin films with enhanced durability and performance for micro-technological applications.

MS1.6 - Mechanics of polymers

Organisers: Julie Diani (LMS), Jean-Luc Bouvard (CEMEF) and Florian Arbeiter (University Leoben)

Modelling and simulations of polymers across scales and methods

Pfaller Sebastian (1), Laubert Lukas (1), Richter Eva (1), Ries Maximilian (1), Weber Felix (1), Zhao Wuyang (1), Vassaux Maxime (2)

1 - Lehrstuhl für Technische Mechanik [Erlangen] (Germany), 2 - Institut de Physique de Rennes (France)

Speaker: Pfaller Sebastian. Keynote. **Monday**. Start time: **13:40**. Room: Roseraie 3 LVL3. Link to abstract.

Considering the atomistic or molecular structure of complex materials like polymers is still a challenge since these kinds of materials typically exhibit multiple hierarchical levels spanning a large range of length and time scales. In addition, the formation of entanglements and/or crosslinks of the chain-like macromolecules demand for simulation techniques that can appropriately capture these peculiarities. This, in turn, means that established strategies specifically developed for crystalline materials are usually not sufficient. This contribution discusses briefly the foundations of continuum mechanical and molecular approaches for polymers and introduces the Capriccio method as a means to link molecular dynamics and the finite element method to consider molecular processes for typical engineering applications at the macroscale. By design, the Capriccio method is a multiscale domain-decomposition strategy that employs the fine-scale, discrete atomistic or molecular description only in regions of a specimen exposed to high loads or exhibiting, e.g., material or geometric discontinuities. Some examples from recent research activities in the context of fracture of amorphous materials highlight the capabilities of the Capriccio method.

Mechanical behavior of glassy amorphous poly(ethylene oxide) under cyclic tensile loading via atomistic molecular dynamics simulations

Ilia Panagiotis (1), Gkolfi Eirini (1) (2) (3), Reda Hilal (1), Savva Nikos (1) (4), Harmandaris Vagelis (1) (2) (3)

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Speaker: Ilia Panagiotis. **Monday**. Start time: **14:20**. Room: Roseraie 3 LVL3. Link to abstract.

The mechanical properties of a material define its response to external forces and are critical for applications in biomedical engineering, automotive, and aerospace industries. This study investigates the cyclic tensile deformation behavior of glassy amorphous polyethylene oxide (PEO) using atomistic molecular dynamics (MD) simulations, focusing on elastic and plastic deformation regimes. In the elastic regime, polymer chains exhibit reversible behavior, returning to their original conformations upon load removal. In contrast, plastic deformation, triggered by exceeding the yield stress, results in irreversible molecular rearrangements such as segmental motions and chain slippage, leading to permanent deformation. Our findings reveal the molecular mechanisms driving these behaviors, offering insights into PEO's mechanical properties and performance under repeated loading. These results provide valuable guidance for the design and application of PEO-based materials in aerospace, automotive, and food packaging industries.

Stress transition in lamellar semi-crystalline polymers evaluated by molecular dynamic simulations

Lame Olivier (1)

1 - Matériaux, ingénierie et sciences (Bâtiment Blaise Pascal 7, avenue Jean Capelle 69621 VILLEURBANNE CEDEX France)

Speaker: Lame Olivier. **Monday**. Start time: **14:40**. Room: Roseraie 3 LVL3. Link to abstract.

The macroscopic mechanical behavior of semi-crystalline polymers is described using concepts such as tie molecules to explain the stress is transition between crystalline lamellae through the amorphous phases. However, these particular chains are not possible to observe directly by any means. The dependence of the mechanical properties with the chain topology and entanglement has been then analyzed by a coarse-grained molecular dynamic model(1). After cooling from a melt, and isothermal treatment, semi-crystalline systems of different chain lengths and oriented lamellar structures were obtained. The different systems exhibit different entanglement densities and chains topologies. Thanks to tensile tests in the chain direction a relation between the chain topology, the entanglements and mechanical properties such as yield stress or hardening is proposed. It has been shown first that the loop chains are prevalent and play the most important role on the mechanical properties. Secondly the entanglement density is linked to the chain topology and can effectively be the descriptor of most of the mechanical properties. The link between the chain topology and the entanglement density is discussed.

Computational indentation in highly cross-linked polymer networks

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1 - Institut für Mikrosystemtechnik Albert-Ludwigs-Universität Freiburg (Germany), 2 - Department of Mechanical Engineering, University of British Columbia (Canada), 3 - University of Göttingen - Georg-August-Universität Göttingen (Germany), 4 - Indian Institute of Technology Kanpur (India)

Speaker: Maurya Manoj Kumar. **Monday**. Start time: **15:00**. Room: Roseraie 3 LVL3. Link to abstract.

Indentation is a common experimental technique to study the mechanics of polymeric materials. The main advantage of using indentation is this provides a direct correlation between the microstructure and the small-scale mechanical response, which is otherwise difficult within the standard tensile testing. The majority of studies have investigated hydrogels, microgels, elastomers, and even soft biomaterials. However, a less investigated system is the indentation in highly cross-linked polymer (HCP) networks, where the complex network structure plays a key role in dictating their physical properties. In this work, we investigate the structure-property relationship in HCP networks using the computational indentation of a generic model. We establish a correlation between the local bond breaking, network rearrangement, and small-scale mechanics. The results are compared with the elastic-plastic deformation model. HCPs harden upon indentation.

Modulus measurements via Nanoindentation – a guide for parameter settings for testing polymers

Huszar Michael (1), Christöfl Petra (2), Arbeiter Florian (1)

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Speaker: Huszar Michael. **Monday**. Start time: **15:20**. Room: Roseraie 3 LVL3. Link to abstract.

Knowing local differences in Young's Modulus and hardness can help us to better understand material behavior and heighten the precision of simulations and fracture mechanic evaluations. One tool for gathering information on a small scale is nanoindentation, which is already widely used and established. The Oliver and Pharr Method is also widely used for evaluating stiffer, linear elastic materials, like metals and ceramics.(1) Soft, non-linear and time dependent materials require some adjustments to the testing parameters to achieve reasonable results. (2–4) During these measurements, the unloading speed and the holding time are crucial. The holding time should be kept as short as possible to minimize the influence on the measured hardness and Young's Modulus, while still being long enough to avoid the formation of a "nose" due to the viscous behavior of the material. The unloading speed should be as fast as possible since the unloading segment is used to calculate Young's Modulus. Furthermore, the power law Fit used for the Oliver Pharr evaluation does not sufficiently represent the measured data in some cases.(5) A detailed parameter study for loading, unloading speeds, and holding times on three different polymers, polyethylene, polypropylene, and polymethyl methacrylate, covering a broad spectrum of mechanical properties in polymer science, is presented. The use of different fitting parameters for the unloading curve and their effect on the results obtained using Oliver and Pharr's Method are discussed.

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Modeling Rate Dependency and Relaxation Behavior of Semi-Crystalline Polyamide 6

Kulkarni Sameer (1), Johlitz Michael (1), Lion Alexander (1)

1 - University of the Bundeswehr Munich (Germany)

Speaker: Kulkarni Sameer. **Monday**. Start time: **16:00**. Room: Roseraie 3 LVL3. Link to abstract.

In this study, the influence of the degree of crystallinity on the mechanical behaviour of semi-crystalline polyamide 6 is investigated. To describe the long-term and time-dependent mechanical response of polyamide 6, a phenomenological constitutive model of finite viscoelasticity, motivated by the 1D rheological generalized Maxwell model is used. To account for strain rate dependency, a nonlinear viscous evolution equation is proposed. On the experimental side, polyamide 6 was melt-mixed with amorphous cyclic olefin copolymer to produce blends representative of polyamide 6 with varying degrees of crystallinity (from 15% to 29%). Various isothermal tests, including monotonic tension, relaxation and cyclic tests at temperatures above the glass transition temperature, were performed on the blends to generate a material database. The time-temperature superposition principle is used to obtain the viscoelastic behaviour over an extended period. Initial computations indicated the model could reliably predict the viscoelastic strain rate-dependent loading and relaxation behaviour across different crystallinity levels and temperatures.

Viscoelasticity and Mechanics Properties of Crosslinked Rubbers and Glassy Composite Networks via detailed Atomistic Simulations

Kallivokas Spyridon (1), Hazirakis Anthony (2), Harmandaris Vangelis (1)

1 - The cyprus institute (Cyprus), 2 - Department of Applied Mathematics [Heraklion] (Greece)

Speaker: Kallivokas Spyridon. **Monday**. Start time: **16:20**. Room: Roseraie 3 LVL3. Link to abstract.

We study the viscoelasticity and mechanics of crosslinked Styrene Butadiene Rubber (SBR) and the fracture mechanics of glassy epoxy crosslinked networks. Both are studied with molecular dynamics simulations. SBR systems are used widely in tire industry while the epoxy glassy composite networks with Solid Polymer Electrolytes (SPE) are used widely as supercapacitors.

As regard the SBR system, we present a detailed study of the structural and mechanical properties an SBR elastomeric network crosslinked with Sulfurs at the molecular level, via detailed atomistic molecular dynamics (MD) simulations in United Atom (UA) scale. The structural ratio is (styrene/trans/vinyl/cis): (15/33/26/26) by weight % and a 4 atom sulfur chain, acting as a hardener for the crosslinking process. As regard the fracture and mechanical properties of glassy –composite- networks, we study in All Atomistic (AA) scale with molecular dynamics. Properties of structure and elasticity are presented as well.

Characterization and modeling of temperature- and rate-dependent mechanical behaviors applied to an epoxy resin from Room: to cryogenic temperatures

Kong Xiang (1), Li Xueyang (2), Grolleau Vincent (2) (3), Mohr Dirk (2), Govaert Leon (4), Tervoort Theo A. (1)

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Speaker: Kong Xiang. **Monday**. Start time: **16:40**. Room: Roseraie 3 LVL3. Link to abstract.

The mechanical behavior of epoxy resin, used as an impregnation material in superconducting coils, was investigated under uniaxial compression from ambient to cryogenic temperatures across a range of strain rates (10^-4 to 10^3/s). The viscoelasticity and yield stress exhibit strong dependence on temperature and strain rate, with a notable change in yield stress slope at higher strain rates and lower temperatures, likely associated with the side-chain mobility dominated secondary transition in polymers. An effective Ree-Eyring equation, capable of describing yield stress across a wide range of temperatures and strain rates, separates stress contributions into two molecular processes: the α-process, related to main-chain segmental mobility, and the β-process, associated with partial main-chain or side-chain mobility. The latter activates only under high strain rates or low temperatures. Using a nonlinear fractional Maxwell model with a time-temperature superposed relaxation spectrum enables a smooth transition from elastic to viscous behavior with only two material parameters. The reduced relaxation time approach, employing horizontal shifts by stress and temperature factors, successfully fits experimental data and predicts the extrapolated responses under dynamic tests.
The 1D Ree-Eyring model is extended to a full 3D constitutive model, known as the Eindhoven Glassy Polymer (EGP) model, utilizing the same spectrum of relaxation times represented through a multi-mode approach by each individual process. The elasto-visco-plastic model, implemented in finite element software, effectively captures the intrinsic behaviors of the epoxy resin across a broad range of temperatures and strain rates.

Computing Virtual DMA Response of Viscoelastic Materials with an Enhanced Composite Voxels Method

Mabrouk Nadia Boisse Julien André Stéphane (1)

1 - Laboratoire d'Energies et de Mécanique Théorique et Appliquée (France)

Speaker: Mabrouk Nadia. **Monday**. Start time: **17:00**. Room: Roseraie 3 LVL3. Link to abstract.

Following the recent development of a FFT solver for computing DMA response of viscoelastic composite materials (1), we present several improvements. First, the tool has been transposed in python language using CUDA (Cupy) library for GPU acceleration, secondly and mainly, composite voxels methods (CVs) have been implemented. CVs are voxels crossed by an interface separating two distinct phases and whose effective properties are calculated by a homogenization law. This allows modeling the mechanical behavior of microstructure interfaces that are not perfectly localized between two FFT coordinates. CVs methods introduced by Kabel et al. (2) and developed in Amitex_fftp code (3) for FFT codes simulating classic mechanical response of materials as a function of time was adapted to our virtual DMA tool, in which storage and loss moduli are computed has a function of frequency and/or temperature.
We present developed preprocessing tools generating microstructures meshed with CVs using 3 methods: subsampling, integration or analytical. These methods have been validated through DMA computed frequency response: 1) considering a 3D Hashin structure (2) (spherical inclusion with a core shell configuration satisfying specific material properties relationship between 3 phases) and compared made with the corresponding analytical solution, and 2) considering a 128^3 digital microstructure made of 17% short glass fibers embedded in a polyamide (PA66) matrix and a composite voxel approach which is compared to the 512^3 same microstructure without composite voxels. The known homogenization laws for composite voxels properties: Voigt, Reuss, or laminate, were tested in the frequency framework. Results reveal significant improvements in accuracy and enable us to work at lower resolutions than conventional FFT DMA simulations.

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Modeling Thermo-Visco-Elastic Behavior of Polymer Materials based on Relaxation Models

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Speaker: Hille Frederik. **Monday**. Start time: **17:20**. Room: Roseraie 3 LVL3. Link to abstract.

Polymer materials are increasingly used in engineering applications due to their excellent attributes suited for lightweight engineering. To model their thermo-mechanical behaviour it is crucial to sufficiently capture relaxation effects in mechanical as well as calorical quantities (1). Ensuring thermodynamical consistency, i.e. being in compliance with the second law of thermodynamics, is a non-trivial matter for these effects. A common approach to prevent possible short-comings in modeling relaxation phenomena is to extend the variable space by additional non-equilibrium fluxes, such as the heat flux or the viscous stress tensor, which are relevant for dissipation effects (2).
In this talk we present an overview of existing relaxation models in the context of extended thermodynamic theories (2, 3). Special focus will be put on the connection to standard rheological models, e.g. the generalized Maxwell model or the Poynting-Thomson model, since they have been proven effective to deliver reasonable results for basic cases under certain assumptions. However, the here presented thermodynamic frameworks shall be used to investigate possible non-linear generalizations appropriate for a wider spectrum of applications. Subseqently a possible physical interpretation shall be given to link the theoretical framework to the ongoing microscopic mechanisms and to gain a deeper understanding of such.

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Filament coalescence in 3D printed magneto-rheological elastomers

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Speaker: Garzon-Hernandez Sara. **Tuesday**. Start time: **10:00**. Room: Roseraie 3 LVL3. Link to abstract.

Components manufactured by extrusion-based additive manufacturing technologies (EB-AM) are characterized by a mesostructure formed by the coalescence of filaments. For optimal structural integrity, good adhesion between filaments is desirable to reduce porosity and enhance their mechanical response. Recently, AM technologies have taken a step further towards the so-called 4D printing. This new term allows not only the control the structural characteristics of components but also includes other functionalities with properties that vary in space and/or time. Therefore, understanding and predicting the resulting mesostructure is crucial not only for improving mechanical behaviour but also for controlling their additional functionality.

In this work, we propose the development of a physically-based virtual testbed to simulate the EB-AM process, with the primary aim of controlling the final mesostructure of the EB-AM components to meet specific functional requirements. Without loss of generality, we focus on direct ink writing (DIW), a technique in which a pre-cured polymeric "ink" is extruded through a nozzle. In DIW, the material's viscosity must be low enough to facilitate extrusion and coalescence with other filaments but, at the same time, high enough to ensure shape fidelity. Therefore, it is necessary to understand the mechanics of the coalescence between printed filaments and the role that viscosity and surface tension play in the process. Our approach combines experimantal and computational tools. Firsts, we carry out a comprehensive rheological analysis of PDMS reinforced with magnetic particles as the base material. Then, we record the filament coalescence under different printing conditions. Finally, we implement a phase-field model with time-dependent properties to simulate the behavior of two immiscible phases (the printed material and its surrounding medium), accurately capturing the dynamics of filament fusion and enabling the optimization of DIW manufacturing processes.

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Validation of the constitutive model for 3D printed shape memory polymers

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Speaker: Virag Lana. **Tuesday**. Start time: **10:20**. Room: Roseraie 3 LVL3. Link to abstract.

Shape memory materials are smart materials characterized by the ability to return from a deformed (temporary) state to their original (permanent) shape when induced by an external stimulus. Triggers for shape recovery include heat, hydration, magnetic fields, or light. Because of this feature, one such alloy, nickel-titanium alloy (NiTi, nitinol), is used as a base material for a variety of medical devices, such as flow diverters, stents, catheters, wires connecting the teeth and many more.
With the recent advancement of biocompatible shape memory polymers, their applicability in the field of medical technology industry is increasing. While mechanical properties of metals and metal alloys are generally considered better compared to polymers, a significant difference in stiffness between soft tissue and metals can lead to various medical complications. Additionally, most shape memory polymers (SMPs) can be easily 3D printed, whereas such additive manufacturing for nitinol is still challenging (1).

Stereolithography (SLA) is a 3D printing technology that uses a light source to cure liquid resins. Given the very high printing precision, this technology can be used to print small parts, e.g. stents with a strut thickness of about 0.1 mm. This approach enables the creation of patient-specific stents tailored to follow the unique curvature of individual arteries and atherosclerotic plaque. Furthermore, self-expanding stents (made from shape memory materials) have been shown to reduce the risk of restenosis compared to balloon-expanding stents (2).

The aim of this work is to ensure the accuracy of the constitutive model for chosen biocompatible shape memory polymers (SMPs) so that they can later be used for numerical analysis of carotid stents. Thus, we conducted uniaxial tests for the selected biocompatible SMPs at different strain rates. Based on the experimental results, the optimal material model was chosen and associated material parameters determined. This constitutive model was verified on mesh plates with the cell shapes that can be used for stents. The plates were 0.1 mm thick, and several cell shapes were used for the mesh. Cell shapes, size, and cell density were chosen based on ability of such stent to narrow the cross section during elongation sufficiently for stent implementation in carotid artery, as well as on the preliminary numerical estimation of medical efficiency of such stent.
For each mesh plate, stresses and displacements in the plate were computed numerically for both uniaxial and biaxial loading. These results were compared to experimentally obtained results. Displacements were measured at several points on the plate; however, note that for mesh plates stresses cannot be experimentally assessed.

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Shape memory effects in multi-phase semi-crystalline networks: from phenomenological modeling to 4D printing

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Speaker: Scalet Giulia. **Tuesday**. Start time: **10:40**. Room: Roseraie 3 LVL3. Link to abstract.

Multi-phase semi-crystalline polymer networks may exhibit both the one-way and two-way shape-memory effects, therefore representing an appealing material for numerous applications. The present work aims to propose a general framework for the finite strain continuum phenomenological modeling of the complex thermo-mechanical and shape-memory behavior of such systems. Model capabilities are then validated against experimental data on different homopolymer and copolymer networks, giving new insights on material behavior. Finally, a novel approach for the additive manufacturing of such systems via extrusion-based 4D printing is briefly presented. A discussion on the process parameters and on their effect on material behavior is provided, together with representative application examples.

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Novel Uniaxial and Biaxial Tensile Test Specimen for Polymer Materials

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Speaker: Labar Luka. **Tuesday**. Start time: **11:00**. Room: Roseraie 3 LVL3. Link to abstract.

The geometry of the uniaxial tensile test specimen for polymer materials and the testing procedure are defined by the ISO norms. Depending on the type of polymer material, two types of norms are specified: ISO 37 for rubber-like polymers and ISO 527 for more rigid polymer materials. Although these norms defined the specimen geometries and testing procedures, both experiments and finite element simulations indicated that none of the geometries defined in these norms resulted in fracture within the zone with homogeneous stress and strain (i.e., the gage zone), thereby leading to inaccurate results. For hyperelastic materials this means that tensile strength and maximal strain are slightly underestimated; however, for elastoplastic materials, plastic strain mostly occurs outside the measured zone, and experimental results are completely unreliable.
On the other hand, biaxial test specimens are not defined by any norm, and a wide variety of biaxial test specimen geometries were reported in the literature. Although the geometry of biaxial test specimens has been the subject of extensive research, no geometry ensuring uniform stress and strain distribution in the central part of the specimen, with maximum stress in that region, has been developed.

To address this issue, the aim of this work was to develop a novel uniaxial test specimen with uniform stress and strain distribution and maximum stress in the gage zone. The development was guided by using the topology and shape optimization tools in ABAQUS software for finite element analysis. Although such simulations did not yield a satisfactory solution directly, they provided guidance for optimizing the geometry through a trial-and-error method. Several variations of uniaxial test specimen geometries were defined numerically and subsequently tested experimentally. To ensure independence of fracture location on the method of production and material type, uniaxial test specimens were 3D printed using three printing technologies (Fused Deposition Modeling (FDM), PolyJet, and Stereolithography (SLA)) and four different materials (poly-lactic-acid (PLA), ABS-like resin, Tango Black Plus, DM70)). The experiments demonstrated that for each technology and geometry type, fracture consistently occurred in the gage zone, thereby improving accuracy compared to specimens from the ISO norms. From the collected data, the elastic modulus, failure stress, and strain at break were calculated and compared with values reported in the literature.

Similar methodology was applied for biaxial cruciform specimens. Again, the optimization process did not yield a suitable geometry but provided direction for manual optimization. This process resulted in the development of a novel cruciform biaxial specimen. According to simulations, the resulting geometry exhibited maximum stress in the central region and uniform stress and strain distribution in that part of the specimen. Simulations were conducted for isotropic and anisotropic materials, and the results indicated that the positions of maximum stress were independent of material behavior. For validation, the developed geometry was 3D printed using PolyJet technology and experimentally tested. Due to the limitations of the load cells on the biaxial tensile tester, only specimens made of Tango Black Plus material were tested. The experiments revealed that fracture initiation occurred in the central region and propagated outward.

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Measurement of volume change in sheet elastomer testing using back-to-back stereo DIC

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Speaker: Peshave Amar. **Tuesday**. Start time: **11:20**. Room: Roseraie 3 LVL3. Link to abstract.

Elastomers are generally considered incompressible meaning that their density remains constant during loading. However, depending on the material system, this assumption can be incorrect and there is a necessity to measure such volume change. In the past, this has mainly been done on dog-bone rubber-like material specimens by measuring the strain field over two or more of their faces to calculate the volume change (1-2). A similar methodology was applied to plasticity in (3). The main limitation of such approaches is that it can only be applied to uniaxial stress states while volume changes are likely to be dependent on stress multi-axiality.
An alternative is to use more complex test geometries in the spirit of Material Testing 2.0 (4-5) so that volume change could be measured as a function of stress multiaxiality. For this, it has been shown that two back-to-back stereo Digital Image Correlation (DIC) systems could lead to an average through-thickness deformation (6). This is obtained as the difference of the out-of-plane displacements measured on the front and back faces. However, because of the large mismatch between the deformation in the longitudinal direction and that in the transverse ones, it is essential to have a very accurate registration of the two stereo-systems otherwise, some 'leakage' occurs from the vertical displacement to the out of plane one leading to spurious volume changes (7). This also casts some doubts about the values obtained in (6) as this registration had not been performed accurately there.

The present study revisits this methodology by carefully looking at the registration procedure. The novelty lies in the availability of a tool that allows to simulate camera images from a stereo DIC calibration file and a finite element model (8-9) to verify the data processing procedure. A finite element model of a rectangular tensile specimen was developed in Abaqus using a Neo-Hookean incompressible material model with shell elements. Image deformation from (8-9) was performed using the FEDEF module of MatchID (10). These images were then processed as if they were experimental which allowed to verify the complete data processing chain and to illustrate the sensitivity of the data processing to the local orientation of the material coordinate system.

Experimental data was acquired on a 50 x 50 x 3 mm natural rubber sheet specimen, loaded in tension at a crosshead speed of 0.1 mm/s. Speckle patterns were obtained by paint spraying both faces. Two back-to-back stereo DIC systems were used, employing four 5 Mpx cameras. The specimen was tested up to 60% of longitudinal strain and 80 loads steps were recorded at 0.28 Hz, generating 160 pairs of stereo images. Slippage in the grips occurred which led to specimen warping. This challenges the extraction of the through-thickness deformation. To understand this, experimentally measured boundary conditions were extracted and applied to an FE model. This was used to revise the procedure and ensure that this 'leakage' could be minimized. In the future, the procedure will be applied to a range of different elastomers tested on a biaxial machine to understand the compressibility of these materials as a function of stress multiaxiality and strain levels. The procedure will also be applied to the material system tested in (6) to verify their results. It would also be very interesting to study polymeric materials and also investigate the influence of strain rate on the compressibility of such materials.

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Impact of recycling on the mechanical properties, surface roughness and antibacterial efficiency of copper-loaded PLA for 3D Printing Applications

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Speaker: Helfenstein-Didier Clémentine. **Tuesday**. Start time: **11:40**. Room: Roseraie 3 LVL3. Link to abstract.

In recent years, the rapidly growing field of 3D printing has revolutionized the traditional manufacturing industry. The appeal of this technology lies in its ability to intricately design and optimize complex geometric models, as well as in its remarkable design flexibility, recyclability, and minimal material waste. One current challenge for 3D printing technology is the development of antimicrobial surfaces that can come into contact with food and humans to control bacterial colonization and prevent disease spread.
To achieve antimicrobial 3D-printed surfaces, the use of Poly-Lactic Acid (PLA). polymers loaded with copper (Cu) nanoparticles has increased over recent years in 3D printing applications. These advancements introduce new properties to the composites, opening up possibilities for future applications in developing medical devices, food processing equipment, and other surfaces requiring antimicrobial characteristics.
However, both standard PLA and copper nanoparticle-loaded PLA (PLA-Cu) undergo changes in their properties during recycling. While previous studies have shown the potential to recycle failed 3D-printed objects into reusable PLA filaments, there is limited research on the recycling of PLA-Cu.
In this context, our preliminary study explores the impact of recycling on the mechanical, topographical, and antibacterial properties of PLA and PLA-Cu used in 3D printing.
Mechanical tests show that PLA-Cu, before recycling, has better mechanical resistance than standard PLA, owing to a higher elasticity modulus. However, after recycling, the ductility of recycled PLA-Cu (rPLA-Cu) significantly decreases, in contrast to recycled PLA (rPLA), which remains relatively stable. Surface roughness of printed parts also increases significantly after recycling, particularly for rPLA-Cu, which also exhibits porosity due to a decrease in print quality.
Recycling also reduces the antibacterial efficacy (against *E. coli*) of PLA-Cu, possibly by altering the size and distribution of copper particles, which are crucial factors for antibacterial activity. In conclusion, the study shows that recycling PLA-Cu leads to significant performance losses, suggesting the need for additional nanoparticles or adjustments to extrusion parameters to limit these degradations and enhance the durability of the recycled material.

Couplings in the decompression failure of hydrogen-exposed rubbers: from analytical and FEM simulations to phase-field modelling

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Speaker: Castagnet Sylvie. Keynote. **Tuesday**. Start time: **14:15**. Room: Roseraie 3 LVL3. Link to abstract.

Exposure of rubber materials to high-pressure diffusive gases can undergo cavitation and/or cracking processes upon subsequent decompression. Such decompression failure processes result from too-slow gas desorption as compared with the pressure release rate; the gas expands within the volume of the material and damages it. This phenomenon has been reported for different gas polymer systems in the past, rather qualitatively however, mostly under fast pressure release rates and in other gases than hydrogen (Gent 1969, Gent 1990, Briscoe 1994, Stewart 1970). Over the past decade, it has become a concern for the storage and transportation of compressed gaseous hydrogen. Indeed, the pressure range (up to 90 MPa) and the safety requirements specifically related to this gas challenge material formulation and component design for sealing.
The morphology and intensity of decompression failure are known to depend on the exposure conditions, as well as on the mechanical and sorption properties of the rubber material (Yamabe 2011, Jaravel 2011, Kane Diallo 2016, Schrittesser 2016, Jeon 2022). Damage initiation can be more or less delayed after decompression. Cavities usually inflate and deflate during the decompression and desorption stages. Except in the case of micro-cracks, it is very difficult and most of the time impossible to detect residual damage.

Such phenomenology results from full couplings between mechanics, temperature, and gas transport. At the macroscopic scale, the main subsequent challenge is to capture the statistics of cavity or crack fields and the damage gradients, among which edge effects (Fazal 2020). At the cavity scale, which is under consideration in the presented work, the existence of full diffuso-mechanical couplings is a key issue too. Considering a single cavity, the expansion and deflation depend on the balance between the external hydrostatic pressure and the internal pressure (which depends itself on the volume of the cavity and the gas content inside it, possibly varied by the gas flux at the cavity wall) but also on the intrinsic properties of the rubber at large strains at the cavity wall, and on the global gas content field. It depends also on the micro-cracking contribution which is very difficult to be measured in the inflated configuration (Morelle 2021). The problem even becomes more difficult when close cavities possibly interact within clusters.

A first strong limitation to experimentally characterizing the phenomenon is the inability to access all physics (e.g. the time-evolution of gas content and temperature fields). Another one is the complexity of performing in-situ measurements, especially in tracking the transient evolution of damage.

Only a few modelings have been proposed to simulate decompression failure (Jaravel 2013, Yersak 2017, Kulkarni 2021). Most of them were 1D solving of one cavity, taking into account (Yersak 2017) or not (Jaravel 2013) a gas flux at the cavity wall and thus a full computation of the internal pressure at the cavity scale. The effect of decompression conditions could be discussed from these works. Kulkarni et al. (Kulkarni 2021) proposed 2D FEM simulations of a cavity fields over a very small time range around the maximal value of the pressure, with a fixed internal pressure at the boundary of the cavities. They addressed interaction effects between close cavities, without diffusion effects between them however.

In such context, two key challenges for both experimental characterization and modeling of decompression failure are (i) to accurately capture the full couplings between diffusion and mechanics and (ii) to overcome the poor knowledge obtained from residual damage with time-resolved and 3D tracking of damage all along the process.

The experimental works reported here aim at a better understanding of the mechanisms of cavity growth,

and some possible interaction effects at variable range, with a free surface or between close cavities, in a weakly cross-linked unfilled EPDM. The work was based on a 3D time-resolved quantification of the kinetics and morphology of the damage, from an in-situ X-ray tomography experiment initially developed on a laboratory source (spatial resolution 16μm, temporal 100s) and extended under a synchrotron environment on the Anatomix line of SOLEIL synchrotron (France). The gain in spatial (3μm) and temporal (4s) resolution made it possible to access the very first stages of growth, to track the transient growth kinetics of close cavities, and to detect residual damage.

A phase-field method, based on the Cahn-Hilliard equation, was used to simulate the growth of cavities during decompression. Such approach is particularly well-suited for modeling diffusive phenomena and phase transitions in complex systems.

In this framework, the phase field represented the local hydrogen concentration. One major advantage of this method was its ability to naturally handle the interface between the cavity and the matrix, the diffuse nature of the interface being inherently managed by the model. The coefficients governing the physical processes depended on both the mechanical and concentration fields and the coupling was facilitated through the phase field. Diffusion was modeled using Fick's law, with flux-based boundary conditions. Henry's law was applied to convert the hydrogen concentration in the cavity into pressure, which was subsequently applied as a boundary condition at the cavity wall. The mechanical behavior of the matrix was incorporated to account for stress and strain fields around the growing cavity. Cavities were initially introduced with the varying initial sizes and positions detected from the in-situ tomography views. As a first step, not all the complexity was retained in the modeling; the matrix was assumed to be linear elastic and no micro-cracking was introduced as a driving force of the cavity growth.

The simulation code was developed in Python, using the Fenics API to solve the mechanical fields around the cavities using the finite element (FE) method. Our 2D simulations provided insights into the temporal evolution of hydrogen concentration and cavity volume. The size of the simulated volume matched that of the sample for this case. In other tests with one or two cavities, the simulation domain differed. However, the integration of mechanical and diffusive aspects offers a promising tool for better understanding the contribution of various processes to the nucleation and growth mechanisms of cavities upon gas decompression.

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Study of the Ductile Fracture of PA11/EVOH Multilayer Films with the Essential Work of Fracture Method for Hydrogen Storage Applications

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Speaker: Gauge Ariane. **Tuesday**. Start time: **14:55**. Room: Roseraie 3 LVL3. Link to abstract.

The new requirements for gaseous hydrogen storage have leaded the way for research into materials with high mechanical and barrier performance. The multilayer coextrusion process enables the combination of properties from multiple polymers by freely increasing the number of layers through the successive folding technique known as the " layer-multiplying " or " baker's " technique (1). The polymer composite films created in this way can contain layers on the scale of hundreds of nanometers, with interfacial properties that strongly influence the material's microstructure and mechanical response. These films are prone to transitions in fracture behaviour from ductile to brittle, which can potentially lead to structural failure (2). These transitions can be influenced by many parameters, such as polymer's sensitivity to environmental conditions (humidity, temperature), long-term mechanical loads (creep, fatigue) and short-term loads (dynamic stress, impacts). Multi-physical coupling can also initiate such transitions in fracture behaviour. In this application, the interaction between gaseous hydrogen and high pressure can lead to the formation of small voids, known as cavitation (3). These diffuse cavities within the material volume can significantly increase the likelihood of brittle fracture in the polymer. Thus, the fracture properties of the multilayers polymer films in ambient and embrittling conditions is to be determined, in relation with the application context. Multilayer films of PA11-EVOH models have been produced using the coextrusion technique, with the number of layers varying from 3 to 4097 layers. Preliminary physicochemical characterizations have been carried out on these produced films. Initial results allow for an assessment of the ductile fracture properties of these PA11/EVOH multilayer films, with a focus on the influence of film structuring at the layer-fold scale on their crack resistance. To this end, quasi-static fracture tests in mode I were conducted at ambient conditions. These tests rely on a formalism specific to the Elastic-Plastic Fracture Mechanics for testing elastoviscoplastic materials under plane stress conditions. This methodology, developed by Cotterel and Reddel in 1977, is known as the Essential Work of Fracture (4). Based on a separation of the energies involved in macroscopic fracture, this methodology enhances the description of ductile fracture mechanisms. It allows, in particular, the comparison of fracture resistance across different multilayer films (5). Post-mortem microscopic observations (optical and electron) of the fracture surfaces allowed for a discussion of the link between the local mechanisms involved at the micro and nanoscale, and the macroscopic fracture behaviour of these complex composite materials. This multi-scale material is subject to complex fracture mechanisms, involving a principle fracture in the plane perpendicular to the tensile direction, as well as multiple fractures in the tensile plane, aligned with the orientation of the polymer layers. Initial observations suggest weak adhesion between the PA11 and EVOH layers, leading to significant delamination between the layers. Moreover, diffuse damage due to cavitation within the EVOH layer were observed. The intensity of these mechanisms and their distribution are strongly related to the number of layers in the films, as well as to the stresses experienced during tensile testing. These mechanisms could explain the general ductile macroscopic behaviour of the films, as well as the differences in macroscopic fracture resistance observed, which are related to the number of layers. In parallel, the EVOH-PA11 films were subjected to rapid decompression cycles under gaseous hydrogen in severe conditions to develop cavities. Their fracture behaviour will be compared to that of the intact films under the same ambient conditions.

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Effect of topological disorder on the toughness of spring networks

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1 - Institute for Building Materials, ETH Zurich (Switzerland)

Speaker: Sanner Antoine. **Tuesday**. Start time: **15:15**. Room: Roseraie 3 LVL3. Link to abstract.

On a coarse-grained level, polymer gels and architected materials correspond to a network of (nonlinear) springs. Here, we investigate how topological disorder affects crack propagation in spring network simulations. In particular, we quantify the fracture energy, or toughness, that corresponds to the energy dissipated per unit crack advance. Our simulations show that the heterogeneity introduced by randomly removing springs pins and deflects the crack, leading to an increase in fracture energy. The crack paths are different depending on the critical strain of the springs. While for a critical spring strain of 1, the crack path remains nearly planar, for a critical strain of 0.1, additional springs break away from the main crack plane, i.e. damage is diffuse. We explore possible links between this diffuse failure and rigidity percolation.

A new approach of multiaxiality for tension-torsion fatigue testing of elastomers

Martin Benjamin (1), Verron Erwan Coret Michel Selles Nathan

1 - Institut de Recherche en Génie Civil et Mécanique (France)

Speaker: Martin Benjamin. **Tuesday**. Start time: **15:35**. Room: Roseraie 3 LVL3. Link to abstract.

The unique mechanical properties of elastomers explain their use in most industrial sectors. In particular, they can withstand very large strain without breaking, before returning to their initial state almost instantaneously. These large strains are associated with complex mechanical responses that are sometimes difficult to characterize. To consider their multiaxial behavior, elastomers are generally characterized by a combination of uniaxial tensile/compression tests, plane tensile tests, and equibiaxial tensile tests (1). Taking account of this multiaxial character under fatigue loading is more complex, and tensile-torsion tests carried out on diabolo type specimens are generally considered. It turns out that in these studies, the authors adopt various definitions of multiaxiality but none of them has been used to construct mechanical tests(2,3).
Here, we propose a new definition of multiaxiality based on invariants of the logarithmic strain tensor (Hencky or true strain tensor). Three physically motivated invariants, K1, K2, and K3, were proposed in the early 2000s (4). They describe respectively the volume change, the intensity of deformation, and the mode of deformation. As they are derived from continuum mechanics, they are defined at any material point. Thanks to these invariants, and to avoid any confusion with existing terms, we introduce the notion of modality with the following two definitions:
1. A test is 'uni-modal' at a given point if, during the test, the value of the invariant K3 is constant;
2. A test is 'multi-modal' at a given point if the value of the K3 invariant changes during the trial.

To exploit these definitions in the context of fatigue tension-torsion testing, we numerically simulate a loading cycle by the finite element method to relate the loading conditions (U, α) where U is the vertical displacement and the angular displacement applied by the testing machine to a local mechanical state characterized by (K2, K3). By scanning a wide range of loading conditions (U, α), it is thus possible to identify loading paths that keep the K3 invariant constant; in other words, it is possible to construct tension-torsion tests that ensure a uni-modal deformation state in the crack initiation zone in a diabolo specimen.

In practical terms, we study in detail the mechanical state of the crack initiation zone during a uni-modal cycle, i.e. iso-K3, for two very different diabolo geometries: AE2 and AE42. We then show that the loading path depends on the geometry of the sample, but that the mechanical states in the samples are virtually identical: they admit the same principal stretch ratios and stresses. This demonstrates that it is possible to construct tension-torsion fatigue tests on elastomers that are comparable in terms of mechanical states despite very different geometries. This is a first step towards rationalizing multiaxial fatigue tests for soft materials.

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Slow crack growth in acrylic-based polymers: quasi-static embrittlement leads to improved fatigue resistance?

Van Loock Frederik (1), Smallenburg Daan (1), Govaert Leon E. (1)

1 - Mechanical Engineering Dept - TU Eindhoven (Netherlands)

Speaker: Van Loock Frederik. **Tuesday**. Start time: **15:55**. Room: Roseraie 3 LVL3. Link to abstract.

There is an ongoing effort to use mechanically recyclable thermoplastic matrices instead of conventional (crosslinked) thermoset matrices for fiber-reinforced polymer composites. However, outstanding questions remain regarding the durability of these novel thermoplastic polymers. In this work, we examine the effect of crosslinking and monomer contamination due to the mechanical recycling process on the subcritical crack growth of acrylic-based polymer systems. We make use of the double torsion testing technique (in quasi-static indentation and relaxation modes) at different temperatures to characterize one or more regimes of stable crack growth. Paris law slopes are identified, and the observed differences in crack growth behavior between the material systems are highlighted through stress-lifetime plots. We complement the static double torsion test data with fatigue crack growth behavior measured using cyclically loaded compact tension tests. Our aim is to explore possible relations between resistance to subcritical (fatigue) crack growth and the polymer's ductility when tested in uniaxial tension.

Mechanics of gels: a method to measure swelling induced stress

Levin Michal (1), Cohen Noy (1)

1 - Department of Materials Science and Engineering, Technion - Israel Institute of Technology [Haifa] (Israel)

Speaker: Levin Michal. **Tuesday**. Start time: **16:35**. Room: Roseraie 3 LVL3. Link to abstract.

Stimuli-responsive gels are soft and stretchable polymer networks that swell reversibly upon submersion in an appropriate liquid, making them extremely useful in a variety of applications such as biomedical devices, actuators, and sensors. The swelling of gels under constraints results in generation of stress. Understanding and estimating this stress is crucial for optimizing swelling-based systems.
In this talk we will present a 3D-printing based method for easy measurement of the swelling-induced stress exerted by constrained gels. We designed and 3D-printed boxes comprising four rigid and two soft walls of varying stiffness and sizes. A superabsorbent hydrogel was placed in each box, and then the whole system was immersed in water, causing the soft walls to deform and bend due to the stress exerted by the gel. By measuring these deformations and applying elastic plate theory, we developed a systematic approach to quantify the stress applied by the swelling gel on the soft walls.
Our results reveal that the swollen configuration of a gel under mechanical constraints is influenced by the type of geometric confinement and the stage of swelling. These findings can enhance and optimize the design and performance of swelling-based systems for actuators, sensors, drug delivery and soft robotics fields.

Characterization of the Nonlinear Viscoelastic Behavior of PAAm-Alginate Double-Network Hydrogels

Dhaouadi Wassim (1), Kolinski John (1)

1 - EPFL (Switzerland)

Speaker: Dhaouadi Wassim. **Tuesday**. Start time: **16:55**. Room: Roseraie 3 LVL3. Link to abstract.

Polyacrylamide (PAAm)-alginate double-network (DN) hydrogels exhibit exceptional mechanical properties due to its hybrid covalent and ionic networks, offering opportunities for innovative applications and tailored design in soft materials science. Our study focuses on the characterization of the nonlinear viscoelastic behaviour of PAAm-alginate DN hydrogels under diverse loading conditions. Using rheological techniques, including Large-Amplitude Oscillatory Shear (LAOS) tests, we investigate the strain- and rate-dependent mechanical response of this material.

Simulation of chemo-mechanical coupled gastric digestion process of starch hydrogels

Liao Zisheng (1), Markypidis Alexandros (1), Dagbasi Aygul (2), Lett Aaron (2), Frost Gary (2), Papathanasiou Maria (3), Charalambides Maria (1)

1 - Department of Mechanical Engineering [Imperial College London] (United Kingdom), 2 - Department of Metabolism, Digestion and Reproduction, Imperial College London (United Kingdom), 3 - Department of Chemical Engineering [Imperial College London] (United Kingdom)

Speaker: Liao Zisheng. **Tuesday**. Start time: **17:15**. Room: Roseraie 3 LVL3. Link to abstract.

Starch, a naturally abundant and biocompatible material, is widely used in hydrogel form in the food and pharmaceutical industries. Its digestion involves a complex interplay of mechanical breakdown by peristaltic waves and chemical degradation through diffusion and enzymatic reactions in the gastric environment, posing challenges to its design and application.
This study investigates the mechanical behaviour of starch hydrogels under chemical loads in in vitro conditions mimicking the digestion environment, providing insight without the need for in vivo tests on humans. Compression tests were conducted on starch hydrogels subjected to varying levels of hydrolysis catalysed by α-amylase. A pseudoelastic-viscoelastic constitutive model was developed to describe the chemo-mechanical behaviour of starch gels. Material parameters related to diffusion, reaction, and mechanical deformation parameters were calibrated using experimental data. The calibrated model was implemented in finite element analysis, where gastric peristaltic waves were applied via displacement boundary conditions, and chemical degradation due to the gastric fluids was modelled via a mass field and its reaction kinetics.
This integrated approach provides insights into the breakdown mechanisms of starch hydrogels and informs its design for the food and pharmaceutical industries.

Mechanics of cellulose gels to aerogels

Borzecka Nina (1), Rege Ameya (1) (2)

1 - German Aerospace Center (Germany), 2 - University of Twente (Netherlands)

Speaker: Borzecka Nina. **Tuesday**. Start time: **17:35**. Room: Roseraie 3 LVL3. Link to abstract.

Cellulose aerogels are novel, biodegradable alternatives to state-of-the-art plastic-based porous materials, particularly interesting for thermal insulation and mechanical stability. Moreover, with increasing demand of sustainable processes and materials, biopolymer-based aerogels are attracting a considerable attention. The key to their exceptional properties, such as low density, well-developed surface area, high sorption capacity and excellent insulating properties is their high porosity. To obtain that porosity, the aerogel synthesis requires application of supercritical drying – transition of the liquid filling the gel network to gas state without causing significant volume shrinkage. The fundamental understanding of the correlation between gel structure, drying conditions and the final porosity is crucial for better understanding of the system on fundamental level, but also for process and product optimization in the future. Cellulose gels synthesis steps and mechanical behavior were simulated with discrete element method (DEM) extended with bonded particle model (BPM). The diffusion and aggregation of cellulose chains is represented with a coarse-grained Langevin dynamics with consideration of hydrogen-bonding formation due to van der Waals forces. The computationally obtained gel undergoes the postprocessing steps corresponding to the actual experimental procedure: washing, solvent exchange and supercritical drying. The mechanical behavior of the structure depending on its structural properties was examined with uniaxial tests and the supercritical drying was represented by applying hydrostatic compression mimicking the pressure subjected within the autoclave on the gel network.
The parameters sensitivity analysis results provide a fundamental understanding of the influence of the polymer-polymer interaction on the structure formation process and final pore structure. The developed approach was validated with experimental data and it indicates a high potential for prediction of cellulose aerogels' properties with high accuracy. The proposed model is a significant step towards creation of a digital twin for cellulose aerogels, but also has a great potential to be extended for systems based on other polymers.

A Thermodynamically Consistent Constitutive Model for Hydrolytic Degradation of Oil Paint

Dizman Emir (1), Bosco Emanuela (1) , Suiker Akke S. J. (1)

1 - Eindhoven University of Technology, Department of the Built Environment, Eindhoven (Netherlands)

Speaker: Dizman Emir. **Tuesday**. Start time: **17:55**. Room: Roseraie 3 LVL3. Link to abstract.

In this study, a thermodynamically consistent hygro-chemo-mechanical model is proposed to describe the hydrolytic degradation of oil paint. Oil paint has been used throughout centuries as a painting medium in historical artworks and consists of a drying oil binder with embedded pigment particles that forms a durable film upon curing. Oil paint is particularly vulnerable to chemical and physical degradation over time, driven by environmental factors such as humidity and temperature changes. These aging phenomena may ultimately lead to cracks and delamination, affecting the integrity and durability of historical paintings (1). The chemical processes responsible for oil paint degradation include hydrolysis, which consists in the cleavage of ester bonds within the oil binder when exposed to moisture, forming carboxylic acids and alcohols. Considering the cross-linked polymeric network structure of the oil paint binder, a diffusion-reaction model is formulated to predict the extent of the hydrolysis reaction. The diffusion-reaction model is coupled with a mechanical analysis, where a viscoelastic constitutive model for oil paint is proposed and calibrated using experimental data obtained from the literature (2). A hydrolytic degradation model based on continuum damage mechanics is further developed to capture the effects of moisture diffusion on the degradation process. The sequentially coupled chemo-mechanical model is implemented within the commercial finite element software Abaqus. A comprehensive parametric study is conducted to investigate the influence of different model parameters affect the degradation behavior of oil paints, providing insights into the key factors driving deterioration. This work aims to enhance the understanding of degradation mechanisms in heritage oil paintings and lay the groundwork for developing predictive tools to support efficient conservation strategies.

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Viscoelastic soft elasticity of nematic liquid crystal elastomers in tension and compression

Rezaei Leila (1), Riazi Sahar (1), Scalet Giulia (2), Peigney Michaël (3), Azoug Aurélie (1)

1 - Oklahoma State University [Stillwater] (United States), 2 - Università degli Studi di Pavia = University of Pavia (Italy), 3 - Laboratoire Navier (France)

Speaker: Azoug Aurélie. **Tuesday**. Start time: **18:15**. Room: Roseraie 3 LVL3. Link to abstract.

Liquid Crystal Elastomers (LCEs) are a class of smart elastomers where the polymer chains forming the network include mesogenic molecules, *i.e.* the liquid crystals, attached as side groups or included in the backbone. Their mechanical response then combines the elasticity of the polymer network with the orientation and disorientation of the mesogens. As a result, LCEs are effective actuators, exhibiting an isochoric, reversible contraction strain of up to 180 % when triggered by a stimulus, for example heat or light, due to the mesogens disorienting from the nematic (ordered) to the isotropic (disordered) phase. In the nematic phase, LCEs exhibit soft elasticity, meaning they show an increase in strain at constant stress as the mesogens reorient themselves in the direction of the mechanical stretch. In compression, mesogens orient planarly rather than uniaxially, which is not necessarily associated with soft elasticity. Additionally, LCEs dissipate more energy than equivalent traditional elastomers. These nonlinear behaviors indicate a strong coupling between the movements of the polymer chains and the tendency of the mesogenic parts to form intermolecular ordered structures.
We focus on the viscoelasticity of LCEs during the soft elasticity phenomenon, leading to coupled time-dependent relaxation mechanisms and significant damping. We measured the rotation of the mesogens during stretching via polarized Raman spectroscopy and Nuclear Magnetic Resonance. We developed a finite strain phenomenological constitutive model of the viscoelastic soft elasticity of LCEs, inspired by the Souza-Aurrichio plasticity model dedicated to the superelasticity of shape memory alloys. Material parameters are fitted to dynamic mechanical analysis master curves as well as uniaxial tensile and compression experiments at multiple strain rates.
Experimental results show the increase in order parameter during stretching at different strain rates. The model predicts the change in modulus before, during, and after the soft elasticity region in tension and the change in modulus in compression. We investigate the coupling between relaxation mechanisms and soft elasticity, showing that the long-time mechanisms are coupled to the soft elasticity while the short-time mechanisms are decoupled. The threshold stress determining the onset of the soft elasticity is time-dependent but the viscosity of the mesogen rotation is negligible.

Micromechanics of the yield behaviour of semi-crystalline PEEK

Van Dommelen Hans (1), Geveling Rosa (1), Govaert Leon (1)

1 - Eindhoven University of Technology (Netherlands)

Speaker: Van Dommelen Hans. **Wednesday**. Start time: **10:00**. Room: Roseraie 3 LVL3. Link to abstract.

Thermoplastics are a class of polymers that can be moulded and reshaped repeatedly upon heating and cooling, making them sustainable, cost-effective, but also easy to process. The mechanical properties of thermoplastic polymers strongly depend on the processing conditions, which affect molecular orientation, in the case of amorphous as well as semi-crystalline polymers. For these materials, it is of key importance to understand the relationship between microstructure, isotropic or oriented, and their mechanical properties.
PEEK is a high-performance technical semi-crystalline thermoplastic, with attractive high-temperature properties. In load-bearing technical applications, the mechanical performance, including time-to-failure, depends on the yield kinetics, i.e. the rate- and temperature dependence of the yield behaviour, of the polymer. In the yield behaviour of PEEK, a combined effect of evolving texture of the crystalline phase and mechanical rejuvenation of the aged amorphous phase can be observed.
In this work, a micromechanical model for the mechanical performance, in particular the yield behaviour, of PEEK based on its microstructure is developed. For this purpose, a mean-field micromechanical model that has previously been applied successfully to other semi-crystalline polymers, is employed and characterized for PEEK, using experimental results. For this purpose, also fully amorphous samples were manufactured and used for a direct characterization of the amorphous phase, which was not previously possible for other semi-crystalline systems. With a careful characterization based on the semi-crystalline yield kinetics and post-yield behaviour, the contributions of the amorphous phase, in which the aged state rejuvenates upon deformation, and the crystalline phase, of which the slip activities evolve due to texture changes, is systematically unravelled.

Numerical study of the hyperviscoelastic response of polymer foams under compression

Merlette Thomas (1), Diani Julie (1)

1 - Laboratoire de Mécanique des Solides (France)

Speaker: Merlette Thomas. **Wednesday**. Start time: **10:20**. Room: Roseraie 3 LVL3. Link to abstract.

We study numerically the compression up to large deformation (typically 50%) of a commercial closed-cell polymer foam with 90% porosity when the polymer exhibits hyperviscoelasticity.
The polymer's viscoelasticity has been largely overlooked in related existing studies in the literature, highlighting the novelty of the current work. This effect is important when considering the influence of the compressive strain rate, or when studying more complex loading histories taking place over long time periods such as the succession of compression, stress relaxation and creep tests for instance. The predicted viscoelastic response of the foam is compared to experimental data.
In the literature, microstructures are usually either derived from SEM or tomography images, or generated as perdiodic lattices in order to reach high porosity values such as 90%. In the current study, random microstructures with 90% porosity are generated with Voronoï techniques, such as M-Voronoï (1). This enables to get microstructures closer to the real ones than periodic arrangements of pores on the one hand, while not depending on real images and therefore having some control on microstructural parameters such as porosity and pores spatial and size distributions on the other hand. The influence of the microstructure on the mechanical response at the macroscale is studied and discussed.

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Visco-pseudo-hyperelastic characterization of polymer foams

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Speaker: Berezvai Szabolcs. **Wednesday**. Start time: **10:40**. Room: Roseraie 3 LVL3. Link to abstract.

Polymer foams are widely applied cellular materials due to their excellent energy absorption properties, chemical resistance and thermal conductivity, whereas the production foams are low-cost and simple. Due to their cellular (open- or closed cell) structure, polymer foams are lightweight, and its elastic properties can be characterized with low moduli. The utilization of natural and synthetic foam covers a wide spectrum of both industrial and everyday applications including sport equipment, seat cushions, thermal insulations, electromagnetic shielding, filtrations, tissue scaffolds, flexible sensors, etc. Therefor there is a significant need to accurately characterize the mechanical behaviour of foams and to develop suitable constitutive models for numerical simulations.
From the mechanical point of view, the polymer foams show a complex behaviour including: i) highly nonlinear elastic behaviour in the finite strain regime with significant volumetric strains, ii) significant rate- or time-dependent, viscoelastic properties and iii) stress-softening properties (i.e. Mullins-effect) when it is subjected to loading-unloading cycles. Similarly, to filled elastomers, this latter behaviour is the most significant in the first few cycles, and after it disappears from the material response if the maximal stretches are kept constant. As the maximal stretches are increased, the material response returns to the original loading path and the Mullins-effect reappears.

In this contribution a visco-pseudo-hyperelastic constitutive model is introduced for polymer foams that is able characterize the above mentioned combined finite strain nonlinear elastic and viscoelastic properties with the stress-softening Mullins effect including also the residuals strains. The proposed constitutive models comprise of a Maxwell-type linear viscoelastic network in parallel with a time-independent pseudo-elastic branch that characterize the long-term hyperelastic behaviour with the Mullins effect. In the proposed constitutive model, the time-dependent material behaviour can be given in the form of Prony-series, while for the time-independent behaviour is given by the compressible Hyperfoam hyperelastic model which is combined with the Dorfmann-Ogden model that also characterise the residual strains as well.
For the stress-solution a linear numerical integration scheme has been adopted both for the volumetric and the deviatoric part of the hereditary integral of the constitutive model. The proposed numerical integration scheme can also be utilized in the parameter identification process.
For this, uniaxial and biaxial compression tests, relaxation tests, cyclic loading tests were performed on open and closed cell polyurethane foam specimens, where all deformation components are well-observable. Based on the stress-integration scheme various parameter fitting strategies are proposed including a separated fitting approach where the parameters of the different sub-models are fitted separately and a one-step fitting procedure where all the parameters are fitted simultaneously to all available material test data. Finally, the efficiency and the sensitivity of the fitting procedures are evaluated using a complex non-homogeneous validation compression tests.

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A Fracture Mechanics-Based Approach to the Structural Integrity of Fibrous Scaffolds

Terzano Michele (1), Kainz Manuel P. (1), Rolf-pissarczyk Malte (1), Holzapfel Gerhard A. (1) (2)

1 - Graz University of Technology (Austria), 2 - Norwegian University of Science and Technology (Norway)

Speaker: Terzano Michele. **Wednesday**. Start time: **11:00**. Room: Roseraie 3 LVL3. Link to abstract.

Biodegradable polymeric scaffolds are increasingly used in tissue engineering due to their ability to replicate the intricate architecture of the extracellular environment in human soft tissues. Specifically, electrospinning is an established technique for producing micron-scale non-woven fibrous meshes, characterized by structural anisotropy, porosity, and biocompatibility, all crucial properties for successful *in vivo* integration and tissue repair (1).
From a mechanical perspective, electrospun synthetic polymers exhibit complex behavior combining inelastic and rate-dependent phenomena typical of native collagenous tissues, albeit with notable qualitative differences (2). When applied to engineered cardiovascular tissues such as blood vessels or heart valves, it is also essential that polymeric scaffolds maintain their structural integrity and durability under cyclic hemodynamic loading.
This study proposes a fracture mechanics-based approach to assess the resistance to crack propagation of fibrous polymeric materials designed for regeneration of aortic valves. On the experimental side, we adopted classical fracture tests developed for soft polymers, such as pure-shear tests (3), combined with digital image correlation (DIC) to map strain fields under load, and a crack-tip algorithm to determine the crack propagation speed. Due to the material's remarkable anisotropy, cracks perpendicular to the mean fiber direction do not propagate in a self-similar manner, preventing direct computation of fracture toughness from the material's strain energy. We propose an alternative approach based on generalized energy balance integrals (4), integrated with DIC and a constitutive model developed by our group (2). The combined experimental and computational approach provides a robust framework for assessing the fracture and fatigue properties of non-woven fibrous materials.

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Bridging Natural Principles and Material Science: Advances in Lithomimetic-Inspired Polymeric Multi-Material Composites

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1 - Montanuniversität Leoben (Austria)

Speaker: Waly Christoph. **Wednesday**. Start time: **11:20**. Room: Roseraie 3 LVL3. Link to abstract.

The tailored design of material structures to meet the stringent demands of modern engineering applications has long been a focal point in materials science. Among the diverse strategies available within the extensive toolbox of materials design, lithomimetics (1) emerges as a novel and underexplored paradigm for polymeric materials, drawing inspiration from the complex patterns and structures naturally formed in the Earth's lithosphere. These structures, often featuring zig-zag or wave-like patterns, are characteristic elements recurring across various mineral types. The self-organization processes driven by extreme temperatures and pressures in the Earth's crust create these patterns, offering valuable inspiration for potential material design guidelines.
Recent studies, such as that by Waly et al. (2), have demonstrated the potential of wave-like "*lithomers*" - a fusion of lithomimetics and polymers - to surpass biomimetic straight-layered configurations in performance. These lithomers exhibit improved structure-property relationships, particularly in fracture toughness (damage tolerance) and stiffness, due to their complex architectures. These improvements are primarily attributed to the complexity and architecture of the structures. By incorporating soft interlayers within a hard matrix, the material inhomogeneity effect (3) can be harnessed to arrest crack propagation and enhance damage tolerance. Furthermore, the intricate geometry of the structures promotes mechanical interlocking, frictional effects, and increased shear stiffness within the soft layers, thereby contributing to improved initial stiffness of the overall system.

This study addresses two primary objectives. First, it seeks to optimize structural designs to enhance structure-property relationships. Through a combination of simulations and laboratory experiments, key parameters such as radii, amplitudes, frequencies, and layer thicknesses were analyzed, revealing their intricate interdependencies. This approach led to critical design guidelines and identified structural variants that outperform traditional straight-layered systems in damage tolerance and stiffness.

The second objective is the development of scalable fabrication methods for these structures, moving beyond additive manufacturing to mimic characteristics of the Earth's lithosphere. While such structures have been successfully fabricated in metals using specialized techniques like high-pressure torsion (4), no conventional polymer-based processes currently exist. To bridge this gap, a rotational mixer was developed, enabling the production of complex structures under high pressure, elevated temperatures, and relative motions analogous to geological processes. These fabricated structures demonstrated improved mechanical and fracture properties in testing compared to conventional designs.

Although still in their infancy, lithomers offer a promising avenue for advancing design principles in polymeric multilayer systems. Rather than serving as direct blueprints, they should be viewed as sources of inspiration for improving mechanical performance in materials. Additionally, they offer a versatile platform for innovating fabrication processes and refining existing methods, always aiming to meet the growing demands of modern applications.

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Constitutive Framework for Brittle Failure in Thermo-Chemically Aged Elastomers Using Phase-Field

Shakiba Maryam (1)

1 - University of Colorado (United States)

Speaker: Shakiba Maryam. **Wednesday**. Start time: **11:40**. Room: Roseraie 3 LVL3. Link to abstract.

This presentation discusses a physics- and chemistry-based constitutive framework that predicts the stress and brittle failure behaviors of thermo-chemically aged elastomers. High-temperature aging in the presence of oxygen triggers chemical reactions that significantly alter the elastomer's macromolecular network. This work directly links the evolution of the macromolecular network of elastomers to the mechanical properties governing the stress and failure responses of thermo-chemically aged elastomers. The Arruda–Boyce hyperelastic constitutive model is modified to predict the stress-strain response up to failure, incorporating a phase-field approach to capture brittle failure using a strain-based fracture criterion. Four material properties, critical to stress and failure responses, evolve based on the network evolution. The evolution of the macromolecular network, effective crosslink density in this case, is determined from chemical characterization tests for various aging temperatures and durations. The proposed constitutive framework is first analytically solved for uniaxial tension in a homogeneous bar, highlighting the interdependencies among the four material properties. It is then numerically implemented within a finite element (FE) framework using a user-element subroutine (UEL) in the commercial FE software Abaqus. Validation against experimental results from the literature demonstrates the framework's ability to accurately predict the stress-strain and failure behaviors of thermo-chemically aged elastomers. Additionally, numerical examples illustrate the influence of evolving material properties on specimens with pre-existing cracks, leveraging the phase-field approach to model brittle fracture.

MS1.7 - Multiscale materials modelling from atoms to macroscale

Organisers: Sylvain Patinet (ESPCI), Renald Brenner (Institut Jean Le Rond D'alembert) and Sebastian Pfaller (FAU Nuremberg)

Contiunous modeling of dislocation in concentrated random alloys

Geslin Pierre-antoine (1), Démery Vincent Rosso Alberto (2), Rodney David

1 - Matériaux, ingénierie et science [Villeurbanne] (France), 2 - LPTMS, CNRS, Univ. Paris-Sud (France)

Speaker: David Rodney. Keynote. **Monday**. Start time: **10:10**. Room: Saint Clair 3A LVL2. Link to abstract.

The study of dislocation-solute interactions is central in metallurgical sciences because of the significant influence of solutes on the mechanical response of alloys. In particular, solid solution strengthening is taken advantage of in the recent development of high entropy alloys. To investigate solid solution strengthening in concentrated alloys, our work is articulated around two steps. We first develop an elastic model of random alloys where atoms of different sizes are modeled as Eshelby inclusions embedded in an isotropic elastic medium. This allows to derive analytical expressions for the variance of the elastic fields (displacements, strains, stresses) as well as their spatial correlations. We show that stress correlations are highly anisotropic despite the use of isotropic elasticity and the randomness of the alloy (1,2). The second step consists in using this correlated stress environment in a dislocation dynamics framework to derive the critical stress related to the dislocation depinning (3,4) as well as the dislocation roughness at the depinning threshold. Adding a Langevin noise also enables following the dynamic of the dislocation with temperature and to investigate how the applied stress influences the energy barrier distribution. These numerical results enable to critically assess the validity and the limitations of average models from the literature (5).

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Dislocation dynamics in Ni-based superalloys: parameterising edge dislocation trajectories with uncertainty quantification

Anis Geraldine (1), Hudson Thomas (2), Brommer Peter (3)

1 - EPSRC Centre for Doctoral Training in Modelling of Heterogeneous Systems, University of Warwick (United Kingdom), 2 - Warwick Mathematics Institute, University of Warwick (United Kingdom), 3 - Warwick Centre for Predictive Modelling, School of Engineering, University of Warwick (United Kingdom)

Speaker: Anis Geraldine. **Monday**. Start time: **10:50**. Room: Saint Clair 3A LVL2. Link to abstract.

The extraordinary strength exhibited by Ni-based superalloys at high temperatures is attributed to the presence of nanoscale precipitates in their microstructure, which hinder dislocation motion. In our work, we study edge dislocation-precipitate interactions using Molecular Dynamics (MD) simulations with classical effective potentials. The motion of a pair of edge dislocations moving under shear between pure Face-Centred Cubic (FCC) Ni into Ni3Al with an L12 structure was simulated using MD, where Ni is used to represent an idealised γ solid solution phase and Ni3Al for the γ' precipitate phase. The obtained trajectories are parameterised using a model developed by extending an equation of motion (1) to account for dislocation-dislocation and dislocation-precipitate interactions. Differential Evolution Monte Carlo (DE-MC) within a Bayesian framework is used to determine parameter distributions and the correlations between them. These distributions are then used to quantify the uncertainty in the model outputs, namely the dislocations' positions and velocities. Parameterising dislocation dynamics in this way yields physically meaningful parameters. Accordingly, the present approach offers a means of extracting quantitative information from the atomistic scale that can be used to inform larger length scale simulations of dislocations such as Discrete Dislocation Dynamics (DDD). Using DE-MC as a sampling approach also means that parameter uncertainties can be propagated through a hierarchy of multiscale models. We illustrate how such uncertainty propagation can be achieved by considering a dislocation mobility law with quantified uncertainties. This work is part of a wider study aiming to develop a more comprehensive surrogate model to describe the deformation behaviour of Ni-based superalloys with a focus on propagating and quantifying uncertainties (2).

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Structural Heterogeneity in the Shock-induced Plastic Deformation Mechanism of Nanocrystalline High-Entropy Alloys

Song Weidong (1)

1 - Beijing,China (China)

Speaker: Song Weidong. **Monday**. Start time: **11:10**. Room: Saint Clair 3A LVL2. Link to abstract.

The grain size distribution greatly influences the macroscopic mechanical and functional characteristics of polycrystalline materials. However, comprehending the distinct characteristics of nanocrystalline metals under dynamic loading poses challenges due to stringent spatio-temporal resolution requirements. In this study, the shock response of nanocrystalline CoCrCuFeNi high-entropy alloys (HEAs) with varied sizes of both homogeneous and heterogeneous grain microstructures are systematically investigated through molecular dynamic simulations. Our findings reveal that the shock front width, Hugoniot elastic limit (HEL), and shock wave velocity all exhibit an increase with larger grain sizes. Under shock loading, the dominant plastic mechanism transitions from grain-boundary-accommodated processes to dislocation-mediated (dislocation, twin, L-C lock, and HCP phase) ones with increasing grain size, resulting in the shear strength increases with the increase in grain size. In comparison, heterogeneous structures enhance plasticity through a synergistic deformation model, efficiently distributing loads between grains of varying sizes. Additionally, it is found that the smaller grain sample performs a higher spall strength due to its higher fracture surface energy. The damage mechanism transforms from multiple nucleation of voids and individual growth to intergranular damage and void coalescence as the grain sizes increase. An energy balance fragmentation model considering void damage evolution and fracture surface energy is adopted to accurately predict the spall strength of nanocrystalline HEAs. Compared with the traditional metal Ni, HEA performs a higher HEL, spall strength, and twinning tendency due to the low stacking fault energy and pronounced lattice distortion. These atomistic insights contribute to the identification of practical applications for HEAs as structural materials in extreme loading environments.

Multiscale modeling of dislocation-mediated plasticity of refractory high entropy alloys

Zhang Yin (1)

1 - Peking University [Beijing] (China)

Speaker: Zhang Yin. **Monday**. Start time: **11:30**. Room: Saint Clair 3A LVL2. Link to abstract.

Refractory high entropy alloys (RHEAs) have drawn growing attention due to their remarkable strength retention at high temperatures. Understanding dislocation mobility is vital for optimizing high-temperature properties and ambient temperature ductility of RHEAs. Nevertheless, fundamental questions persist regarding the variability of dislocation motion in the rugged energy landscape and the effective activation barrier for specific mechanisms, such as kink-pair nucleation and kink migration. Here we perform systematic atomistic simulations and conduct statistical analysis to obtain the effective activation barrier for the mechanisms underlying various types of dislocation motion in a typical RHEA, NbMoTaW. Moreover, a stochastic line tension model is developed to calculate the activation barrier with substantially reduced computational costs. By incorporating the activation barrier into the crystal plasticity model, a multiscale simulation framework for predicting the mechanical properties of RHEAs is established. The ambient temperature yield strength of NbMoTaW is well-predicted by the kink-pair nucleation mechanism of screw dislocations, while the strengthening originating from screw dislocations does not predominate at high temperatures. Our work provides a robust foundation for atomistic studies of effective dislocation behaviors in random solution solids, elucidating the intricate relationship between microscopic mechanisms and macroscopic properties.

All possible binary dislocation locks in face-centered cubic materials unearthed via a novel discrete mathematics-based approach

Bajaj Dhruv (1), Chen Daolun (1)

1 - Department of Mechanical, Industrial and Mechatronics Engineering, Toronto Metropolitan University, Toronto, Canada (Canada)

Speaker: Chen Daolun. **Monday**. Start time: **13:40**. Room: Saint Clair 3A LVL2. Link to abstract.

The concept of dislocations, along with their movement, reaction/intersection and the formation of locks/barriers, is a cornerstone in understanding the mechanical behavior of crystalline materials including strength and strain hardening. Although some dislocation locks in face-centered cubic (FCC) materials, such as the well-known Lomer lock and Cottrell lock, have been identified via high-resolution transmission electron microscopy observations and molecular-dynamic simulations, it remains unknown how many binary dislocation locks are possible when two dislocations come from intersecting slip planes and how immobile these locks are. In this work, a novel discrete mathematics-based approach is proposed to unveil dislocation locks in FCC materials, resulting from all possible reactions of mobile/glissile dislocations (i.e., perfect and Shockley partial dislocations) in two cases: (i) non-coplanar dislocations residing on two {111} slip planes intersecting at both obtuse (109.47○) and acute (70.53○) angles, and (ii) coplanar dislocations. In total, eight binary dislocation locks are derived from all possible 50 non-coplanar dislocation reactions together with all coplanar dislocation reactions. Specifically, more dislocation locks (68% of 25 dislocation reactions) are formed when the incoming reactant dislocations are obtusely oriented. Only 24% of 25 dislocation reactions are energetically feasible when the incoming reactant dislocations are acutely oriented. All the dislocation lock planes are found to be uniquely situated in a "fan-shaped" sector convergently. A new definition of the degree of lock immobility is also put forward according to the misorientations between non-close-packed lock planes and close-packed {111} slip planes. Details will be presented at the conference.

Mobility and cross-slip of the 1/2<110> scriw dislocation in UO2

Amodeo Jonathan (1), Pivano Adrien (2), Suchorski Jules-elémir (2)

1 - Aix-Marseille Université, Université de Toulon, CNRS, IM2NP, F-13397 Marseille (France), 2 - CEA/DES/IRESNE/DEC/SESC/LM2C (France)

Speaker: Amodeo Jonathan. **Monday**. Start time: **14:00**. Room: Saint Clair 3A LVL2. Link to abstract.

The plastic deformation of UO2 single crystal is characterized by dislocations gliding mainly in the primary slip systems $\frac{1}{2}$ {001} of the fluorite structure. However, recent numerical studies conducted at the meso-scale have highlighted the possible role of dislocation cross-slip in secondary slip systems, $\frac{1}{2}$ {110} and $\frac{1}{2}$ {111}, as a possible explanation for the Schmid law breakdown and the anisotropic mechanical response observed in UO2 single crystal experiments performed at high-temperature (1,2,3). Despite these insights, hypothesis relying on elementary deformation processes in UO2 remain qualitative for now, primarily due to the limited understanding of the screw dislocation structure and mobility at elevated temperature.
In this study, we employ a combination atomistic and discrete dislocation dynamics simulation to investigate the mobility of the $\frac{1}{2}$ screw dislocation in UO2. The fundamental deformation mechanisms of dislocation motion at the atomic scale are explored from room temperature to 2200 K, with a particular emphasis on the progressive activation of cross-slip in the {111} planes. Models for the screw dislocation mobility and cross-slip are developed based on the tendency of the screw dislocation core to spread across the various crystallographic planes of the fluorite structure, and are tested within a discrete dislocation dynamics framework. In addition to a through comparison with atomistic simulations, meso-scale simulations are employed to validate the the cross-slip models through test-cases relevant to irradiation and strain hardening in UO2.

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Statistics of fluctuations in mesoscopic tensorial model of crystal plasticity: the effect of different energy minimization algorithms.

Lundheim Elias (1), Salman Oguz Umut (2), Patinet Sylvain (1), Truskinovsky Lev (1)

1 - PMMH, CNRS–UMR 7636 (France), 2 - LSPM (France)

Speaker: Lundheim Elias. **Monday**. Start time: **14:20**. Room: Saint Clair 3A LVL2. Link to abstract.

Significant efforts have been dedicated recently to the understanding of fluctuations associated with crystal plasticity (1). The scale-free statistical signature of such fluctuations is not resolved by the engineering continuum plasticity and is computationally too costly to be studied by molecular dynamics. Recently a mesoscopic tensorial model (MTM) has emerged as a promising compromise (2-4). Unlike discrete dislocation dynamics, which relies on phenomenologically prescribed rules, the MTM is a finite element approach which relies exclusively on a globally periodic energy landscape compatible with lattice-invariant shears. Under quasistatic loading, the mathematical problem reduces to incremental energy minimization, and the system proceeds through intermittent dislocation avalanches (5,6). However, it has been unknown whether the statistics of the ensuing scale-free fluctuations is affected by the choice of the energy minimization algorithm. To answer this question we tested three algorithms: the state-of-the-art Limited-Memory Broyden-Fletcher-Goldfarb-Shanno (L-BFGS) method, the more classical Conjugate Gradient (CG) method, and the pseudo-inertial Fast Inertial Relaxation Engine (FIRE). We showed that despite driving the system through rather different set of local minima, all these three 'dynamical approaches' are practically statistically indistinguishable in the sense that they yield similar scale-free avalanche size distributions and predict very close values of the power law exponents. Our findings highlight the robustness of the MTM approach to crystal plasticity and point to the universality of the corresponding scaling regimes. References

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Modelling Frank-Read dislocation sources as pinned and driven mean curvature flow

Hudson Thomas (1), Rindler Filip (1), Rydell Joshua (1)

1 - Warwick Mathematics Institute (United Kingdom)

Speaker: Hudson Thomas. **Monday**. Start time: **14:40**. Room: Saint Clair 3A LVL2. Link to abstract.

Frank-Read sources are thought to be a possible mechanism for the generation of dislocation loops with crystalline materials. A first-principles derivation of a simple model for these sources will be presented, focusing on the effect of line tension, the applied stress, and frictional forces acting on a single slip plane, together with a pinning constraint on the ends of the dislocation line. Subsequently, the model is numerically discretised, requiring the implementation of suitable re-meshing and 'topological cutting' algorithms. Despite its conceptual simplicity, the model and discretisation described yield remarkably accurate predictions about the shape and properties of the Frank-Read source, indicating that such sources may be dominated by line tension effects. In particular, it is shown that only one dimensionless parameter controls the dynamics of the Frank-Read source if one neglects crystal anisotropy, and an emergent law relating the length of dislocation line generated by the source over time is observed.

Simulation-Informed Models for Amorphous Metal Additive Manufacturing

Xu Bin Wu Zhao Lu Jiayin Shields Michael (1), Rycroft Chris (2) (3), Bamer Franz (4), Falk Michael (1)

1 - Johns Hopkins University (United States), 2 - Paulson School of Engineering and Applied Sciences (Harvard University, 29 Oxford Street, Cambridge, MA 02138 United States), 3 - Computational Research Division (Lawrence Berkeley National Laboratory, 1 Cyclotron Road Mailstop XXX, Berkeley, CA 94720 United States), 4 - RWTH Aachen University = Rheinisch-Westfälische Technische Hochschule Aachen (Germany)

Speaker: Bamer Franz. **Monday**. Start time: **16:00**. Room: Saint Clair 3A LVL2. Link to abstract.

To enable design of additively manufactured amorphous metal parts with desired mechanical properties, including strength and toughness, we are pursuing simulation-informed modeling as an integral component of a simultaneous design approach. This work involves development of two machine learning frameworks. The first utilizes a variational autoencoder to build connections between experimental nanodiffraction data and atomistic structural glass models. The second develops a data-centric stochastic constitutive formulation of metallic glass plastic constitutive response. Through the interrogation of an 3D atomistic representative volume element of a binary glass, we harvest simulation data that quantifies plastic constitutive response. The resulting data quantifies the stress drops characteristic of metallic glass mechanical response in terms of state variables related to the stress and the structural state of the glass. This data informs a stochastic finite state automata model that can reproduce aspects of the mechanical response and the associated evolution of the material's structural state. This serves as a lower-scale constitutive model for a continuum model capable of achieving predictions of mechanical response on significantly larger length scales. Validation of the continuum model is undertaken in comparison with large scale atomistic simulations.

This work is supported by the US National Science Foundation under Grant Nos. DMR-2323718/DMR-2323719/DMR-2323720.

Atomistic origin of network glass fracture

Bamer Franz (1), Wu Zhao (1), Bachhav Bhagyashri (1), Shekh Alshabab Somar (1), Shields Michael (2), Falk Michael (2)

1 - RWTH Aachen University = Rheinisch-Westfälische Technische Hochschule Aachen (Germany), 2 - Johns Hopkins University (United States)

Speaker: Bamer Franz. **Monday**. Start time: **16:20**. Room: Saint Clair 3A LVL2. Link to abstract.

Disordered network materials, such as silica glass, behave fundamentally differently than densely packed systems, such as metallic glass. Their network consists of corner-sharing SiO_4 tetrahedra (or SiO_3 triangles) that form rings of various shapes and sizes. Densely packed systems respond as an accumulation of local atomic-scale rearrangements occurring in point defects, also called shear transformation zones. After generating two-dimensional network glass models using a dual Monte Carlo bond-switching strategy, we perform rigorous mechanical investigations using the athermal quasistatic deformation method. We show that the onset of network glass fracture occurs in soft spots similar to shear transformation zones; however, in the case of network glasses, the local rearrangement picture in those zones can mainly identified as a bond-breaking type destroying the network topology locally. First, we will identify the peculiarities of these local fracture events. Then, we will present several prediction strategies to identify these zones in network glasses prior to mechanical loading. Hereby, we will identify local rearrangement spots presenting purely geometrical predictors and predictors using local probing techniques. Finally, we will show that neural network models can identify these zones if they are trained with sufficient data available.

Clustering of negative topological charges precedes plastic failure in 3D glasses

Bera Arabinda (1), Baggioli Matteo (2), Petersen Timothy (3), Sirk Timothy (4), Liu Amelia (3), Zaccone Alessio (1)

1 - Università degli Studi di Milano = University of Milan (Italy), 2 - Shanghai Jiao Tong University [Shanghai] (China), 3 - Monash university (Australia), 4 - US DEVCOM Army Research Laboratory, Maryland (United States)

Speaker: Bera Arabinda. **Monday**. Start time: **16:40**. Room: Saint Clair 3A LVL2. Link to abstract.

The deformation mechanism in amorphous solids subjected to external shear remains poorly understood because of the absence of well-defined topological defects mediating the plastic deformation. The notion of soft spots has emerged as a useful tool to characterize the onset of irreversible rearrangements and plastic flow, but these entities are not clearly defined in terms of geometry and topology. In this study, we unveil the phenomenology of recently discovered, precisely defined topological defects governing the microscopic mechanical and yielding behavior of a model 3D glass under shear deformation. We identify the existence of vortex-like and anti-vortex-like topological defects within the 3D non-affine displacement field. The number density of these defects exhibits a significant anti-correlation with the plastic events, with defect proliferation-annihilation cycles matching the alternation of elastic-like segments and catastrophic plastic drops, respectively. Furthermore, we observe collective annihilation of these point-like defects via plastic events, with large local topological charge fluctuations in the vicinity of regions that feature strong non-affine displacements. We reveal that plastic yielding is driven by several large sized clusters of net negative topological charge, the massive annihilation of which triggers the onset of plastic flow. These findings suggest a geometric and topological characterization of soft spots and pave the way for the mechanistic understanding of topological defects as mediators of plastic deformation in glassy materials.

The Critical Role of Material Length in Amorphous Fracture

Molnar Gergely (1), Barthel Etienne

1 - Laboratoire de Mécanique des Contacts et des Structures [Villeurbanne] (France)

Speaker: Molnar Gergely. **Monday**. Start time: **17:00**. Room: Saint Clair 3A LVL2. Link to abstract.

The talk that delves into the origins of fracture toughness in amorphous silica, focusing on the influence of a rounded crack tip and the limitations of linear elastic fracture mechanics. Griffith's theory states that in the absence of a sharp crack, the energy release rate becomes zero, rendering linear elastic fracture mechanics inadequate for assessing resistance in geometries featuring a rounded crack. To overcome this limitation, the talk employs coupled criterion and phase-field simulations to assess fracture initiation.
Through extensive large-scale atomic-scale simulations, the research identifies damage within the atomic structure. A finite element model update scheme is utilized to pinpoint the critical energy release rate and the regularization length scale during crack propagation.
In conclusion, the talk offers a comprehensive comparison of the identified properties, examining their consistency with the predictions of the homogeneous phase-field solution and the material's tensile strength. Furthermore, the research endeavors to contrast the outcomes of all three methodologies, thereby shedding light on the foundational assumptions that underlie continuum models, including phase-field and finite fracture mechanics. By exploring the interplay between crack geometry and fracture resistance, this study advances our understanding of fracture toughness in amorphous silica and contributes to the ongoing development of more accurate models for predicting fracture initiation and propagation in complex materials.

Numerical Modeling of Sol-Gel Materials: An Aerogel Use-Case

Pandit Prakul (1), Rege Ameya (1) (2)

1 - Institute of Materials Research, German Aerospace Center (Germany), 2 - Department of Mechanics of Solids, Surfaces & Systems, University of Twente (Netherlands)

Speaker: Pandit Prakul. **Monday**. Start time: **17:20**. Room: Saint Clair 3A LVL2. Link to abstract.

The increasing demand for sustainable material development in various industries has led to a significant focus on computational algorithms to accelerate material design. Among these materials, aerogels - highly porous, low-density and thermally insulating structures - have gained attention for applications in insulation, energy storage and carbon capture. Despite extensive research, the synthesis of aerogels has historically relied on iterative experimental approaches. While over the years, there have been simulation-based approaches in understanding the gelation behavior, these studies often simplify the material behavior by often neglecting the physics of the formation of the primary particles themselves. This study presents a computational workflow for modeling aerogel formation, capturing the evolution from nucleation of primary particles to the gel network development. The presented workflow makes it possible to explore the interplay between sol-gel chemistry and the resulting microstructures, allowing a deeper understanding of the synthesis process. In addition, the computational model incorporates solvent exchange and drying effects both implicitly and explicitly. The finite Element Method is used to study drying-induced stresses, identifying critical load paths and potential damage mechanisms under high load conditions. By providing a fully digital approach to aerogel modelling, this workflow accelerates sustainable materials development and improves the understanding of aerogel‘s properties under varying synthesis conditions

Coarse-graining aggregate polymer nanocomposites : towards a microscopic Interpretation of the Payne Effect

Merabia Samy (1), Wang Yang Detcheverry François Couty Marc Maurel Gaëtan

1 - Université Lyon 1 and CNRS (France)

Speaker: Merabia Samy. Keynote. **Tuesday**. Start time: **10:00**. Room: Saint Clair 3A LVL2. Link to abstract.

Polymer nanocomposites (PNCs) are known to display exceptional non-linear mechanical properties, even for deformation amplitude as low as a few percent. One of the most studied phenomenon is the so-called Payne effect, a drop in storage modulus with increasing amplitude. Several mechanisms have been put forward to rationalize such effect, including filler network breaking, polymer chain desorption and yielding of the polymer confined between the nanofillers (1). In this contribution, we demonstrate that for PNCs involving fractal-like aggregates, the Payne effect may originate from the shear-induced alignment of the aggregates. We reach this conclusion by using a coarse-grained model, which combines an explicit representation of fillers with an implicit description of the polymer matrix (2). We systematically characterize the effects of aggregate size and polydispersity in the amplitude of the Payne effect (3). Moreover, we probe the mechanical response of the model PNCs after a first cycle of deformation. We observe slow recovery kinetics of the original storage modulus of the PNCs and relate this memory effect to the alignment of the aggregates. Our findings should contribute to clarify the relation between the macroscopic mechanical response of the PNCs and the mesoscopic state of the filler.
If time permits, we will eventually discuss our recent results on thermal transport at metal/amorphous silica interfaces (4), which enable to build a multiscale model to predic the photothermal response of core-shell colloidal nanoparticles, with applications in nanoparticle assisted cancer therapy (5).

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Molecular dynamics simulations of polymers under shock loading: the importance of the local stress trensor

Lemarchand Claire (1) (2), Pineau Nicolas (1) (2)

1 - Direction des Applications Militaires (France), 2 - Laboratoire Matière sous Conditions Extrêmes (France)

Speaker: Lemarchand Claire. **Tuesday**. Start time: **10:40**. Room: Saint Clair 3A LVL2. Link to abstract.

Understanding the behavior of polymers under shock loading is essential for their applications in car equipment, aircraft, space structure and plastic bonded explosives. Despite much effort, both experimentally and numerically over the last twenty years (1,2), there are specificities of the shock behavior of polymers that are still unclear. These include the relation of the shocked state to the dynamic glass transition. Direct shock simulations of three different polymers, cis-1,4-polybutadiene, polystyrene and phenoxy resin, with different glass transition temperatures, were performed (3). First, I will show that the polymer melts created in this work have a structure factor and a Hugoniot locus very close to their experimental counterparts. Second, I will focus on the shear stress relaxations behind the shock front. It is found that the polymers with the highest glass transition temperature have the most slowly relaxing shear stress behind the shock front. Finally, to refine the local stress behavior around the shock front, I will present a new expression of the local stress tensor for molecular systems which verifies by construction the local balance of linear momentum (4,5).

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Physical origin of strain hardening in glassy polymers and constitutive modeling based on molecular dynamics simulations

Zhao Wuyang (1)

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Speaker: Zhao Wuyang. **Tuesday**. Start time: **11:00**. Room: Saint Clair 3A LVL2. Link to abstract.

Glassy polymers typically exhibit strain hardening at large deformations due to their chain-like molecules, effectively increasing the toughness of the materials. The rate- and temperature-dependence of strain hardening increases the difficulty of accurately modeling the mechanical response in the hardening region, which is essential for studying the failure mechanisms of glassy polymers. This contribution presents the study of the micromechanisms underlying strain hardening in glassy polymers based on molecular dynamics (MD) simulations (1). Firstly, the stress response in the hardening region is attributed to the interactions of bond and angle potentials through decomposition of the virial components. Furthermore, the primary contribution to strain hardening is identified as the stretch of polymer bonds by evaluating the microscopic properties, where the disentanglement only plays a small role. Interestingly, rather than the average bond stretch, we find that the key contributions to stress response come from a subset of bonds at the upper tail of the stretch distribution, where the stress in the hardening region can be correlated with the average stretch of the most extended bonds in each polymer chain, independent of temperatures and strain rates. We further incorporate this mechanism into a constitutive model in continuum mechanics with orientation-induced back stress, developing a model that accurately reproduces the stress response of the molecular systems in uniaxial tension over a wide range of temperatures and strain rates in their glassy state. With 13 parameters in the constitutive model, 10 of them can be directly estimated from the MD simulation results. (1) W. Zhao. Rate- and temperature-dependent strain hardening in glassy polymers: Micromechanisms and constitutive modeling based on molecular dynamics simulations. arXiv preprint arXiv:2411.07811.

Simulation and Analysis of Epoxy Polymer Networks: Advanced Crosslinking Approaches and Topological Modifications in LAMMPS

Lamamra Moussa (1) (2), Detrez Fabrice (1) (2)

1 - Université Gustave Eiffel (France), 2 - Laboratoire Modélisation et Simulation Multi-Echelle (France)

Speaker: Lamamra Moussa. **Tuesday**. Start time: **11:20**. Room: Saint Clair 3A LVL2. Link to abstract.

In this study, we focus on generating and analyzing the polymer network topology of epoxy resins, specifically DGEBA and DETDA molecules, using two crosslinking approaches within the LAMMPS simulation software. The first method utilizes the REACTER(1,2) approach to simulate the curing process, while the second approach employs a modified version of the bond/create(3,4) to ensure the topology of molecules is dynamically updated after bond formation. This modification enhances the precision and reliability of the simulated network structures. Both methodologies are evaluated to compare their effectiveness in capturing the network formation process, with an emphasis on their suitability for characterizing microstructure-property relationships and mechanical behavior. The results provide insights into the advantages and limitations of each approach for simulating crosslinked polymer systems, with potential implications for the design of highperformance bio-sourced epoxy materials.

A Semi-Continuum Multiscale Model of Graphene Polymer Nanocomposites: Mechanical Characterization

Barakat Malak (1) (2), Reda Hilal (2), Harmandaris Vagelis (2)

1 - Lebanese University (Lebanon), 2 - The cyprus institute (Cyprus)

Speaker: Barakat Malak. **Tuesday**. Start time: **11:40**. Room: Saint Clair 3A LVL2. Link to abstract.

The interest in polymeric nanostructured materials has been growing ever since their successful application became a sensible reality. Yet, capturing their performance using computational methods necessitates coupling between different scales and the consideration of underlying heterogeneities to ensure fidelity. For this purpose, we present a three-phases hierarchical multiscale Finite Element based model that aims to efficiently predict the mechanical behavior of graphene reinforced polymer nanocomposites. First, a discrete model of graphene is constructed using linear beam finite elements which mimic the interatomic interactions occurring at the level of the nanofiller's microstructure. The mechanical properties of graphene are then computed for several sizes to eliminate size-effects. Next, the polymer/graphene interphase is represented by non-linear spring elements which resemble van der Waals interactions occurring between the host polymer matrix and the nanofiller. With the matrix represented as a continuum, Young's modulus and Poisson's ratio of the designed polymer nanocomposite are computed by performing tensile testing in all three Cartesian directions. The semi-continuum three-phases multiscale model traversing nano to macro scales is compared against other models in the literature where it shows accuracy and efficiency in computational material modeling.

Bridging Scales in Boundary Lubrication: Atomistic-Continuum Coupling Enabled by Machine Learning

Holey Hannes (1), Gumbsch Peter (2), Pastewka Lars (3)

1 - University of Milan (Italy), 2 - Karlsruhe Institute of Technology (Germany), 3 - University of Freiburg (Germany)

Speaker: Holey Hannes. **Tuesday**. Start time: **14:15**. Room: Saint Clair 3A LVL2. Link to abstract.

Friction and lubrication are inherent multiscale problems, particularly when the gap between contacting bodies is on the order of molecular interaction length scales. These conditions occur predominantly in the so-called boundary lubrication regime under high normal loads, low sliding speeds or with low viscosity lubricants. Continuum descriptions of the interfacial flow problem can be augmented with atomistic simulations to account for various nonlinear effects, such as fluid-wall slip. However, modeling lubrication across scales beyond purely sequential approaches has so far remained elusive.
In this talk, I will present a reformulation of the classical lubrication equations that allows straightforward concurrent coupling between continuum and molecular models. Instead of using fixed-form constitutive expressions that are parametrized a priori using atomistic methods, we build surrogate models for the interfacial shear stress and normal pressure on-the-fly.
Concurrent coupling is achieved by an active learning scheme based on Gaussian process regression, which allows for a data-efficient interpolation of the microscopic stresses obtained from molecular dynamics simulations in a high-dimensional parameter space. Furthermore, the Gaussian process posterior variance enables quantifying the uncertainty of pressure and shear stress distributions within the gap.
We validate the proposed method for nanoscale flow of simple fluids around single and multi asperity topographies, which paves the way for accurate simulations of boundary lubrication on experimental length and time scales.

Multi-Scale Characterization and Modelling of the Deformation Behavior in an Aged Duplex Stainless Steel

Cong Lin (1), Ling Chao (1), Li Dongfeng (1), Busso Esteban P. (1)

1 - Center for Materials Modelling and Characterization, School of Science, Harbin Institute of Technology-Shenzhen (China)

Speaker: Cong Lin. **Tuesday**. Start time: **14:35**. Room: Saint Clair 3A LVL2. Link to abstract.

Duplex stainless steels (DSSs), composed of austenitic and ferritic phases, are used in nuclear power plant components. Before service, they are subjected to long-term thermal aging, which results in the spinoidal decomposition of the ferritic phase into Cr-rich and Cr-poor regions and leads to the strengthening of the decomposed ferrite and alloy. An in-depth understanding of the microstructure-mechanical behavior relationship of the steel after aging is still lacking and deserves further investigation. In this work, a three-scale (nano-micro-meso) approach is proposed to study the mechanical behavior of the DSS at room temperature. At the mesoscopic scale, polycrystalline representative volume elements (RVEs) of homogenised austenitic grains with approx. 9.5% embedded (coherent) ferrite islands are constructed from EBSD orientation maps to formulate and calibrate the homogenized single crystal grain behaviour before and after ageing from uniaxial stress-strain responses of the DSS. Micro-scale RVEs, which consist of an austenitic single crystal grain with embedded coherent as-received (AR) and aged ferritic phase islands, are relied upon to develop and calibrate constitutive models for the AR and aged ferrite, based on the homogenized RVE response identified at the meso-scale and the austenite behaviour determined from an austenitic stainless steel. At the nano-scale, a phase field model is relied upon to predict the formation of Cr-rich and Cr-poor regions due to the spinodal decomposition of the ferrite. The resulting phase field predictions are then used to construct nanoscale RVEs of the spinodally decomposed ferritic phase (with an approx. 26% vol. fraction) to formulate and calibrate the single crystal behaviour of the Cr-rich phase, assuming that the Cr-poor phase behaves like undecomposed ferrite, with the nano-scale RVE behaviour given by the ferrite response identified at the micro-scale. Based on these results, an isotropic elasto-visco-plastic constitutive model for the DSS is proposed at the macro-scale and validated experimentally. The proposed multi-scale modelling approach is shown to satisfactorily capture the evolution of the microstructure and stress-strain behaviour of the DSS as a function of ageing conditions. Furthermore, localisation of inelastic strain at different scales are predicted, and the effect of ageing time identified, providing a mechanistic basis to tailor ageing treatments for optimum service behaviour. Ongoing work extends this approach to temperatures typical of service in the 280-320oC range.

Multiscale Modelling of Single Crystal PMN-PT Ferro-Electric Films as a Morphotropic Phase

Wang Zian (1), Xie Yujie (2), Sun Ligang (2), Chao Ling (2), Dongfeng Li (2), Jun Wei (3), Busso Esteban (2)

1 - Center for Materials Modelling and Characterisation, Harbin Institute of Technology, Shenzhen (China), 2 - Center for Materials Modelling and Characterisation, Harbin Institute of Technology, Shenzhen (China), 3 - Shenzhen Key Laboratory of Flexible Printed Electronics Technology, School of Materials Science and Engineering, Harbin Institute of Technology, Shenzhen (China)

Speaker: Wang Zian. **Tuesday**. Start time: **14:55**. Room: Saint Clair 3A LVL2. Link to abstract.

Recent advancements in wearable flexible hybrid electronic systems have driven the demands on their self-powered modules. Single crystal PMN-PT thin films near morphotropic phase boundary are well known for their exceptional piezoelectric properties, and are often chosen as the crucial functional material in these modules. However, the mechanisms behind their outstanding piezoelectric performance remain insufficiently understood due to the complex multiphase coexistence and multiscale hierarchical structure, necessitating a multiscale analysis strategy.

In this work, a phase-field modelling framework based on the Landau potential is employed to describe and predict the domain evolution as well as the mechanical and electrical responses of PMN-PT thin films used in flexible electronic devices. Due to the complicated microstructure of PMN-PT thin films, it is nearly impossible to extract the pure domain or domain wall material parameters from experimental data. Therefore, first-principles calculations at the electronic scale are utilised to calibrate the phase-field model parameters. The resulting phase-field model is numerically implemented into the finite element method to explore the electromechanical responses of PMN-PT thin films via the representative volume elements.

The simulated behaviour, including macroscopic polarization–electric field hysteresis and piezoelectric response, is verified against experimental data obtained as part of this work. The proposed approach integrates electronic/atomic-scale properties into a continuum modeling framework to provide a comprehensive understanding of PMN-PT thin films performance. These simulations can offer valuable guidance to optimise their piezoelectric properties and performance stability, advancing the development of self-powered systems for the next-generation of flexible electronic devices.

Multiscale numerical simulations for elastic properties and the flexural response of graphene sheets at finite temperature

Singh Sandeep (1), Raikwar Akash (1)

1 - Indian Institute of Technology Indore (India)

Speaker: Singh Sandeep. **Tuesday**. Start time: **15:15**. Room: Saint Clair 3A LVL2. Link to abstract.

Abstract: Among the different nanomaterials synthesized in recent decades, carbon-based nanomaterials such as carbon nanotubes, nanocones, etc., have garnered the attention of the scientific community due to their exceptional mechanical, electrical, properties and biomedical compatibility. Considering graphene as a basic building block to these nanomaterials and their wide range of potential applications in sensing, actuation, biosensors, biomedicines and other electronic devices, it is imperative to investigate their elastic properties thoroughly and study mechanical behaviour under different loading conditions. To the best of the authors' knowledge, few experimental studies were conducted for the elastic and mechanical characterization of carbon nanostructures. For instance, Treacy et. al. (1996) reported Young's modulus of CNTs with a value ranging from 1.06 to 3.7 TPa using a transmission electron microscope. Due to the experimental difficulties involved in the direct measurement at the nanoscale level and in the physical characterisation of these nanomaterials, the theoretical modelling techniques are found to be quite efficient and appropriate alternatives. The different theoretical techniques include quantum mechanics calculations, molecular statics/molecular dynamics (MS/MD) simulations, continuum models and multiscale modelling methods. The atomistic simulations based on quantum mechanics using first-principles calculations, density functional theory (DFT) and ab initio study are considered the most accurate methods among the different theoretical techniques. However, their applications are suitable for systems with a few hundred atoms only due to the requirement of high computational time and power. Contrary to this, atomistic simulations based on MS/MD study can handle systems which may require significant computational resources. It is crucial to note that the accuracy of simulations based on MS/MD study primarily depends upon the proper parameterization of interatomic potentials governing the atomic interactions. The popular interatomic potentials for carbon-based nanomaterials are (i) Tersoff potential (Tersoff, 1989), MM3 potential (Allinger et al., 1989), first and second-generation reactive bond order potential (REBO- I & II) (Brenner, 1990; Brenner 2002), and Tersoff-Brenner potential with revised parameters (Singh, 2021). The results observed using these interatomic potentials are found to be underestimated and overestimated when compared to available DFT calculations. For instance, the Brenner potential underestimates the tensile stiffness (_~236 nN/nm) and where parameters proposed by Singh (2021) overestimate the bending stiffness (_~0.42 nNnm) of graphene sheet in comparison to values of _~350 nN/nm and _~0.256 nNnm, respectively using DFT based models (Shao et al., 2012; Zhang et al., 2011). Keeping in view the same, the present work involves the investigation of elastic properties of the graphene sheet using recalibrated empirical parameters and its mechanical response under transversely distributed load at different finite temperatures. An atomistic continuum-coupled multiscale approach is used to integrate the atomic level deformations (bond lengths, bond angles) to a continuum scale through quadratic-type Cauchy-Born (Zhang et al., 2002). The cohesive interactions between the carbon atoms are modelled through Tersoff-Brenner interatomic potentials by accounting for the effects of dihedral energy terms in the constitutive model (Singh, 2018). The derived stress/moments resultants and tangent constitutive matrix are embedded in the Gauss-quadrature numerical integration of elemental level governing equations of finite element formulation. Both material and Green-Lagrange geometric nonlinearities are considered in the present study. The results of the recalibrated interatomic potentials are tested for different numerical problems such as investigating the elastic properties and bending response of graphene sheets at finite temperatures under different boundary conditions. The results are compared with available DFT-based models and with those obtained using other interatomic potentials (Brenner, 1990; Singh, 2021). It is observed that the proposed set of empirical parameters predicts better results compared to other interatomic potentials for carbon-based nanomaterials and close to DFT studies reported in the literature. *Keywords*: Multiscale modelling, Elastic properties, Bending response, Finite element method, Graphene, Finite temperature.

Full magnetoelastic behavior of Dual-phase steel in biaxial mechanical loading condition

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1 - Ecole Normale Supérieure Paris-Saclay (France)

Speaker: Le Soudeer Jeanne. **Tuesday**. Start time: **15:35**. Room: Saint Clair 3A LVL2. Link to abstract.

Advanced High Strength Steels (AHSS) raise a growing interest as weight saving solutions with high mechanical properties due to a complex (low scale and multiphased) microstructure. Online non-destructive magnetic monitoring is used to control the quality of these steels. This control is done on laminated steel sheets which undergo variable multiaxial mechanical loads. And due to magneto-mechanical coupling, miss-indication of the quality and false-positives can occur. This explains why stress influence on magnetic properties has to be taken into account, especially considering multiaxial mechanical loading. An adequate online control supposes then to develop predictive magneto-mechanical models and to use them to correct online measurements. This global approach requires to carry out experiments involving magnetic measurements under multiaxial stress for an accurate validation and/or identification of model parameters.
In this study a new set-up is presented (1) allowing for the measurement of anhysteretic and cyclic magnetic and magnetostriction behaviors under biaxial stress. Results show a clear asymmetry of the magnetic behavior in uniaxial tension and compression. A bitension hardly changes the susceptibility while a bicompression divides it by two. A shear situation with negative stress along the magnetic measurement direction leads to the lowest susceptibility values. A magneto-mechanical model is next proposed, using a multiscale approach (2) and considering a mix of soft (ferrite) and hard (martensite) phases. This model is based on the description of the magnetic domains distribution depending on their Gibbs free energy density. Localization and homogenization steps require to use a self-consistent scheme following Eshelby's inclusion model at the grain scale. Experiments and modeling are finally compared highlighting some similar trends.

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Micromechanically-based Multiscale Modeling of Materially Nonlinear and Rate Effects in Ferroelectrics

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Speaker: Warkentin Andreas. **Tuesday**. Start time: **15:55**. Room: Saint Clair 3A LVL2. Link to abstract.

Ferroelectrics exhibit many interesting effects, both linear and nonlinear, which is why these materials are widely used in science and industry. Moreover, it is noteworthy that the majority of these effects, particularly those which are nonlinear, are strongly rate-dependent, rendering the modeling of these intricate materials with multiple material scales quite challenging. The rate dependence is contingent on the material scale at which these distinct effects occur, yet they are all reflected in the macroscopic material behavior. Furthermore, nonlinear effects are irreversible and are accompanied by energy dissipation, which generally leads to a temperature rise of the material. For modeling the distinctive nonlinear rate-dependent effects of ferroelectric materials, there are numerous options, including microphysical and phenomenological models.
Aspects of different rate-dependent effects, as well as mutually coupled dissipative processes in ferroelectrics, in particular ferroelectric domain switching and viscoelasticity, are investigated theoretically, based on a microphysical motivated thermo-electromechanical multiscale constitutive framework. For this purpose, a hybrid micromechanical–rheological constitutive model is developed and embedded in the framework of a multiscale modeling approach (1, 2, 3). The mathematical theory is consistent against the background of rational thermodynamics and deals with two types of internal variables. The advanced modeling approach is among other things applied to identify novel energy harvesting cycles exploiting dissipative effects, resulting in a major electric work output.

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Capabilities and improvement ability of classical many-body potentials: application to hcp-Zr

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Speaker: Varvenne Celine. **Tuesday**. Start time: **16:35**. Room: Saint Clair 3A LVL2. Link to abstract.

Point defects in crystalline solids, such as vacancies, self-interstitials, solute atoms or small clusters, play a central role in controlling materials mechanical properties, diffusion or the kinetic evolution of a microstructure. The knowledge of the elastic dipole of a point defect – a second rank tensor corresponding to the first moment of its force distribution – allows one to directly obtain the long-range elastic fields induced by the point defect, together with its interactions with other elastic fields either arising from other defects (dislocations, grain boundaries, etc.) or applied externally. As a consequence, continuum elasticity modeling of point defects is an efficient tool for upscaling approaches, where mesoscale techniques are required to treat long term evolution and/or interactions of point defects with a complex defect microstructure, while retaining some important atomic scale information (1). However, a proper use of the elastic dipole tensor approach requires (i) a careful parameterization from atomistic simulations for a given material (ii) a correct treatment of the boundary conditions and (iii) an appropriate choice of the reference matrix for the studied material.
Starting from dilute alloys where the reference state is unambiguously the principal element, we first compare different methods to extract an elastic dipole from atomistic simulations: fitting of the displacement field, summation of the Kanzaki forces or identification from the residual stress. It appears that if carefully applied, all methods lead to the same dipole values, but only the residual stress approach is compatible with the much reduced supercell size of ab initio simulations (2). Then, we highlight the possible artifacts induced by the long-range elastic fields of a point defect in simulations with periodic boundary conditions, and show how to handle this in simulations of isolated point defects or in mesoscopic modeling of ensemble of point defects. Various real space and reciprocal space techniques are compared, paying attention to their accuracy and numerical efficiency (3).

Secondly, we consider the case of concentrated substitutional solid solutions, of which high entropy alloys (HEAs) are representative examples. The random alloy is a popular model for this class of materials and naturally suggests a homogeneous average alloy reference matrix, from which all defect types can be defined (4). In the real solid solutions and due to the varying chemical environments from site to site, elastic dipoles of point defects are statistically distributed and thus more challenging to compute. Their accurate determination therefore requires to control the representativity of the solid solution and the uncertainty quantification within small supercells and high number of components. Using a combination of extensive empirical potential calculations and some ab initio calculations on specific HEA compositions, we discuss the most efficient techniques to either access to average point defect elastic dipoles or to the full elastic dipole distributions, and at which precision, which matters when introducing in higher scale models of materials properties like solution strengthening (5).

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An atomistic thermo-chemo-mechanical coupled model: Hydrogen storage in Mg nanowires

Ariza Pilar (1), Molinos Miguel Ortiz Michael

1 - University of Seville (Spain)

Speaker: Ariza Pilar. **Tuesday**. Start time: **16:55**. Room: Saint Clair 3A LVL2. Link to abstract.

Understanding the transport of hydrogen within metallic nanomaterials is crucial for the advancement of energy storage and the mitigation of hydrogen embrittlement. Using nanosized magnesium particles as a model, recent studies have revealed several highly nonlinear phenomena that occur over long time periods. The time scale of these phenomena is beyond the capability of established atomistic models such as molecular dynamics. In this work, we present a new approach, referred to as diffusive molecular dynamics (DMD), to the simulation of long-term diffusive mass transport at the atomic scale. The basic assumption underlying DMD is that the time scale of diffusion is much larger than that of microscopic state transitions. In terms of numerical implementation, our approach involves the numerical integration of the master equation, and the numerical solution of a highly nonlinear optimization problem at every time-step. By working with atomic fractions, the characteristic time-step size of our DMD simulations can be much larger than those based on either AMD or KMC methods. In the present work, we focus on the characterization of thermodynamic and kinetic properties of magnesium hydride nanoparticles. Modeling phase transitions of Mg/MgH2 systems introduce an additional difficulty due to the change of lattice structure. We also note that the scope of DMD is not limited to metal hydrides and a broad range of multi-species systems of practical interest suggest themselves as worthwhile foci for future studies.

In-Situ Void detection in Large-Scale Molecular Dynamics Simulations: A Case Study on Tantalum Spall Fracture.

Dubois Alizée (1), Babilotte Killian (1), Soulard Laurent (1), Lafourcade Paul (1), Molinari Jean-françois (2)

1 - CEA, DAM, DIF (France), 2 - Computational Solid Mechanics Laboratory LSMS EPFL (Switzerland)

Speaker: Dubois Alizée. **Tuesday**. Start time: **17:15**. Room: Saint Clair 3A LVL2. Link to abstract.

Advancements in computational power have enabled molecular dynamics (MD) simulations to model billions of particles, providing unprecedented insights into crystal defects, phase transformations, and void dynamics. These simulations generate vast data, creating challenges for storage, post-processing, and analysis. On-the-fly methods address these challenges by enabling real-time data processing, though their implementation is non-trivial. This work compares a recent on-the-fly analysis technique with the established software OVITO, focusing on void detection and volume quantification. We validate and assess uncertainties in both methods, introducing an empirical scaling law to correlate analysis parameters with measurement errors. While results for single voids align, significant disparities arise in large-scale spall fracture simulations. The study highlights challenges in defining "true" outcomes, underscoring the need for robust parametric studies to interpret physical phenomena effectively.

Effects of structural parameters of nanotube networks on mechanical properties and fracture mode of carbon nanotube thin films and fibers

Volkov Alexey (1), Siahtiri Saeed

1 - University of Alabama (Tuscaloosa, AL 35487 United States)

Speaker: Volkov Alexey. **Tuesday**. Start time: **17:35**. Room: Saint Clair 3A LVL2. Link to abstract.

In carbon nanotube (CNT) films and fibers, individual nanotubes form networks of bundles. In the present work, the effect of structural parameters of the CNT network, such as porosity, bundle thickness, degree of internal connectivity in bundles, and density of bundle-bundle interconnects, on the elastic and inelastic properties as well as fracture mechanisms of thin CNT films and fibers are studied in systematic coarse-grained mesoscopic simulations, when the computational samples include tens of thousands of individual CNTs. In the mesoscopic model, each CNT is represented by a chain of stretchable cylindrical segments. The mesoscopic force field accounts for stretching and bending of individual CNTs, van der Waals interaction between them, and load transfer through covalent cross-links. All components of this mesoscopic force filed are parameterized based on results atomistic simulations or calculated using the molecular mechanics methods. The inter-tube interaction potential, in particular, is based on the tubular potential method, which eliminates artificial friction between CNTs and is capable of describing the self-assembly of nanotubes into a network of bundles, where the bundle cross sectional size can span a few orders of magnitude. The model is used to generate single-walled CNT thin films and bundles with continuous networks of entangled bundles as a result of dynamic self-assembly driven by van der Waals interaction and to characterize the structural properties of the network in the broad range of material density. The process parameters, e.g., temperature and self-assembly time, allow one to obtain steady-state quasi-equilibrium CNT networks with variable by demand structural properties. The *in silico* generated films and fibers composed of raw and cross-linked CNTs are then used to predict their mechanical properties in quasi-static in-plane stretching and compression. The simulations showed that the bundle size distribution strongly affects the mechanical properties of CNT films. The stretching of CNT films with small average bundle sizes is characterized by strong irreversible reorganization of the network structure during the deformation process. An increase in the bundle size results in the decrease of the film modulus and strength but strongly increases the ultimate strain. The compression of the CNT films results in nearly reversible coordinated folding and wrinkling of the films. The effects of other structural parameters become strong only for networks composed of thick bundles. The same conclusions remain valid for CNT fibers as well. This shows that, qualitatively, the effects of the structural parameters of the CNT network do not depend on the degree of structural anisotropy of CNT materials. This work is supported by U.S. National Science Foundation through the award CMMI-1554589.

FFT-based disclination mechanics for solute segregation at grain boundaries inferred from atomistic simulations

Wazne Abdallah (1), Petrazoller Joé (1), Guénolé Julien (1), Berbenni Stephane (1), Richeton Thiebaud (1)

1 - Laboratoire d'Etude des Microstructures et de Mécanique des Matériaux (France)

Speaker: Berbenni Stéphane. **Wednesday**. Start time: **10:00**. Room: Saint Clair 3A LVL2. Link to abstract.

This study examines solute segregation at grain boundaries (GBs) in FCC materials with a continuum approach based on the disclination structural unit model (DSUM)1 and elastic dipole tensors2 for modeling GB / solute interactions. In contrast with isotropic elastic analytical solutions3, the fast Fourier transform (FFT) method for field disclination mechanics3 is here applied in the more general context of heterogeneous anisotropic elasticity, to solve the elastic fields of the disclination dipole distributions representing two specific high angle (HA) GBs: Σ29 (5 2 0) (0 0 1) 46.40∘ and Σ149 (10 7 0) (0 0 1) 20.02∘. For the elastic interaction of such interfaces with solute atoms, the elastic dipole tensor contains both the permanent second-rank tensor, which is related to a size effect, and the fourth-rank polarizability tensor2, which is related to a modulus effect by capturing the dependence on the external strain. Numerical comparisons between FFT simulations and Molecular Statics (MS) are performed for three systems: Al, Cu and Ag, with Ag and Ni as solute atoms in substitution. The findings highlight the crucial role of anisotropic elasticity in accurately modeling solute segregation. While FFT and MS calculations show an overall agreement, some discrepancies only occur close to the defect cores attributed by non-linear effects in the atomistic model. Additionally, this study reveals the strong impact of the modulus effect on solute concentration at GBs for some of these particular systems.

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Mechanics of Dislocation-Precipitate-Grain Boundary Interactions in Aluminum Alloys: An Analytical Approach

Tatavarty Anantha Lakshmi Prasanna (1), Singh Amit (1)

1 - Indian Institute of Technology Bombay (India)

Speaker: Tatavarty Anantha Lakshmi Prasanna. **Wednesday**. Start time: **10:20**. Room: Saint Clair 3A LVL2. Link to abstract.

The mechanical behaviour of precipitation-hardened aluminium alloys is intricately governed by the interactions among dislocations, precipitates, and grain boundaries, which collectively define their strength, ductility, and resistance to deformation. Dislocations, as carriers of plastic deformation, encounter barriers such as precipitates and grain boundaries that alter their motion and distribution, thereby enhancing the mechanical properties of the material. This study develops an analytical framework to explore the equilibrium configurations of two symmetric edge dislocations located near elliptical precipitates and a grain boundary containing a disclination dipole.
The model considers two semi-infinite grains with identical elastic properties, shear modulus and Poisson's ratio, separated by a grain boundary containing a disclination dipole characterized by its strength and length. Elliptical precipitates, described by their dimensions and misfit strain, are symmetrically embedded in both grains. The equilibrium positions of the dislocations are determined by minimizing the elastic energy of the system, which is influenced by the stress fields generated by dislocations, precipitates, and the grain boundary disclination dipole. The analysis incorporates the Peach-Koehler force to calculate the energy variations and identify stable configurations.

The results highlight the significant impact of microstructural parameters, including the strength and length of the disclination dipole, precipitate morphology, and misfit strain, on dislocation equilibrium and mobility. Specifically, increasing the disclination dipole strength modifies the interaction fields, causing dislocations to either align near the grain boundary or repel into positions within the grains, depending on the eigenstrain magnitude. Additionally, the elliptical geometry of the precipitates introduces anisotropic stress fields that create a complex landscape of attractive and repulsive forces influencing dislocation motion.
This study provides a detailed theoretical understanding of the coupled effects of dislocation-precipitate-grain boundary interactions in precipitation-strengthened aluminium alloys. Explaining these mechanisms contributes to optimizing alloy microstructures to achieve superior mechanical performance. The findings are expected to inform the design of advanced materials through tailored microstructural configurations, enabling better control over strength, ductility, and other critical properties.

Micromechanical modelling and atomistic simulations of solute atom segregation towards grain boundaries in Mg

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1 - Laboratoire d'Etude des Microstructures et de Mécanique des Matériaux (France)

Speaker: Petrazoller Joé. **Wednesday**. Start time: **10:40**. Room: Saint Clair 3A LVL2. Link to abstract.

Alloying has been proven to have broad potential for enhancing the poor ductility of magnesium alloys which is associated to an insufficient number of easy slip systems and the development of twinning. Segregation behaviour of solute atoms at grain boundaries (GB) has been widely reported to affect GB stability, GB migration, and crystallographic texture of Mg alloys. It is therefore important to gain a deeper fundamental understanding of the origin of the GB segregation phenomena for the tailored properties material design of Mg alloys. A solute atom can be represented by a point force distribution, corresponding to the forces imposed on the surrounding atoms. The first order moment of this distribution, named *elastic dipole*, can be used to evaluate the long-range elastic fields due to the presence of the solute. Using the method described in (1), the permanent elastic dipole, which can be related to a size and a shape effect, and the polarizability tensor, which is related to the change of the elastic moduli, have been determined by atomistic simulations considering an Y atom embedded in a Mg matrix. Then, the interaction energy between the elastic dipole and the stress fields of several symmetric tilt grain boundaries have been calculated, with tilt axis along and directions. The stress fields have been evaluated from the Virial stress fields provided by molecular static simulations or from the stress fields of dislocation walls, either in heterogeneous anisotropic elasticity using Stroh's formalism (2), or in isotropic elasticity considering a non-singular theory of dislocations (3). Additionally, the segregation energy fields of a single solute towards different GBs have been computed using series of molecular statics simulations. Comparisons were studied between these segregation energy distributions and the distributions given by the different interaction energies. To fully model solute interaction with GB, we highlight the importance to consider, in some situations, the shear stress components of the GB, in addition to the traditionally considered hydrostatic stress. These results bring us one step forward to bridge the scales by contributing to build an improved continuum-based segregation model predicting solute concentration distributions at GBs (4).

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Continuum mechanics of non-affine fibre network materials

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1 - Empa, Swiss Federal Laboratories for Materials Science and Technology (Switzerland), 2 - ETH Zurich, Institute for Mechanical Systems (Switzerland), 3 - EMPA - Swiss Federal Laboratories for Materials Science and Technology (Switzerland)

Speaker: Ehret Alexander E.. **Wednesday**. Start time: **11:00**. Room: Saint Clair 3A LVL2. Link to abstract.

Random fibre networks characterise the microstructure of various natural and man-made materials, endowing them with fascinating deformation and fracture properties at the macroscopic length scales (1-3). These special characteristics are strongly linked to the micro-kinematic behaviour at the fibre-scale, which is typically non-affine, i.e. the fibres deform differently from vectorial line elements in a continuum. This non-affine relation between macroscopic and fibre-scale deformations still leaves a gap in the development of microstructurally motivated constitutive models for this class of materials, since even if the single fibre's non-linear material properties are known, their state of deformation cannot be inferred from the macroscopic one.

Computational models of discretized fibre networks certainly circumvent this problem and have become the method of choice to gain understanding of the intricate deformation mechanisms of the network, to study the microscopic origin of special macroscopic characteristics in representative volume elements, or to even analyse reasonably sized problems by a full fibre-discretisation of the domain of interest. What is more, the analysis of the corresponding simulations can also be used to inform new continuum mechanical approaches to model the homogenized behaviour of these materials which overcome the limitation of affinity and hence close the constitutive gap. Based on such analyses, we have recently shown that the distribution of stretch within the network represents a suitable target for constitutive modelling of both affine and non-affine central force networks of elastic fibres (4,5). It makes the latter case amenable to continuum mechanics principles, and brings numerical benefits over traditional approaches in the former (6,7). Essentially, the deformation-dependent stretch distribution within a fibre network is a central characteristic property, which maintains information about the micromechanical state on the one hand, and serves to compute the homogenised macroscale mechanical response on the other hand.

In the present contribution, the theory will be reviewed, and an extension will be presented to account for fibre failure, and hence damage and finally fracture at network and homogenised scales, respectively. To this end, we analyse the stretch distributions in computational models of brittle fibre networks, and prescribe their evolution in terms of macroscopic strain, representing the homogenised state of network deformation. In addition to informing a continuum mechanical model suitable to simulate the fracture behaviour of fibre network materials, these studies reveal how effectively loads are redistributed within random networks after fibre failure, and hence shed light on the outstanding defect tolerance of these materials (cf. 3).

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Numerical modelling of sintering and thermal damage in a non-densifying refractory ceramic

Bigeard Amélie (1) (2), Jauffres David (1), Bouvard Didier (1), Mesnager Camille (2), Buchovecky Eric (3)

1 - Science et Ingénierie des Matériaux et Procédés (France), 2 - Saint-Gobain Research Provence (France), 3 - Saint-Gobain Research North America (United States)

Speaker: Bigeard Amélie or Jauffres David. **Wednesday**. Start time: **11:20**. Room: Saint Clair 3A LVL2. Link to abstract.

High performance refractory ceramics for the glass industry are designed to resist the extreme thermal, chemical (corrosion) and thermomechanical conditions of glass furnaces operations. Experiments can be performed at the lab scale to study the properties of such materials and improve their performance and durability. However, for industrial purposes, it is of interest to transfer the findings to larger scales, and numerical modeling is an essential tool to achieve this. In this work, a phenomenological model of the two main physical processes occurring in an alumina mullite zirconia refractory during high temperature thermal cycles, namely sintering and thermal damage, is proposed.
In classical sintering models, the density of the material is followed throughout a temperature cycle and provides information on the progress of sintering along the cycle (1-3). However, the global shrinkage of the studied material is negligible, and density is therefore not a good indicator for sintering. That is why a different approach was used, based on the dynamic elastic modulus, which is measured during a thermal cycle and assumed to be a relevant parameter for characterizing sintering progress during heating and early cooling. The same approach was used to model thermal damage, i.e., assuming that the variation of the dynamic elastic modulus during late cooling is a good indicator of damage state. Sintering and damage rates were described with evolution laws and the model was calibrated to properly describe the behavior of the refractory during a thermal cycle up to 1350∘C, 10h dwell time and heating and cooling ramps of 200∘C/h. The relevance of the model was then analyzed by applying it to other thermal treatments. The model accurately predicts the evolution of the dynamic HMOE for thermal cycles with different sintering temperatures and it provides the variation of the associated sintering and damage degrees.

In order to demonstrate the industrial interest and applicability of the model, the case study of a brick under a thermal gradient is presented. For this purpose, a thermal gradient test was developed experimentally, and the corresponding numerical model was implemented on COMSOL. The hardness was finally used as a sintering indicator to confront the numerical and the experimental results.

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Odd elasticity as the multi-continuum homogenization limit of Cosserat elasticity

Nika Grigor (1)

1 - Karlstad University [Sweden] (Sweden)

Speaker: Nika Grigor. **Wednesday**. Start time: **14:30**. Room: Saint Clair 3A LVL2. Link to abstract.

We derive an effective system from a periodically heterogeneous Cosserat continuum. The homogenization process encompasses intrinsic lengths related to scale-size effects and leads to an asymmetric effective stress which requires an extra balance of torques and is related to concept of *odd elasticity*. The corresponding local problem exhibits asymmetry as well, due to the micropolar couple modulus inherited from the original microscopic Cosserat problem. We validate our results by conducting numerical simulations using the finite element method on circularly perforated square and rectangular unit cells, highlighting the impact of the micropolar couple modulus on effective coefficients. Furthermore, we numerically show that there exists a threshold micropolar couple modulus which affects the behavior of the cell and compare the cell displacement in the presence and absence of a micropolar couple modulus.

Toupin-Mindlin first strain gradient elasticity for anisotropic and isotropic materials at small scales

Lazar Markus (1), Agiasofitou Eleni (1)

1 - Institute for Mechanics, Technical University of Darmstadt (Germany)

Speaker: Lazar Markus. **Wednesday**. Start time: **14:50**. Room: Saint Clair 3A LVL2. Link to abstract.

Nonlocal elasticity and strain gradient elasticity theories are challenging generalized continuum theories to model crystals at small scales like the Angström-scale (see, e.g., (1,2)), where classical elasticity is not valid and leads to unphysical singularities. The theory of first strain gradient elasticity in its modern form dates back to Toupin (3) and Mindlin (4). A mathematical modeling of the elastic properties of cubic crystals with centrosymmetry at small scales by means of the Toupin-Mindlin anisotropic first strain gradient elasticity theory is presented (2). In this framework, two constitutive tensors are involved, a constitutive tensor of fourth-rank of the elastic constants and a constitutive tensor of sixth-rank of the gradient-elastic constants. The 3+11 material parameters (3 elastic and 11 gradient-elastic constants), 3 characteristic lengths and 1+6 isotropy conditions are derived. The 11 gradient-elastic constants are given in terms of the 11 gradient-elastic constants in Voigt notation. The numerical values of the obtained quantities are computed for some representative cubic materials using an interatomic potential (MEAM) (2, 5). Moreover, the isotropy conditions of strain gradient elasticity are given and discussed. A generalization of the Voigt average towards the sixth-rank constitutive tensor of the gradient-elastic constants is given to determine the 5 isotropic gradient-elastic constants (2).

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Wave propagation in nonlocal elasticity of Klein-Gordon type with internal length and time scales

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Speaker: Agiasofitou Eleni. **Wednesday**. Start time: **15:10**. Room: Saint Clair 3A LVL2. Link to abstract.

Generalized continuum theories like nonlocal elasticity and gradient elasticity are powerful continuum theories valid at small scales unlike classical continuum theories such as classical elasticity which cannot capture effects at small scales (see, e.g., (1,2)). Nonlocal elasticity considers long-range interatomic interaction, it has a close link to the underlying microstructure and is valid down to the Ångström-scale and therefore it can be considered as a generalized continuum theory of Ångström-mechanics (2).
In this work, a nonlocal elasticity model of Klein-Gordon type, characterized by nonlocality in space and time, is developed including one characteristic internal time scale parameter in addition to the characteristic internal length scale parameter (3). Such a nonlocal elasticity theory describes spatial and temporal nonlocal effects at small scales. The wave propagation for homogeneous isotropic media in the framework of nonlocal elasticity of Klein-Gordon type is investigated. The dispersion relations are analytically derived showing for the first time in the framework of nonlocal elasticity theory, optic modes (high-frequency modes) and frequency band-gaps in addition to the acoustic modes (low-frequency modes). The phase and group velocities for all four modes (acoustic and optic branches of longitudinal and transverse waves) are determined showing that all four modes exhibit normal dispersion with positive group velocity (3,4). The proposed nonlocal model of Klein-Gordon type possessing only 4 constitutive parameters (2 elastic constants, 1 length scale and 1 time scale) provides an appropriate framework for the modelling of accurate frequency band-gaps and overall physically realistic dispersive wave propagation.

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Elastic properties of Kaolin group minerals at high pressures

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Speaker: Benazzouz Brahim. **Wednesday**. Start time: **15:30**. Room: Saint Clair 3A LVL2. Link to abstract.

Kaolin group minerals are one of the clay minerals found in the earth's crust. Kaolin group consists of the minerals polymorphs: kaolinite, dickite and nacrite. The unit cell of kaolin group has the similar chemical composition, Si4Al4O10(OH)8. In this study, the molecular dynamics simulations based on energy minimization technique have been used, in order to better understand the elastic properties of clay layers that are only a few kilometres deep in the crust, and identify the nature of the phase transition at high pressures. In the first part of this study, the elastic properties of kaolin minerals, including elastic constants, bulk modulus, shear modulus, the S- and P-wave velocities, have been presented. The elastic properties computed appear overall in good agreement with available experimental and previous theoretical results. These three minerals (dickite, nacrite and kaolinite) with different may show varying elastic properties, although are sharing the same chemical formula.The high pressure effects on the elastic properties of Kaolin group have been evaluated and compared. In addition, their phase transition have been found by an abrupt change in the curve of the structural and elastic properties.

Progress Towards Micromorphic Upscaling Multiscale Damage Models of Fibrous Materials

Merson Jacob (1), Knowlan Zachary

1 - Rensselaer Polytechnic Institute (United States)

Speaker: Merson Jacob. **Wednesday**. Start time: **15:50**. Room: Saint Clair 3A LVL2. Link to abstract.

Fibrous materials are common in engineered structures and biological tissues. Despite significant progress, traditional constitutive models struggle to capture the full range of nonlocal and nonaffine material behavior that is driven from complex microstructures. To fill this gap, upscaling multiscale methods have been developed that can take advantage of the scale separation between the fiber and continuum scales. And, by using GPU accelerated supercomputing and machine learned constitutive models, these multiscale models can be effectively deployed to study problems of interest. However, the current methods rely on strong scale separation which breaks down during localization events such as material fracture. This talk will background on the current state of multiscale modeling of damage in fibrous materials through upscaled computational homogenization including the use of phase-field models for propagation of diffuse microstructural damage. Additionally, it will describe efforts undertaken to incorporate microstructural localization events. And, the inclusion of a micromorphic continuum model which can be used to limit the need for scale separation near fractures.

MS1.8 - Mechanics of active and coupled materials

Organisers: Daniel Garcia Gonzalez (University Carlos III, Madrid) and Kostas Danas (LMS)

A continuum model for novel electromechanical-instability-free dielectric elastomers

Xiao Rui (1)

1 - Zhejiang University (China)

Speaker: Xiao Rui. Invited. **Monday**. Start time: **13:40**. Room: Rhône 3A LVL1. Link to abstract.

Traditional dielectric elastomers exhibit an unstable response when the electric field reaches a certain threshold, known as electro-mechanical instability, which significantly limits the broad application of these soft active materials. Recently, a bimodal-networked dielectric elastomer has been designed without suffering from the electro-mechanical instability due to a clear strain stiffening effect in the median strain regime. In this work, we develop a constitutive model to fully describe the mechanical and electro-activated response of this novel dielectric elastomer. The free energy density consists of a time-independent hyperelastic component, time-dependent viscous components and an electrical component. A hyperelastic function dependent on both the first and second strain invariants is proposed to fully capture the stress response. The form of ideal dielectric elastomers is adopted for the electrical free energy. With further incorporation of viscous effects, the model is able to describe both static electro-actuated behavior as well as the frequency-dependent actuation performance upon a square wave voltage loading. The model is also implemented for finite element analysis to design tubular actuators which have been extensively used in the area of soft robotics.

Discrete One-dimensional Models for the Electromomentum Coupling

Muhafra Kevin (1), Haberman Michael (2), Shmuel Gal (1)

1 - Technion - Israel Institute of Technology (Israel), 2 - The University of Texas at Austin (United States)

Speaker: Shmuel Gal. Invited. **Monday**. Start time: **14:00**. Room: Rhône 3A LVL1. Link to abstract.

Willis dynamic homogenization theory revealed that the effective linear momentum of elastic composites is coupled to their effective strain. Recent generalization of Willis' dynamic homogenization theory to the case of piezoelectric composites further revealed that their effective linear momentum is also coupled to the effective electric field. Here, we introduce the simplest possible model - a one-dimensional discrete model that exhibits this so-called electromomentum coupling in subwavelength composites. We utilize our model to elucidate the physical origins of this phenomenon, illustrate its mechanism, and identify local resonances which lead to elevated Willis- and electromomentum coupling in narrow frequency bands. The results provide intuitive guidelines for the design of this coupling in piezoelectric metamaterials.

Electric breakdown of dielectric membranes via axisymmetric necking

Yu Xiang Fu Yibin (1)

1 - Keele University (United Kingdom)

Speaker: Fu Yibin. Invited. **Monday**. Start time: **14:20**. Room: Rhône 3A LVL1. Link to abstract.

It is well-known that when a dielectric membrane coated with electrodes is subject to an electric field through its thickness and a dead-load all-round tension at its edge, the nominal electric field versus the nominal displacement typically has a maximum (or a limit point) (1). Based on this fact, it is commonly believed that when this maximum is reached during electric loading, rapid but uniform thickness-thinning will take place that eventually leads to electric breakdown. However, recent research on the tube inflation problem has shown that although a limit point also exists in the internal pressure versus the volume, the tube does not always snap through to another uniformly inflated configuration with a larger radius; other possibilities also exist depending on how inflation is conducted (2). Equipped with this knowledge, we have recently carried out an in-depth study on the bifurcation behaviour of the above-mentioned dielectric membrane (3). In particular, we have explored the possibility of electric breakdown via axisymmetric necking (4, 5) and have shown that the condition for axisymmetric necking is different from the condition for the limit-point instability. It is further shown that for a class of free-energy functions, axisymmetric necking may compete with the limit-point instability and the Treolar-Kearsley instability (whereby equal nominal forces result in unequal stretches in the membrane plane), and become the preferred mode of instability depending on how the membrane is loaded.
In this talk, we present our latest results on the development of a one-dimensional (1d) reduced model for characterising axisymmetric deformations of a dielectric membrane (including axisymmetric necking). Our reduction is built on the variational asymptotic method (6,7), so that the resulting 1d model is asymptotically self-consistent. The 1d model offers an easier and more efficient way to analyze axisymmetric necking in a dielectric membrane in the linear, weakly nonlinear and fully nonlinear regimes. It delivers results identical to the 3d theory in the linear and weakly nonlinear regimes, and near-identical results in the fully nonlinear regime. We demonstrate the straightforward implementation of the 1d model by solving it using the Rayleigh–Ritz method and validate it by comparison with finite-element simulations. The 1d model enables a precise calculation of the minimum thickness that a dielectric membrane can reach when
necking instability occurs and the effects of imperfections so that the integrity of a dielectric elastomer actuator can be assessed with respect to electric breakdowns. The developed methodology is not problem-specific and so is also applicable to other soft materials subjected to any other fields.

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Electro-mechanical behaviour of fractional viscoelastic and anisotropic dielectric elastomers

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Speaker: Cajic Milan. **Monday**. Start time: **14:40**. Room: Rhône 3A LVL1. Link to abstract.

Dielectric elastomers, widely used as smart materials in soft actuators (1), face significant challenges that limit their performance. Fiber-reinforced dielectric elastomers, with their anisotropic behavior, offer enhanced mechanical properties, such as faster response rates under electric fields (2). While many studies incorporate hyperelasticity and anisotropy, time-dependent viscoelastic effects are often included to improve material models. Classical viscoelastic models can describe these effects accurately in specific cases, but fractional viscoelasticity offers a more powerful alternative. By assuming a power-law relaxation spectrum, fractional viscoelasticity reduces the number of required parameters while effectively capturing a continuous distribution of timescales (3). This study presents a unified framework for modeling the coupled nonlinear electro-mechanical behavior of fiber-reinforced anisotropic dielectric elastomers with fractional viscoelastic effects. The approach builds on an anisotropic hyperelastic nearly-incompressible model and employs a multiplicative decomposition of the deformation gradient, incorporating fractional viscoelasticity to model time-dependent mechanical responses with minimal number of additional parameters. The weak form is derived for efficient numerical implementation using the open-source finite element platform FEniCSx. Validation through dynamic deformation simulations, including electro-mechanical instability and bending, demonstrates the favorable influence of anisotropy on actuation performance, the capability of fractional viscoelasticity to capture complex time-dependent behavior, and the computational efficiency of the developed framework. This work provides a foundation for future extensions to thermal and magnetic couplings, advancing the modeling of soft active materials.

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Microscopic and macroscopic instability analysis of magnetoactive soft composites

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Speaker: Xie Chen. Invited. **Monday**. Start time: **15:00**. Room: Rhône 3A LVL1. Link to abstract.

This study investigates the structural instability of magnetoactive soft composites under coupled mechanical and magnetic fields. Analytical and numerical models are developed using hyperelastic magnetic frameworks, including the Neo-Hookean model combined with linear soft and hard magnetic assumptions. Critical behavior in the analytical models is determined by detecting the loss of ellipticity. By considering two distinct definitions of magnetization in the reference configuration, the transition points between microscopic and macroscopic instability modes are identified. Post-buckling analysis is performed to predict instability onsets by adding small geometric imperfections in the microstructure through finite element simulations. To enable effective and remote control of these composites, the influence of external magnetic fields, remanent magnetization, volume fraction, and microstructural parameters on magneto-mechanical instabilities is systematically examined.

Snap-through instabilities in magneto-elastic slender beams interacting with rigid obstacles.

Sabhwani Bharat (1), Mukherjee Dipayan (1)

1 - Department of Mechanical Engineering, Indian Institute of Technology Kanpur (India)

Speaker: Mukherjee Dipayan. Invited. **Monday**. Start time: **15:20**. Room: Rhône 3A LVL1. Link to abstract.

Permanently magnetizable soft slender structures are employed in remote locomotion of soft robots, catheter tips in the enclosed channels (1), etc.. Recently, the magnetic field-assisted catheter locomotion has gathered immense research focus due to its facile fabrication and low-field remote actuation of _~ 10 − 50 mT. The catheter locomotion inside enclosed, tortuous channels leads to extreme mechanical deformation and often snapping-type instabilities. This work theoretically investigates the possibility of employing the snapping of pre-magnetized magneto-elastic beams while interacting with rigid surfaces in understanding the surface quality of the obstacle, i.e., the surface roughness and other tribological characteristics. Our analysis shows that the snapping response of the beams under magnetic fields may differ substantially depending on the surface roughness and curvature. Thus, the health of tissues can be monitored in a minimally invasive setting by recording the magnetoelastic snapping signature of a beam against it. This may lead to a protocol for non-invasive tissue health monitoring.
The geometrically exact beam theory is employed to model the planer (2D) motion of flexible magnetoelastic beams. The magnetic body torque-based model can successfully predict the flexural deformation of slender pre-magnetized structures (2). Here we use the magnetic body torque model with the 2D geometrically-exact beam theory to model the flexible catheter. The ensuing governing equations are solved via the classical Newton-Raphson-based nonlinear finite-element method. The computed results are validated against available benchmark tests for pre-magnetized magnetoelastic beams. The rigid confinements around the beam are modeled as straight or curved lines on which a no-penetration condition is applied. This no-penetration contact model is implemented via the classical Lagrange multiplier method. The beams exhibit snapping instability in a specific range of applied magnetic field magnitude and directions. At the onset of snapping, the effective Hessian matrix associated with the FE discretized system loses its positive definiteness. So, the classical Newton-Raphson method is not capable of realizing the unstable equilibrium configurations of the beam during snapping. Thus, pseudo-arclength-type algorithms are employed to capture this. Specifically, we have implemented the Crisfield, Ramm, and modified Crisfield-Ramm continuation algorithms to numerically realize the configuration of snapping beams under external magnetic fields. Viscous friction and the power law-type nonlinear friction between the beam tip and the obstacle wall reduce and eventually suppress the snapping with increasing coefficient of friction. Thus, via quantifying the snapping and non-snapping boundary, one can infer the nature of friction between the catheter tip and target tissue.

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Controlling Deformation and Instability of Magnetoactive Metamaterials

Feehilly Tigernach (1), Geers Marc (1), Peerlings Ron (1), Rokoš Ondřej (1)

1 - Eindhoven University of Technology [Eindhoven] (Netherlands)

Speaker: Feehilly Tigernach. Invited. **Monday**. Start time: **16:00**. Room: Rhône 3A LVL1. Link to abstract.

Mechanical Metamaterials are materials with exotic behaviours not commonly found in nature, such as negative Poisson's ratio (Saxena, 2016). The material's microstructure, in addition to the choice of base materials, governs these behaviours. Initially, metamaterial designs typically were limited to the small strain regime. However, recent studies have begun to focus more on large deformations, taking optimal benefit of nonlinearities (geometrical and material). Under large deformations, buckling can lead to large changes in the effective metamaterial behaviour. For example, buckling has been used to enhance the vibration of dampening elastic materials while maintaining a high specific stiffness and low density of the material (Dykstra, 2023). However, when fabricating metamaterials, only a single microstructural morphology is typically used; thus, the material's properties cannot be altered during its use. Creating materials that can alter their properties during use requires methods to interact with the material in a fashion that does not impede the intended use. Including stimuli to actuate the material, such as electromagnetic, chemical, thermal, photo, or pneumatic stimuli, adds new mechanisms for active material control during use. Magnetism is particularly interesting in applications for metamaterials as it allows untethered rapid control and have also recently gained interest in controlling deformation and altering properties (Lu, 2024).

In this contribution, we present a study embedding magnetisation into existing hyperelastic metamaterials to achieve switchable stiffness. In doing so, we can achieve materials with a variable structural stiffness, exploiting the understanding of the coupled effects of magnetic and mechanical loading. We show numerically that with a proper strategy, it is possible to design materials with tuneable critical buckling load under uniaxial mechanical compression, with negligible change in the pre- and post-buckling stiffness. Alternatively, it is also possible to switch post-buckling deformation and alter post-buckling stiffness by up to 10% by application of an externally applied magnetic field. Thus, we demonstrate a class of materials with switchable and tuneable properties without fabricating new microstructures.

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Magnetically assisted self-healing: modelling and experiments

Lucarini Sergio (1) (2), Fernádez-maestu Josu (1), Lanceros-méndez Senentxu (1) (2)

1 - BCMaterials Basque Center for Materials, Applications and Nanostructures (Spain), 2 - Ikerbasque - Basque Foundation for Science (Spain)

Speaker: Lucarini Sergio. Invited. **Monday**. Start time: **16:20**. Room: Rhône 3A LVL1. Link to abstract.

Magnetic composites and self-healing materials have attracted considerable attention in their respective fields of application. Magnetic fillers enable the tunning of the properties of materials, as well as the change of shapes and motion when external magnetic fields are applied to them. Self-healing materials have the ability to repair structural damage and consequently restore their functional properties during the healing process. The fusion of these two unique features results in remarkable advances in both fields. This study explored the magnetically assisted self-healing behaviour of magnetic polymer composites (1) by combining an experimental characterisation with numerical modelling to provide insights into the understanding of the healing process under magnetic fields. The numerical framework was based on a finite element implementation of the magneto-mechanical problem coupled with phase-field fracture and diffusion-based healing to reproduce the fracture-healing behaviour of the polymer and the influence of magnetic fields. This model allowed for the prediction of inter-chain diffusion healing mechanisms under varying magnetic fields and temperature conditions, providing insights into healing efficiency and the overall mechanical performance of the material under applied magnetic fields. Moreover, a customised experimental setup was developed to precisely control the magnetic field and thermal conditions during the self-healing process on pre-damaged samples. The material under study was a composite of magnetic nanoparticles embedded in an elastomeric matrix. After healing, the mechanical testing revealed the recovery of tensile strength and elasticity, showing enhanced self-healing capabilities in the presence of magnetic fields. A good agreement was observed between numerical simulations and experimental data of analysed self-healing properties and good predictability. This combined experimental and numerical approach offers a comprehensive understanding of the self-healing mechanisms, lays the foundation for further development, and has significant implications for applications in magnetic soft robotics where autonomous damage repair implies a potential improvement (2).

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Magnetostriction of soft-magnetorheological elastomers

Stewart Eric (1), Anand Lallit (2)

1 - University of Cincinnati (United States), 2 - Massachusetts Institute of Technology (United States)

Speaker: Stewart Eric. Invited. **Monday**. Start time: **16:40**. Room: Rhône 3A LVL1. Link to abstract.

Soft-magnetorheological elastomers (s-MREs) are particulate composites made of a non-magnetic elastomeric matrix dispersed with micron-sized particles of a "soft-magnetic" material. The phenomenon of magnetostriction in specimens made from s-MREs is the change in their shape when they are subjected to an external magnetic field. Experiments in the literature show that for circular cylindrical specimens subjected to an axially applied magnetic field the magnetostriction is strongly dependent on their aspect ratio, with specimens with a low ratio of the length to the diameter exhibiting a larger tensile magnetostrictive strain than specimens with a large aspect ratio — the "shape-effect." This response is also hysteretic because of the underlying viscoelasticity of the matrix material. In this talk we report on a large deformation magneto-viscoelasticity theory for s-MREs and its finite element implementation. Using our theory we show that we can model this non-intuitive geometry-dependent magnetostrictive response of cylindrical s-MRE specimens. We show that the effect of the magnetization of the cylinder is to decrease the magnetic field within the cylinder relative to the applied magnetic field outside the cylinder, the well-known demagnetization effect, and that this demagnetization is diminished in more slender cylinders due to magnetic fringing at the boundaries of the cylinder. This is the physical reason behind the macroscopically-observed "shape-effect." Our magneto-viscoelasticity theory is quite broad, and it has many potential applications beyond modeling the magnetostriction of cylindrical specimens. As an example we apply the theory to study the bending actuation response of beams of s-MREs when they are subjected to magnetic fields at different incidence angles to their longitudinal axis.

Modelling coupled magneto-mechanical growth in hyperelastic materials

Hossain Mokarram (1), Li Zhanfeng (2), Kadapa Chennakesava (3), Wang Jiong (2)

1 - Zienkiewicz Centre for Computational Engineering, Faculty of Science and Engineering, Swansea University (United Kingdom), 2 - South China University of Technology (China), 3 - Edinburgh Napier University (United Kingdom)

Speaker: Hossain Mokarram. Invited. **Monday**. Start time: **17:00**. Room: Rhône 3A LVL1. Link to abstract.

Magneto-mechanical coupling in the growth of soft materials presents challenges due to the complex interactions between magnetic fields, mechanical forces, and growth-induced deformations. While growth modeling has been extensively studied, integrating magnetic stimuli into growth processes remains underexplored. In this work, we develop a 3D governing system for capturing the coupled magneto-mechanical growth behaviors of soft materials. Based on the governing system, we implement a finite element framework using second-order hexahedral elements to simulate these interactions. The robustness and accuracy of the proposed framework are demonstrated through numerical simulations, including the uniaxial loading of a circular tube, a mesh convergence study, and surface pattern evolution. We also conduct experiments on surface pattern modulation in magneto-active soft materials. Specifically, we fabricate film-substrate samples and apply growth-induced instabilities combined with external magnetic fields to generate tunable surface patterns. To demonstrate the capabilities of our method, we apply our numerical framework to mimic the biological morphogenesis, such as the inversion process of the algal genus Volvox. Our study shows that integrating magneto-mechanical coupling with growth effects allows for flexible control over surface patterns, significantly enhancing the adaptability and responsiveness of soft materials. This work paves the way for innovative designs of adaptive and programmable soft materials, with potential applications in soft robotics, biomimetic structures, and tissue engineering

Magnetostriction of fractionally viscoelastic MREs

Paunović Stepa (1), Cajic Milan (1), Karlicic Danilo (1)

1 - Department for Mechanics, Mathematical Institute of SASA (Serbia)

Speaker: Paunović Stepa. **Monday**. Start time: **17:20**. Room: Rhône 3A LVL1. Link to abstract.

Magnetorheological elastomers (MREs) are composite materials consisting of non-magnetic elastomer matrix combined with powder-like magnetic particles dispersed throughout it. Such materials exhibit magnetostriction, i.e. they deform when exposed to an acting magnetic field, and due to this property they have found numerous practical applications ranging from soft robotics and biomedical engineering devices to soft actuators and sensors and magneto-active vibration absorbers and pumps. Theoretical modelling of MREs has been rapidly developing over the past decade, gradually including more and more complex effects such as viscosity of the elastomeric matrix, ferromagnetic hysteresis of the magnetic particles, and influence of the magnetic fields in the surrounding air on the MREs' response. However, these models usually account for the viscoelastic dissipation by introducing several internal variables in the form of discrete relaxation times and material constants, and increasing the model accuracy is achieved by increasing the number of these variables, thus making the model computationally more demanding. In this contribution, an MRE model is proposed where viscoelastic properties are modelled with fractional-order derivatives, and the derived model is then applied to analyse a soft magneto-active actuator in the form of a tri-layer MRE beam exposed to a variable exterior magnetic field. Fractional-order damping model assumes power-law relaxation spectrum, thus enabling formulation of the model by using only two parameters - fractional derivative order and one relaxation time, which provides more efficient numerical simulation possibilities. The governing equations describing the large nonlinear deformations of MREs are derived by using thermodynamically consistent framework, and the free energy (i.e. magnetic enthalpy) is obtained by considering continuum mechanics constitutive theory in combination with magnetostatic Maxwell's equations. The weak form of the problem is then derived and the obtained system is numerically implemented in the open-source finite element software FEniCSx, providing a robust solution code for the analysed case of magneto-active fractionally viscoelastic tri-layer beam actuator. This study shows an example of a successful application of fractional viscoelasticity in conjunction with magnetorheological elastomeric materials and provides a solid base for further extension by including thermal effects or electric field effects for even broader application spectrum.

Magneto-viscoelastic modeling and experiments for isotropic soft magnetorheological elastomers

Danas Kostas (1), Nakano Masami (2), Sebald Gaël (3)

1 - Laboratoire de mécanique des solides (France), 2 - Tohoku University [Sendai] (Japan), 3 - Institut National des Sciences Appliquées de Lyon (France)

Speaker: Danas Kostas. Invited. **Monday**. Start time: **17:40**. Room: Rhône 3A LVL1. Link to abstract.

I will present a recent study dealing with the experimental, theoretical and numerical investigation of the nonlinear viscoelastic response of magnetically soft magnetorheological elastomers (commonly known as s-MREs and denoted here simply as MREs) subjected to combined magnetic and simple shear loads. We consider a fairly soft mechanically MRE. The experiments show a strong effect of the magnetic field on the resulting viscosity and hence dissipated energy expanded by the material during a simple shear cycle. Moreover, the effect of frequency on the response is weak indicating strongly nonlinear viscous effects similar to non-Newtonian fluids. An analytical magneto-viscoelastic model is proposed exhibiting magneto-mechanical coupling at both equilibrium and non equilibrium energies as well as on the dissipation potential. The model is calibrated by solving in a semi-analytical way a simplified boundary value problem (BVP) of an infinite thin MRE strip embedded in an infinite air domain. These simplified solutions are cross validated by full-field finite element simulations of the experimental setup showing very good agreement between the experimental data and model estimates. This illustrates the validity of the simplified material model for the proposed experimental setup and sets the ground for a more universal experimental protocol to characterize properly the finite strain response of MREs more generally.

Chemoelasticity with anisotropic species

Guin Laurent (1)

1 - Laboratoire de mécanique des solides (France)

Speaker: Guin Laurent. Invited. **Tuesday**. Start time: **10:00**. Room: Rhône 3A LVL1. Link to abstract.

Recent experiments using X-ray tomography to measure the three-dimensional strain field in rubber through have produced intriguing results (1). They show that rubber undergoes local volume changes while the overall specimen volume remains constant, and that it has an apparent negative bulk modulus. Additional radiography observations reveal the presence of a mobile phase in the material. It has been proposed that such observations can be rationalized by a chemomechanical coupling involving diffusing anisotropic species, i.e., with different eigenstrains in the different spatial directions, such as needle-like or plate-like shapes.

In this work, motivated by these new experimental results, we discuss the interplay between an isotropic linear elastic material and an anisotropic diffusing species (with initial isotropic distribution). Following a variational approach, stable equilibrium states are determined under different assumptions on the diffusivity of the species and its rotational degrees of freedom in rotation. In particular, we study the stress, deformation and concentration profiles across the cross-section of beam undergoing bending. We show that, if the species is free to rotate, then the apparent bulk modulus can only be positive, thus simply recovering the conditions set by stability on the bulk modulus of a purely elastic material. An apparent negative bulk modulus is obtained under the condition that the anisotropic species cannot rotate and, if the initial distribution of the species is isotropic, with restrictions on it its diffusion directions. In the absence of an obvious reason from the molecular structure of the material for such restrictive conditions, the explanation of such an unusual behavior remains an open question.

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Microstretch modeling of liquid crystalline elastomers

Kasarla Aishwarya (1), Haldar Krishnendu (1)

1 - Indian Institute of Technology Bombay (India)

Speaker: Kasarla Aishwarya or Haldar Krishnendu. **Tuesday**. Start time: **10:20**. Room: Rhône 3A LVL1. Link to abstract.

Liquid crystals (LCs) exhibit a state between crystalline solids and liquids and can deform under the influence of an external electric or magnetic field. Also, the birefringent response of the LCs to the light is being primarily studied and utilized in many applications, such as LCDs, actuators, sensors, etc. Liquid crystal elastomers (LCEs) are elastomers with liquid crystalline molecules (mesogens) as part of the polymer chains. They can change their shape whenever the orientation of these mesogens undergoes changes due to external stimuli like electric, magnetic field, or temperature. For liquid crystalline elastomers, that is elastic liquid crystalline polymers, Bladon, Terentjev, and Warner developed a non-linear theory for nematic elastomers by extending the classical Gaussian network theory of rubber elasticity to allow for anisotropic distributions of the end-to-end vector between two crosslinks, also known as neo-classical theory. However, in this theory, they assumed the molecules to be 'rigid rods' which is not the case for polymeric liquid crystals. The theory also assumes 'affine deformation' for the end-to-end distance vector of the polymer chain. As a result of these limitations, this theory fails to agree with some significant experimental results. This motivates us to go for the generalized microstretch continuum theory by E.C.Eringen. In the microstretch continuum, a material point has macro-deformation given by three translations, and micro-deformation given by three microrotations and one microstretch of the three deformable directors. To start with, we extend the existing model for a special neo-Hookean type elastic energy with mixed invariants of macro and micro deformation gradients. We aim to develop a theoretical model for the static behavior of liquid crystalline elastomers to derive the stress responses following the thermodynamic laws. We calibrate the model parameters for the proposed free energy function using the experiments reported in the literature and verify the model with the widely accepted neo-classical theory for liquid crystalline elastomers in the cases of uniaxial stretching and simple shear.

Multi-scale experimental characterisation and modelling of the thermo-electro-mechanical behaviour of 3D printed conductive composites

Crespo-miguel Javier (1), Lucarini Sergio (2), Garzon-hernandez Sara (1), Martinez-pañeda Emilio (3), Garcia-gonzalez Daniel (1)

1 - Universidad Carlos III de Madrid [Madrid] (Spain), 2 - BCMaterials (Spain), 3 - University of Oxford (United Kingdom)

Speaker: Crespo-Miguel Javier. Invited. **Tuesday**. Start time: **10:40**. Room: Rhône 3A LVL1. Link to abstract.

Additive manufacturing (AM) allows for the fabrication of complex-shape components with multi-functional properties, as conductive composites. In these materials, the conductive particles embedded in the polymeric matrix allow for a current flow. The electrical response is bidirectionally coupled with the thermal state, via resistivity modulation with temperature and heating generation due to Joule effect. In the same manner, the mechanical behaviour also affects its electrical counterpart. In addition, the use of 3D printing techniques carries the formation of defects that alter the response of these materials at a functional level. Given the nature of these materials, a comprehensive characterisation cannot be tackled only from a macroscopic or functional point of view. In this regard, the problem should be addressed following different approaches, attending to the different scales (i.e., micro, meso and macroscale) as well as to the different physical interplays (i.e., thermal, electrical and mechanical responses).
In this work, we conducted a multi-responsive characterisation of Carbon Black (CB) filled composites, using two different matrices; a thermoplastic (polylactic acid, PLA) and an elastomer (polydimethylsiloxane, PDMS). This characterisation was performed at: i) a material level, discarding the structural effects derived from the printing process; and ii) at a functional-level, accounting for the effects of the printing process. In addition, computational approaches were employed to model the multi-physical interdependencies that appear at both material and functional levels.

From an experimental perspective, we tackle the problematic by performing tests where pairs of physics were isolated. In this regard, different sets of experiments were performed, e.g., electro-thermal, analysing the material heating caused by the application of an electric field; or mechano-electrical, measuring the variation of electrical properties when deforming the composite. For our modelling approaches, full-field homogenisation techniques as well as macroscopic continuum techniques were employed to simulate the interdependencies observed in our experimental campaign.
The results obtained in this work show the strong thermo-electro-mechanical interdependencies in conductive composites. Additionally, it has been proven that our *in-silico* methodology has a great potential for conductive composite manufacturers to optimise their material properties and 3D printing users to do the same with the printing parameters.

Chemomechanics of Phase Transformation in Amorphous Silicon

Bruant Xavier (1) (2), Le Anh Tuan (1), Rosso Michel (2), Ozanam Francois (2), Jabbour Michel (1), Guin Laurent (1)

1 - Laboratoire de mécanique des solides (France), 2 - Laboratoire de physique de la matière condensée (France)

Speaker: Bruant Xavier. **Tuesday**. Start time: **11:00**. Room: Rhône 3A LVL1. Link to abstract.

Silicon electrodes for lithium-ion batteries exhibit a theoretical capacity ten times higher than that of graphite electrodes currently used in commercial systems. When lithiated/delithiated, silicon experiences stresses on the order of 1 GPa, thus inducing damage in the material which results in poor cyclability and dissipation unfavorable to energy storage. These stresses affect the material from its very first lithiation, which proceeds through a phase transformation involving the progressive invasion of the pristine Si phase by an amorphous lithiated LixSi phase (1). Nonequilibrium continuum thermodynamics predicts that mechanical stresses affect the lithiation itself differently when the material is homogeneously lithiated (monophasic lithiation) than when it undergoes a phase transformation (biphasic lithiation) (2).

When monophasic lithiation takes place (without any phase transformation), mechanical stresses affect lithium insertion through the chemical potential of the diffusing species (Larché-Cahn theory). This coupling was first probed experimentally in homogeneous lithiation using a method whereby the stress state of silicon was modified indirectly through incremental delithiation (3). In contrast, in a first study we have investigated experimentally the coupling under homogeneous lithiation conditions by imposing an external mechanical loading on an amorphous silicon thin-film electrode at various lithiation rates and measuring its effect on the electrochemical response of the battery cell (4). This mechanical loading was applied by deforming elastically the steel substrate of the silicon thin film, which made it possible to directly probe the contribution of mechanics to the lithiation/delithiation processes. In this preliminary study, we showed that the instantaneous change in the electrochemical potential and its subsequent relaxation are well captured by a viscoplastic flow rule for the amorphous material, which could then be fitted to the data with good predictive capabilities. This material behavior law can then be used to model the phase transformation.

In the present work, we concentrate on the effect of an external mechanical load on the phase transformation that occurs during the first lithiation, both experimentally and through modeling. Our experiments show that when undergoing a phase transformation, the very same external mechanical loading as that applied during homogeneous lithiation leads to a very different response of the silicon electrode potential. Under galvanostatic conditions and in the absence of any external mechanical load, the electric potential follows a plateau, indicating that the lithiation proceeds through a phase transformation. While the application of a strain increment on the thin film during this plateau results in an instantaneous change in potential similar to the one observed during homogeneous lithiation, the subsequent voltage relaxation displays a very distinct yet reproducible pattern, which we attribute to the interplay between stress evolution and phase-boundary kinetics.

To rationalize these observations, we resort to different modeling techniques aiming at describing the mechanisms underlying the phase boundary motion. First, an Arbitrary Lagrangian-Eulerian framework is developed to solve a sharp-interface model of the phase transformation in the one-dimensional setting of a thin film. This approach aims at describing the interactions between bulk rheological behaviour, chemical transport and phase boundary motion during the first lithiation. An implicit finite-element numerical implementation is formulated, and reaction-limited and diffusion-limited kinetic regimes are investigated.

This sharp-interface model is then employed to calibrate a phase-field model based on a grand-canonical formulation (5), which is more amenable to simulations of complex phase-front geometries. Such a model allows for a natural formulation of chemical equilibrium at the phase front while offering an independent degree of freedom for the phase-front kinetics, one which is not available in the popular Cahn-Hilliard models (6). In this sense, the proposed phase-field model is a mere numerical regularization of the sharp-

interface model whose application is limited to the one-dimensional setting. The problem is formulated in a variational framework and numerical strategies are discussed.

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Direct printing the director field of liquid crystal elastomers to program Gaussian curvature under the nematic-isotropic phase change.

Ibarra Alejandro (1), Najiya Najiya Lagerwall Jan

1 - Université du Luxembourg = University of Luxembourg = Universität Luxemburg (Luxembourg)

Speaker: Ibarra Alejandro. **Tuesday**. Start time: **11:20**. Room: Rhône 3A LVL1. Link to abstract.

Active materials aim to transform the material itself into a mechanism, in this area the nematic-to-isotropic transition of the liquid crystal elastomer is an interesting candidate to create this material mechanism and this is due to the contraction/expansion experienced in the nematic-isotropic transition experienced by this type of materials. To accomplish this, it is necessary to set the director field of the nematic phase before crosslinking the elastomer to encode a given structure or mechanism. In this area, there are interesting advances in the forward design, this means if a director field is set, predicts the deformed configuration of the structure of the material when it is driven to the isotropic phase(1), and the inverse design of the director field, given a target shape in the isotropic state what it is the director field in the nematic phase(2). In both cases, the director field is a scalar field that must be imprinted in the material, usually in thin films. In this area exists different technologies, but the most common are optical and mechanical alignment, the last one aligns the oligomers or polymer chains by mechanical shearing, so to pattern the director field molds are used but recently has been shown the possibility to get high levels of alignment by extruding the material through a nozzle, this open the possibility to directly print the director field(3)(4), this impose a challenge because the description of the director field is a continuum or discrete scalar field of directions, this have to be translated to a discrete print path with a constant or constrained width.
In this work we present the procedures for a given director field to find the proper discretization of it to be able to print it, by constructing a stripe pattern from the director field with a constant spacing given by the nozzle of the 3d printer, for this we use the procedural phasor noise technique(5), and order the be able to print a printing path is extracted from this stripe pattern. The 3D printing technique used is direct ink writing(6) implemented in the laboratory with UV light source to crosslink the oligomers at the moment the material leaves the printer nozzle, allowing to set the director field of the nematic phase in the direction of motion of the nozzle. This manufacturing tool allows us to experimentally study the mechanical effect of creating different point defects or discontinuities in the director field, yielding out-of-plane deformation with a characteristic Gaussian curvature. Also, we present our implementation of the inverse design of shells following the works of Hillel et al.(2) but setting the director field by 3D printing.

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On the Numerical and Experimental Investigation of Light-Matter Interactions in Polymers

Mehnert Markus (1), Steinmann Paul (2)

1 - Friedrich-Alexander Universität Erlangen-Nürnberg = University of Erlangen-Nuremberg (Germany), 2 - LTM, Friedrich-Alexander University Erlangen-Nürnberg (Germany)

Speaker: Mehnert Markus. Invited. **Tuesday**. Start time: **11:40**. Room: Rhône 3A LVL1. Link to abstract.

The aim of this research project is to investigate the photo-mechanical response of polymers with embedded switching molecules. To this end we formulate a continuum modeling approach coupling the mechanical response to the behavior of the switching molecules and an electric field representing the incident light. This theoretical approach is accompanied by photo-mechanical experiments performed with the silicone Elastosil P7670 mixed with various different Azobenzene molecules provided by Prof. Wegner (Giessen University). We perform two different kinds of experiments on the photo-sensitive polymers to characterize the response. In order to obtain information on the macroscale we use uniaxial deformation experiments (multistep and cyclic loading) with or without UV illumination. On the other hand, we perform infrared-absorption spectroscopy experiements to investigate the material response on the molecular scale. Ultimately, the combination of both experiments will provide a detailed characterization of the material.

Mechanics of soft living actuators

Raman Ritu (1)

1 - Department of Mechanical Engineering [Massachusetts Institute of Technology] (United States)

Speaker: Raman Ritu. Invited. **Tuesday**. Start time: **14:15**. Room: Rhône 3A LVL1. Link to abstract.

Human beings and other biological creatures navigate unpredictable and dynamic environments by combining compliant mechanical actuators (skeletal muscle) with neural control and sensory feedback. Abiotic actuators, by contrast, have yet to match their biological counterparts in their ability to autonomously sense and adapt their form and function to changing environments. We have shown that engineered skeletal muscle actuators, controlled by neuronal networks, can generate force and power functional behaviors such as walking and pumping in a range of untethered robots. These muscle-powered robots are dynamically responsive to mechanical stimuli and are capable of complex functional behaviors like exercise-mediated strengthening and healing in response to damage. Our lab uses engineered tissues as a platform to understand neuromuscular architecture and function in physiological and pathological states, restore mobility after disease and damage, and power soft robots. This talk will cover the advantages, challenges, and future directions of understanding and manipulating biological actuators.

Magnetic-driven viscous mechanisms in ultra-soft magnetorheological elastomers offer history-dependent actuation with reprogrammability options

Gonzalez-saiz Ernesto (1), Lopez-donaire Marisa (2), Gutierrez Lucia (3), Danas Kostas (4), Garcia-gonzalez Daniel (2)

1 - 60Nd (Spain), 2 - Universidad Carlos III de Madrid (Spain), 3 - Universidad de Zaragoza (Spain), 4 - Ecole Polytechnique (France)

Speaker: Garcia-Gonzalez Daniel. Invited. **Tuesday**. Start time: **14:35**. Room: Rhône 3A LVL1. Link to abstract.

This study addresses a significant open question in soft magnetorheological elastomers (MREs): how microstructural rearrangements during magnetic actuation influence their viscoelastic behavior. Through experiments on mechanically confined MREs, we show that magnetic actuation increases relaxation times by more than one order of magnitude compared to purely mechanical cases. Our findings reveal that this modulation of viscous response can be precisely controlled by adjusting the strength and frequency of the magnetic stimulus and is inherently tied to the microstructural rearrangement of magnetic particles. Inspired by these results, we developed magnetic actuation protocols that endow soft materials with force-memory capabilities. Specifically, we achieved magnetically-driven yielding that introduces material hardening under cyclic loading due to sustained magnetically-induced viscous relaxation. This mechanical memory effect can be released by removing the magnetic stimulus for one hour, fully restoring the material's original properties. These mechanisms are clarified through diverse experimental approaches and theoretically supported by a novel continuum model. The findings presented here address fundamental questions in soft MREs and establish a transformative approach for creating a new class of soft sensor-actuator systems.

Reprogrammability of structural energy absorption via passive and active magnetic interactions

Perez-garcia Carlos (1), Zaera Ramon (1), Aranda-ruiz Josué (1), Bordiga Giovanni (2), Risso Giada (2), Lopez-donaire Maria Luisa (1), Bertoldi Katia (2), Garcia-gonzalez Daniel (1)

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Speaker: Perez-Garcia Carlos. Invited. **Tuesday**. Start time: **14:55**. Room: Rhône 3A LVL1. Link to abstract.

Magnetoactive polymers (MAPs) have gained significant research attention in recent years for their ability to respond dynamically to magnetic fields, allowing their application in soft robotics by taking advantage of previous research on metastructures that can change their structural behaviour through internal design modifications (1, 2, 3). Flexible magnetic metastructures present an advanced approach to designing structures with adaptive mechanical properties, taking advantage of the strategic integration of hard-magnetic elements to enable reprogrammable mechanical responses without the need for external actuation. These magnetic nodes, designed for specific stiffness and magnetization properties, are embedded into a flexible matrix that connect all them by hinges. When the structures are compressed, the hinges buckles leading to abrupt changes in the evolution of the force-displacement behavior due to the interaction of magnetic nodes during structural deformation.
The distribution of magnetic nodes enables changes in stiffness, in maximum force before structural collapse, in energy absorption, or even bistable configurational transitions without external actuation under quasi-static regime. When performing impact test in these metastructures, under dynamic regime, structures show remarkable tunability with changes in energy absorption and in impact arrest time. This response can still be modulated further by external magnetic fields that provide additional changes in energy absorption. More elaborate configurations of magnetic nodes can optimize specific structural responses.

This research highlights a new approach for the design of structural components with reprogrammable mechanical properties, achieved through the redistribution of magnetic elements or the application of external magnetic actuation.

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Reprogrammable nonlinear responses via magneto-mechanical metamaterials

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1 - Harvard University (United States), 2 - Universidad Carlos III de Madrid (Spain)

Speaker: Risso Giada. Invited. **Tuesday**. Start time: **15:15**. Room: Rhône 3A LVL1. Link to abstract.

Flexible structures with reprogrammable nonlinear mechanical responses-capable of being reversibly switched post-fabrication-hold immense potential for advancing soft robotics, wearable devices, and energy-absorbing systems. However, developing such adaptable materials remains a significant challenge. In this work, we present a flexible mechanical metamaterial with embedded rigid magnets that can be reprogrammed by simply altering their orientation to achieve desired nonlinear mechanical responses. First, we demonstrate that periodic changes in magnet orientation enable a broad spectrum of mechanical behaviors. Building on this, we introduce an inverse-design framework, leveraging a fully differentiable simulation environment, to discover non-periodic magnet orientations that achieve specific target nonlinear static and dynamic responses, which are experimentally validated. These results highlight magnetic interactions as a powerful platform for developing reprogrammable systems, paving the way for the next generation of smart structures and devices.

The magneto-mechanical response of mechanically-soft hard magnetorheological elastomer foams

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1 - Laboratoire de mecanique des solides, École polytechnique (France), 2 - Department of Engineering, Cambridge University (United Kingdom)

Speaker: Lin Zehui. Invited. **Tuesday**. Start time: **15:35**. Room: Rhône 3A LVL1. Link to abstract.

Hard magnetorheological elastomers (h-MREs) are two-phase composite materials comprising micron-scale particles with significant remanent magnetization properties that are embedded in a soft elastomer matrix. In this work, we extend our work to h-MRE foams with soft mechanical response (Young's modulus in the order of a few kPa). In this study, we analyze the magneto-mechanical behavior of h-MRE foams by combined modeling and experimental testing. In particular, we study the change of the magnetic field surrounding the h-MRE foams under compressive mechanical loads. A qualitative continuum modeling of the h-MRE foam guides a set of experimental tests, which allows in-turn to calibrate the model parameters. Additional numerical simulations permit to probe further the response of such foams under non-trivial loading conditions and design potential sensing devices by exploiting the surrounding magnetic changes. This study allows for a better understanding of h-MRE foams, providing fundamental insights for their future applications like soft force sensors.

Employing thermal activation to tune auxeticity in periodic lattice structures

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Speaker: Cohen Noy. Invited. **Tuesday**. Start time: **16:35**. Room: Rhône 3A LVL1. Link to abstract.

Auxetic periodic lattice structures are characterized by a negative Poisson's ratio, a property which is useful in a variety of fields such as architecture, soft robotics, and bio-medical devices. The auxeticity stems from the topology and the geometry of the struts. The current literature reports a wide range of unit cells that exhibit an auxetic response, with Poisson's ratios that range from 0 to near -1.
In this talk I will present a design concept for smart structures that transition from non-auxetic to auxetic via thermal excitation. The lattice is made of bi-layer struts with different thermo-mechanical properties, such that thermal excitation leads to bending. As a result, the lattice can be programmed to transition to an auxetic design.
To investigate the thermo-mechanical behavior, we employ moderate rotations theory, which captures the response of beams that experience large deflections, and model the thermally induced geometric changes of the struts in the lattice. I show that an appropriate design and choice of thermo-mechanical properties can result in a thermally induced transition from non-auxetic to auxetic behavior. In addition, temperature enables one to control the degree of auxeticity in the lattice.
To demonstrate the concept, I will present two periodic lattices and show that temperature can be used to program the Poisson's ratio over a wide range. The findings from this work can be used to design lattices with thermally tunable properties.

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Extending material-based actuators towards meter-scale applications

André Niels (1), Chiriatti Léon (1), Le Houerou Vincent (1)

1 - Laboratoire des sciences de l'ingénieur, de l'informatique et de l'imagerie (France)

Speaker: André Niels. **Tuesday**. Start time: **16:55**. Room: Rhône 3A LVL1. Link to abstract.

Nastic (non-directional) and tropistic (directional) phenomena can be observed in nature: e.g. the opening and closing of the pinecone scales and the growth of sunflowers, respectively. The underlying physico-chemical principles can be integrated into material-based actuators (MBA) leading to the basis for autonomous response to changes in environmental conditions (temperature, relative humidity, etc.). So far, their application potential is essentially addressed at the centimeter scale. An extension to the meter scale is indeed hindered by a number of obstacles that remain to be tackled, mainly: disproportionate response time and insufficient load bearing capability.

In this work, MBA based on the bilayer principle are considered: actuation is achieved by the mechanical combination between a responsive "active" layer, whose expansion/contraction is constrained by a less responsive "passive" layer, resulting in the curvature of the assembly. The strategy lies in optimizing the actuator in terms of displacement and load bearing capabilities, notably by taking advantage of the increase of the second moment of area of the assembly. This approach intends to improve the mechanical response without having to increase the thickness, which would drastically increase the response time.

Accordingly, 180 μm-thick MBA samples comprised of a common paper sheet thermo-laminated with a commercially available adhesive PET sheet were placed in an environmental chamber and subjected to relative humidity cycles ranging between 5 % to 90 %. Water absorption and desorption by the MBA was monitored by weighing the sample with a rate of 2 acquisitions/min. The evolution of the curvature of the MBA was captured in-situ using a 3D laser scanner generating a point cloud of the sample surface exposed to the light beam. Using these measurements, the water content and the second moment of area of the MBA were calculated as a function of the surrounding air relative humidity. These results are discussed in terms of both response time and load bearing, raising perspectives for the upscaling of such MBA.

Multiphysics-based controlled shape change in soft materials

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1 - Università degli Studi di Firenze = University of Florence = Université de Florence (Italy), 2 - Technion - Israel Institute of Technology [Haifa] (Israel)

Speaker: Monchetti Silvia. Invited. **Tuesday**. Start time: **17:15**. Room: Rhône 3A LVL1. Link to abstract.

A precise controlled shape change of responsive materials requires the development of theoretical and computational approaches capable of reproducing the involved physical phenomena and their interaction. When polymer-based materials are considered, shape change capabilities can be obtained from external stimuli, such as temperature, light, humidity, electric field, etc. These stimuli, if precisely spatiotemporally controlled, can deform a structure into a desired configuration in a given time. The paper investigates the multiphysics-based driven shape change in highly deformable composite structures made of a passive elastic structure and an active one capable of responding to environmental stimuli. By harnessing different mechanisms, namely 1) the swelling of gels (1) and 2) the deformation of electro-active dielectric elastomers (DE) (2), controlled mechanical stresses can be transmitted to the passive portion leading to its deformation. In the present study, an elastic tube filled with a gel, whose volume deformation is driven by the fluid uptake (3), and a bilayer structure made of an elastic substrate and a DE active layer, whose deformation is induced by an electric potential (4), are considered as morphing structures. It is shown that by properly distributing the mechanical properties in the hyperelastic passive element interacting with the responsive active material, a precise shape change can be achieved. To this end, we numerically solve the multyphysics coupled problems and adopt a machine learning (ML) approach for solving the inverse problem. Given a prescribed target shape, the proposed approach enables to obtain the proper spatial stiffness distribution of the passive elastic element enabling the achievement of the desired deformed configuration.

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Shape morphing with photo responsive structures

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Speaker: Fabio Nistri. **Tuesday**. Start time: **17:35**. Room: Rhône 3A LVL1. Link to abstract.

We present the design and analysis of a mechanical structure composed of an array of beam elements fabricated using a photo-responsive polymer matrix infused with an azobenzene chromophore. This material generates light-induced strain upon illumination, enabling precise, remote control of structural behaviour. By inducing a buckled configuration in the beams through compression, the application of light-induced strain triggers a snap-through effect, transitioning the beams to a different stable state. This mechanism allows for dynamic shape morphing of the entire structure, with the resulting global configuration depending on both the number and sequence of snapped beams, enabling large overall deformation and a non-linear response.
This study demonstrates both numerically and experimentally the potential of photo-responsive materials to enable contactless control of shape-morphable structures. The ability to achieve structural transformations remotely using light opens avenues for advanced applications in soft actuators and elastic waveguides. Such lightweight systems enable flexible actuation and dynamic control of mechanical wave propagation, offering innovative solutions for adaptable and multifunctional applications.

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A robust computational method for coupled processes in inelastic materials under active damping regimes

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1 - Heriot-Watt University (United Kingdom), 2 - Taras Shevchenko National University of Kyiv (Ukraine), 3 - University of Aberdeen (United Kingdom)

Speaker: Guz Igor. **Wednesday**. Start time: **10:00**. Room: Rhône 3A LVL1. Link to abstract.

A robust computational method for investigating the thermomechanical response of physically inelastic non-linear systems to dynamic loading was developed. A non-linear dynamic problem of thermo-electromechanics for layered beams was formulated using the Kirchhoff–Love hypotheses. For the case of harmonic loading, a simplified formulation was given based on a single frequency approximation and utilizing the concept of complex moduli to characterize the non-linear cyclic properties of the material. As an example, the forced vibrations and dissipative heating of a roller-supported beam were considered. The developed formalism of thermo-electro-mechanical problem was used for estimating the self-heating caused by the electromechanical losses in piezoactive layers and the mechanical losses in electrically passive metal layer. The heating temperature evolution with time was computed. It was shown that even very small temperature increases due to the dissipation of electromechanical energy over the single vibration cycles may lead to a significant temperature rise for the multi-cycle processes. Following (1-3), the cyclic behaviour of PZT was considered to be a viscoelastic one with relatively small loss moduli. Complex moduli for this material were assumed to be independent of the frequency, temperature, and strain intensity. To avoid dangerous overheating, safe vibration regimes were found. For this purpose, the thermal fatigue life characteristic was introduced. It corresponds to the classical fatigue life, but with the Curie temperature taken as the failure criterion. To prevent overheating, active suppression of the vibration can be used. This was illustrated by numerical examples. The developed method was also successfully used for describing the thermal state under active damping regimes for other thin wall structures with piezoelectric layers for the case of small to moderate inelastic strains in the metal layer.

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In situ cyclic micro deformation of a NiMnGa ferromagnetic shape-memory alloy with concurrent AE detection

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1 - Eötvös Loránd University (Hungary), 2 - Faculty of Mechanical Engineering, Technion (Israel)

Speaker: Ugi David. **Wednesday**. Start time: **10:20**. Room: Rhône 3A LVL1. Link to abstract.

Ferromagnetic shape memory alloys (FSMAs), such as NiMnGa alloys, possess the unique combination of large displacements and fast mechanical response which offers novel prospects for applications that make use of the mechanism of converting between magnetic and mechanical energies. The measurement of acoustically emitted (AE) waves that are generated by rapid changes of the local strain field that occur during the plastic process through which the material responds to stress. These measurements are much more sensitive than macroscopic ones and are capable of detecting events with an energy down to 1 aJ and below.

During our experiments, we prepared a tension-compression microsample from a single-crystal FSMA, which was cyclically deformed using a custom-developed in situ nanoindenter, which is also suitable for AE detection. The deformation took place through the expected twinning process and it was accompanied by significant AE. The stress-strain data revealed that during compression, twinning typically occurs at high mechanical stresses, followed by a stress drop and AE signals, while during tension, AE signals associated with stress drop appear in the low-stress ranges of the loading and unloading sections.
In my presentation, I will showcase our results related to the investigation of AE signals generated by different type of mechanical twinning. These analyses could be suitable for providing information about microscopically precise mechanical processes based solely on AE.

Investigating thermal coupling on diffusive processes in metallic and non-metallic materials

Gisy Johannes (1), Böhlke Thomas (1)

1 - Institute of Engineering Mechanics, Chair of Continuum Mechanics, Karlsruhe Institute of Technology (KIT) (Germany)

Speaker: Gisy Johannes. Invited. **Wednesday**. Start time: **10:40**. Room: Rhône 3A LVL1. Link to abstract.

The phenomenon of diffusion, where species move relative to a solid material, is present in various applications such as lithium-ion transport in batteries or oxygen-ion transport in solid oxide fuel cells (1). Since, the properties of materials can change due to a diffusion process, considering metallic materials exposed to hydrogen (2) or polymer materials exposed to moisture (3), precise diffusion models need to be established. Therefore, the thermal influence on a diffusion process is crucial for accurate predictions of material properties.
To account for a thermal coupling, a thermo-chemo-mechanical model is developed. The model is embedded within a geometrically linear theory and considers a linear approach for the elastic behavior. A diffusion equation describes the redistribution of species, where the species flux is coupled to the mechanical and thermal fields. An equation of heat conduction is derived accounting for heat production through mechanical dissipation. The model is implemented using a Finite Element approach with the help of the user-defined element (UEL) subroutine of Abaqus, where the displacement field, the chemical potential and the temperature are used as solution variables. The thermal coupling is investigated for metallic and non-metallic materials with a focus on the local temperature evolution as well as on the influence of non-isothermal conditions on the diffusion process. The study outlines the role of thermal coupling while modeling diffusion phenomena.

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Mechanical and Electrochemical Properties of Conductive Oxide Glasses

To Theany (1), Braiek Sonia (1), Houizot Patrick (1), Le Coq David (2), Calvez Laurent (2), Moreac Alain (1), Rouxel Tanguy (1)

1 - University of Rennes (France), 2 - University of Rennes (France)

Speaker: To Theany. **Wednesday**. Start time: **11:00**. Room: Rhône 3A LVL1. Link to abstract.

In this study, mechanical and electrochemical properties of ionic conductive oxide glasses have been measured. The fracture toughness, crack resistance, hardness, and elastic moduli of Li-rich oxide glasses were characterized. Glasses become softer, less resistant to crack-initiation and -growth, as the lithium content is increased. In parallel, their ionic conductivity and activation energy show that the ionic diffusion of lithium is easier in the Li-rich compositions. Following our previous study (1), the measurement of the ionic conductivity under a compressive load aligned with the electric field demonstrated the existence of a mechano-electrical coupling. The change of the activation energy with the stress is associated with an activation volume that increases with the lithium content.

Keywords: Glass, Electrolyte, All-Solid-State Battery, Mechanics, Electrochemistry
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Mechanisms of interface kinetics during phase transformation of Shape Memory Alloys

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Speaker: Gao Xingke. **Wednesday**. Start time: **11:20**. Room: Rhône 3A LVL1. Link to abstract.

The phase transformation of Shape Memory Alloys (SMA) occurs via the austenite-martensite interface nucleation and propagation. The kinetics of the interface propagation is a key issue in studying the SMA's behaviours as it demonstrates the relation between the phase transformation rate (the interface propagation speed) and the driving force (energy dissipation), which implies the energetic efficiency or the damping performance of the material in the engineering applications (1-4). Although the macroscopic interface kinetics based on phenomenological models have been studied a long time ago, there are only a few concrete experiments that show the meso- and micro-scopic evolution of the propagating interface. Recently, the microscopic evolution with the nucleation/merging/annihilation of various martensite twin laminates was reported at the martensite-austenite interface propagation during the temperature-induced phase transformation of a magnetic shape memory alloy (Ni-Mn-Ga single crystal) (5-9). Compared to polycrystalline SMAs, single crystal SMA can better demonstrate the compatibility between the two transforming phases at the propagating interface, from which the stored energy and the associated energetic driving force can be estimated (3-5, 10). But it is still a challenging task to characterize simultaneously the macroscopic kinetics and the microscopic evolution in the single crystal. In this paper, we synchronize the microscopic observation (twinning/detwinning/phase-transformation) and the macroscopic measurement of the kinetics (the macroscopic interface speed versus the applied temperature/stress/magnetic-field) so as to better understand the mechanism of the phase transformation by the macroscopic interface propagation, which would help material design (modification/improvement on material performance) and engineering applications (tailor-made materials for particular situations).

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Plant-inspired actuator, motion prediction and measurement.

Fiore Louison (1), Lacorre Paul Tadrist Loïc Linares Jean-marc

1 - Institut des Sciences du Mouvement Etienne Jules Marey (France)

Speaker: Fiore Louison. **Wednesday**. Start time: **14:30**. Room: Rhône 3A LVL1. Link to abstract.

The pulvinus of Mimosa pudica (Touch-me-not plant) is a fast motion-generating organ resilient to damage. It is made of roughly 350 000 cells that may inflate or deflate to create motion by deformation. Based on this functioning, we investigate the possibility of creating a versatile and resilient actuator made of pressurizable cells.

We present a 64-cells prototype that moves in 3D. The control of such an actuator with 64 degrees of freedom is complex. We investigate two models to predict the shape of the actuator considering different pressure patterns: (i) A rough modeling of the deformations at the cellular level combined to a kinematic chain (Denavit–Hartenberg parameters) and (ii) A neural network model trained on finite element simulations. The two predictions are compared with the physical prototype.

The neural network is very efficient at determining the shape of the actuator. It is more accurate than the analytical model. It is extremely light (50 ko), runs in a web browser and is trained in a few seconds on a laptop. The most consuming step is the training data generation by numerical simulations (FEA).

Finally, we show that considering small deformations and a linear material the neural network is equivalent to an optimization by Moore-Penrose inverse matrix.

These findings represent an important step forward in understanding the movement mechanisms of pressurized cellular actuators and provide a solid basis for further exploring the resilience induced by the multi-scale architecture of the pulvinus of Mimosa pudica.

Surface growth models for solid-state batteries

Nevenchannyy Yury (1), Guin Laurent (1), Jabbour Michel (1)

1 - Laboratoire de Mécanique des Solides (France)

Speaker: Nevenchannyy Yury. **Wednesday**. Start time: **14:50**. Room: Rhône 3A LVL1. Link to abstract.

Traditional liquid electrolyte-based lithium-ion batteries are close to reaching their limits on energy density, while higher specific capacity is required from modern energy storage units (1). Solid-state batteries, combining a solid-state electrolyte with a lithium anode have emerged as a promising alternative, offering higher energy density (up to 50% on the cell level) and improved safety. However, during charge and discharge cycles uneven current density often causes dendrites to develop in the form of needle-like protrusions of lithium that propagate through the solid electrolyte by fracturing it. Suppression of their growth presents a critical challenge to developing solid-state battery technology as dendrites lead to mechanical degradation of the solid electrolyte, short-circuiting, and subsequent cell failure (2).
Lithium plating and stripping (deposition and ablation) during charge and discharge cycles are inherently surface growth phenomena that couple the stress state in the electrode, interface kinetics between the electrode and the electrolyte (commonly described by Butler-Volmer kinetics (3)), and ion transport in the bulk of the solid electrolyte with a dependence on the morphology of the interface. Current modeling of dendrite growth in solid-state batteries eludes the surface growth associated with lithium deposition.

As a first step towards formulating a fully coupled sharp-interface model of lithium plating or dendrite growth, we formulate a surface growth theory using a Lagrangian framework inspired by the work of Yavari and Sozio (4). To account for accretion of the body, an arbitrary time-dependent reference configuration is constructed that embeds an inelastic-strain field determined at the instant of deposition. We utilize the multiplicative decomposition of the deformation gradient to obtain the elastic strain tensor, related stress tensor in the growing body by a standard constitutive relation. As new material is accreted to the body, its stress components along the directions tangent to the growing surface remain undetermined by general principles, thus forming an additional constitutive quantity, referred to as the deposition protocol (5). We show that the choice of the deposition protocol as well as the history of deformation play a crucial role in the arising stress field and the inelastic-strain field. In contrast to existing formalisms of surface growth, the proposed theory does not rely on concepts of differential geometry, making it more accessible to the general mechanics community. It is also more amenable to numerical calculations using standard tools of nonlinear elasticity.

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Writhing of Plant Tendrils: Where Kirchhoff Meets Lockhart

Zanchi Dražen (1), Dilly Emilien (2), Derr Julien (2)

1 - Matière et Systèmes Complexes (France), 2 - Reproduction et développement des plantes (France)

Speaker: Derr Julien. **Wednesday**. Start time: **15:10**. Room: Rhône 3A LVL1. Link to abstract.

Buckling phenomena in elastic rods have recently attracted renewed interest (1,2,3). Among the well-understood singular buckling events is the writhing transition. Consider a straight rod clamped at both ends and subjected to traction T. Next, suppose internal stress is generated in the rod in a non-homogeneous manner across its cross-section. For T=0, this generates an intrinsic curvature of the rod, *K0*, which is related to the effective residual stresses within the unloaded rod. At $T>0$, the writhing transition occurs at a critical internal stress, represented by a critical value *K0c*. The phenomenon is supercritical, meaning the buckling amplitude scales as (*K0–K0c*)^1/2.
A spectacular realization of the writhing transition is found in plant tendrils, rod-like organs by which plants (such as cucumbers, vines, and passionflowers) attach to supports. Experiments were conducted on approximately 100 living cucumber tendrils. The time evolution of tendril curvature was monitored over three days under controlled traction T. Once a straight tendril finds a support and attaches to it, it begins generating differential intrinsic stresses. Whether these stresses cause writhing and subsequent coiling depends on the external load T. These differential stresses arise from the physiological evolution (growth) of the tendril. Conversely, tendril growth itself is stress-dependent. A standard approach for describing this relationship is implemented in Lockhart-like models (4,5). By combining insights from the Kirchhoff model of writhing and the Lockhart model of growth, we propose a simple morphoelastic model to describe the evolution of plant tendrils under axial constraints. The results align well with the experimental data, reproducing a well-identified jump associated with the writhing instability.

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Experimental Study of an Untethered Magnetorheological Elastomer based Phase Change McKibben Actuator

Gupta Devansh (1), Santapuri Sushma (1)

1 - Indian Institute of Technology Delhi (India)

Speaker: Gupta Devansh. **Wednesday**. Start time: **15:30**. Room: Rhône 3A LVL1. Link to abstract.

McKibben actuators are a type of pneumatic artificial muscle (PAM) actuators which consists of an elastomeric bladder encapsuled within a braided mesh. The elastomer is pressurized and the radial expansion of the tube is translated into axial contraction due to the geometric constraint of the braided mesh. These actuator are renowned for their exceptional power-to-weight ratio (10 kW/kg (1)) when the weight of peripheral components is excluded. However, their reliance on heavy peripheral systems, such as compressors, valves, and pressurized gas tanks, limits their application in lightweight, portable systems like exosuits or wearable robotics. To address this challenge, this work explores a phase-change-based actuation mechanism designed to minimize peripheral weight.
The proposed mechanism involves a magnetically induced liquid-to-gas phase transition of a low boiling-point fluid to generate the pressure required for actuation. The actuator consists of a magnetorheological elastomer (MRE) tube filled with the engineered fluid, which is infused with suspended magnetic particles. This tube is enclosed in a braided shell that restricts axial elongation, ensuring efficient force generation. The actuator is placed inside an induction coil, causing it to heat which triggers the phase transition, causing a rapid volumetric expansion of the fluid. The combined effect of the phase transition and mechanical constraints produces sufficient pressure to actuate the artificial muscle.

The use of a low boiling-point fluid enables faster cyclic actuation, while the induction coil facilitates untethered power transfer without significantly increasing the system's weight. The fabricated actuator achieves impressive performance, lifting a maximum load of 4.5 kilograms while weighing only 23 grams. This novel approach offers a lightweight and efficient solution for portable robotic applications, advancing the integration of artificial muscles into wearable systems.

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MS1.9 - New challenges in the mechanics and physics of Solids

Organisers: Vikram Deshpande (University of Cambridge)

Mechanomaterials: Towards Proactive Design of Fracture Resistance in Mechanical Metamaterials

Gao Huajian (1), Wang Yujia (2)

1 - Mechano-X Institute, Tsinghua University (China), 2 - School of Mechanical and Aerospace Engineering, Nanyang Technological University (Singapore)

Speaker: Gao Huajian. Keynote. **Wednesday**. Start time: **10:00**. Room: Saint Clair 3B LVL2. Link to abstract.

Fracture is a classical topic in solid mechanics, while mechanical metamaterials represent an emerging field enabling innovative applications. The intersection of these areas presents both significant challenges and unique opportunities. In this study, we demonstrate that the fracture toughness of lattice metamaterials is profoundly influenced by their topology, with shell-based lattice metamaterials exhibiting superior fracture resistance compared to their truss-based counterparts. We reveal a topology-induced intrinsic toughening mechanism in shell-based lattices and identify a distinct fracture dissipation mechanism, termed structural plasticity. Additionally, we show that fracture behaviors in mechanical metamaterials can be proactively controlled. By harnessing elastic instability, we regulate the plastic zone size in pseudoplastic metamaterials, thereby amplifying structural plasticity. Through a combination of experimental and computational approaches, we realize distinct fracture behaviors, including the intrinsic-to-extrinsic transition in fracture toughness. This work demonstrates a framework for transitioning from passive understanding to proactive control of fracture behavior through mechanical metamaterials, deepening the understanding of the interplay between fracture and mechanical metamaterials and opening avenues for advanced material design.

Where the Nano-Worlds Collide: Nanoporosity-Driven Deformation of Nano-Architected Metals

Greer Julia R (1) (2), Zhang Wenxin Li Zhi Gao Huajian

1 - California Institute of Technology (United States), 2 - Kavli Nanoscience Institute (United States)

Speaker: Greer Julia R. Invited. **Wednesday**. Start time: **10:40**. Room: Saint Clair 3B LVL2. Link to abstract.

The emergence of 3D printing methods for small-scale metals has enabled attaining a unique dimensional niche, on the order of 10-100 nm, at the nexus of the functional feature sizes, the critical microstructural detail, and atomic-level defects. This convergence fundamentally challenges the conventional relationships across structural hierarchies and has significant nanomechanical implications. We demonstrate the fabrication of nano-architected metals with superior resolution and structural integrity enabled by a novel nanoscale additive manufacturing approach based on two-photon lithography and hydrogel infusion (nano-HIAM). The produced nickel nanoarchitectures – beam-based and shell-based, periodic and non-periodic – exhibit remarkable specific mechanical strengths, achieving _˜10-100 MPa.gˆ-1cm3 at feature dimensions of _˜100-500 nm. The *In situ* nano-compression experiments unveiled unique nanomechanical behaviors in the regime where structural, functional, and microstructural dimensions converge, _˜10-100nm. A predominant global "material failure" mechanism allows for a direct correlation between the structural response and the experimentally measured strength of nano-building blocks that comprise the nano-architected materials. Through integrated experimental characterizations and physics-informed, multi-hierarchy finite element analysis, nodal nanoporosity is identified as the key factor controlling deformation modes and size-dependent strength, which ultimately links the nano-building block properties to the structural response of representative octahedral nanolattices. This study highlights nano-architected Ni as a model system to demonstrate the capability of nano-HIAM for fabricating complex 3D geometries with high resolution. Future work could explore theapplication of the nano-HIAM method to more complex material systems and microstructures, including multi-principal elements alloys, ceramics, doped carbon composites, hetero-structured nanostructures, and muti-stable nanoarchitecture. The versatile infusion and thermal treatment processes of nano-HIAM, combined with its superior 3D-freeform capability, could enable wide multifunctional applications in nanotechnology. The nano-defect-meditated size-dependent structure properties identified here likely extend to other nanoarchitectures with converging characteristic dimensions, posting new challenges for developing high fidelity multi-hierarchy modelling frameworks for evaluating and designing nanoarchitectures with superior target properties.

Mechanics-guided 3D assembly for electronics and microsystems

Zhang Yihui (1) (2)

1 - Mechano-X Institute, Applied Mechanics Laboratory, Department of Engineering Mechanics, Tsinghua University (China), 2 - Laboratory of Flexible Electronics Technology, Tsinghua University (China)

Speaker: Zhang Yihui. Invited. **Wednesday**. Start time: **11:00**. Room: Saint Clair 3B LVL2. Link to abstract.

3D micro-/nano-structures have widespread applications in a broad spectrum of cutting-edge areas, such as bio-integrated electronics, microrobots, tissue engineering, among others. Existing manufacturing approaches to form such 3D micro-/nano-structures, however, can only be used directly with a narrow range of materials and/or 3D geometries. A grand challenge in the field is in the development of schemes that allow construction of 3D structures in device-grade crystalline inorganic materials essential for high-quality electronics and microsystems. In this talk, I will introduce a mechanics-guided assembly approach that exploits controlled buckling to construct complex 3D micro/nanostructures rapidly from patterned 2D micro/nanoscale precursors. This approach applies to a broad set of materials (e.g., semiconductors, polymers, metals, and ceramics) and even their heterogeneous integration, over a wide range of length scales (e.g., from 100 nm to 10 cm). Development of a rational microlattice design allows transformation of 2D films into programmable 3D curved mesosurfaces through this assembly approach. Analytical modeling and a machine learning–based computational approach serve as the basis for shape programming and determine the heterogeneous 2D microlattice patterns required for target 3D curved surfaces. By studying fundamental aspects of adhesion and delamination in the film/substrate system, general design diagrams are developed to serve as guidelines for the selection of engineering parameters to avoid interface-related failure. A wrinkling-assisted strategy is also proposed to substantially facilitate the delamination at desired regions of the film/substrate system. The compatibility of the approach with the state-of-the-art fabrication/processing techniques available in semiconductor industries, allow transformation of diverse existing 2D microsystems into 3D configurations, providing unusual design options in the development of fundamentally new devices. I will introduce a few examples of unusual bioelectronic devices and bioinspired microrobots enabled by the mechanics-guided 3D assembly.

Nonlinear metamaterials with engineered heterogeneities

Guduru Pradeep (1), Gupta Mohit Stang Eric

1 - Brown University (United States)

Speaker: Guduru Pradeep. Invited. **Wednesday**. Start time: **11:20**. Room: Saint Clair 3B LVL2. Link to abstract.

Nonlinear metamaterials with engineered mesoscale architectures consisting of different constituents with contrasting mechanical properties are expected to offer superior combinations of strength and toughness. Such structures are found in nature as well; whereas biological materials rely on a limited choice of organic and mineralized constituents, modern additive manufacturing methods offer a wider palette of materials and material combinations including metals, ceramics and polymers to design multi-material architectures that can display superior performance under a wide range of loading conditions. Here, an investigation of the fracture behavior of a "lamellar" meso-scale architecture is presented as a model system, which is made up of alternating layers of two steels with contrasting strength and ductility. The lamella widths are varied between 0.3 and 10 mm, which represents the "meso-scale" for this material combination. The load-deflection response of the lamellar specimens comprises of alternating segments of plateau and sharp load drops. For certain lamella length scales, the peak load and the energy dissipation are seen to be higher than those of even the base materials, demonstrating that meso-scale architecting is an effective materials design strategy to enhance effective strength and toughness simultaneously. An investigation of the underlying mechanisms reveals that the enhancement of effective properties is due to a combination of crack tip shielding and unstable crack propagation; analysis also suggests an optimal length scale, which is seen in the experiments as well. Although this investigation discusses a lamellar architecture, the question of optimal topology remains open. Further, a combined experimental and computational investigation of dynamic shear localization of heterogeneous architectures is also presented. It reveals the potential for designing materials with superior performance for impact loading conditions. Challenges and opportunities in developing new experimental diagnostic techniques and theoretical analyses in characterizing and predicting the response of heterogeneous materials are also discussed.

Hybrid Piezoresistivity and Piezocapacitivity of Architected Porous Nanocomposites

Lu Nanshu (1)

1 - The University of Texas at Austin (United States)

Speaker: Lu Nanshu. Invited. **Wednesday**. Start time: **11:40**. Room: Saint Clair 3B LVL2. Link to abstract.

Electronic skins (e-skins) that mimic the mechanical softness and tactile sensations of human skins crucial for future prosthetics and humanoids. However, despite decades of research, soft capacitive pressure sensors still face two persistent challenges – a rapid decrease in pressure sensitivity with increasing pressure and interference from lateral stretching on pressure readings.(1) Our group pioneered the Hybrid Response Pressure Sensor (HRPS) (2) and Stretchable Hybrid Response Pressure Sensor (SHRPS) (3) by leveraging the synergistic piezoresistivity and piezocapacitivity of optimally doped porous nanocomposites (PNC). Using commercially available Ni foam as a template, we manufactured CNT-doped-Ecoflex PNC through dip-coating and curing of the composite, followed by etching away the Ni foam. Our HRPS exhibited unprecedented pressure sensitivity at high pressures, and the ultra-high pressure sensitivity of SHRPS can trivialize its response to stretch. As a demonstration, SHRPS has been mounted on an inflatable robotic end effector to safely and effectively check human pulses and potentially blood pressure without the need for a cuff. Through simplified circuit models and electromechanical analysis, we have uncovered the fundamental mechanisms of HRPS and SHPRS and obtained analytical predictions of their behaviors.(4, 5) Additionally, we fabricated architected porous nanocomposite (APNC) based on micro-architected Ni foams produced by digital light processing (DLP) and hydrogel infusion method.(6) We discovered that the APNC-based architected stretchable hybrid response pressure sensor (ASHRPS) demonstrated even higher pressure sensitivity than the SHRPS. We explain this discovery through combined micro-CT and computational analyses.(7) We hope to collaborate with mechanicians specializing in architected materials and AI tools to develop a design framework for creating ASHRPS e-skins. Architected electromechanical materials hold significant potential for soft electronics and robotics.

Multi-Modal Haptic Actuators

Huang Yonggang (1)

1 - Northwestern University [Evanston] (United States)

Speaker: Huang Yonggang. Invited. **Wednesday**. Start time: **14:30**. Room: Saint Clair 3B LVL2. Link to abstract.

The rich set of mechanoreceptors found in human skin offers a versatile engineering interface for transmitting information and eliciting perceptions, potentially serving a broad range of applications in patient care and other important industries. Targeted multisensory engagement of these afferent units, however, faces persistent challenges, especially for wearable, programmable systems that need to operate adaptively across the body. Here we present a miniaturized electromechanical structure that, when combined with skin as an elastic, energy-storing element, supports bistable, self-sensing modes of deformation. Targeting specific classes of mechanoreceptors as the basis for distinct, programmed sensory responses, this haptic unit can deliver both dynamic and static stimuli, directed as either normal or shear forces. Systematic experimental and theoretical studies establish foundational principles and practical criteria for low-energy operation across natural anatomical variations in the mechanical properties of human skin. A wireless, skin-conformable haptic interface, integrating an array of these bistable transducers, serves as a high-density channel capable of rendering input from smartphone-based 3D scanning and inertial sensors. Demonstrations of this system include sensory substitution designed to improve the quality of life for patients with visual and proprioceptive impairments.

A Microstretch Approach for Modeling the Large Deformation Thermoviscoelastic Behavior of Liquid Crystal Elastomers.

Nguyen Thao (vicky) (1)

1 - Johns Hopkins University (United States)

Speaker: Nguyen Thao (vicky). Invited. **Wednesday**. Start time: **14:50**. Room: Saint Clair 3B LVL2. Link to abstract.

Liquid crystal elastomers (LCEs) exhibit complex thermomechanical behaviors that can be exploited for a wide variety of applications in soft robotics, biomedical devices, and impact and vibration protection. Monodomain nematic elastomers (MNEs) undergo orientational ordering when cooled below the nematic-isotropic transition temperature and in response to mechanical loading. For main-chain MNEs, where the mesogens are located in the polymer backbone, mesogen ordering produces a large anisotropic shape change and a semi-soft stress response to large deformation. Furthermore, the soft behavior of the mesogens provided nematic elastomers with enhanced viscoelastic dissipation, compared to conventional elastomers, over a wide range of frequencies, strain rates, and temperatures. Predictive modeling is needed to efficiently design and optimize LCE structures to achieve the desired performance to fully leverage the potential of nematic elastomers. This presentation will describe our recent efforts to develop a finite deformation viscoelastic microstretch model for MNEs. The nematic microstructure is represented in the model as an order tensor, characterized by a director orientation for the mean alignment direction of the mesogens, an order parameter for the degree of alignment along the director, and a biaxiality parameter to indicate a secondary alignment of mesogen in the plane perpendicular to the director. The director orientation can rotate, and order parameters and biaxiality parameters can stretch independently of the deformation gradient. We further assume that the stress couple tensor response to the director microrotation and microforce vectors response to the microstretch of the order parameter and biaxiality parameter can be decomposed additively into elastic and viscous parts. The stress response of the network can also be decomposed additively into equilibrium and nonequilibrium parts. Following the Coleman and Noll procedure, we developed thermodynamic restrictions for the constitutive relations for the stress, stress couple, and micro-stretch force vectors. The model reduces to the finite deformation viscoelastic micropolar model developed in prior work. Finally, we applied the model to study the time-dependent and rate-dependent effects of the spontaneous stretch behavior of the nematic-isotropic temperature transition and rate-dependent uniaxial tension behavior.

Effects of void size and spatial distribution on ductile damage

Niordson Christian (1), Wu Weijian (1), Winther Grethe (1)

1 - Technical University of Denmark, Department of Civil and Mechanical Engineering (Denmark)

Speaker: Niordson Christian. Invited. **Wednesday**. Start time: **15:10**. Room: Saint Clair 3B LVL2. Link to abstract.

A study of damage due to void growth in 1050 Aluminium is carried out using X-ray Computed Tomography (XCT) conducted in-situ at ID-11 at the European Synchrotron Radiation Facility using the Nanox tensile stress rig. A statistical analysis of the development of void size, void shape, and void volume fraction is carried out through different stages of deformation. The experimental results are compared to predictions from the classical Gurson-Tvergaard-Needleman model, as well as extensions accounting for size effects for micron scale void distributions and statistical variations in spatial void distributions. The effect of size is described by a model based on numerical cell studies of regular void distributions using strain gradient plasticity, where the void size effect is characterized by two extensions to the GTN-model. One is the definition of a size-dependent effective void volume fraction smaller than the physical one, and the other is the introduction of a size-dependent reduction of the influence of the mean stress. The model for statistical variations in the spatial void distribution is based on a recent extension to the classical GTN model, where the microstructural randomness is characterized by a distribution parameter that enters the yield function for the porous material.

Nanomechanics for Deep Elastic Strain Engineering

Lu Yang (1)

1 - The University of Hong Kong (Hong Kong SAR China)

Speaker: Lu Yang. Invited. **Wednesday**. Start time: **15:30**. Room: Saint Clair 3B LVL2. Link to abstract.

Under strain, the physical properties of semiconductors can undergo significant changes. However, bulk semiconductor crystals are usually rigid and brittle, making it challenging to achieve sufficient strain levels for desired functional characteristics. Our experimental research has shown that, by microfabricating semiconductors (such as silicon and diamond) into micro/nanostructures, they can exhibit extraordinary elastic deformability. To realize such strain-engineered device applications, we further microfabricated single-crystalline diamond microbridge arrays and have mechanically achieved sample-wide uniform, up to _~10 %, ultralarge elastic strains under uniaxial tensile loading. This ultralarge strain significantly reduced the diamond bandgap by > 2eV or convert diamond from indirect bandgap to direct bandgap semiconductor, demonstrating its promising applications and immense potential in wide bandgap semiconductors and optoelectronic technologies. Moreover, we have extended deep elastic strain engineering to two-dimensional material systems, exploring their future applications in integrated circuits and electronic devices. This includes pioneering the first tensile and shear tests on free-standing monolayer 2D materials, such as graphene, hexagonal boron nitride and Transition Metal Dichalcogenides, as well as their homo- and heterostructures (e.g., twisted bilayer graphene). These studies not only reveal the anomalous nanomechanical properties of 2D materials, but also underscore the potential of elastic strain engineering (up to _~6%) for tuning 2D electronic and optoelectronic devices.

The Evolution of Mechanical Instabilities for Functional Applications

Zhao Renee (1)

1 - Stanford University (United States)

Speaker: Zhao Renee. Invited. **Wednesday**. Start time: **15:50**. Room: Saint Clair 3B LVL2. Link to abstract.

Mechanical instability is widespread in both daily life and engineering. They were traditionally viewed as failure mechanisms, such as collapse of liquid storage tanks, coating delamination, etc. These instabilities have been studied extensively since Euler's investigation of column buckling in 1744 to enhance safety in engineering and industrial design. More recently, mechanical instability has been harnessed as effective and robust strategies for functional applications, including soft robotics, metamaterials, flexible electronics, shape-morphing structures, and biomedical devices. In this talk, I will present two examples from our recent work demonstrating how mechanical instability can be leveraged to design functional systems. The first example draws inspiration from cylinder shell buckling to develop millimeter-scale origami systems for robotic surgery. The diagonal-shaped buckling pattern of cylindrical shells under torsion is adapted to create origami structures with tunable monostability and bistability. These designs enable multifunctional robotic systems capable of omnidirectional bending and twisting, as well as amphibious millirobots with multimodal locomotion, drug delivery, and cargo transport capabilities. The second example utilizes the buckling of elastic rods with large natural curvature to create a novel type of origami with multiple stable states and programmable strain energy. This origami serves as a fundamental building block for assembling larger structures with adjustable stiffness and 'spring constant', enabling vibration control by switching between functions such as rigid vibration, wave isolation, amplification, and mode tuning.

Second-order homogenization is variational (in dimension 1)

Thbaut Manon (1), Audoly Basile (2), Lestringant Claire (3)

1 - Laboratoire de mécanique des solides (France), 2 - Laboratoire de Mécanique des Solides (France), 3 - D'Alembert laboratory (France)

Speaker: Audoly Basile. Invited. **Wednesday**. Start time: **16:10**. Room: Saint Clair 3B LVL2. Link to abstract.

When applied to one-dimensional periodic elastic lattices, the method of two-scale expansions produces an elastic energy that depends on both the strain and the gradient of strain, and therefore fits into the 'strain gradient theory' of Mindlin (Int. J. Sol. Struct., 1968). The energy is expressed in terms of both a scale separation parameter epsilon$<$ 0. This key property is absent from Mindlin's theory. We show that it constrains the higher-order tractions that are applied at the boundaries of the equivalent strain-gradient continuum. The particular form of the boundary tractions makes it possible to rewrite the boundary energy in a compact and largely universal form. The class of strain-gradient models derived in this way allow second-order homogenization to be revisited as the minimization of a positive energy functional.

Failure of Li-ion cells with ceramic electrolytes: contact loss & dendrite growth

Vema Sundeep (1), Roach Ashley (1), Grey Clare (1), Deshpande Vikram (1), Fleck Norman (2)

1 - University of Cambridge (United Kingdom), 2 - University of Cambridge (United Kingdom)

Speaker: Fleck Norman. Invited. **Wednesday**. Start time: **16:45**. Room: Saint Clair 3B LVL2. Link to abstract.

Failure of solid-state batteries with Li metal anodes by contact loss between the ceramic electrolyte and the Li electrode is commonly attributed to the growth of voids in the Li metal at the electrode/electrolyte interface. We report measurements and observations that suggest contact loss is not primarily a consequence of this mechanism. Lithium creeps at applied stresses of _~ 1 MPa and we report a precipitous rise in interfacial resistance at the stripping electrode (i.e., contact loss) at applied stack pressures of 20 MPa. Electrical contact between the electrode and electrolyte is not restored after continued application of the stack pressure for a few hours with no imposed cell current: any voids would have expected to collapse by creep of the Li. This drove us to investigate a hypothesis that impurity deposition on the interface, as the Li metal is being stripped, is the primary cause of contact loss. High resolution FIB/SEM observations support this hypothesis: a thin layer of oxides is observed at the interface after stripping while the interface prior to stripping is pristine. We present a model for the formation of a porous granular layer at the interface resulting from the deposition of impurities and the consequent blockage of the flow of Li into the electrolyte. The predictions are remarkably consistent with the measurements in terms of the stack pressure and cell current dependence of the onset of contact loss. Importantly they show that $<$ 0.1% by volume impurities in the Li metal electrode are sufficient to cause the observed contact loss. We conclude by discussing the implications of this contact loss mechanism on another failure mechanism of these Li-ion cells, viz. cell shorting by the growth of dendrites through the electrolyte.

Mechanics of Quantum Materials

Duan Huiling (1)

1 - University of Houston (United States)

Speaker: Sharma Pradeep. Invited. **Wednesday**. Start time: **17:05**. Room: Saint Clair 3B LVL2. Link to abstract.

Quantum materials refer to a specific class of materials that exhibit strong electronic correlations and order, resulting in often exotic emergent behaviors that can only be understood by taking cognizance of the underlying quantum nature of these materials. Examples include materials that demonstrate lossless transmission of electricity, such as superconductivity, advanced cryptography, exquisite sensing, artificial intelligence, quantum computing, and information storage and retrieval at science-fiction-like speed and capacity. One example of a quantum material is well-designed high-temperature superconductors, which hold the potential to revolutionize human technological capabilities, including controllable nuclear fusion, levitating vehicles, and next-generation power grids, among others. In this presentation, I will discuss a field theory formulation for quantum materials that connects continuum mechanics concepts with an appropriate quantum mechanical-based order parameter. Our formulation epitomizes the remarkable capacity of the continuum mechanics framework to construct phenomenological models for complex materials systems even with distinctly quantum mechanical underpinnings. I use superconductors as a case study to highlight several novel physical insights.

Microstructure-based Multiscale Modeling of Mechanical Behaviors in Metals

Nan

1 - Peking University [Beijing] (China)

Speaker: Duan Huiling. Invited. **Wednesday**. Start time: **17:25**. Room: Saint Clair 3B LVL2. Link to abstract.

We proposed a multiscale model to predict the thermo-mechanical properties of structural materials and high-entropy alloys, specifically involving the impacts of microstructure, interfaces, and size effects, through a combination of experiments, simulations, and theoretical modeling. Additionally, a probabilistic model was established that integrates with the constitutive model to elucidate the competition between cleavage and ductile void failure in structural materials. We also developed a machine learning-based nonlinear micromechanics framework for materials with complex interfacial behaviors. Moreover, we explored the coupled size effects and microstructural effects on strength, toughness, and creep, providing theoretical fundamentals for understanding the mechanical properties of small-scale samples.

Challenges and opportunities in phase-field modeling for the mechanics and physics of solids

De Lorenzis Laura (1)

1 - Department of Mechanical and Process Engineering [Zürich] (Switzerland)

Speaker: De Lorenzis Laura. Invited. **Wednesday**. Start time: **17:45**. Room: Saint Clair 3B LVL2. Link to abstract.

Phase-field modeling, whose origin can be traced long back in time to the pioneering ideas of van der Waals, has experienced a revived interest in the past few decades and continues to be a subject of intense research by mathematicians, physicists and engineers alike. This talk reviews some of the key steps in the development of this fascinating subject within different disciplines, and, focusing specifically on the mechanics and physics of solids, highlights some challenges and opportunities for the future. For a more concrete discussion, three examples are briefly presented from the recent research in the group of the speaker, focusing on mechanics (fracture), phase transformations (precipitation/dissolution), and the coupling between the two (elastic microphase separation).

ENNStressNet - An Unsupervised Equilibrium-Based Neural Network for End-to-End Stress Mapping in Elastoplastic Solids

Li Lingfeng Li Shun Gao Huajian Chen Changqing (1)

1 - Tsinghua University (China)

Speaker: Chen Changqing. Invited. **Wednesday**. Start time: **18:05**. Room: Saint Clair 3B LVL2. Link to abstract.

Determining internal stress and strain fields in solid structures under external loads has been a central focus of continuum mechanics, playing a critical role in characterizing the mechanical behaviors and properties of both engineering and biological systems. With advancements in modern optical and electron microscopy techniques, strain fields can now be directly measured using sophisticated methods such as digital image correlation and digital volume correlation. However, direct measurement of stress fields remains limited to simple cases, such as photoelastic tests and standard uniaxial or shear tests. For elastoplastic solids, which exhibit complex irreversible and history-dependent deformations, stress fields are typically inferred through numerical calculations based on empirical constitutive models that are not always reliable or even available. Here, we introduce an unsupervised equilibrium-based neural network (ENN) that is trained using readily measurable strain fields and forces from a single specimen to directly predict the internal stress field. The ENN's structure aligns with the general framework of the incremental theory of elastoplasticity, without requiring prior knowledge of its detailed mathematical form. Once trained, the ENN, referred to as ENNStressNet, serves as an end-to-end stress mapper, enabling the direct determination of stress fields from measured strain fields in elastoplastic solids with arbitrary geometries and under various external loads. This approach thus bypasses the need for constitutive modeling and numerical simulations in conventional engineering analysis.

Conquering Generalization Challenges—A Problem-Independent Machine Learning (PIML) Approach for AI enhanced Computational Mechanics

Guo Xu (1)

1 - Dalian University of Technology (China)

Speaker: Guo Xu. Invited. **Wednesday**. Start time: **18:25**. Room: Saint Clair 3B LVL2. Link to abstract.

Artificial Intelligence (AI) for computational mechanics is one of the current research focuses in the field of solid mechanics. The field of computational mechanics involves complex physical phenomena and diverse engineering scenarios. Traditional end-to-end AI models often perform well on specific datasets but exhibit significant loss of generalization ability when facing new boundary conditions, material properties, or geometries. To address this challenge, a problem-independent machine learning (PIML) enhanced large-scale structural analysis and topology optimization framework is developed. The main idea is to focus on the origin of finite element analysis method-the shape function. This is achieved by using machine learning to establish an implicit mapping between the material distribution within coarse mesh elements and corresponding numerical Green's functions. The proposed PIML algorithm is truly independent of specific analysis and topology optimization problems. This is because the numerical shape functions of coarse mesh elements are uniquely determined by the material distribution inside, and do not depend on the external loads, boundary conditions, or shapes of design domain. Numerical examples demonstrate that this algorithm can achieve a two-order-of-magnitude improvement in optimization efficiency for million-scale three-dimensional topology optimization problems compared to mainstream commercial topology optimization software, under the same computational resources. In a 6750-core parallel environment, a 3D topology optimization problem with 10 billion degrees of freedom requires only 42 seconds per iteration. In the future, it is possible to develop a universal CAE software framework based on this technology by integrating AI with traditional numerical methods, enabling more efficient and intelligent engineering simulation and design.

On the state-of-the-art and some open challenges in mechanical inverse design

Sigmund Ole (1)

1 - Department of Civil and Mechanical Engineering, Technical University of Denmark (Denmark)

Speaker: Sigmund Ole. Keynote. **Thursday**. Start time: **10:00**. Room: Saint Clair 3B LVL2. Link to abstract.

Topology Optimization (TO) has evolved as a powerful and versatile tool for solving mechanical and multiphysics design problems across the scales. Examples range from giga-voxel resolutions in suspension bridge design, over tailoring of non-linear stress-strain curves at will, to synthesis of quantum-opto-mechanical resonators in the nano-scale.
The talk will give a State-Of-The-Art overview of TO, discuss recent efforts in substituting efficient gradient-based approaches with AI/LLMs, and discuss some recent developments in including internal contact through Third Medium Contact (TMC) approaches as well as challenges in establishing appropriate design parameterizations when optimizing architected materials for fracture response.

Dissipation Rate Considerations for Continuum Slip Crystal Plasticity

Needleman Alan (1)

1 - Professor Emeritus of Engineering, Brown University (United States)

Speaker: Needleman Alan. Invited. **Thursday**. Start time: **10:40**. Room: Saint Clair 3B LVL2. Link to abstract.

The requirement of a non-negative dissipation rate for all possible deformation histories is generally imposed on continuum slip crystal plasticity constitutive relations. This is a constraint analogous to the Coleman–Noll postulate (Arch. Ration. Mech. Anal., 13, 167, 1964) that the Clausius–Duhem inequality needs to be satisfied for all possible deformation histories. The physical basis for the Clausius–Duhem inequality arises as a statistical limit for a large number of discrete events for a long time and is not a fundamental physical requirement for individual events that take place for a short time. Consequences of considering dissipation rate in formulating crystal plasticity constitutive relation are illustrated for: (i) the form of constitutive relation that emerges for a single crystal continuum slip plasticity constitutive framework that accounts for elastic lattice curvature changes as well as elastic lattice straining and (ii) a conventional (size-independent) continuum slip crystal plasticity constitutive relation that incorporates a non-Schmid term into the plastic flow rule so that a non-negative dissipation rate for all possible deformation histories is not guaranteed and the consequences, if any, of a negative plastic dissipation rate are explored.

Fracture of Solids with Covalent Bonds

Yang Wei (1)

1 - Zhejiang University [Hangzhou, China] (China)

Speaker: Yang Wei. Invited. **Thursday**. Start time: **11:00**. Room: Saint Clair 3B LVL2. Link to abstract.

Solids in nano-scales hold the promise to exhibit extreme strength due to the absence of interior defects and the designability of micro-arrangements. A nano-scaled bulk sample can be made by diamond or cubic boron nitride (cBN), featuring the covalent bonds. A loading stage capable of 4-DoF movements was designed and built to achieve multi-axials mechanical loading inside a transmission electronic microscope (TEM) chamber with sub-nanometer loading precision. For single crystal diamond in the shape of nano-needles, we were able to achieve an extreme bending strength of 125GPa at the tensile side, approaching the theoretical strength of diamond. For cBN crystals, a fracture path inclined to the stacking hexagon planes would result in a new failure mechanism of layered decohesion, triggered by the extremely large elastic strain ($> 7\%$) along the edge of the sub-micron scaled specimen. These results indicate ample room for the understanding of the fracture mechanisms of solids with covalent bonds.

Stored versus energy vs dissipation in gradient crystal plasticity: Application to cyclic plasticity and recrystallization

Forest Samuel (1), Ghiglione Flavien Jebahi Mohamed

1 - Mines Paris PSL CNRS (France)

Speaker: Forest Samuel. Invited. **Thursday**. Start time: **11:20**. Room: Saint Clair 3B LVL2. Link to abstract.

The dislocation density tensor is treated as a new constitutive variable of crystal plasticity in addition to the usual scalar dislocation densities and kinematic hardening internal variables, within the framework of strain gradient plasticity. It is an argument of the Helmholtz free energy density function since the accumulation of geometrically necessary dislocations leads to the storage of energy which can be released under suitable thermomechanical loading conditions. Comparison with dislocation dynamics simulations of cyclic plasticity on small scales shows that dissipative contributions to the evolution of the dislocation density tensor must also be included (1). Previous contributions were based on an additive decomposition of the higher order stress tensor into reversible and dissipative parts. An alternative is presented here that splits the dislocation density tensor itself into reversible and dissipative contributions.
The energy stored by geometrically necessary dislocations and statistically stored dislocations is the driving force for grain boundary migration phenomena and grain nucleation in recrystallization processes. The gradient plasticity framework is specialized to a Cosserat crystal plasticity theory and coupled with a phase field approach to simulate microstructure evolution in polycrystals. A striking example is the simulation of grain nucleation events during the torsion of a copper single crystal wire (2).

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(2) F. Ghiglione, A. Ask, K. Ammar, B. Appolaire and S. Forest, *Cosserat-phase-field modeling of grain nucleation in plastically deformed single crystals* , Journal of the Mechanics and Physics of Solids, vol. 187, pp. 105628, 2024. doi:10.1016/j.jmps.2024.105628

Mechanical tension in neurons: a new frontier for mechanics

Saif M Taher (1)

1 - University of Illinois at Urbana-Champaign [Urbana] (United States)

Speaker: Saif M Taher. Invited. **Thursday**. Start time: **11:40**. Room: Saint Clair 3B LVL2. Link to abstract.

Neurons have long been known to transmit information between each other, and support memory, learning, and cognition in animals. They were not considered as force actuators, unlike muscles. Here, we will discuss recent findings revealing that neurons are also contractile. They develop tension after forming junctions (synapses) with muscles or other neurons, and that this tension is necessary for their function. Without tension, their synapses fail to accumulate neurotransmitters that are essential for neurotransmission. Hence, without tension neurons fail to fire and cannot transmit information between each other. Neurons maintain a rest tension using acto-myosin machinery and a feedback mechanism for their functionality. Due to the central role of mechanical tension on neuronal function, mechanics of neurons is emerging as a new paradigm in neuroscience. This new frontier of solid mechanics may offer insights on mental health and diseases and inspire novel therapeutic approaches.

TOPIC: Biomechanics and Medical Implants

MS2.1 - Mechanics of Cells, Proteins, and Microcapsules

Organisers: Anne-Virginie Salsac (UTC) and Patrick McGarry (NUI Galway), José Manuel Garcia Aznar (Universidad de Zaragoza) and Trantafyllos Stylianopoulos (University of Cyprusà)

Assessment of growth-related mechanical stresses in solid tumors and their spatial correlation with extracellular matrix components

Hadjigeorgiou Andreas (1), Stylianopoulos Triantafyllos (1)

1 - Cancer Biophysics Laboratory, Department of Mechanical and Manufacturing Engineering, University of Cyprus (Cyprus)

Speaker: Hadjigeorgiou Andreas. **Thursday**. Start time: **14:15**. Room: Saint Clair 1 LVL2. Link to abstract.

Mechanical stresses within solid tumors significantly influence tumor development and therapeutic outcomes, yet their comprehensive measurement remains underexplored. This study presents an integrated experimental and computational framework for quantifying growth-induced residual stresses in breast (4T1), pancreatic (PAN02), and fibrosarcoma (MCA205) murine tumor models. Orthotopic tumors grew to a size of 500-1500mm3 and shear wave elastography was employed to measure the tumor mechanical properties in vivo. After surgical excision, tumors were embedded in agarose, and two perpendicular cuts were performed to release residual stresses, captured via image processing of the resulting bulging deformations. Finite element models were constructed to quantify these stress levels and immunofluorescence staining of tumor sections was performed to quantify collagen and hyaluronan content. Our findings reveal significant spatial variation in residual stress, driven by the tumor microenvironment's heterogeneity. The bulging displacement profiles, and average magnitudes of maximum displacement varied markedly among and within the three tumor types. The 4T1 tumors showed the lowest average displacement, while PAN02 tumors exhibited the highest. Residual stress measurements ranged from 0.22–4.18 kPa for bulk stress and 0.55–8.22 kPa for third principal stress after the first cut, with an increase to 1.73–5.61 kPa and 3.31–10.88 kPa, respectively, after the second cut. Elastic modulus measurements indicated that MCA205 tumors were the stiffest, exhibiting significant differences from PAN02 and 4T1, and that tumor volume correlated nonlinearly with elastic modulus in MCA205 and 4T1 tumors, stabilizing at an asymptotic value, likely due to extracellular matrix production dynamics.

Critically, spatial correlations were established between hyaluronan and collagen distributions and residual stress, with MCA205 and PAN02 tumors showing strong associations. For 4T1 tumors, only partial associations were noted, potentially due to localized high hyaluronan levels paired with lower cellular density and reduced stress generation. Collagen orientation did not distinctly influence residual stress, though colocalization of hyaluronan and collagen significantly correlated with stress profiles across all models, suggesting their combined role in stress generation. These findings imply that hyaluronan and collagen are pivotal factors.

This study highlights that residual stress and elastic modulus exhibit notable spatial variability, emphasizing the need for comprehensive mapping correlated to extracellular matrix constituents and cellular phenotypes. Insights gained might enhance estimations of mechanical stress in human tumors from biopsies and support the refinement of normalization therapies that modulate tumor mechanics for improved treatment outcomes.

Hadjigeorgiou, A. G., & Stylianopoulos, T. (2023). Evaluation of growth-induced, mechanical stress in solid tumors and spatial association with extracellular matrix content. Biomechanics and Modeling in Mechanobiology, 22(5), 1625–1643. https://doi.org/10.1007/s10237-023-01716-3

BAYESIAN ESTIMATION AND GAUSSIAN PROCESSES APPLIED TO A AGENT-BASED METABOLIC AND MECHANIC MODEL OF TUMOUR SPHEROIDS

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1 - University of Zaragoza (Spain), 2 - Institute for Computational Mechanics, Technical University of Munich, Garching b. Munich, Germany (Germany)

Speaker: Garcia-Gomez Pedro. **Thursday**. Start time: **14:35**. Room: Saint Clair 1 LVL2. Link to abstract.

Introduction

Tumour spheroid growth is significantly influenced by the cellular microenvironment, with two key factors being the availability of nutrients (1) and the mechanical properties of the surrounding microenvironment (2).

In recent years, various mechanical (2) and metabolic computational models (3), (4) have been developed, shedding light on specific aspects of cancer spheroid behaviour. However, a gap remains in the literature for a single data-driven model that integrates these two approaches. Such a model would be a powerful tool in the study and understanding of tumour spheroids.

Methods

Computational model

The proposed agent-based computational model aims to integrate the two approaches discussed in the previous section: the metabolic and mechanical. For the mechanical component (2), we utilise PhysiCell (5) as the primary simulation platform. The model focuses on the extracellular matrix (ECM) density as the key mechanical factor for the cells. A force that goes against the movement of the cells is introduced to take into account this ECM. The value of this force will depends on the collagen density of the extracellular matrix and has been calibrated with experimental data.

Regarding the metabolic part of the model, we used COPASI (6), a software that supports SBML (7) to simulate using ODEs the chemical reactions that take place inside the cancer cells. The model proposed has four main metabolic equations: the glycolysis, the OXPHOS reaction, the lactate production reaction and the dissipation of energy.

Bayesian estimation and Gaussian process

Bayesian estimation in conjunction with Gaussian processes are one of the most powerful tools for combining experimental and computational data. These tools not only allow to subtract mathematical tendencies form the model, but also tuning the parameters of the computational model according to the experimental data.

The exploration and calibration of the parameters of the model require a lot of computational simulations. In order to minimise the computational time of these simulations, we implemented a Gaussian process. This computational processes have to be trained with a set of simulations of the model. After the training, the Gaussian processes is able to reproduce the outputs of the model without the need to execute the actual model.

Once the Gaussian process is trained, we are able to explore the parameters of the model more in depth and compare them with the experimental data through the Bayesian estimation of parameters.

Later, the Bayesian estimation compares the output of the computational model with the in vitro experiments, and gives a set of parameters that reproduce the data of the experiments more precisely.

Results

This model is designed to replicate spheroid growth and metabolite consumption observed in vitro. The model reproduces some qualitative behaviours well observed in cancer spheroids such as the formation of a necrotic core in medium sized spheroids. In addition to that, it has been observed that the model is able to mimic the range of spheroid sizes observed in microfluidic devices in in vitro experiments.

A study of the maximum cross sectional area of the spheroids depending on the metabolic activity of

the cancer cells has also been made using this model. This study shows smaller spheroids when the metabolism rate of the cells is low. The spheroids grow as the metabolism activity of the cells is increased until a maximum where the size saturates due to the limited amount of nutrients available to the cell. Moreover, it has been observed that the model produces bigger spheroids for denser collagen matrix.

Discussion

The presented model successfully reproduces qualitative and quantitative phenomena observed in tumour spheroids, such as the necrotic core formation. After the Bayesian optimization process, the model can replicate quantitative in vitro measurements, including spheroid growth and metabolite consumption. Additionally, the Bayesian optimisation process estimates crucial biological parameters that are challenging to measure, such as the metabolic equilibrium constants of the chemical reactions that take place in the cell.

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Acknowledgements

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DIGITAL FUNCTIONAL IMAGING AT MICROSCALE: A STUDY OF OSTEOSARCOMA TREATMENT RESISTANCE

Marty Tristan (1), Gomez-mascard Anne (2), Quintard Michel (1), Swider Pascal (1), Assemat Pauline (1)

1 - Institut de mécanique des fluides de Toulouse (France), 2 - Centre de Recherches en Cancérologie de Toulouse (France)

Speaker: Marty Tristan. **Thursday**. Start time: **14:55**. Room: Saint Clair 1 LVL2. Link to abstract.

INTRODUCTION

Osteosarcoma is a malignant primary bone tumor that primarily affects children and young adults. It is characterized by the disorganized production of bone by tumor cells. The high genomic complexity of osteosarcoma has hindered the identification of recurrent therapeutic molecular targets or specific biomarkers of treatment resistance. This complexity results in both intra-tumoral and inter-individual heterogeneity (1), which can be analyzed at various scales: genomic, molecular, metabolic, cellular, tissue, or macroscopic. Additionally, the structural and fluid mechanical effects acting on osteosarcoma components further complicate the understanding of the tumor microenvironment.

To investigate treatment resistance, this study focused on the tissue scale, guided by clinical routine histological images. At this scale, tumoral tissue can be modeled as a spatially heterogeneous porous medium, consisting of fluid, cellular, fibrous, and osseous solid phases.

METHODS

Using machine learning techniques, we developed a methodology to explore the correlation between tissue porosity and microenvironment cell density (2), aiming to uncover relationships between cells and the extracellular matrix, which differ in their characteristic dimensions. This approach involves the development of efficient segmentation and statistical tools tailored for large-scale images (50 000 px $\times$ 50 000 px) extracted from histological and immunohistological slices obtained during clinical routines.

From the segmentation results, the solid phase was isolated, and using porous media theory, we developed a novel digital functional imaging technique to analyze the mechanical and transport properties of the tissue based on human histological and immunohistological data. We propose a robust upscaling method to characterize the mechanical properties of the tumor microenvironment, which can be modeled as a strongly heterogeneous porous medium. This method employs a sequential grid-block approach (3,4), following image segmentation. Interstitial fluid transport and elastic models were investigated, and piece-wise constant equivalent parameters, such as tissue permeability and stiffness coefficients, were reliably determined.

RESULTS

From the geometrical analysis of the data, we identified a negative correlation between bone matrix porosity and macrophage density, which served as a marker of favorable response to chemotherapy in osteosarcoma patients. Additionally, a relatively high lymphocyte density was found to correlate with patient survival without metastasis or relapse.

From the mechanical analysis, we identified correlations between elastic properties, transport properties, and cell distribution in the microenvironment, depending on treatment response. These findings highlighted the impact of the microarchitecture of neo-formed bone on chemotherapy patients' response. Specifically, chemotherapy was found to be more effective in lacy-like neo-formed bone regions compared to trabecular-like regions. Areas with favorable treatment response corresponded to a decreasing number of residual cells and reduced local tissue permeability and stiffness.

CONCLUSION

In conclusion, we developed an innovative approach based on heterogeneous porous media theory and clinical data to investigate the properties of the tumor microenvironment. This novel *in silico* functional imaging technique is generic and can be adapted to different physical properties and other cancer types. Currently being validated on a large patient cohort, the new osteosarcoma response and prognostic signatures identified in this study could be integrated into post-surgical therapeutic stratification algorithms

to optimize patient-specific therapies.

References

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Multicellular computational and in-vitro models to uncover the mechanisms underlying mechanosensitive tumour growth

Eoin Mcevoy (1)

1 - School of Engineering, University of Galway (Ireland)

Speaker: Eoin Mcevoy. **Thursday**. Start time: **15:15**. Room: Saint Clair 1 LVL2. Link to abstract.

Introduction

Tumour growth is a complex mechanosensitive process guided by feedback between cells and the extracellular matrix (ECM). Sensitivity to mechanical cues can influence tumour progression and impact disease outcomes (1). Critically, the underlying biomechanisms by which external loading impacts tumour growth remain unknown. In this study, we first develop an in-vitro culture system for heterogeneous tumour spheroids to identify key biomechanical factors that restrict spheroid growth. We then propose a novel framework consisting a novel hydromechanical cell growth model, a 3D deformable cell framework and a deep-neural network (DNN)-accelerated finite element (FE) solver to uncover the mechanisms underlying mechanosensitive growth.

Methods

In-vitro spheroids: Murine breast cancer (4T1) cells were cultured, isolated and propagated to obtain distinct phenotypes (epithelial-like, amoeboid-like). Tumour spheroids were generated by either seeding cells within gelatin hydrogels of varying stiffness to investigate stress-dependent responses, or into 96-well plates layered with agarose cryogels (formed by freeze/thawing of solid agarose hydrogels) to determine how mixing ratios govern growth. Hydromechanical cell model: A mathematical model was developed to predict cell growth as driven by a competition between hydrostatic pressure arising from active cell stress and external loading, and osmotic pressure arising from biomolecule synthesis and ion fluxes (2). Biomolecules are synthesized during the G1 growth phase, which drives a fluid influx and growth through entropic osmotic forces. Multicellular growth: The hydromechanical model was integrated with MPacts (3), a discrete element method platform for multicellular mechanics, where cells are described as foam-like fluid-filled membranes. Cell growth is achieved by predicting the internal pressure required to attain the target cell volume with a proportional integrated controller. Coupled with tractions from cell and matrix contact interfaces, there is feedback in turn to govern the cell growth rate, and we consider that mitosis is subject to surpassing a critical volume checkpoint for which the underlying mechanisms are characterised. DNN-FE acceleration: The deformable cell model is embedded in a 3D finite element model of a hyperelastic matrix. To efficiently simulate this matrix deformation, a deep neural network (DNN) framework was developed. Synthetic training data for a diverse range of loading scenarios was generated using Abaqus and subsequently provided to a fully connected DNN comprised of 4 layers with 8,192 neurons per layer to obtain a converged solution.

Results and Discussion

Analysis of the in-vitro spheroids reveals that tumour spheroid size reduces with increasing gel stiffness. Importantly, there was a significant reduction in the number of cells per spheroid and lower number of proliferative cells as determined by Ki-67 immunofluorescence. 4T1 spheroids developed from predominantly amoeboid-like cells were observed to have 2-3 fold larger diameters than epithelial-like spheroids. Our computational models predict that cell growth increases with biomolecule synthesis and the subsequent increase in osmotic pressure, which deforms surrounding matrix. Standard simulation of multicellular growth with matrix contact carries a significant computational cost (203s per FE increment). Although there is a relatively high one-time up-front computational cost for synthetic training data generation and model training, our trained NN models can predict highly non-linear material behaviour with a negligible computational cost (133

Evaluation of cancer cells mechanical phenotype associated with the resistance to treatment in myeloid leukemia

Martin Cardozo Camila (1) (2), Lefort Sylvain (2), Giannini Mariette (2), Faivre Magalie (3)

1 - INL - Dispositifs pour la Santé et l'Environnement (France), 2 - Centre de Recherche en Cancérologie de Lyon (France), 3 - INL - Dispositifs pour la Santé et l'Environnement (France)

Speaker: Martin Cardozo Camila. **Thursday**. Start time: **15:35**. Room: Saint Clair 1 LVL2. Link to abstract.

Acute myeloid leukemia (AML) is a cancer of the myeloid line of blood cells, characterized by an abnormal proliferation of leukemic cells (or blasts) that build up in the bone marrow and the blood. Despite the recent progress in therapies, which consist essentially in intensive cycles of chemotherapy or the use of targeted therapies, most of the AML patients do not recover, having a five-year survival rate of 20% (1). This poor prognosis may be explained by tumor cell heterogeneity, which could be related to cellular differentiation, as well as to the tumor microenvironment. Indeed, the rapid clonal expansion of leukemic blasts within the bone marrow alters the physical characteristics of the tumor microenvironment and decreases the available space for each cell type. This project seeks to establish a correlation between drug resistance and leukemic cell intrinsic stiffness, in the context of the dynamic dialogue between leukemic cells and their microenvironment.
One of the most widely utilized passive microfluidic methods in literature for measuring cellular mechanical properties with high throughput involves the monitoring of cell deformations as they flow passively through constricted channels (2). Here we propose an original readout traducing the way the cell perturbs the pressure distribution within the device, as it blocks the flow when passing through the constriction (3). Preliminary results suggest different mechanical profile associated with AML cell lines that are sensitive or resistant to chemotherapy, consistent with findings in the literature (4), hence demonstrating the pertinence of our approach. Furthermore, our data suggests that the mechanical properties of resistant AML cell lines may be treatment-dependent, varying with the applied therapeutic agent.

Moreover, our findings demonstrate that our microfluidic device allow for detecting alteration of the mechanical properties of drug-sensitive cells following short exposure to therapeutic drugs (as early as 2 hours). Indeed, we report an overall increase in the intrinsic rigidity of cells after treatment; this increased rigidity is the first stage of the cell death to come, hence traducing drug sensitivity, which is also reported in other studies (5).We confirm the relevance of our approach by evaluating the drug sensitivity of primary cells, specifically bone marrow and peripheral blood samples, examining their cell mechanics following a 2-hour chemotherapy exposure.

The long-term objectives of this study are to (i) to develop a device for personalized drug screening capable of rapidly (within 2 hours) identifying the most effective treatment for a patient's cells; and (ii) to detect the presence or emergence of cells with a resistant profile.

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Endothelium response to supraphysiological stretch

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Speaker: Mazza Edoardo. **Friday**. Start time: **10:00**. Room: Saint Clair 1 LVL2. Link to abstract.

The endothelium is a cell monolayer lining the luminal surfaces of blood vessels. It forms a barrier between blood and surrounding tissues controlling the transport of molecules in both directions. Numerous clinical applications are associated with supraphysiological deformations of the endothelium, such as in angioplasty, stent placement, ventilator-induced injury, vein grafts in coronary artery bypass and blood-hammering. In such cases acute vascular damage and consequent endothelial cell loss are observed, which can lead to severe complications. In all these conditions endothelial cells undergo a mechanical loading to supraphysiological levels of stretch in short time. Our investigations aimed at determining critical conditions of endothelium stretching leading to partial or complete rupture of monolayers. To this end, we cultured endothelial cells to form a confluent monolayer on an elastomeric substrate to which we then applied uniaxial and multiaxial deformation at different strain rates. Stretch-induced damage of monolayers consisting of young, senescent, and aged endothelial populations was quantified for different stretching conditions (1). A computational discrete network model of endothelial cells under acute stretch was developed to rationalize stretch-induced damage based on phenotypic differences between cell groups (2).

High-rate experiments aimed at characterizing the instantaneous (i.e. without active cell remodeling) deformation and rupture behavior to stretches in uniaxial stress, uniaxial strain and equibiaxial conditions. The level of damage was evaluated by immunofluorescence or scanning electron microscopy as intercellular and intracellular void formation. Damage increased proportionally to the applied level of deformation, with equibiaxial stretch inducing much larger damage compared to the other conditions at the same value of maximum principal stretch.

For uniaxial strain of 40%, the aged and senescent phenotype experienced significant detachment of cells following stretch-induced damage, while the young counterpart was able to maintain or restore monolayer integrity. Larger damage in aged cells was observed also in cyclic experiments at moderate stretch levels. Based on the computational model, fragile behavior of aged cells was linked with their more mature focal adhesions, which lead to a more stable cell-substrate attachment of senescent cells. In fact, more affine deformation increases intracellular deformation energy, thus enhancing the tendency for cellular damage and impending detachment. Supportive of this hypothesis, cell damage was significantly reduced when senescent cells were treated to block integrin $\beta 1$, thus reducing their overall adhesion to the substrate.

Larger stretch levels, such as those associated with balloon angioplasty and stent placement, induced widespread cellular loss when applied at high rates. Remarkably, at slower rates (i.e. loading within few minutes) even for stretches larger than 200% aged cells were able to adapt, with depolymerization of the actin fibers and extension of the intermediate filaments, maintaining monolayer integrity.

In summary, the present study characterized for the first time critical levels of endothelial stretch and the rupture pattern of endothelial monolayers, depending on mechanical loading conditions. The results indicate that young cells are generally more resilient to deformation than senescent cells. Importantly, cells were able to survive very large deformations when stretching occurred at rates lower than those typically applied during clinical interventions. This may indicate a potential avenue for reducing medical complications.

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Microrheometric study of damage and rupture of capsules in simple shear flow

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Speaker: Salsac Anne-Virginie. **Friday**. Start time: **10:20**. Room: Saint Clair 1 LVL2. Link to abstract.

Microcapsules, which are fluid droplets enveloped by a thin elastic membrane, are widely used in industry to protect and transport active substances, aromas, cells, etc. When subjected to an external flow, they undergo strong deformations, which can potentially lead to their breakup. Since the 1990's, capsule membrane properties have been studied until breakup subjecting the particles to various flow conditions: simple shear flow (1), hyperbolic flow (2), spinning flow (3), tube flow (4), etc. But hardly any study provided a comprehensive set of experimental data on rupture or investigated the underlying damage phenomena that eventually lead to breakup. To overcome the lack of experimental data in the literature, we have conducted a microrheometric study of microcapsules, subjecting them to simple shear flow conditions leading to their damage and rupture. Our objectives are to characterize the impact of damage on the mechanical properties of the capsule membrane and determine the occurrence of rupture depending on the parameters of the problem. Suspensions of ovalbumin microcapsules are prepared using an interfacial cross-linking technique (5). This technique provides spherical deformable capsules with radii ranging from a few dozens to a few hundreds of microns. To avoid any osmotic prestress in the membrane caused by differences in concentration between the internal and external fluids, capsules are suspended in a glycerol solution containing 3 %(w/v) of ovalbumin. They are then sheared in a counter-rotating microrheometer under increasing values of shear rate and exposure time to shear. They are visualized using a high speed camera in the mid-plane of the shear flow in order to determine whether each of the capsules entering the shear flow mid-plane has been damaged or not by hydrodynamic forces. The surface shear modulus of observed capsules is identified using the inverse analysis method of Wang et al (4): it consists in comparing the measured capsule profiles with those computed by a full numerical model solving the capsule-flow interactions and in finding the best fit. For time exposures above 2 minutes, a significant decrease in surface shear modulus is observed over time for capsules of radius larger than 50 μm.

The study of rupture is based on the quantification of the number of capsules present before and after shear exposure for different values of shear rates and exposure times to shear. The difference between both is assumed to be the number of ruptured capsules. The percentage of broken capsules increases with their radius. A phase diagram is obtained varying the capillary number (ratio of the viscous to the elastic characteristic forces) and the exposure time to shear. For a given exposure time to shear, increasing the capillary number increases the probability of rupture. And as the exposure time to shear increases, the capillary number required to observe capsule breakup decreases.

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Predicting tumor response to chemo-immunotherapy using attention-enhanced deep learning models and shear wave elastography

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Speaker: Voutouri Chrysovalantis. **Friday**. Start time: **10:40**. Room: Saint Clair 1 LVL2. Link to abstract.

Personalized cancer therapy demands precise tools for predicting tumor response to treatment, as tumor heterogeneity often results in varied therapeutic outcomes. In this study(1), we introduced a novel deep learning-based framework that leverages shear wave elastography (SWE) imaging and convolutional neural networks (CNNs) augmented with attention mechanisms to predict the therapeutic response of tumors. Tumor stiffness, a mechanical property quantifiable through SWE, has been increasingly recognized as a critical biomarker for predicting treatment outcomes. However, its predictive potential remains underexplored in the context of chemo-immunotherapy, particularly when combined with advanced AI methodologies. Addressing this gap, we developed the Prognose-CNNattention model, specifically designed to utilize SWE imaging data to categorize tumors as responsive, stable, or non-responsive to therapeutic interventions.
The study leveraged a dataset comprising 1,365 SWE images obtained from 630 murine tumors across a variety of cancer types, including breast adenocarcinoma (4T1, E0771), melanoma (B16F10), fibrosarcoma (MCA205), and osteosarcoma (K7M2). Tumors underwent pre-treatment with mechanotherapeutic agents to modulate their stiffness before initiating chemo-immunotherapy. The Prognose-CNNattention model achieved a remarkable predictive performance, with an area under the curve (AUC) of 0.96 and an accuracy of 87%, significantly outperforming conventional CNN architectures and pre-trained models such as Xception, VGG16, Inception-v3, and ResNet50. These results underscore the capability of attention mechanisms to enhance predictive accuracy by focusing on salient features within the imaging data, particularly long-range spatial relationships that conventional CNNs might overlook.

The framework also integrated an automated segmentation module, termed Auto-Prognose-CNNattention, combining SWE and B-mode ultrasound images to delineate tumor regions of interest. This fully automated pipeline significantly streamlined the predictive workflow by eliminating the need for manual tumor segmentation. Utilizing a U-Net-based architecture for segmentation, the system achieved high concordance with manual annotations, as evidenced by Dice scores ranging from 0.79 to 0.81 across various tumor types. The integration of segmentation and classification in a unified pipeline demonstrated slightly reduced predictive performance compared to the Prognose-CNNattention model alone but remained robust, offering a practical solution for real-world applications where manual annotations are often impractical.

This research contributes significant advancements to the field of predictive oncology. First, it demonstrates that tumor stiffness, quantified through SWE imaging, can serve as a reliable non-invasive biomarker for predicting therapeutic outcomes, providing actionable insights before treatment initiation. Second, it highlights the transformative potential of attention-enhanced CNNs in medical imaging. The inclusion of attention mechanisms within the model architecture enabled it to identify and focus on critical regions of interest, such as areas of high stiffness, while also considering global image context. This approach markedly improved the interpretability and diagnostic performance of the model, making it a valuable tool for clinical decision-making.

The study also addresses the challenges associated with tumor heterogeneity, both across and within tumor types. By analyzing SWE data from diverse tumor models collectively, the findings suggest that the biomarkers identified through this approach are broadly applicable, independent of specific tumor

types. This generalizability is particularly important for clinical translation, as it indicates that the model can potentially be adapted to a wide range of cancer settings.

Furthermore, the automated segmentation and classification framework was rigorously evaluated for robustness and reproducibility. Assessments of inter- and intra-user variability revealed consistent performance across different evaluators, including laboratory experts and radiation oncologists. This consistency underscores the reliability of the framework in practical applications, where variability in human interpretation can significantly impact outcomes. By reducing dependence on manual input, the automated pipeline enhances the reproducibility of tumor response predictions, a critical factor for clinical adoption.

The clinical implications of this work are profound. SWE imaging is already an established tool in oncology for assessing tumor stiffness and staging. Integrating it with AI-driven predictive frameworks could revolutionize its utility, transforming it from a diagnostic modality to a prognostic tool. The ability to predict tumor response to therapy using non-invasive imaging techniques has the potential to significantly improve patient outcomes. By enabling early and accurate identification of non-responsive tumors, clinicians can avoid ineffective treatments and explore alternative therapeutic strategies, thereby minimizing patient exposure to unnecessary side effects and optimizing resource utilization.

Additionally, the study lays a foundation for future clinical trials aimed at validating the proposed framework in human patients. Early collaborations with oncology centers have shown promising preliminary results, with ongoing efforts to adapt the model for human tumors. Transfer learning techniques are being employed to fine-tune the model on smaller datasets of human SWE images, leveraging the extensive preclinical data to bridge the gap between laboratory research and clinical practice. These efforts are expected to accelerate the clinical translation of this technology, bringing it closer to integration into standard diagnostic and treatment workflows.

The research also acknowledges the limitations of its preclinical focus. While the use of murine models offers a controlled environment for developing and validating predictive methodologies, the mechanical and biological properties of human tumors present additional complexities. Addressing these challenges will require extensive validation studies and iterative refinement of the model. The incorporation of additional data modalities, such as genomic and molecular biomarkers, could further enhance the predictive power of the framework, paving the way for a more holistic approach to personalized cancer therapy.

In conclusion, this study presents a comprehensive and innovative approach to predicting tumor response to therapy, combining the strengths of SWE imaging and advanced AI methodologies. The Prognose-CNNattention model, with its attention-enhanced architecture, sets a new benchmark for predictive performance in this domain. The integration of automated segmentation further enhances its practicality, offering a scalable solution for clinical settings. By providing early and accurate predictions of therapeutic outcomes, this framework supports the development of personalized treatment strategies, ultimately improving patient care. Future directions will focus on validating the model in clinical trials, exploring its applicability to other imaging modalities, and integrating additional biomarkers to create a robust, multi-dimensional prognostic tool.

(1) Voutouri, C., Englezos, D., Zamboglou, C. et al. A convolutional attention model for predicting response to chemo-immunotherapy from ultrasound elastography in mouse tumor models. Commun Med 4, 203 (2024). https://doi.org/10.1038/s43856-024-00634-4

MS2.2 - Mechanics of Soft Biological Tissues

Organisers: Aline Bel-Brunon (LAMCOS) and Gerard Ateshian (Columbia)

Mechanics of entropic biopolymer networks from the thermodynamics of molecular motors

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Speaker: Etienne Jocelyn. **Wednesday**. Start time: **10:00**. Room: Rhône 4 LVL1. Link to abstract.

Contractile biopolymer networks, such as the actomyosin meshwork of animal cells, are ubiquitous in living organisms and contribute in a large part to their function such as muscle contraction or embryonic morphogenesis. Their contractility relies on the active behaviour of molecular motors which crosslink the biopolymer of the network and can transduce at the molecular scale chemical energy into mechanical work (Jülicher et al, *Rev Mod Phys* 69, 1997).

The active gel theory (Kruse et al, *Eur Phys J E* 16, 2005), which provides a thermodynamic framework for these materials, has been mostly used in conjunction with the assumption that the microstructure of the biopolymer network is based on rigid rods (Liverpool and Marchetti, *Phys Rev Lett* 97, 2006). However, experimentally, crossed-linked actin networks exhibit entropic elasticity (Gardel et al, *Science* 304, 2004). Here we combine an entropic elasticity kinetic theory, in the spirit of the Green and Tobolsky model (*J Chem Phys* 14, 1946) of transiently crosslinked networks, with an active flux modelling motor activity (arXiv:2405.07287). We determine this active flux using Onsager reciprocal relations applied at the microscopic scale of individual motors. We derive the macroscopic active stress that arises from the resulting dynamics and obtain a closed-form model of the macroscopic mechanical behaviour. Although similar to models commonly chosen in the active gel theory, the choice of entropic elasticity provides it with specific features of quantitative importance (Etienne et al, *Proc Natl Acad Sci USA* 112, 2015). Additionally, the analytical clarity of the derivation allows us to give microscopic interpretation of macroscopic active behaviours of contractile networks.

Predicting the mechanical properties of spring networks

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Speaker: Grossman Doron. **Wednesday**. Start time: **10:20**. Room: Rhône 4 LVL1. Link to abstract.

The elastic response of mechanical, chemical, and biological systems is often modeled using a discrete arrangement of Hookean springs, either representing finite material elements or even the molecular bonds of a system. However, to date, there is no direct derivation of the relation between a general discrete spring network and it's corresponding elastic continuum. Furthermore, understanding the network's mechanical response requires simulations that may be expensive computationally. Here we report a method to derive the exact elastic continuum model of any discrete network of springs, requiring network geometry and topology only. We identify and calculate the so-called "non-affine" displacements. Explicit comparison of our calculations to simulations of different crystalline and disordered configurations, shows we successfully capture the mechanics even of auxetic materials. Our method is valid for residually stressed systems with non-trivial geometries, is easily generalizable to other discrete models, and opens the possibility of a rational design of elastic systems.

MULTI-SCALE MECHANICS OF THE HUMAIN CORNEA

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Speaker: Jean Marc Allain. **Wednesday**. Start time: **10:40**. Room: Rhône 4 LVL1. Link to abstract.

Keywords*:* Cornea; biomechanics; soft tissue; experimental; DVC

1. Introduction

Cornea is the transparent outermost layer of the eye. It provides approximately two-thirds of the eye's refractive power. Healthy human cornea is spherical-shaped. In patients with keratoconus, the cornea becomes thinner and gradually extends outward into an irregular cone shape. The disease can lead to blurred or distorted vision.

Stroma is the middle and thickest layer of the cornea. It is formed of stacked lamellae made of aligned collagen fibrils. The stroma is responsible for corneal biomechanical stability. Weakened biomechanical properties are believed to cause progressive steepening and thinning in keratoconus (Padmanabhan and Elsheikh 2023, Giraudet et al. 2022).

Vogt's striae are frequently observed in the posterior stroma in advanced keratoconus, undergoing classical clinical evaluation such as slit-lamp examination. However, with more powerful diagnostic techniques such as histology, confocal microscope, full-field optical coherence microscopy, the striae can be detected in 82% of patients with and without keratoconus. Notably, in patients with keratoconus, striae were significantly more numerous than in normal ($p = 0.01$) (Grieve et al. 2017).

Vogt's striae may cause biomechanical deterioration in keratoconus eyes (Rakhshandadi et al. 2021, Mocan et al. 2008). However, their contribution to stroma mechanical behavior remains poorly understood. In the first part of the study, we carried out inflation tests on human healthy corneas coupled with optical coherence tomography (OCT) imaging, to investigate the mechanical properties of stromal striae.

Human corneas are stored in a culture medium to preserve the metabolic activities of corneal cells. This preservation method induces corneal swelling due to natural penetration of fluids. The deturgescence is carried out to compensate for this swelling and obtain stabilized physiological thickness of cornea.

In the first part, we observed that, despite the corneas being placed in a deturgescence medium for 48 hours before the experiments, their initial thickness remained greater than physiological values. This suggests that the corneas were not in a physiological hydration state.

The second part of the study aims to better understand the underlying mechanism of the deturgescence process and compare various protocols to propose the most suitable one for stabilizing corneal thickness.

2. Methods

We performed inflation tests under Optical Coherence Tomography (OCT) on eleven fresh and healthy corneas taken from human donors.

The corneas were placed freely in deturgescence medium (StemAlpha3) 48 hours prior to the experiments to recover the relative dehydration state of the tissue.

For the inflation test, the cornea was placed on the top of an artificial anterior chamber. A software-controlled injector injected StemAlpha3 and control the pressure inside the anterior chamber. The cornea was brought to high pressure of 200 mbar though small steps of 15 mbar (physiological pressure being 20 mbar). To ensure hydration of the anterior surface of the cornea, a drop of ophthalmic gel (Lacrigel 0.2%) was placed over the cornea.

During the inflation test, OCT 3D images were taken from the central area of each cornea containing stromal striae. The OCT images were then segmented into binary images, with white pixels corresponding to striae and black pixels to other areas. The striae planes were extracted from these binary images, while the principal strain maps were obtained by digital volume correlation (DVC).

To investigate deturgescence, we tested four distinct configurations. In the first three configurations, the cornea was positioned on an artificial anterior chamber, as for the inflation test presented previously. However, instead of using an injector, the chamber was maintained at a constant hydrostatic pressure through a fluid column filled of StemAlpha3. In the first configuration, Lacrigel was regularly applied over the cornea. In the second configuration, Lacrigel was applied once and remained permanently in

place. For the third configuration, the anterior surface of the cornea was immersed in StemAlpha3. In the final, the cornea was freely immersed in StemAlpha3.

3. Results and discussion

Mechanical role of corneal stromal striae

The principal strains inside striae are higher than outside striae ($p < 0.01$). The mean normalized principal strain in striae group is two times higher than another group. Maximum principal strains are co-localized with the striae. Consistently, Hollingsworth (2005) observed stromal banding using confocal microscopy and suggested that these correspond to areas of reduced strength in the cornea.

The distribution of angle deviations between normal directions of striae planes and directions of principal strains is centred on 1.04∘ (+/- 32.06∘). The maximum principal strains are oriented mostly perpendicular to the striae. The distribution of angle deviations depends on principal strain level: small values are found for high principal strains higher than 5%, while the values are distributed over a much larger range for low principal strains. The large angle deviations at low principal strain could be explained by errors from fitting process of striae plane and correlation process, and noise from experimental measure.

We observe that principal strains increase with depth in the cornea. In posterior stroma, the increase inside striae is steeper than outside areas, while in anterior cornea, the increase is almost the same for both. The extra deformability in posterior stroma is due to the presence of striae, which become more and more visible on the OCT images when it approaches the bottom of the cornea. The literature on corneal elastic moduli consistently reported that the anterior stroma is stiffer than the posterior stroma (Leonard et al. 2019).

We observe also that striae pattern and location don't change with pressure, even far above physiological pressure. The striae probably are stable microstructure, as stromal lamellar undulations were discovered in the study of Grieve (2017). The striae become less visible when the pressure increases, likely as their undulation features fade with pressure.

Although keratoconus corneas were not assessed in our study, our findings in normal corneas suggest that the more numerous the striae, the more deformable the cornea, and therefore the more severe the keratoconus. This correlation between the number of striae and the disease severity is well documented in the literature (Zadnik et al 1996, Grieve et al. 2017).

Control of corneal deturgescence

We plotted the corneal thickness over time during deturgescence. Across all four configurations, we observed an initial decrease in corneal thickness. In the conurations with Lacrigel, there were rebounds in thickness. In the configuration where Lacrigel was added regularly, thickness rebounded at each addition. In the configuration with permanent Lacrigel, the thickness increased continually. Conversely, in the configurations with StemAlpha3, corneal thickness stabilized after 25-30 hours.

4. Conclusions

Our results indicate that striae are structures associated to higher deformability. The principal strain occurs in the direction almost perpendicular to the striae. The local biomechanical change may be due to microstructural changes in stromal striae such as undulations in continuous lamellae (Grieve et al. 2017, Mocan et al. 2008).

In the posterior stroma, the increase of principal strain inside the striae is steeper than that outside the striae. This means that the striae provide an extra compliance to the stroma in the posterior region.

Next steps would be to observe the behavior and structure of the striae more closely by using second harmonic microscopy, and analyze the strain around the stromal striae at the scale of collagen lamellae. Furthermore, stromal striae should be considered in the biomechanical modelling of the entire cornea.

Furthermore, we demonstrated that the configurations with StemAlpha3 completely surrounding the cornea maintained a stable corneal thickness after 25 hours. Among these, the configuration with the cornea attached to the artificial anterior chamber proved to be the optimal setup, as it approximates the conditions used in the inflation tests.

Acknowledgements

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Conflict of interest statement
The authors declare that there is no conflict of interest.

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Exploring the link between cellular mechanisms and cortical folding in the developing human brain

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Speaker: Budday Silvia. **Wednesday**. Start time: **11:00**. Room: Rhône 4 LVL1. Link to abstract.

Brain development is a complex process that involves a precisely orchestrated sequence of genetic, biochemical, and physical events. At the cellular scale, different types of progenitor cells divide to eventually produce neurons that then migrate towards the brain surface to form the cortex. At the organ scale, physical forces play a central role in translating these cellular mechanisms into the complex surface morphology of the human brain. The folding pattern is not only the prerequisite for higher cognitive functions, but also a classical hallmark of diseases such as epilepsy. In this context, computational models are a valuable tool to understand the link between cellular brain development and cortical folding to eventually advance diagnosis and treatment strategies for cortical malformation associated with neurological disorders. Here, we present a computational model that couples advection-diffusion equations representing the behavior of different cell types in the developing brain with the theory of finite growth to describe cortex expansion and cortical folding at the macroscopic scale. The model allows us to explore the link between cellular division and migration at the cell scale and (ab)normal folding patterns at the tissue or organ scale. We calibrate our model based on histological sections of the human fetal brain and prove its validity through comparisons with magnetic resonance images. The presented framework can not only improve our understanding of human brain development but could eventually help diagnose and treat neurological disorders arising from disruptions in cellular development and associated malformations of cortical development.

Poro-piezo-electromechanical model demonstrates how voltage gated ion channels can be activated by mechanical loading intervertebral disc tissue

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Speaker: Huyghe Jacques. **Wednesday**. Start time: **11:20**. Room: Rhône 4 LVL1. Link to abstract.

Strain-generated potentials (SGPs) are known to activate mechanosensitive ion gating (2). Measured strain generated potentials have been attributed to electrokinetic phenomena such as streaming potentials. However, streaming potentials are generated between the extracellular space and the external solution, while the voltage gated ion channels sense the intra-extracellular voltage differences. Hence, our research question is: what potential can possibly activate the voltage gated ion channels during loading of the intervertebral disc? Using piezo force microscopy (1,3), we provide experimental evidence to support the potential contribution of piezoelectricity (mechano-transduction of electricity) in a linear and reversible manner with charge accumulation measured within human intervertebral discs (IVD) of 43.2 μC/m2 which is comparable to the threshold value (44.5 μC/m2) reported for cell membrane depolarization. Based on this finding in dehydrated tissue, we present a poro-ptezo-electromechanical model to demonstrate the effect of piezoelectricity of a hydrated extracellular space on the voltage-gating of ion channels. The piezoelectric effect was computed to increase the voltage gradient within the double layer of the membrane by 1 million V/m, resulting in a voltage signal of around 1 mV across the cell membrane, while streaming potential was predicted to have the sole ability to generate a mV response between the tissue and blood vessels outside the disc tissue. The latter signal cannot possibly be captured by the ion gates of the cell, while the piezoelectric signal can.

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A Thermodynamic framework for the mechanically driven remodelling and fiber reorientation in soft biological tissues

Kumar Rahul (1)

1 - Indian Institute of Technology Madras (India)

Speaker: Kumar Rahul. **Wednesday**. Start time: **11:40**. Room: Rhône 4 LVL1. Link to abstract.

Fiber alignment in soft biological tissues is governed by cellular responses to mechanical stimuli arising from the properties of the surrounding material. This interaction, which couples mechanical anisotropy with tissue remodelling, can be effectively captured through fibre-reinforced hyperelastic models. In this study, we present a thermodynamics-based framework for modelling fibre reorientation, emphasizing the role of the second law of thermodynamics in governing the remodelling process. Fibre reorientation is modelled analytically in a rectangular elastic tissue reinforced with two symmetrically arranged fibre families subjected to constant external loads. The framework predicts fiber alignment with the maximum principal stretch and demonstrates that the system converges to stable equilibrium states. This modelling approach is robust across a wide range of material parameters and loading conditions, providing a comprehensive understanding of tissue adaptation mechanics. Insights from prior experimental studies on vascular remodelling and arterial wall mechanics during pathological conditions, such as hypertension and abdominal aortic aneurysm (AAA) progression, are incorporated. Structural and mechanical data are integrated into the model, revealing connections between collagen fibre orientation, anisotropic material behaviour, and disease progression.

Computational modelling of the peristaltic contractions of the human stomach

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1 - Hamburg University of Technology (Germany), 2 - University of the Bundeswehr (Germany), 3 - Campus Bio-Medico University of Rome (Italy)

Speaker: Cyron Christian. Keynote. **Wednesday**. Start time: **14:30**. Room: Rhône 4 LVL1. Link to abstract.

Health problems related to the mechanics of the stomach (gastric mechanics) are among the most important causes of morbidity in industrialized countries. Around 10% - 45% of the general population suffer from dyspepsia (difficult digestion), which seriously compromises individual well-being and economic productivity and is often linked to the motility of the stomach. At the same time, the biomechanics of the stomach still remains poorly understood, especially compared to the cardiovascular system. Currently, biomechanical modeling of the human stomach lags around one to two decades behind biomechanical modeling of the cardiovascular system. To help close this gap between medical needs and the state of science, we are developing a comprehensive computational model of the motility of the stomach. Here we present the theoretical and computational foundations of this model and how it can be combined with patient-specific magnetic resonance imaging (MRI) data. The framework builds upon a robust gastric electrophysiological model with an active-strain finite elasticity model to account for tissue mechanics. It can reproduce essential phenomena of gastric electromechanics, including slow wave entrainment and the propagation of ring-shaped peristaltic contraction waves. It provides a powerful tool for future in-silico studies of physiological and pathological mechanisms of gastric electromechanics.

Mechanical response of the human stomach wall to radial compression and associated microstructural changes

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Speaker: Holzer-Stock Clarissa S.. **Wednesday**. Start time: **15:10**. Room: Rhône 4 LVL1. Link to abstract.

During gastric tumor resection or bariatric surgery, the stomach wall is often compressed by clamps, sutures, or staple lines (1,2). These imposed short- and long-term deformations can impair the functionality of the stomach and make it difficult for the tissue to remodel/heal in the desired manner. This can lead to severe intra- and postoperative complications, e.g., leak formation along the staple line. Therefore, this study investigated the tissue response to radial compressive loading of the stomach wall and the associated microstructural changes.
For this purpose, human stomach resectates from sleeve gastrectomies were acquired at a local hospital. All samples were frozen at –20∘C within 1.5 hours after explantation, thawed, and tested in cardioplegic solution to ensure passivity of smooth muscle cells. Region-specific stress-relaxation tests were performed in radial compression mode at three different stretches (λrad = 0.8, 0.6, and 0.4). The samples were then fixed with 4% formaldehyde solution under compression in the testing setup. In addition, adjacent samples were fixed in the undeformed state. All samples were investigated using complementary imaging techniques. On the one hand, the histochemical analysis of the main constituents was achieved by combining the histological stainings Elastica van Gieson and Alcian blue (3). On the other hand, two-photon and second-harmonic generation microscopy revealed the region- and stretch-specific elastin and collagen fiber characteristics, namely orientation, thickness, and waviness (4).

During the stress-relaxation tests, significant regional differences in the peak stresses were found for all compression levels. The histological study highlighted the heterogeneity of the stomach wall and its influence on the mechanical behavior. Furthermore, it implied that the stomach layers deform sequentially and not homogeneously from the undeformed configuration to the highest compression level. The microscopy scans showed that the radial compression of the stomach wall leads to a straightening of the naturally wavy elastin and collagen fibers and their reorientation towards the circumferential-longitudinal plane.

This study shows that radial compression of the stomach wall leads to significant alterations in the characteristics of multiple tissue components within each stomach layer. Besides, the remarkable interplay between mechanical tissue response and the microstructural composition in each of the three stomach regions was highlighted, which must be taken into account when developing and improving surgical devices.

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Impact of the surgical technique on the biomechanical response of the repaired abdominal wall evaluated on a physical model

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Speaker: Fadil Zakaria. **Wednesday**. Start time: **15:30**. Room: Rhône 4 LVL1. Link to abstract.

1. Introduction

Ventral incisional hernia (VIH) occurs when abdominal content protrudes through a weakness in the abdominal wall. VIH repair is among the most commonly performed surgical procedures, with approximately 300,000 and 500,000 procedures carried out annually in Europe and in the United States respectively (Sauerland et al., 2011, Miller et Novitsky, 2019). This number continues to rise, with a 30 % increase over the past ten years, likely due to the growing prevalence of obesity (Gillion et al., 2019). Although the use of textile meshes has improved clinical outcomes, post-operative complication (e.g., recurrence) rates remain high and may reach a 25%-plateau of recurrence at 3 years post-operatively, from 2000 to 2024 (Luijendijk et al., 2000, Zolin et al., 2023, Bhardwaj *et al.,* 2024). These complications require additional surgery, exposing patients to further risks and imposing significant social costs, which are annually estimated at 3.2 billion dollars in the United States (Miller and Novitsky, 2019).

The abdominal wall is a complex anatomical structure that defines the boundary of the abdominal cavity. Its anterior and lateral periphery is defined by a flexible and complex mechanical multi-layered structure composed of muscular and fibrous tissues, which each exhibit non-linear and anisotropic properties (Astruc et al., 2018). The abdominal wall provides protection to viscera and plays a central role in regulating intra-abdominal pressure (IAP) during physiological activities. An increase in IAP is directly related to the formation and recurrence of hernia together with other factors such as pregnancy, weightlifting and chronic cough (Luijendijk et al., 2000). During a hernia repair procedure, hernia meshes can be placed on different planes of the abdominal wall, and it is recommended to secure them to the abdominal wall using surgical tacks or sutures. The primary goal of a mesh is to reinforce the abdominal wall, reducing the stress the wound is subjected to. This reduction in stress can create better conditions for the formation of high-quality neotissue, ensuring a safe repair over time post-operatively (Franz, 2008, Karrech et al., 2023). Hernia meshes are porous, warp-knitted structures that exhibit anisotropic, non-linear behavior with a strong coupling between directions (Pierrat et al., 2021) and load-profile dependent (Tomaszewska et Reznikov, 2024).

Ventral hernia repairs suffer from a lack of standardization (e.g., number of fixations, mesh type, mesh size, fixation method, mesh position) as well as a lack of personalization (e.g., based on the patient anatomy), which may explain the high variability observed in clinical outcomes. Little consensus on the surgical approach has yet been established leading to a successful repair (Cherla et al., 2018), so a high variability still exists in the adopted surgical approaches. According to Aquina and al., part of this variability is due to both the repair techniques and patient-specific factors (Aquina et al., 2017). Each of these factors impacts the initial state of the repair and, consequently, its healing behavior over time (Franz, 2008, Karkhaneh Yousefi et al., 2023).

One way to investigate the impact of different surgical techniques on the biomechanical response of the repaired abdominal wall is to use physical models. Most of them were developed based on *ex vivo* abdominal walls (Lyons et al., 2015, Végleur et Le Ruyet, 2023) subjected to a mechanical load which mimics daily activities. However, using biological tissues is challenging to handle, lacks control over their properties, and shows significant mechanical variability, reducing the repeatability of conditions. The use of synthetic materials can address this limitation, as it provides more control over the anatomy and mechanical properties of the different structures (Kroese et al., 2017).

In this study, we assessed the influence of key parameters of the surgical procedure for ventral hernia

treatment on the overall behavior of repaired abdominal wall using a physical model. More specifically, the impact of the mesh type, mesh size, fixation configuration and abdominal wall stiffness on the mechanical response of the abdominal wall was investigated while subjected to pressure loading.

2. Materials & Methods

2.1. Physical model

A 5-mm thick synthetic silicone rubber wall was chosen as a substitute for the abdominal wall (Silex LTD, Silicone Rubber Sheet). A mesh was then fixed at 1-cm of the 4 mesh edges with a suture thread (Covidien PolysorbTM, SL-721, 0, 3.5 Metric) to 4 force sensors anchored in the synthetic wall. The sensors placed at the corners of the mesh allowed for the measurement of the forces applied at the textile's fixation points. A silicone membrane (0.250 mm, 22 $\pm$ 5 shore A, BISCO® HT-6220, Rogers Corporation) was placed under the synthetic wall to ensure that the mesh was loaded during the increase in intra-system pressure (Végleur et Le Ruyet, 2023). These synthetic layers were placed into a pressure chamber, which simulates the physiological conditions observed in the human abdomen (Campbell et al., 1953).

2.2. Experimental design

The forces at mesh fixations points were recorded at 100 Hz, characterizing the biomechanical interaction between the mesh and the wall constituents when subjected to an inflation test at 140 mmHg, simulating daily activities involving muscular contraction (Cobb et al., 2005). The forces were always measured at the same four points, regarless of the fixation configuration. A pressure sensor (2 bar, XP5-M-2BG, Measurement SpecialtiesTM, 100 Hz) was used to measure the resulting pressure applied in the chamber. An acquisition system (Dewesoft SIRIUS®, V23-1) was used both to collect signals from the sensors and to send electric signal to precisely regulate the airflow (0–2 bar, QB2, Proportion Air). Additionally, two cameras (5MP, GS3-U3-41C6M, Point Grey®) equipped with 3D-calibrated lenses (16 mm focal length, Schneider Kreuznach) were positioned above the setup to record the sample's response throughout the test Correlation (Correlated Solutions, VIC 3D, VIC Snap).

2.3. Parametric study

The effect of different surgical strategies on the biomechanical response of the abdominal wall was studied, along with the influence of the abdominal wall's elasticity.

Two synthetic walls with mechanical characteristics similar to those of thawed biological abdominal walls, were used (Kriener et al., 2023), exhibiting 30-Shore A and 40 Shore A hardness properties respectively, with elastic moduli of 1.1-MPa and 1.7-MPa respectively (Silex LTD, Silicone Rubber Sheet, 30 $\pm$ 5 Shore A and 40 $\pm$ 5 Shore A). These moduli were obtained using a correlation formula between durometer values and elastic moduli (Larson, 2019).

Three different meshes, among all the products in the Medtronic portfolio, were used in this study, with relatively low (type A, polyethylene terephthalate, monofilament, 45-g/m^2), semi-flexible (type B, polypropylene, monofilament, 70-g/m^2) and high (type C, polyethylene terephthalate, multifilament, 114-g/m^2) stiffness properties, with tangent moduli of 8-MPa, 19-MPa and 33-MPa respectively.

Two mesh sizes 8x8-cm and 14x14-cm were considered in this use case.

Three fixation configurations were included in this study, with 4, 8, and 12 fixation points: in the first configuration, 4 fixations were placed on the corners of the mesh (A). The 4 mesh fixations were maintained as in (A) but the mesh was also secured at 4 additional spots, symmetrically 1-cm from the mesh edge (B). In the last configuration, still based on the first configuration (A), 8 additional fixation points were added, forming a crown 1 cm from the mesh edge. Surgical tacks were used for these additional fixation points (Covidien ProTack™, REF-174006, 5 mm).

A sensitivity analysis based on a full factorial design was conducted, including in total 36 configurations. For each simulation, the model's response was analyzed in terms of the force at the mesh fixations and the principal strains on the external surface of the wall. Correlations between the model inputs and responses were examined through a multiple linear regression analysis.

2.4. Data Processing & Statistical analysis

The force values measured at the 4-sensors were averaged at maximum pressure. Following DIC analysis, the principal Green-Lagrange strains (e1) were assessed by averaging the values over a 4-cm diameter at the center of the wall. Data analysis was subsequently performed using Minitab, a statistical software (Minitab, LLC. 2021). Regression analysis was employed to identify the most influential parameters on each biomechanical response.

3. Results & Discussion

All configurations were successfully tested. The statistical analysis associated with the sensitivity study revealed that all the factors significantly affected the forces at the mesh fixations and strain of the wall. Regarding the forces at the fixation points, the analysis showed that the factor with the greatest impact was the wall properties (standardized effect = 27.6, $p < 0.001$), followed by the mesh properties (standardized effect = 16.3, $p < 0.001$), then the mesh size (standardized effect = 8.07, $p < 0.001$), and finally the fixation configurations (standardized effect = 2.4, $p < 0.05$). For the strains, the analysis indicated that the most influential factor was also the wall properties (standardized effect = 62.07, $p < 0.001$), then the mesh size (standardized effect = 16.6, $p < 0.001$), the fixation configurations (standardized effect = 12.06, $p < 0.001$) and lastly, the mesh properties (standardized effect = 6.4, $p < 0.001$).

These results suggest that the wall properties dominate the biomechanical response of the repair. Additionally, while a relatively stiff mesh (e.g., type C) tends to reduce deformations at the center of the wall, offering a better reinforcement, it also increases the forces at the mesh fixations, thereby raising the risk of mesh or fixation failure and post-operative pain. In contrast, a relatively elastic mesh (e.g., type A) tends to reduce the forces at the mesh fixations but leads to greater deformation of the wall. Studies have shown that mechanical mismatch between the implant and the host tissue is a contributing factor to surgical failure (He et al., 2023, Hernández-Gascón et al., 2011).

These results also demonstrated the significant impact of the mesh size used. It was observed that an increase in mesh size led to higher forces, while reducing strains at the center of the wall, due to a broader coverage of the mesh on the abdominal wall. Clinically, although larger meshes provide improved reinforcement of the abdominal wall, their use can also result in decreased mobility of the abdominal wall, as well as more invasive surgical procedures with a higher risk of post-operative complications.

Finally, this study was able to explore the impact of the fixation configurations. Indeed, increasing the number of fixations points significantly reduces both the forces and strains. This is likely explained by a more widespread distribution of forces across each fastening point, reducing the individual load supported by each fixation. Clinically, these results raise the question of the benefit of additional fixation, which, although it reduces the risk of mesh migration, seems to make the force at the mesh fixation decrease, while also increasing intra-operative time and leading to post-operative pain.

The experimental model developed has certain limitations due to its simplification. While it was designed to closely mimic real conditions, it should be noted that it does not fully represent the complexity of physiological conditions. Specifically, the synthetic wall used does not account for the natural anisotropy and nonlinearity of the human abdominal wall, or the active contribution of its various muscles (Deeken et al., 2017; Podwojewski et al., 2013).

4. Conclusion

This study helped deepen our understanding of the interactions between implant and the abdominal wall. By analyzing a wide range of model variables, it was possible to identify the key parameters influencing the biomechanical responses. The results show that surgical variables, whether related to the patient, the implant, or the operative choices, play a significant role in the forces at the fixations points and the deformation of the wall. This approach is a step toward patient-specific strategies for preoperative hernia planning. The focus on future work will be on enhancing and validating the realism of the mechanical response of the synthetic abdominal wall to assess the impact of various surgical techniques on the biomechanical properties of a hernia repair.

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Effects of Testing Conditions on the Mechanical Characterization of the tunica albuginea

Minster Pierre-hugo (1), Duguey Mathis (1), Parat Clément (2), Morel-journel Nicolas (2), Carnicelli Damien (2), Neuville Paul (2), Bruyère-garnier Karine (1)

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Speaker: Minster Pierre-Hugo. **Wednesday**. Start time: **15:50**. Room: Rhône 4 LVL1. Link to abstract.

Introduction & Objectives

Erectile dysfunction is a common condition that may require penile prosthesis implantation. To improve these devices, it is essential to understand the contribution of tissues during erection with penile prosthesis, particularly the tunica albuginea (TA).

Few studies report the mechanical properties of these tissues, and those that do often test under various conditions (e.g., preload, cycling, hydration) (Berardo et al., 2024; Khorshidi et al., 2024; Kandabarow et al., 2022; Luet et al., 2021). These variations make comparisons and aggregation of results challenging.

This study aims to evaluate the effects of testing conditions on the mechanical characterization of the TA. Properties obtained from cycling loadings coupled with a saline solution bath are compared to those obtained without cycling in air.

Materials & Methods

One penile was obtained from a post mortem human subject (94 yo) and then frozen (-18∘C). After thawing, dissection was performed to isolate the TA and 10 I-shaped samples were cut along the longitudinal (n=4) and circumferential (n=6) anatomical directions.

Uniaxial tensile were realized at a 0.01 s-1 strain rate with 5 preconditioning cycles up to 10% strain followed by a test up to failure. Test were performed in a saline solution bath at approximately 37 ∘C.

For strain measurement, two points were marked at the extremities of the reduced section area and their displacements were measured by video tracking. The force was measured using a 250N sensor. The initial cross-sectional area of each sample was measured from a 3D reconstruction of each sample to calculate the nominal stress.

Nominal stress versus stretch curves were plotted for the first loading (cycle1) and the loading up to failure. The tangent modulus of the steepest linear region, the stretch of the low-stress region (which was defined as the stretch between the gravity configuration and the 0.01 MPa preloaded configuration) were determined for both curves. For loading up to failure, the maximum nominal stress and the strain at this maximum stress were also assessed as ultimate properties. Properties obtained for the first loading and the loading up to failure were compared. Results were also compared to those obtained by Luet et al. (2021) for 8 TA samples tested in air without cycling.

Results

About the stretch of the low-stress region, the first cycle exhibits a value of 0.03±0.02 longitudinally and 0.03±0.01 circumferentially, while the loading up to failure exhibits a value of 0.06±0.02 longitudinally and 0.05±0.02 circumferentially.

Considering the tangent modulus of the linear region, the first loading exhibits moduli of 29.8±18.7 MPa longitudinally and 23.4±12.4 MPa circumferentially, while the loading up to failure exhibits moduli of 56.5±21.4 MPa longitudinally and 41.1±19.3 MPa circumferentially. In comparison, Luet et al. (2021) observed higher moduli from tests in air, of 70±36 MPa longitudinally and 82±43 MPa circumferentially. Thus, cycling between the first loading and the loading up to failure increases the tangent modulus and the length of the low-stress region, in the both directions.

Moreover, by comparison of the first loading behavior to the results from Luet et al.(2021), hydration appears to reduce the average value and the standard deviation of the tangent moduli , suggesting less variability of the TA behaviour in bath. Finally, it is important to note that the anisotropy found in our study is the opposite of that found by Luet et al. (2021) (here, the longitudinal modulus is larger than the circumferential one).

Discussion and Conclusion

The results of this study indicate that cycling has a significant impact on the mechanical properties of the TA under hydration conditions, which might explain the significant discrepancies often observed between studies. However, the observed ultimate stress and stretch are consistent with those reported in the literature.
A major limitation of this study is the limited number of samples and the inability to decouple the effects of hydration and cycling. Future work should aim to isolate these factors to better understand their individual contributions. Additionally, while cycling provides valuable insights into material behavior, it is not necessarily representative of the physiological loadings of the TA. Further studies focusing on physiological loading conditions would be interesting.
In conclusion, this study provides important data on the mechanical behavior of the TA under specific cycling and hydration conditions. The results underscore the importance to standardize experimental conditions to offer more data describing the mechanical behavior of penile tissue in view of contributing to the improvement of penile prosthesis.

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First macro-scale damage properties for Wharton's jelly membrane undergoing tensile loading using finite element analysis.

Da Rocha Alexis (1) (2), Lavrand Anaïs (3), Kerdjoudj Halima (4), Laurent Cédric (5), Mauprivez Cedric (6), Po Chrystelle (7), Baldit Adrien (8)

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Speaker: Da Rocha Alexis. **Wednesday**. Start time: **16:45**. Room: Rhône 4 LVL1. Link to abstract.

1. Introduction:

Over the last decades, a growing interest has been developed in using biologically derived tissues for regenerative medicine. Wharton's jelly (WJ) distinguishes itself due to its availability both from technical and ethical standpoints. Indeed, this mucous connective tissue present in the umbilical cord is a perinatal waste that offers a valuable source of biological material for wound dressing applications (1). The identification of its mechanical properties are, however, still required to both predict its behavior and integration as well as to guarantee easy handling during surgery. WJ exhibits a nonlinear viscous behavior that is indeed poorly described in the literature (2). Bilinear characterization approach has been often used to give insights into its stiffness, maximal stress and strain before failure (1, 3). A thorough understanding of this tissue behavior at both the macro and micro-scale is essential for developing innovative medical devices. While macro-scale characterization aids in designing materials that are user-friendly for surgeons, information at the micro-scale provides insights into cell interactions critical for mechanotransduction and tissue regeneration.

This work is focused on a macro-scale approach to address the gap in the literature regarding the WJ mechanical and damage properties. A hyperelastic behavior law (Ogden (1972)) was adapted to include damage response in WJ tensile behavior using the continuum damage mechanics (CDM) approach (4). Tensile test data combined with a uni-dimensional analytical approach give access to the first time to the WJ damage properties. These results are implemented as initial values in a three dimensional finite element method (FEM) on FEBio software enabling the visualization of failure locations in the WJ structure.

2. Materials and Methods

2.1 Samples

Umbilical cords were obtained from informed patients and in compliance with the usual legal ethical rules. The amniotic membrane and the blood vessels were removed from the umbilical cord to keep the remaining WJ. The latter was washed to remove the remaining blood using buffered saline solution (PBS) and freeze-dried, resulting in a devitalized WJ membrane.

2.2 Mechanical assessment

Rectangular-shaped samples (n= 6) were cut from WJ membranes with average dimensions 0.90 ± 0.20 x 4.40 ± 0.55 x 11.8 ± 0.44 mm3. The tensile tests were performed in close physiological conditions and consisted of a preload followed by several loading cycles up to 10% engineering strain and a last load up to failure with a displacement rate of 0.01 mm/s matching quasi-static conditions.

2.3 Data Processing

Analytical and FEM approaches were used for the material's parameters determination, the first approach giving the initial optimization conditions for the second. A third-order Ogden hyperelastic law was considered for material characterization due to its ability to represent nonlinearity (2). The assumption of incompressibility was made due to high water content inside the membrane and previous work done by Pennati (2001) (3) where Poisson's coefficient was about 0.47. Hence a bulk modulus parameter was fixed to enforce incompressibility, the latter determined using linear elastic modulus obtained from

bilinear characterization. The Ogden behavior law was enhanced by CDM (4) with a damage variable expressed through a Weibull distribution with two parameters (α and μ both unitless) depending on a damage criterion expressed in terms of Green-Lagrange strain. The μ and α parameters gave respectively a strain threshold and the transition sharpness between the damaged and undamaged states. The optimization loop for both approaches was performed using Python scripts and the COBYLA method. This externalized loop has allowed the optimization over the FEM for load path up to failure.

3. Results and Discussion:
The following results are expressed through the mean and standard deviation. The experiments showed a nonlinear viscous behavior expressed by the WJ consistent with previous work (2). The rectangular shape of the samples and the stress concentration at their extremities made it challenging to induce failures in the central region. Over 6 samples only one failed in the central region. The maximum engineering stress and corresponding stretch were respectively about 595.39 ± 118.16 kPa and 1.43 ± 0.14. The analytical study allowed quick determination of material parameters while the FEM optimization process took from 10 hours up to one day per sample. Poisson's effect was visible in the simulation and the shear modulus obtained was about 150.14 ± 40.52 kPa in accordance with previous analytical works (2) providing confidence regarding the parameter's determination. The μ and α parameters were respectively 0.56 ± 0.22 and 1204.41 ± 2842.64. The α parameter exhibits a strong standard deviation due to the variability regarding the more or less progressive failure propagation and points out the need of micro-structure investigations to decrease this uncertainty. The maximum damage which gives insight regarding the failure location is centered on the FEM geometry. This observation differs from the experimental and might be due to the idealized rectangular geometry used for the FEM simulations which can not be perfectly replicated experimentally. Indeed, samples may exhibit irregularities leading to stress concentration and failure in different locations.

4. Conclusion & Outlooks:
The macro-scale damage response was reproduced using both analytical and FEM approaches giving the very first results for such WJ's properties. The externalized optimization loop performed using Python script linked to FEBio has allowed the use of an inverse method over load paths up to failure. However, the hypothesis of incompressibility as well as the hydro-chemo-mechanical couplings within WJ derivatives pose significant challenges for regenerative medicine applications. These challenges are particularly relevant when considering water content to describe the observed viscous response. This aspect is currently being investigated through simulations and medical imaging.

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Characterization of the anisotropic viscoelastic behavior in aneurysm tissue of the ascending thoracic aorta using biaxial tensile tests and constitutive modeling

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Speaker: Prot Victorien. **Wednesday**. Start time: **17:05**. Room: Rhône 4 LVL1. Link to abstract.

Objectives. The aim of this study is to characterize the viscoelastic behavior of aneurysm tissue of the ascending thoracic aorta (ATAA) using quasi-static and relaxation biaxial tensile mechanical tests along with state-of-the-art constitutive modeling.

Method. Samples were collected from ATAA patients and sectioned into six regional specimens: three from the major curvature (proximal to distal), one from the minor curvature, and two from the anterior and posterior regions. Each specimen was subjected to quasi-static biaxial stretching and biaxial relaxation tensile tests. Planar deformation was assessed using digital image correlation. After testing, the specimens were chemically fixed, dehydrated and optically cleared. The architecture of the collagen fibers was examined through the thickness using second harmonic generation microscopy in the central region of the specimen. Based on previous work (1,2), a new constitutive material model was developed to describe the anisotropic viscoelastic behavior of the tissues.

Results and Discussion. Fiber dispersion was quantified using von Mises distributions and incorporated into the discrete fiber constitutive model. Elastic and viscoelastic material parameters were determined by curve fitting. The viscoelastic model independently accounts for anisotropic and isotropic viscous components.

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Mechanics and histology of lung tissue from ARDS animal models

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Speaker: Bruna-Rosso Claire. **Wednesday**. Start time: **17:25**. Room: Rhône 4 LVL1. Link to abstract.

Introduction: Acute respiratory distress syndrome (ARDS) is a severe condition that affects lung parenchyma, often necessitating mechanical ventilation to ensure adequate oxygenation. Clinicians typically observe reduced lung compliance in ARDS patients, indicating a greater difficulty in lung inflation. This observation qualitatively suggests alterations in the mechanical properties of lung tissue affected by ARDS. However, to our knowledge, this change in mechanical properties has not been quantitatively assessed nor correlated with changes in tissue composition (e.g., cellular content, elastin, collagen).

Materials & Methods: To address this gap, tensile tests were conducted on tissue samples collected from ovine models with ARDS. Samples were excised within 8 hours post-euthanasia, with six samples taken per animal on 6 animals from the top, middle, and bottom regions of each lung, reflecting varying degrees of pathology. Cyclic loading tests were applied to the samples, consisting of 10 cycles to 20% strain followed by 10 cycles to 40% strain at a strain rate of 5% per second to approximate physiological conditions. The stress-strain curves for each sample were characterized by measuring maximum stress, tangents at 15% and 35% strain, and strain energy. Additionally, biopsies adjacent to the tensile test samples site were collected for histological analysis using four types of staining-Hematoxylin and Eosin, Masson's trichrome, Reticulin, and Orcein-to reveal different structural components: cellular content, type I and type III collagen fibers and elastin respectively.

Results: The stress-strain curves align with those reported in previous studies in the literature (1) (2). The tensile test results indicate minimal viscoelasticity, consistent with recent findings from lung biaxial testing (3). Qualitative observations of histological images show that the uppermost samples look more oxygenated than samples retrieved from the bottom parts of both lungs. Preliminary findings indicate that samples from the least oxygenated lung regions exhibit lower stiffness than tissue from healthier areas. Specifically, samples from poorly oxygenated regions show lower tangents (0.32 vs. 0.45 MPa at 20% strain), maximum stresses (5.3 vs. 7.0 kPa at 20% strain), and strain energies (0.13 vs. 0.20 MPa.% at 20% strain), correlating with histological observations of reduced oxygenation .

Discussion & Conclusion: These preliminary results appear paradoxical when compared to clinical observations, as intensivists report that these poorly oxygenated regions are the most challenging to inflate. A potential explanation is that in the early stages of ARDS, the resistance to alveolar inflation may stem not from intrinsic tissue stiffness but from increased surface tension due to fluid accumulation, potentially impairing the surfactant's function in reducing surface tension. However, given the limited sample size and current reproducibility of our experiments, these findings require further validation through additional studies.

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Mechanical Characterization of the Porcine Atrial Appendage Under Uniaxial Tension

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Speaker: Reibel Kundry. **Wednesday**. Start time: **17:45**. Room: Rhône 4 LVL1. Link to abstract.

1. Introduction

Stroke is the third leading cause of mortality in France and the leading cause of acquired disability (Al-Saady et al., 1999). About one-third of strokes are linked to atrial dysfunction, particularly atrial fibrillation (AF). AF often leads to thrombus formation in the left atrial appendage (LAA) due to blood stasis, caused by the irregular shape and trabeculations of this anatomical structure. Recent therapies, such as LAA closure, aim to prevent AF-related strokes, highlighting the importance of understanding its mechanical behavior and material properties.

Finite element (FE) models have been used to study the LA's mechanical response during AF, often assuming homogeneous wall properties and constant thickness (Zhang et al., 2008). However, to the authors' knowledge, only a few studies report experimental data on the LAA's tensile properties (Bellini et al., 2012; Di Martino et al., 2011; Javani et al., 2016; Jernigan et al., 2007). While hyperelastic models effectively capture the non-linear stress-strain behavior, there is no consensus on the most suitable constitutive model for this tissue. Approaches range from isotropic models like Neo-Hookean and Mooney-Rivlin to anisotropic models such as Holzapfel-Gasser-Ogden (HGO) and Fung SEFs, each reflecting different assumptions about the LAA's complex structure and function.

The goal of the current study is to characterize the mechanical behavior of the atrial appendage under uniaxial tension. In this context, the aim is to understand relationships between the global mechanical response of the tissue and its meso-scale architecture (trabeculations) and underlying microstructure.

2. Methods

2.1 Uniaxial testing

Uniaxial tensile tests were conducted on n=96 samples taken from 24 fresh adult porcine hearts. Four samples were extracted from each heart (two per appendage: one proximal and one distal from the atria) with a square region of interest (ROI) of 15mm edge. The heterogeneity of each sample's geometry was analyzed through a 3D scan. Half of the samples were tested in the longitudinal direction (i.e. along the trabeculae's orientation) and the other half in the transverse direction. Experiments were conducted in a saline bath using a biaxial tensile machine equipped with a 20 N force sensor (Futek LSB205, 5lb). Two cameras (Alvium 1800 U-811, 8.1 MP) with macro lenses were positioned with a stereo angle of 20 to 25 degrees. Stereo digital image correlation (s-DIC) analyses were performed. A speckle pattern was sprayed using black paint to track the displacement field, which was computed with the software VIC 3D. The samples were subjected to 9 preconditioning cycles up to 35% strain, at a strain rate of 1%/s. Force, jaw displacement, and images were acquired at a frequency of 10Hz during a final 10th cycle.

2.2 Data analysis

The 1st Piola-Kirchhoff (PK1) stress was calculated as the ratio of the reaction force to the initial average cross-sectional area of the specimens. The engineering strain was defined as the ratio of the imposed displacement to the initial clamp-to-clamp distance.

An average stress-strain curve was calculated from the individual curves. The results were compared to the literature.

Left and right appendages were compared as well as proximal and distal samples. The anisotropy was quantified by comparing the mechanical responses of the samples tested in the longitudinal and transverse direction.

FE models were built in FEBio using the specific sample scans and the tensile experiments were reproduced. The local distribution of the strains in the numerical model was compared with the DIC data for

a better understanding of the tissue heterogeneity on the mechanical response.

3. Results and discussion

Fung, HGO and second order Mooney-Rivlin models provide satisfying results when fitting the PK1 stress-strain curve of the FE models. In contrast, the Neo-Hookean model is less adapted to reproduce the strain-stiffening behaviour of this tissue.

These preliminary results demonstrate the capability of our tensile test set-up to characterize the mechanical response of the LAA tissue under uniaxial tension as the results are comparable with literature. The present work provides an overview of the variability in results obtained from experimental studies on LAA tissues. This variability can be attributed to the complexity of the tissue, including variations in its geometry and composition. Future studies will help clarify the extent to which these two factors impact the tissue's mechanical response. Sensitivity analyses will be conducted to explore the effect of the two following sources of uncertainty on the mechanical response of the LAA:

Orientation of the tissue. Characterizing the multiscale fibrous architecture of this tissue (trabeculae, muscular fibers, and collagen fibers) using micro-computed tomography would give insights on the structural organization of the tissue and enable to link it to the global mechanical behaviour.

Dimensions of the samples. The LAA exhibits significant geometrical heterogeneity. Accurately characterizing local thickness through the 3D scans will help explain variations in local strain and stiffness resulting from geometric factors.

4. Conclusions

This preliminary study highlights a notable disparity in the experimental characterization of the LAA's mechanical behavior. This tissue presents numerous experimental challenges, requiring an adapted protocol considering its heterogeneity and anisotropy. Enhancing our comprehension of the mechanical properties of the LAA is essential for developing predictive numerical models. Future work will address lack of available data in existing literature regarding pathological human LAA by performing biaxial tests on fresh tissues.

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Characterizing mechanical properties of the cadaver vocal folds: Preconditioning or the Mullins effect?

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Speaker: Mohammadi-Gorjaei Abolfazl or Nazari Mohammad Ali. **Wednesday**. Start time: **18:05**. Room: Rhône 4 LVL1. Link to abstract.

Introduction

Human communication relies heavily on speech, which is produced by the coordinated action of multiple organs (Titze & Alipour, 2006). An important participant region in voice generation, the middle part of the larynx at the upper boundary of the cricoid cartilage area, plays a crucial part in this complex process. Voice is generated when air from the lungs interacts with the vocal folds (VFs) from a small opening of the VFs, then the vocal folds will barely vibrate, and the sound will arise from turbulences.

It's critical to comprehend the intricate physical details of this phenomenon. Modeling the VFs needs the specification of their mechanical properties in addition to their geometry. Synchrotron X-ray microtomography has been used to extract the size, shape, and orientation of muscle fibers in the VFs (Bailly et al., 2018). Studying *in-vivo* mechanical properties of the VFs is not possible, but several ex-vivo measures on excised VFs exist in the literature. Alipour & Vigmostad (2012) have used uniaxial tension on human samples assuming linear properties. Cochereau et al. (2020) have examined the mechanical behavior of human cadaver's VFs layers under shear, compression, and tension. Scheible et al. (2023) utilized *ex-vivo* micropipette aspiration on porcine samples to find the elastic properties of VFs. In this kind of measures using samples from cadavers it is usual to do some preconditioning loading cycles on the tissue samples, but there is no clear characterization of this experimental step in literature. The primary objectives of this research are to investigate whether any damage occurs during this process and to examine how such damage affects the results of viscoelastic properties.

Method

Six mixed-breed dog cadavers were included in our in vitro study to look into the mechanical characteristics of canine VFs. dogs have been sacrificed for reasons unrelated to this study. The VFs were extracted from the larynx. Using a 100 kg load cell in the STM-1 device (SANTAM Co., Tehran, Iran) each sample underwent seven uniaxial cyclic tests with displacement rates of 1, 5, 10, 20, 40, 60, and 120 mm/min. In order to evaluate purely elastic properties, a very slow rate of 1 mm/min was selected. These slow rate experimental measures were fitted using a variety of hyperelastic models such as Ogden, 2 and 3 parameter Mooney Rivlin, Yeoh. The Yeoh 2nd order model was found to be the most appropriate option as the most fitting choice.
Then, by using a convolution integration between hyperelastic 2nd order Yeoh model and first degree Prony theory viscoelastic, the viscoelastic parameters, shear modulus and corresponding time constants, were found in a tensile test (assuming full incompressibility) using stretch ratio in tensile direction. Since loading was applied at a constant rate, the stress-time relation was found linear:
The experimental data showed a softening effect while increasing strain rates but in high strain rates the tissue showed the hardening behavior. We supposed that this effect can be due to damage effects during slow rate tests. In order to test this hypothesis, we included damage effects using Mullins cumulative damage model. A pseudo-elastic Mullins' strain energy and a modified Ogden-Roxburgh damage function was used. The material damage constants were found with an inverse method using a simple tensile model and minimizing the error between the experimental data at different rates and the proposed model in ANSYS mechanical.

Result and Discussion

As it was mentioned, the Yeoh 2nd order were fitted well with the very slow rate experiment data. The associated material constants derived from this model and averaged across all six canine samples were

found as: $C10$=109.5 kPa, $C20$=3799.4 kPa.
The viscoelastic response was described using a Prony series with one term and the computed shear coefficient and time constants were found equal to 0.2734 Pa and 0.1316 s, respectively. The parameters for the Mullins cumulative damage effect combined with viscoelastic parameters were found as: r=0.005, m=100, and β=0.1 in an optimization iterative process.
Using the damage effects through the Mullins model showed the softening effect while increasing strain rates in low strain rates and expected hardening effects in high strain rates. This observation highlights the importance of pre-conditioning in accurately replicating the mechanical response of vocal folds. Pre-conditioning involves repeated loading-unloading cycles before primary testing, which helps stabilize the material properties and reduces the variability due to initial stress softening. Using this effect for modeling live organs is an open question. Including the Mullins effect in the processing of the viscoelastic data gives better estimates of the viscoelastic parameters for modeling organs. The integration of hyperelastic, viscoelastic, and the Mullins effects into a unified framework enabled us a more comprehensive understanding of the mechanical behavior of cadaver soft tissues and in our case for VFs.

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Strain-dependent relaxation time of viscoelastic soft tissues

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Speaker: Iaquinta Sarah. **Wednesday**. Start time: **18:25**. Room: Rhône 4 LVL1. Link to abstract.

Perineal tears occur in about 80 % of vaginal deliveries. During childbirth, the descent of the infant causes repeated stretching of the perineal body. The tissues of the perineum undergo significant elongation, with the stretch maintained until the next pushing effort, which induces an even greater level of stretch-reaching up to 400% elongation. This sequence of stretching and relaxation is repeated several times, potentially causing tissue failure and leading to perineal lacerations, which may result in pelvic floor disorders.
Conservative techniques exist to alleviate perineal stretch, such as maneuvers or episiotomy. The latter involves a controlled incision in the perineal body. However, these techniques can sometimes cause more harm than the natural occurrence of tearing, particularly if the risk of deep lacerations during delivery is overestimated. Therefore, it is crucial to develop a non-destructive method for assessing perineal damage to support physicians in making informed decisions during childbirth.

To address this, the mechanical response of the perineal body to repeated elongation-relaxation loads was investigated via cyclic pure-shear testing conducted ex vivo on porcine perinea. Analysis of the relaxation phase using Zener model identification revealed that the relaxation times continuously decreased with increased stretching until a discontinuity occurred. This discontinuity appeared to precede visible structural damage (tears) in the sample.
These findings demonstrate the evolution of the viscoelastic response of the perineal tissue during cyclic loading. Furthermore, non-invasive techniques such as relaxed indentation or suction testing are currently used in vivo for the assessment of properties relative to the viscoelasticity of soft materials. As such, the results presented in this study, combined with the existing techniques, are promising for the future development of real-time assessments of the mechanical state of the perineum during childbirth.

Extracting attenuation and wave speed from diffuse wave field in soft tissues : a semi-analytical study.

Giammarinaro Bruno Grégoire Sibylle (1), Aichele Johannes (2), Laloy-borgna Gabrielle (3), Catheline Stefan (1)

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Speaker: Giammarinaro Bruno. Keynote. **Thursday**. Start time: **10:00**. Room: Rhône 4 LVL1. Link to abstract.

Estimating the elasticity and the viscosity is a major concern for diagnosis. These parameters represent important biomarkers for tumor detection. Standard approaches are based on active generation of shear waves, either by external source or acoustic radiation force. However, the human body is full of natural waves. These waves propagate in every direction as diffuse wave field which can be used for elasticity estimation using passive elastography algorithms. These techniques are based on the assumption of far-field sources for a purely elastic medium, neglecting the effect and thus the possibility to directly estimate the attenuation. However, the feasibility of retrieving the attenuation has been demonstrated in seismology with noise correlation techniques on diffuse wave field generated by volumetric distribution of sources, distribution of sources directly present in the medium to characterize. The study aims at investigating the condition to retrieve wavespeed and attenuation in soft biological tissues. We perform semi-analytical simulations using analytical Green's function to create random diffuse wave field. The viscoelastic parameters are then estimated using spatial auto-correlation to obtain coherence function whom the shape is directly linked to medium characteristics. The effects of the source distribution compared to the attenuation length and wave length is studied.

A predictive model of UV-A-riboflavin crosslinking treatment on porcine corneas

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Speaker: Pandolfi Anna or Bonfanti Alessandra. **Thursday**. Start time: **10:40**. Room: Rhône 4 LVL1. Link to abstract.

The crosslinking technique (CXL) is an effective low-risk therapeutic treatment of keratoconus and other ectatic disorders of the human cornea. The effect of corneal CXL is to increase the stiffness of the stroma to prevent the progression of the cornea distortion. Several clinical and experimental studies have shown that the stiffening effects predominantly localise on the anterior portion of the stroma and that the in-depth stiffening distribution is highly dependent on the duration of treatment. Yet, how the stiffening effects distribute through the cornea thickness as a function of the treatment duration is an open question. Here we propose an analytical model of the stiffening profile due to CXL-treatment as a function of the irradiation time. We consider linear and nonlinear variations of the crosslinking effects across the thickness and implement them into a finite element model of the porcine cornea. We present a time-dependent in-depth stiffening profile that allows us to predict the post-operative corneas response to physiological intraocular pressure for different irradiation times. We anticipate that this predictive model will support the development of patient specific 3D models that will allow clinicians to design customised CXL treatment, thus enhancing treatment outcomes.

Mechanics and Modelling of Brain Tissue Interaction with a Slender Ribbon-Shaped Neural Probe

Noseda Lorenzo (1), Maillard Pierre (1), Sakar Mahmut Selman (1)

1 - Institute of Mechanical Engineering, École Polytechnique Fédérale de Lausanne (Switzerland)

Speaker: Noseda Lorenzo. **Thursday**. Start time: **11:00**. Room: Rhône 4 LVL1. Link to abstract.

Understanding the mechanics of brain tissue interaction with minimally invasive neural probes is critical for developing safer and more effective neurosurgical interventions. This work investigates the insertion behavior of a steerable, slender ribbon-shaped neural probe in brain tissue.
Ex-vivo experiments were conducted using porcine brain tissue to investigate the mechanics of probe-tissue interaction during insertion. A custom-built robotic platform was developed to facilitate these studies, including precision force sensing, imaging, and automated manipulation of the probe. This setup enabled the characterization of the mechanical response of brain tissue, including the fracture behavior and contact forces during insertion, providing valuable insights into the mechanics of interaction between probes and the brain.

In parallel, we developed a computational framework to model the interactions between the ribbon and soft tissue. A one-dimensional mechanical model of the ribbon was coupled with a simplified soft tissue model to simulate the stress distribution during insertion of the ribbon. This model provides a deeper understanding of the tissue-probe interactions, enabling the refinement of probe design and insertion strategies to minimize tissue damage.
With our combined experimental and computational approach, we aim to better understand the mechanics of brain-probe interactions and to help design safer and more agile neural probes for clinical applications.

Unraveling the Mechanics of Tough Hydrogels: A Micro-to-Macro Perspective

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1 - DICATECh / Polytechnic University of Bari / Politecnico di Bari (Italy)

Speaker: Vitucci Gennaro. **Thursday**. Start time: **11:20**. Room: Rhône 4 LVL1. Link to abstract.

It is widely accepted that the emerging mechanical properties of polymer-based materials can be explained by analysing the macromolecular composition, structure and arrangement. Complex polymeric networks are indeed the result of a range of strong and weak interactions which dictate the energy landscape. Models which are able to predict the macrostructure response as an interplay of simpler microscopic phenomena are highly valuable in that they allow for engineering new materials with tailored behaviour.
In the present investigation, we turn our attention to tough hydrogels, which are gaining importance in tissue engineering and replacement. Inheriting from an approach which has revealed its capability in predicting the complex mechanical response of single copolymer networks (1,2), we expand it to double network hydrogels. The methodological framework for our novel constitutive model consists in the following main ingredients: a model for the response of a representative ductile chain deduced from well known statistical mechanics observations; a corresponding micro-to-macro bridge based on the so-called microsphere homogenization; a constitutive model for the soft I2-based behaviour of a second network which is brittle.
The obtained model is validated against the to-date most comprehensive experimental dataset encompassing many deformation states and cyclic loading history. Despite a narrow number of physics grounded parameters, the model shows its versatility in reproducing finite elasticity and internal hysteresis. Furthermore, the clarity of its derivation allows for an understanding of the contributions from both networks, which could be linked to the synthesis process. This understanding can enhance material design, particularly for biomedical applications.

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I2

Statistical analysis of precompression time in laparoscopic sleeve gastrectomy using finite element modeling

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Speaker: Schrammel Stefan. **Thursday**. Start time: **11:40**. Room: Rhône 4 LVL1. Link to abstract.

Laparoscopic sleeve gastrectomy is one of the most common procedures used to treat obesity. In this procedure, the stomach is cut and closed with a staple line to form a smaller gastric sleeve. Before stapling, the employed surgical stapler fixes the tissue by mechanically clamping the region of interest. Clinical studies indicate that a certain precompression time between clamping and stapling is effective in reducing complications such as inter- and postoperative bleeding (1,2). However, the relationship between this precompression time and the mechanical processes in the tissue remains unclear.
To investigate this relationship, we developed a finite element model of the clamping process. The stomach tissue is modeled as an anisotropic solid, including dissipative processes such as viscosity and loss of stiffness, similar to the Mullins effect (3). The stapler interacts with the tissue via two contact surfaces, taking into account the compliance of the device. The material model was implemented in the finite element software LS-Dyna and verified with a semi-analytical solution. A distribution of material parameters was identified from a series of uniaxial compression tests on porcine stomach tissue using distinct loading protocols. The geometrical variability of tissue thickness was also quantified probabilistically. We then ran about 150 simulations using these distributions, which enabled statistical analysis of the process.

Our model establishes a connection between the precompression time and mechanical quantities such as (accumulated) dissipation and displacements. In addition to these global metrics, we can investigate the local tissue response during clamping, which becomes particularly important in subsequent simulations of staple formation. Our results will help further develop surgical staplers and optimize the definition of user guidelines, leading to more reliable stapling results and fewer post-operative complications.

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Study of the Adhesive Properties of Porcine Mandibular Periosteum

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1 - Laboratoire de Mécanique et ses Interfaces (France)

Speaker: Hamma Alexandre. **Thursday**. Start time: **14:15**. Room: Rhône 4 LVL1. Link to abstract.

The periosteum is a complex connective tissue that plays a fundamental role in bone regeneration, mechanical stability, and response to mechanical stress. Our study focuses on the adhesive properties of the porcine mandibular periosteum, with the objective of better understanding its mechanical interactions with the underlying bone. This knowledge is essential for optimizing clinical applications such as mandibular distraction, a surgical technique used to correct mandibular deformities, particularly in children.

Peeling tests were performed on porcine mandibles, collected from specimens of horizontal and ascending branches. These tests allowed us to measure the forces required to detach the periosteum and quantify the adhesion energy. The results show that the horizontal branches exhibit significantly higher adhesion (695 ± 434 J/m^2) compared to the ascending branches (324 ± 133 J/m^2). This difference is attributed to an inhomogeneity in the density of Sharpey's fibers and muscle insertions between the branches of the mandible.

Our approach is based on a cohesive zone model to describe the adhesion mechanisms. This model incorporates the contribution of mechanical stresses and the visco-hyperelastic properties of the periosteum. The results reveal adhesion energy similar to that of certain industrial adhesives.

Clinically, this work opens up new perspectives for the development of more effective bone grafts and the improvement of mandibular distraction treatments. By more accurately modeling the interactions between the periosteum and bone, it may be possible to optimize surgical protocols and minimize the risks of complications, such as graft detachment or non-integration.

First results on poro-mechanical characterization of temporomandibular joint disc through multiple testing

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Speaker: De Oliveira Cafiero Caio. **Thursday**. Start time: **14:35**. Room: Rhône 4 LVL1. Link to abstract.

Introduction

The human temporomandibular joint (TMJ) connects the skull to the mandible and contributes to a series of fundamental functions such as speech and chewing. Several pathologies can affect its proper functioning, impacting 34% of world's population (1). The joint possesses a fibrocartilaginous disc that acts in force distribution and movement guidance of the mandible. TMJ dysfunctions are frequently associated with problems linked to the disc and the understanding of its mechanical behavior is essential for improving TMJ simulations and therefore proposing new solutions to pathologies. Since the TMJ is a synovial joint with low vascularization, it is also interesting to understand the fluid diffusive phenomena inside the tissue which play a major role on cell metabolic waste and nutrient distribution within the disc.

The mechanical behavior of the disc has been minimally explored in the literature, resulting in a limited current knowledge about its biphasic nature and consequently in a lack of effective solutions to its dysfunctions. The disc tissue is a porous medium that undergoes large deformations and is primarily composed of water (66 to 80%), with its dry mass consisting mainly of collagen fibers (68 to 80%). The biphasic theory enables the inclusion of fluid pressurization and flow influence in the material's viscous and nonlinear mechanical response through its permeability. The limited data currently available for the disc tissue was mainly obtained thanks to curve-fitting of confined compression tests (2). The present study aims to perform the poromechanical characterization of a same temporomandibular joint disc by means of three different methods: i) finite element analysis parameter identification on spherical compression data, ii) direct permeation measurement and iii) confined compression creep test, enabling a direct comparison of the permeability values as well as solid phase mechanical properties for two methods.

Materials and Methods

For this preliminary work, a porcine TMJ disc central part underwent multiple experimental tests. Starting with spherical compression tests (3), the curves were compared to (i) an axisymmetric finite element model of a disc compressed by a rigid sphere, in a coupled pore fluid diffusion and stress analysis (Abaqus 2022, Dassault Systèmes France). Using Ogden hyperelastic material definition with initial parameters for solid phase obtained from two models existing in the literature (3,4), an optimization process was performed to determine the permeability value and solid phase mechanical parameters that fitted experimental data.

The second part of the work consisted in testing a 10mm diameter cylinder cut from the central part of the same disc, to be tested in a direct permeation device designed on purpose. A constant pressure was applied to drive physiological fluid through the material, enabling the estimation of its permeability by (ii) direct fluid flow measurement. This allowed the measurement of the TMJ disc material's permeability through the direct application of Darcy's law, dissociating it from the compression of the material.

Finally, confined compression tests were conducted on the same sample, enabling the comparison between the three permeability measurement methods. The specimen was positioned on a porous base within a laterally restricted chamber and compressed by a porous piston, which allowed fluid exudation during the compressive process of a creep test. Like for the previous tests, the sample was kept at all times in saline solution at 37◦C and the stress-strain curve was fitted to the biphasic theory through an optimization procedure minimizing the mean square errors (RMSE), also enabling the determination of (iii) permeability and solid phase parameters.

Results and Discussion

The finite element spherical compression model allowed testing the parameters defined in the literature for the solid phase of the material, showing a large difference with the experimental results for these

cases (RMSE = 6.44e-3 for (3) and RMSE = 3.97e-1 for (4)). The optimization process allowed determining parameters that best fitted the experimental data (RMSE = 1.12e-3), with a final definition of shear modulus of 40.0kPa and bulk modulus of 36.7kPa. The permeability of the material was eventually obtained equal to 8.22e-15 m^4/Ns.
The permeability measurement by direct permeation was performed for the first time on this material, leading to a value of 9.56e-16 m^4/Ns. The same sample, when subjected to confined compression, provided a permeability value of 2.20e-15 m^4/Ns and aggregate modulus of 99.0kPa, both in the same order of magnitude as in (2), which also performed confined compression tests. Besides, a shear modulus of 21.5kPa and bulk modulus of 30.0kPa were obtained, consistent with that observed for the spherical compression identification results.

Conclusion

The aim of this work was to characterize the TMJ disc, contributing with valuable insights to the currently limited literature available on its poromechanical definition. According authors knowledge, this work represents the first permeability measurement by direct permeation on this tissue, enabling cross-referencing of results from multiple methods on the same sample, which are typically applied individually and rarely compared. Looking ahead, the aim is to conduct the same tests on additional discs, confirming the preliminary results and further enriching the database. Magnetic resonance imaging is also being conducted to examine the tissue's microstructure and measure local water diffusivity.

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Finite-element-assisted design of a bulge inflation experiment to reproduce the anisotropic in-vivo tensions in the ascending aorta

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Speaker: Pierrat Baptiste. **Thursday**. Start time: **14:55**. Room: Rhône 4 LVL1. Link to abstract.

Introduction

Cardiovascular pathologies involving mechanical damage or rupture of the ascending aorta such as aneurysms or dissections are one of the most prevalent cause of mortality, affecting 5 out of 100 000 individuals/year (1). These events are driven by patient-specific mechanical and anatomical factors (degraded wall strength and cohesion, anatomy of the aortic arch) combined with an acute stressor often related to blood hypertension. In order to evaluate the risk of rupture for a given patient, a first step consists in quantifying the critical pressure at which the tension in the tissue overcomes the wall's strength. Previous studies (2) showed how the ultimate wall tension at failure can be determined by inflation experiments on fresh excised tissue (e.g. elective thoracic aneurysm surgery). In (2) and others, a circular ring was used for holding the tissue during the inflation. However, in order to obtain an accurate experimental model of aortic rupture, the bulge inflation test could be better designed if it reproduced more closely the anisotropic tension field of the pressurized aortic arch. Here we propose a numerical approach to design the shape of the ring that will reproduce the tension computed from a medical image and arterial pressure for a given patient.

Methods

We start with gated CT-scans of the patient obtained together with arterial pressures, at systole and diastole. Using inverse membrane elastostatics (3), the three components of the in-plane tension field at systole and diastole can be estimated despite the ignorance of the patient-specific constitutive behavior of the wall.

Next, a parametric Finite Element (FE) quarter model of the bulge inflation test was built in Python using the FenicsX library (4). The patch of tissue is described by a superellipse, so that its shape is controlled by the following parameters: radius along the x and y directions and roundness. These parameters effectively constrain the design of the clamping ring of the experimental setup. The sample is meshed with hexahedral 3D elements. A mixed formulation is used with Q2 (displacement) and P1 (pressure) elements to enforce incompressibility. A hyperelastic material with an GOH strain energy function (5) is used. The outer clamped surface was fixed, and a pressure was applied to the bottom surface until the circumferential tension reached the systolic value. A Newton solver was used to compute the displacement field, from which the 1st Piola-Kirchoff stress field was obtained. This stress field was integrated along the thickness to obtain the tension field.

Although the resulting tension field is mostly determined by the pressure, it is also weakly related to the constitutive behavior of the material. This influence becomes stronger when the membrane assumption becomes invalid, for instance for small patches of tissue when the radius cannot be considered as much larger than the thickness. Because the patient-specific constitutive data is not known a priori, we compute the response for 12 sets of constitutive parameters, representing the expected variability of the tested tissue (6).

Finally, an optimization procedure was used to find the set of shape parameters for the ring of the inflation experiment that minimizes the difference between the components of the tension field at the apex of the sample and the patient-specific tension in the right lateral wall of the ascending aorta obtained from medical images.

Results

The design procedure was demonstrated for a given clinical case. The tensions computed from the CT-scans were found to be anisotropic with a circumferential-to-axial ratio of 2.17 (diastole) and 2.25 (systole). The optimization procedure was able to converge to values close to this reference: 2.04 (dias-

tole) and 2.38 (systole). The final ring shape had an elongated shape: the radii were 12 (axial) and 37 (circumferential) mm and the ring shape was close to an ellipse.

Discussion and conclusion

This study introduces a method to design a bulge inflation test that replicates the anisotropic tension field in the aortic wall, from a given patient-specific CT scan. Rapid prototyping could be used to quickly manufacture these rings, enabling patient-specific experiments.

The interest of this method lies in the fact that model assumptions like constant tissue thickness and the choice of constitutive parameters have limited influence on the final result due to the mechanical equilibrium between wall tension and pressure. Still, the stiffness ratio of the tissue between the circumferential and axial directions does influence the tension ratios to some extent. This stiffness ratio could be estimated clinically by extensibility measurements. Constraints could be added to the optimization procedure to restrict the sample area to the amount of available excised tissue.

This approach is a first step towards the development of an experimental model of aortic dissection with the aim of characterizing how the microstructure and existing medial defects affect the mechanical resistance and cohesion of the aortic wall, and how this impacts the critical pressure.

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Volumic deformation of human cornea under pressure

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Speaker: Allain Jean-Marc. **Thursday**. Start time: **15:15**. Room: Rhône 4 LVL1. Link to abstract.

The cornea is the tissue that forms the outer part of the eye. It plays an essential role in vision, both through its transparency and its shape. This shape is ensured by the cornea's natural curvature and mechanical properties. Previous mechanical experiments have shown that the cornea has a non-linear stress-strain behavior, similar to other collagen-rich tissues. Indeed, it is mainly formed by the stroma (90% of its thickness), which is made up of a stack of collagen fibril lamellae, reminiscent of plywood. However, up-to-now, there has been no study of the volumic deformation of the human cornea during a mechanical assay: most of the studies have focused on the behavior in the tangent direction to the surface of the cornea. In this study, we measured the volume deformation of human corneas during an inflation test. Our observations show a very different behavior in directions tangent to corneal surfaces compared to thickness, with in particular a strong sensitivity to osmotic fluxes in the thickness.
We used 7 corneas for an inflation test. Each intact cornea was placed on an inflation chamber, and liquid was injected while the pressure was recorded. At different pressure levels, the injection was stopped to image a volume near the apex of the cornea with an Optical Coherence Tomograph. Once the pressure has reached a pressure around 20kPa (for a physiological pressure of 1.5kPa), the volume was kept constant. Using the natural contrast of the tissue, we quantified the strain tensor in 3D at the different pressure levels using Digital Volume Correlation.

We were able to measure the strains in all directions. We observe a horizontal strain in the expected range of few percent. It increases with depth, and shows some heterogeneity in the posterior (deeper) region. We didn't observe a significant variation in the shear components.
The most striking deformation is observed in the vertical direction, with a compressive strain which progressively goes down to -20 to -30%, far above the expect value with a compression which starts mainly in the anterior (outer) part of the cornea, and which propagates as the pressure increases. We also note that there is an initial stretch in the center of the cornea, and that, once the pressure is stabilized, the cornea keeps deforming, showing a dynamical aspect in this change of volume. We observe that the strain near the apex is almost homogeneous, apart in some regions in the posterior parts, as expected from the collagen organization. The horizontal strains are around 3%. They increase with depth, contrary to expectations for a spherical cap under pressure. This is in agreement with the deformation of a spherical cap under pressure. The vertical strain shows a strong compression, which starts in the 1/3st part of the cornea depth, and which will propagate in the tissue. We associate this effect to a water outlet driven by the mechanical stretch. The initial stretch in the middle part is likely due to an osmotic imbalance, despite the fact that the cornea has been placed in adapted solutions before the experiments. Thus, a proper model of the cornea should include both a vertical heterogeneity of a transverse isotropic medium, but also a poro-osmotic component to describe the vertical water exchanges.

Experimental and computational studies of the time-dependent mechanical behavior of cellular and acellular collagen hydrogels

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Speaker: Busenhart Kim. **Thursday**. Start time: **15:35**. Room: Rhône 4 LVL1. Link to abstract.

Collagen hydrogels are often employed as in vitro model systems for mechanobiological investigations of soft biological tissues, and also serve as tissue replacements in tissue engineering applications (1,2,3). We developed experimental protocols to comprehensively characterize their complex non-linear, anisotropic, time-dependent deformation behavior. At the same time, we formulated enhanced numerical models to gain deeper understanding of the underlying deformation mechanisms, e.g., (4).
Similar to soft collagenous tissues, the mechanical properties of collagen hydrogels are characterized by a load-bearing network of collagen, swollen to contain a large amount of water, which physically interacts with the collagen and adds an isotropic, mainly hydrostatic stress contribution to the elsewise anisotropic and non-affine mechanical behavior of the material. The control over composition and structure, and hence reduced variability in the observed mechanical characteristics allows systematic studies. We use an established protocol to produce collagen hydrogels (2), including a gel compression step that yields a 16-fold increase in the collagen concentration, and induces structural anisotropy in the material (4). In uniaxial tensile tests, the gels exhibit pronounced stiffening, with tangent stiffness increasing by an order of magnitude over an applied strain range of 10%. This is accompanied by significant lateral contraction, reflected in tangent Poisson's ratios up to 8. The mechanical properties are also highly sensitive to the fabrication protocol (6), as demonstrated by a comparison with another type of collagen hydrogel (5), that shares the same volume fraction of collagen but was prepared following a different protocol. This gel shows an order of magnitude lower tangent stiffness with less stress stiffening, has more rubber-like characteristics, and features a Poisson's ratio of 0.45 at 10% strain, in stark contrast to the gels prepared according to (2,4).

For many relevant applications of collagen hydrogels, their time-dependent behavior plays a critical role. To explore these characteristics, we therefore extended our experimental analysis to stress relaxation and creep experiments, and tests at different loading rates. Significant stress relaxation was observed, highlighting persistent viscoelastic effects, likely driven by fiber rearrangements and poroelastic effects due to fluid movement. Notably, the pronounced stress relaxation occurs even at very low loading rates (), where the stress reduces to just 40% of its peak value within 10 minutes of the relaxation phase. Moreover, the influence of embedded cells on these time-dependent properties was investigated, as cellular activity is expected to dynamically alter the hydrogels' microstructure and mechanical response over time. This information may therefore be key for developing more representative in vitro models for soft collagenous tissues and understanding their behavior under physiological conditions.

To interpret the experimental observations, we first developed an enhanced computational model capable of capturing the complex mechanical behavior of collagen hydrogels in uniaxial tensile tests under static loading conditions, and able to rationalize the observed differences between hydrogels prepared according to different protocols. The model builds on a fully 3D discrete network of fiber connectors, integrated within a continuous compressible neo-Hookean type matrix. To shed light on the origin of time-dependent phenomena seen in the relaxation and creep tests, we extended the model and explored viscoelastic formulations for the fibers' mechanical behavior to represent time-dependent fiber sliding and crosslink dynamics.

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Experimental and Computational Modelling of Brain Tissue Damage Mechanics

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Speaker: Sheridan Conal. **Thursday**. Start time: **15:55**. Room: Rhône 4 LVL1. Link to abstract.

INTRODUCTION

The damage mechanism for concussion in unknown, and diagnosis hinges upon the lack of evidence of damage on MRI/CT scanning (1). The clinical hypothesis for the mechanism of damage of concussion, being the delamination of the grey/white matter boundary (2), (3) has not been validated, while it has been seen that repeated concussion contributes to neurodegenerative conditions such as Parkinson's, CTE and Dementia (4). Many publications refer to "brain tissue" as a homogenous material, neglecting regional and grey/white matter variance (5), (6). As a first step in understanding the response of brain tissue to impact, this study performs regional mechanical testing on the grey and white matter of ovine brain tissue, investigating variance in behaviour between tissue types and regions.

METHODS

Fresh ovine brain tissue obtained from a local abattoir was dissected to isolate samples of each tissue type from each lobe. Unconfined compression, unconfined tension, stress relaxation (tension and compression), and shear tests were then carried out for grey and white matter, across the frontal, parietal, temporal and occipital lobes for both, and for the corpus callosum for white, and the deep brain (thalamus & basal ganglia) for grey. Baseline tests were performed to 50% strain, at a quasi-static load rate of 25%/s. Additionally, regional viscoelastic behaviour was investigated by varying the strain rate (100 and 500 %/s) and by performing stress-relaxation tests in tension and compression. Mode I fracture tests were carried out to characterize and test the clinical hypothesis for damage outlined above, also at 25%/s. A subgroup analysis was performed, investigating fresh vs frozen samples in tension and compression to assess feasibility of frozen tissue in mechanical characterization. Ogden (n=3) parameters were then fit to the fresh tissue behaviour for in silico modelling.

RESULTS

It was found that white matter is significantly stiffer than grey in compression up to 50% strain ($p < 0.05$ throughout), with both showing compression/tension asymmetry, with their tensile loading paths being distinct. White matter displays a linear loading path ($R2 = 0.9905$) to 50% strain, while grey matter shows strain softening, its stress response plateauing after 15% strain. In-silico analysis demonstrates that a single Ogden constitutive law ($\mu 1$ = -0.296 MPa, $\mu 2$ = 0.158 MPa, $\mu 3$ = 0.139 MPa, $\alpha 1$ = -0.148, $\alpha 2$ = 0.181, $\alpha 3$ = -0.468, d(1-3) = 0 MPa^(-1)) cannot capture key features of both grey and white matter. Loading rate was observed to have an impact on the tangent moduli of the tissues more so than the peak stress, with increased load rates causing the brain tissues to undergo higher stresses at lower, clinically relevant strains (7), with all tissues relaxing by _~73-86% at 50% strain, across tension and compression.

In mode I fracture testing, tears were seen to occur not only at the grey/white matter boundary, but also within the bulk grey and white matter.

DISCUSSION

Variation in mechanical behaviour as observed in the above results, between both grey and white matter, and between regions of the brain, indicates that brain tissues cannot be treated homogenously in computational modelling. This is evident in the divergence of the Ogden model fit to white matter from the grey matter behaviour at various points in the strain range. Preliminary models using a phase field fracture approach have shown bulk material delamination, and future work will include incorporation of this model into a microstructurally-based hyperelastic framework. Further investigation in required regarding the clinical hypothesis of boundary delamination, and the temporal variance in mechanical properties throughout healing long-term damage phases.

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On the mutual coupling of viscoelasticity and the Mullins effect

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Speaker: Wollner Maximilian P.. **Thursday**. Start time: **16:30**. Room: Rhône 4 LVL1. Link to abstract.

It is generally accepted that soft biological tissue shows inelastic material behavior, such as viscoelasticity and loss of stiffness after primary loading, akin to the Mullins effect in rubber. Recently, there has been experimental evidence suggesting a coupling of these rate-dependent and damage-related effects in porcine thoracic aorta (1). Two observations in favor of this hypothesis are (i) rate-dependent equilibrium relations and (ii) considerable differences in viscous dissipation between loading to unloading. With respect to continuum-mechanical modeling, thermodynamically-consistent formulations of anisotropic viscoelasticity at finite strains can be achieved with and without a multiplicative split of the deformation gradient, cf. (2) and (3), respectively. However, by definition, these approaches do not include damage-related effects. Regarding the latter, a wide-spread description for the Mullins effect has been proposed by (4) and popularized by (5). Here, the rate of deformation does in turn not influence the magnitude of damage, since the initial material response is taken to be purely elastic. As is often the case when modeling different sources of dissipation, one can superpose these two inelastic effects without truly coupling the phenomena, e.g., cf. (6). Consequently, the material response might allow for both viscous and damage-related dissipation, but rate-dependent equilibrium hystereses remain nonetheless impossible.
We attempt to address these deficiencies by extending the damage model of (4) to initially viscoelastic materials. This leads to a set of simple expressions which can straightforwardly be brought into line with the dissipation inequality, while still allowing for a wide range of possible material behaviors. We then discuss the consequences of this mutual coupling both from a purely theoretical point of view and with respect to experimental data from aortic and gastric porcine tissue.

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PATIENT-SPECIFIC FINITE ELEMENT MODELLING OF INTRACRANIAL ANEURYSM GROWTH AND RUPTURE

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Speaker: Mcdonagh Peter. **Thursday**. Start time: **16:50**. Room: Rhône 4 LVL1. Link to abstract.

Intracranial aneurysms (IAs) are localized dilations of cerebral arteries that pose significant clinical risks, particularly when ruptured, causing subarachnoid haemorrhage (SAH). Unruptured IAs affect 2–5% of the population, with risks influenced by factors like age, gender, genetics, hypertension, and smoking (1,2). During IA evolution, significant extracellular matrix (ECM) changes occur, including elastin degradation, collagen remodelling, and loss of smooth muscle cells (SMCs), leading to reduced vessel wall strength and stiffness (3). Despite advancements in imaging techniques, rupture risk assessments largely rely on qualitative metrics and clinician judgment lacking integration of patient-specific variations in aneurysm morphology, hemodynamic, and vessel wall biology. Patient-specific models aim to address these gaps by incorporating individualized data, such as vessel geometry and tissue remodelling, to predict IA progression. In the current study we propose a framework to predict arterial growth based on cell level remodelling, leading to a diagnostic tool to predict patient-specific IA growth. A constitutive law is implemented to describe elastin pre-tension, anisotropic collagen strain stiffening, and active smooth muscle cell (SMC) contractility (4). The active cell free energy and passive ECM elastic energy is computed and cell and tissue remodelling is initiated when the total artery free energy changes significantly from the homeostatic free energy of a healthy artery. The initiation and evolution of fusiform and saccular IA geometries are simulated. A patient specific geometry of the internal carotid artery is reconstructed using image segmentation with SimVascular, and a finite element mesh of the vessel is created using the GIBBON toolbox. Our active anisotropic artery constitutive law and our thermodynamically based growth model are implemented in a user-defined material subroutine (UMAT) in the Abaqus implicit finite element solver. Steady state conditions for artery homeostasis are predicted for a healthy vessel at 120 mmHg. An initial parametric study investigates the effect of elastin degradation on the vessel radius in the absence of growth and remodelling, revealing that full disruption of elastin results in merely a 14% increase in vessel radius. This suggests that elastin degradation acts as an initiation trigger for IA formation, but does not account for large radius increases observed for fully developed aneurysms. We then simulate the effects of growth in a vessel experiencing hypertensive conditions and elastin degradation. An increase in free energy due to increased stretching of the passive ECM results in initial growth. Following this, SMCs are predicted to transform from a contractile phenotype to a synthetic phenotype, further increasing the free energy of the system and significantly increasing the growth of the IA. We demonstrate the ability of the model to predict both saccular and fusiform IA development, depending on the localisation of elastin damage during initial stages of IA evolution. A cohesive zone formulation is used to predict the rupture risk for the IA, with the cohesive strength dependent on the predicted evolution of collagen concentration and alignment. Results are compared to clinical data for IA evolution and rupture.

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Finite Element Model of Lower Limb Lymphedema Under Elastic Compression

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Speaker: Américo De Almeida Mateus. **Thursday**. Start time: **17:10**. Room: Rhône 4 LVL1. Link to abstract.

Introduction

In the human body, the lymphatic system plays a crucial role in maintaining fluid balance by draining and filtering lymph derived from interstitial fluid that is not reabsorbed by blood vessels. When lymphatic fluid drainage becomes impaired due to obstruction of the drainage pathways or congenital conditions (1–3), lymph accumulates, leading to tissue swelling and the development of fibrosis. This condition, known as lymphedema, particularly affects women undergoing treatments for breast and gynecological cancers (4,5).

Among the treatments available to manage lower limb lymphedema, compressive therapy using compression stockings has demonstrated satisfactory results in reducing tissue swelling and controlling leg volume (6). However, the exact impact of compression stockings on lymphatic drainage remains poorly understood.

Finite Element Analysis (FEA) has been employed to investigate upper limb lymphedema under compression (7), providing valuable insights. However, similar studies addressing lower limb lymphedema are notably absent in the current literature. To address this gap, this study proposes a FEA approach to examine the hydrostatic pressure distribution within the soft tissues of the region between the ankle and knee in a patient with lower limb lymphedema wearing a compression stocking. This investigation includes a sensitivity analysis to evaluate the effects of different soft tissues and compressive therapy on a patient-specific Finite Element (FE) model of a lymphedematous leg.

Methods

The FE model of the leg was reconstructed using segmented three-dimensional Magnetic Resonance Imaging (MRI) data from a patient with lower limb lymphedema, obtained at the University Hospital Center of Nice, France. These images enabled the differentiation of leg tissues, including fat, muscles, and bones. Since bones are significantly stiffer than soft tissues, only fat and muscles were modeled using four-node linear tetrahedral hybrid elements with constant pressure. Additionally, the skin and fascia cruris tissues were modeled from the external surfaces of fat and muscles, respectively, using three-node triangular membrane elements.

Neo-Hookean compressive material properties were assigned to the skin, fat, fascia cruris, and muscles. Four FE models were developed to include different combinations of tissues: one with fat and muscles; one with fat, fascia cruris, and muscles; one with skin, fat, and muscles; and one with skin, fat, fascia cruris, and muscles.

The volume of the bones was not modeled, but the nodes on their surfaces in the inner part of the leg were clamped. Symmetry boundary conditions were applied to the top and bottom surfaces of the model to constrain longitudinal displacement. Finally, the interface pressure, representing the pressure exerted by a compressive stocking on the skin surface, was calculated using Laplace's law, based on the stocking tension and the local curvature radius of the leg. FE simulations were conducted using Abaqus CAE software.

Results

The numerical simulations reveal the impact of leg morphology on the distribution of interface pressure. In areas of the skin surface where the local curvature radius is smaller, the interface pressure is significantly higher. This increase in interface pressure directly generates a higher hydrostatic pressure distribution within the soft tissues beneath these regions of the leg.

The skin and fascia cruris tissues provide resistance against the transmission of interface pressure, playing a crucial role in the hydrostatic pressure distribution within the underlying fat and muscle tissues. However, the simulations indicate that the skin exerts a greater influence than the fascia cruris in this process and contributes more significantly to the relaxation of hydrostatic pressure within the leg, effectively mitigating the pressure gradients imposed by external compression.

Discussion
The morphology of a patient's lower limb directly determines the interface pressure applied by the stocking, which, in turn, significantly impacts the hydrostatic pressure distribution within the tissues. For patients with lymphedema in the lower extremities, this morphology becomes even more complex, as the presence of edema can lead to irregular and non-uniform hydrostatic pressure patterns depending on the distribution of excess fluid within the tissues.
In the literature, existing models of compression in the lower limb do not account for either the skin or fascia cruris tissues (8). However, the findings of this study highlight the important role of the skin in regulating the mechanical response of soft tissues under compressive loading. In FE models that exclude the skin, there is a notable overestimation of hydrostatic pressure distribution in the fat and muscle tissues. Since fluid accumulation predominantly occurs within the fat tissue (9), this overestimation may result in a misunderstanding of how compressive stockings influence fluid drainage and the maintenance of limb volume. Accurately modeling the skin's contribution is, therefore, crucial for generating realistic predictions about the effectiveness of compression therapy.

Conclusions
The results emphasize the critical importance of patient-specific models in evaluating the effectiveness of compressive stockings. To further investigate these phenomena, future research will extend the current approach to a larger cohort of patients. By analysing data from multiple individuals, the study aims to capture a broader range of variations in pressure distributions arising from differences in patient-specific factors such as anatomy, tissue composition, and the severity of lymphedema. Additionally, efforts will focus on identifying correlations between simulated hydrostatic pressure distributions and observed patterns of fluid retention or fat accumulation in the affected tissues. This expanded investigation will provide a more comprehensive understanding of the mechanical and physiological responses elicited by compressive therapy, ultimately contributing to the optimization of personalized treatment strategies.

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Quantification of the Influence of Orthopedic Insole in ex-vivo Feet

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Speaker: Viguie Benoît. **Thursday**. Start time: **17:30**. Room: Rhône 4 LVL1. Link to abstract.

1. Introduction

Rheumatoid arthritis is an autoimmune inflammation affecting 0.77% of the population (Stolt et al., 2017). The disease causes erosion of the joints and the surrounding tissues. The first symptoms appear on the front of the foot in 90% of cases. This results in intense pain, toe deformities, and loss of functionality. On a daily basis, it is a highly disabling condition, causing difficulties in walking and maintaining balance.

Non-pharmacological treatment using orthotic insoles helps alleviate pain. Wearing custom insoles allows for offloading the pressure area during walking and while standing still. The variability of insoles lies in the choice of material, which can be more or less soft, as well as in the geometry, with the addition of a dome of material near the pressure area.

Although the effects of insoles have been demonstrated on foot segment movements (Tenten-Diepenmaat et al., 2019), plantar pressure, and pain reduction, the impact of insole design on the biomechanical behaviour inside the foot is poorly characterised. No link has been made between local shape variation and possible relief of perceived pain. A better understanding of how perceived pain for a given patient is related to mechanical metrics and how these are affected by the insole design could lead to a more rational treatment of the disease.

The study of the mechanical behaviour inside the foot in a patient-specific way requires a priori knowledge of the bone shapes and positions at rest, and a computational model to estimate bone displacements for a particular loading scenario. The numerical models reported in the literature use generic bone geometries to simplify calculations (Chen et al., 2010). Other models focus on the effect of the insole on the metatarsophalangeal joint (Spirka et al., 2014). Even though patient-specific models of complete foot-insole interaction have been developed to study foot biomechanics during the gait cycle (Kroupa et al., 2020), they are not suitable for studying the influence of orthopedic insoles due to computational time constraints.

The objective of this study is thus to develop a comprehensive model of the insole's effect on the internal biomechanics of the foot, using a combined approach of tomography and finite element modelling.

2. Materials and Methods

A generic template model of the foot, including the geometry of each bone and the location of ligament insertions, was constructed by manual segmentation of the Visible Human Project. A series of CT scans were performed on 3 patients under different mechanical loading conditions on the bare foot.

The position of each bone in the unloaded reference configuration was manually segmented. To avoid manually segmenting each loaded configuration, the skeletal configuration of each loaded state was obtained by separating the bones from the soft tissues through threshold-based segmentation. The position of the bones was then determined using an optimisation-based method that minimises the minimum distance between the bones obtained from manual segmentation in the reference configuration and the skeletal configuration. This minimisation seeks a rigid transformation that aligns two point clouds, with optimisation carried out using Sequential Least SQuare Programming (SLSQP) minimisation from the SciPy Python package.

To avoid manually placing each ligament onto the bone geometry, a mesh-morphing technique was employed. Each bone of the generic template model, including the location of ligament insertions, was deformed to match the patient-specific bones. First, a rigid alignment of the two feet was performed, bone by bone. The source geometry was then approximated to the target through a normal projection and smoothing routine. RBF mesh-morphing was subsequently carried out using inverse multiquadratic functions. This mesh-morphing technique allows for semi-automatic interpolation of the patient-specific ligament positions on the bones.

The geometry thus constructed was imported into Abaqus for finite element analysis. The bone meshes were considered as rigid bodies, and the cartilages were represented by the dilation of their surfaces in the joint regions. The passive behaviour of the ligaments and muscles was incorporated by adding linear

spring elements in tension. Soft tissues were modelled as a homogeneous hyperelastic material with a Ogden strain energy function. Two contacts were considered: the contact between the bones and the contact between the plantar surface and the ground.
The boundary conditions were determined by analysing the bone displacements in both the reference and loaded configurations. The calibration of ligament stiffness was then achieved by minimising the static equilibrium for the various loading conditions.

3. Results
The results of bone registration was checked visually and yielded satisfactory positioning. The average Haursdoff distance between the mesh-morphed bone and the target bone geometry is 0.06 mm with a standard deviation of 0.09 mm. A visual inspection validated the interpolated positioning of the ligaments compared to anatomical atlases.
Seventy-four ligaments were modelled and their deformation computed. The impact of insole on ligaments deformation was assessed, 49% of the ligaments exhibited a significant difference in strain between the bare foot and the foot with an insole. Deep transverse metatarsal ligaments connecting adjacent metatarsal heads exhibited a strain reduction equal to 3%. The most deformed ligament is tibiotalar part of deltoid ligament with a strain equal to 0.41.
Shearing stresses applie;d under the metatarsal heads fat pad were assessed. Larger shears appeared under the medial sesamoid bones with a maximum shear stress equal to 6.1MPa.

4. Dicussion
The results show that a complete barefoot-ground interaction model can be constructed. It is a first step before including an insole. However, due to the computational intensity of even simple loadings, the model must be simplified in order to represent a full walking cycle. Several simplification hypotheses will be studied to limit the computational cost. As it is known that the midfoot is stiffened by the shoe during walking, this can be represented numerically. Not all ligaments play an equally significant role in foot biomechanics, so it may be sufficient to model only the main ligaments. The impact of the constitutive law of soft tissues on the mechanical response will also be investigated.
Furthermore, the contact with the ground is properly managed numerically. The addition of an intermediate insole with variable geometry and material is a similar issue and will allow for the study of its impact on the internal biomechanics of the foot. The numerical model thus constructed should be able to provide a set of parameters related to the insole that minimises a given biomechanical criterion.

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Modeling the effects of elastic compression on fluid dynamics in lower limb lymphedema

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Speaker: Reda Maha. **Thursday**. Start time: **17:50**. Room: Rhône 4 LVL1. Link to abstract.

Introduction

Under normal conditions, interstitial fluid (IF) pressure in the lower leg is maintained at or slightly below atmospheric levels, thanks to a delicate balance between fluid filtration from blood capillaries and reabsorption by the lymphatic vessels. However, factors such as increased capillary pressure or venous insufficiency can lead to lymphedema, a condition characterized by IF accumulation in the tissue space (1,2). In the early stages of lymphedema, fluid accumulates primarily within the subcutaneous space. This accumulation inhibits the natural pumping mechanisms present in healthy lymphatic vessels, resulting in inefficient fluid drainage. To this end, compression therapy stands as one of the primary treatments for early stages lymphedema. To better understand fluid dynamics in lymphedematous tissues and under therapeutic compression, computational modeling has been widely used (3,4). However, due to the complexity of the lymphatic system and the multifactorial nature of the disease, modeling the whole network of lymphatic vessels remains challenging.

Methods

In this study, we developed a patient-specific three-dimensional finite element model of the lower limb. We adopted a continuum approach based on poroelasticity where the subcutaneous tissue of the lower limb was modeled as a biphasic medium comprising a solid matrix and a fluid phase representing, respectively, the tissue components and the interstitial fluid. The model was reconstructed after the segmentation of three-dimensional magnetic resonance imaging (MRI) data of the lower limb. The fluid phase in the subcutaneous tissue was based on Darcy's law and the solid matrix was modeled as linear elastic. Capillary and lymphatic vessels were incorporated as distributed sources and sinks within the domain, in accordance with Starling's principle. All other soft tissues were represented as linear elastic. Bones were treated as rigid structures, and their inner part was neglected. Boundary conditions were applied such that the surfaces of the bones were clamped, while the longitudinal displacement of the bottom surface was constrained by symmetry conditions, leaving the top surface free. Gravitational forces were included to account for their impact on both solid and fluid components. Simulations were conducted using COMSOL® 6.0, using porous media and structural mechanics modules. This implementation enabled the analysis of fluid flow, interstitial fluid pressure (IFP), and tissue deformation under varying lymphedematous conditions.

Results and discussion

The model demonstrated its ability to replicate key pathological phenomena associated with lymphedema. For instance, increasing capillary pressure led to a significant rise in IFP and tissue volume, consistent with clinical observations. Furthermore, the model allowed the study of the effects of compression therapy. External compression was simulated by applying pressure on the skin, calculated using the Laplace law to account for the curvature of the limb. Under compression, the model successfully predicted a reduction in limb volume and a decrease in IFP, with the magnitude of these effects varying with the level of applied pressure. To extend the analysis, muscle activity was incorporated to simulate the effects of the calf muscle pump on fluid drainage during gait. This was achieved by applying a periodic internal pressure on the fascia to mimic muscle contraction and relaxation cycles. The results showed the role of muscle activity in restoring equilibrium to IFP, particularly in the presence of external compression. The model however presents several limitations. For instance, blood and lymphatic vessels were not explicitly represented, which limits the model's ability to provide detailed insights into fluid transport within these vessels. Additionally, the uniform distribution of sources and sinks in the tissue does not fully capture the heterogeneity of the vascular network. Addressing these limitations in future iterations could further enhance the model's accuracy and predictive power.

Conclusion

In conclusion, this patient-specific finite element model provides a robust framework for studying fluid

dynamics and tissue mechanics in lymphedema. By simulating both pathological conditions and therapeutic interventions, the model offers valuable insights into the management of lymphedema, particularly the efficacy of compression therapy.

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Mechanical feedback and incompatibility in size regulation

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Speaker: Erlich Alexander. Keynote. **Friday**. Start time: **10:00**. Room: Rhône 4 LVL1. Link to abstract.

In this presentation, we explore the complex relationship between growth, stress, and size regulation in biological systems, focusing on how cells control their growth as they near the final size of the organ. Our approach is twofold: examining the energetic costs of growth and investigating the concept of growth incompatibility.
First, we introduce a modified morphoelasticity framework that accounts for an energetic penalty due to growth. This model provides a size control mechanism, in addition to the usual models of collapse and uncontrolled expansion present in classical Eshelby-driven growth. It aligns with residual stress profiles observed in experiments with multicellular spheroids, offering a thermodynamics-based perspective with testable predictions about organ growth mechanics.
Second, we delve into the concept of incompatibility, the geometric 'seed' of residual stress, as a crucial determinant of growth termination. We explore this both at the cellular and tissue levels, showing that incompatibility-driven growth, measured via the Ricci curvature of the growth tensor, enables a final size for the growing body. This is consistent with behaviors observed in Drosophila wing discs and multicellular spheroids, suggesting that controlling incompatibility at the cellular level can regulate overall properties like stress and size.
In conclusion, in this presentation we will reveal that the dynamic interplay between growth, stress, and incompatibility proposes mechanisms of how organs may regulate their growth to achieve specific sizes, in coherence with experimental data in growing spheroids and Drosophila wing discs.

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On the separation of equilibrium and inelastic effects in arteries

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Speaker: Bogoni Francesca. **Friday**. Start time: **10:40**. Room: Rhône 4 LVL1. Link to abstract.

The mechanical behavior of vascular tissues is characterized by the presence of several inelastic effects. From a theoretical perspective, their constitutive behavior can be generally described by introducing an equilibrium term, assumed to be a rate-independent functional of the deformation history, and a non-equilibrium contribution encapsulating the material rate-dependency (1). Following this theoretical approach, it is convenient to design experimental protocols that allow the distinction of the different constitutive phenomena. In a recent study on porcine thoracic aorta, it was shown that the equilibrium relation cannot be properly assessed with continuous loading protocols, since rate-dependent effects are present even at low deformation rates (2). This makes the assumption of quasi-stationary inadequate for the isolation of the equilibrium relation, making the interpretation of such tests ambiguous.
Alternatively, the equilibrium response can be assessed through step-wise relaxation protocols, which enable the separation of dissipative characteristics by performing only one test. As noted by (3), a unique equilibrium response may not hold for all materials, although to the authors' knowledge no experimental evidence has been provided to substantiate this claim. As far as vascular tissues are concerned, a first attempt in this regard was presented in (2), albeit with a limited sample size and without verifying the homogeneity in the deformation field. In any case, multi-step protocols have not found widespread application in the mechanical characterization of soft tissues, although isolating inelastic effects is of paramount importance. For example, in tissues with a pathological condition, changes in arterial viscoelasticity can be used as an index to gauge wall integrity (4), as changes in wall viscosity have been correlated with different stages of atherosclerosis in the carotid artery (5).
In this work we follow up on the methods proposed in (2) and attempt to remedy its shortcoming by increasing the sample size and verifying the hypothesis of homogeneous deformation. We attempt to investigate the existence of unique equilibrium relations by repeating step-wise tests with different deformation rates on the porcine thoracic aorta under uniaxial tensile conditions. This may in turn imply a rate-dependency of inelastic effects, which motivates the formulation of constitutive models without a straightforward decomposition into rate-independent and rate-dependent contributions.

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A Thermodynamic Framework to Investigate the Role of Cell Morphological Changes in Cerebral Aneurysm Growth

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Speaker: Coleman Ryan. **Friday**. Start time: **11:00**. Room: Rhône 4 LVL1. Link to abstract.

Aneurysmal tissue is pathologically weakened relative to healthy arterial vessels, highlighted by a decreased presence of elastin in cerebral arterial aneurysm tissue post-rupture, relative to healthy aortic vessels (1, 2). Throughout pathogenesis of cerebral aneurysms smooth muscle cells (SMCs) differentiate into synthetic "matrix remodelling" and proliferate phenotypes (3). Observations show thermodynamic fluctuations motivate cellular remodelling towards a homeostatic ensemble in similar contractile cells (4). We propose a novel thermodynamic framework to predict arterial remodelling based on the following processes: (i) initial elastin degradation; (ii) SMC morphological change; (iii) SMC differentiation into a proliferative synthetic state; (iv) synthesis of collagen ECM and growth of arterial tissue. In this framework, evolution in cell morphology and ECM synthesis is driven by a change in the free energy of the system from the homeostatic free energy associated with a healthy artery.
Our proposed mathematical framework incorporates the principle that an energetic stimulus, such as knock-out of elastin, causes free energy of the artery wall to diverge from homeostasis, resulting in cell and tissue remodelling. This results in a competition between cell-stretch and cell replication returning the system to a homeostatic state, with passive energetic requirements of stretch in collagen, elastin, and the passive matrix component. A constitutive law is proposed for active contractility observed in SMCs, predicting the concentration of stress fibres (SFs), dependent on cell stretch, found through thermodynamic equilibrium between chemical potentials of SFs with unbound cytoskeletal actin-myosin proteins (4). This thermodynamic equilibrium also effects the Gibbs free energy density of the cell, resulting in an energetic competition between SF formation and passive stretch of the cell cytoplasm and membrane. This framework is complimented by a constitutive law describing force balance conditions as well as energetic considerations in modelled arterial components of collagen, elastin, and the passive arterial matrix response (5).

Our model predicts that cells change their morphology in order to restore the Gibbs free energy of the artery wall to a homeostatic free energy. Significant deformation of the artery wall due to hypertension or elastin damage increases energetic demands for arterial vessel maintenance, which cannot be sufficiently restored to homeostasis through the mechanism of cell morphology change. This results in the differentiation of SMCs into a synthetic state. The synthetic state exhibits significantly reduced SF formation, such that its energetic contribution and contractile stress is reduced. However synthetic cells act to decrease free energy of the system by replication of additional contractile SMCs, or increase free energy by causing passive tissue growth by deposition of arterial tissue, potentiating growth of the vessel circumference. We utilise this framework to predict fusiform aneurysm formation, and we compare predicted aneurysm growth rates of SMC and ECM morphological changes with clinical observations and histological images. This cell based thermodynamic framework represents a significant advance on previous phenomenological models of aneurysm growth that rely on stress- or strain-based growth algorithms.

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Soft tissue deformability, growth, and anchoring as multiscale facial sagging mechanisms

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Speaker: Santoprete Roberto. **Friday**. Start time: **11:20**. Room: Rhône 4 LVL1. Link to abstract.

Despite growing interest in anti-aging products and surgical procedures, the mechanistic links between age-based biomechanical tissue alterations and the emergence of a sagged facial appearance have remained relatively unexplored. Here, we provide corresponding insights by leveraging accurate *in vivo* characterization of the non-linear, time-dependent mechanics of cheek soft tissues to inform anatomically-accurate computational face models. We report that age-based changes in tissue deformability are locationand layer-specific, measuring-for the first time-stronger softening for the subcutis (2.7×–14.2×) than for the cutis (1.9×). Corresponding experimentally-informed simulations indicate that biomechanical alterations of the cutis, subcutis, and dermal anchoring structures are necessary conditions towards recapitulating jowl formation, though each insufficient on its own. We relate this to the mechanical gradients across facial tissues, whereby softening of the stiffer outer layers is required for deeper tissue aging to appreciably influence the facial appearance and significantly activate stretch-based mechanobiological pathways driving skin growth. We envision these findings to inform the development of surgical and cosmetic anti-aging strategies rooted in biophysical principles.

A Multiscale Framework for Understanding Arterial Tissue Mechanics: Coupling Cellular Dynamics and Macroscopic Behavior

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Speaker: Sauty Bastien. **Friday**. Start time: **11:40**. Room: Rhône 4 LVL1. Link to abstract.

Introduction

Arterial tissue dynamically regulates mechanical tension to maintain stability under varying physiological conditions (Cyron 2014). A key short-term regulatory mechanism, vasoconstriction, involves smooth muscle cells (SMCs) contracting or relaxing through actin-myosin interactions, resulting in rapid, inelastic deformation (Karkhaneh Yousefi 2023). This microscopic vasoactive response governs the macroscopic mechanical behavior of the tissue. However, despite its importance, the short-term effects of vasoconstriction are underexplored compared to long-term mechanisms such as extracellular matrix (ECM) remodeling, which dominate current research on arterial mechanics.

Understanding the mechanical state of arterial tissue-shaped by the interplay of short- and long-term mechanisms-is essential for addressing pathological conditions characterized by instability. While existing studies predominantly focus on the non-linear behavior of collagen fibers and their contribution to passive mechanics, the active mechanical role of SMCs in vivo remains largely overlooked. Recent advances, however, highlight the importance of explicitly modeling SMC activity at the microscopic level to bridge the gap between cellular and tissue-scale mechanics (Eichinger 2021).

In this context, we present a novel multiscale approach to arterial tissue mechanics, designed to assess mechanical interactions among tissue components and elucidate the coupling between cellular and tissue-level behavior. This framework aims to provide insights on the cellular mechanical behavior, a first step toward modelling the multiscale cellular driven homeostatic regulation of the arterial tissue.

Methods

We implement a previously developed multiscale micromechanical model (Morin 2018) within a Finite Element framework using FeniCSx. This methodology employs analytical homogenization of a Representative Volume Element (RVE) to capture the microscale heterogeneity of arterial tissue, including collagen fibers, elastin, smooth muscle cells, and ground substance. Homogenization is based on the Eshelby's theory and Mori-Tanaka method, adapted for finite strain mechanics. This approach allows estimation of mean mechanical fields (stress and strain) within microscopic inclusions and the homogenized macroscopic behavior of the tissue.

For validation, we simulate a cylindrical arterial segment under pressure, representing experimental ex-vivo inflation tests on rat carotid arteries. The arterial wall is modeled as a two-layer structure-media and adventitia. The media comprises collagen fibers, SMCs, and ground substance, with collagen fibers helically arranged around the circumference and SMCs modeled as spheroids with a 1:6.2 shape ratio (O'Connel 2008). The adventitia consists of axially oriented collagen fibers and the ground substance.

To enhance the model, we incorporate a detailed sensitivity analysis of stress distribution within the SMC population, assessing how ECM stiffness and fiber orientation influence mechanical loading on cells. The model is validated against macroscopic experimental data by reproducing the pressure-radius curve from inflation tests, ensuring consistency between predicted and observed behavior. Additionally, we track collagen fiber and SMC kinematics during deformation to provide insights into their orientation and mechanical contributions under physiological loading conditions.

Results and Discussion

The model parameters were calibrated to align with experimental data at both macro- and microscopic scales, reproducing the non-linear pressure-radius curve and collagen fiber kinematics. Preliminary results revealed non-homogeneous circumferential tension in SMCs, varying with their radial position within the arterial wall. This finding underscores the significance of multiscale coupling between tissue macrostructure and microstructure.

Sensitivity analyses highlighted the influence of collagen stiffness on SMC stress distribution, showing that stiffer fibers reduce stress on SMCs. Pre-stretched fibers, in particular, mitigate cellular stress, emphasizing their potential role in mechanical stabilization.
This multiscale approach offers a robust framework for analyzing mechanical interactions between heterogeneous tissue components and understanding how macroscopic geometry affects cellular mechanics. The results demonstrate the critical role of cellular mechanics in driving regulatory processes and tissue behavior, where macrostructure induces non-homogeneous cellular activity.
Future work will incorporate an active feedback loop for SMCs to model vasoactive short-term regulation, advancing our understanding of the complex interplay between cellular and tissue-level processes. Comprehensive validation at both scales will further refine the model's accuracy, providing deeper insights into the mechanobiology of arterial tissue under physiological and pathological conditions.

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MS2.3 - Cardiovascular Biomechanics

Organisers: Caitriona Lally (Trinity College Dublin), Christian Cyron (Hamburg University of Technology) and David Nordsletten (University of Michigan)

Physics-based modeling and machine learning integration towards automating cardiovascular material model discovery and analysis

Peirlinck Mathias (1), Kuhl Ellen (2)

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Speaker: Peirlinck Mathias. **Wednesday**. Start time: **14:30**. Room: Roseraie 3 LVL3. Link to abstract.

Computational modeling of cardiovascular tissues forms a critical tool towards understanding the biomechanical factors underlying cardiovascular diseases, predicting disease progression, and designing personalized interventions. However, the selection of and proper use of appropriate material models for these simulations often requires specialized expertise and is prone to user bias, which can have detrimental consequences for patients.
Recent breakthroughs in constitutive artificial neural networks allow for the automatic discovery of optimal material models and parameters directly from experimental data, including uniaxial, biaxial and triaxial tissue testing protocols. The discovered models are interpretable, consisting of physically meaningful terms and parameters, and can be seamlessly integrated into finite element simulations through a newly developed, open-source available universal material subroutine (1). This subroutine seamlessly integrates trillions of potential constitutive material models that come out of the automated material model discovery pipeline, and automatically capture various traditional models as special cases. By replacing dozens of individual material subroutines with a single universal material subroutine, populated directly via automated model discovery, we can make finite element simulations more user-friendly, robust, and less vulnerable to human error.
Various examples demonstrate the effectiveness of this approach for systemic arteries (2), pulmonary arteries (3), and myocardial tissue (4) where finite element analysis simulations highlight the impact that improved accuracy has on large-scale organ mechanics under complex hemodynamic loading conditions. This integrated approach towards automated material model discovery and finite element analysis empowers a broader community of researchers to perform reliable biomechanical simulations, driving innovation and discovery in the field of cardiovascular tissue mechanics.

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Discrete network simulation of the multiaxial rupture properties of the endothelium

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Speaker: Jakob Raphael. **Wednesday**. Start time: **14:50**. Room: Roseraie 3 LVL3. Link to abstract.

Lining the luminal surface of blood and lymphatic vessels, the endothelium is exposed to various mechanical stimuli such as variable hydrostatic pressure, shear stress due to blood flow, and circumferential stretch due to the heart's pulsatility. Under physiological conditions, these stimuli contribute to endothelial homeostasis, ensuring its biological functions. However, in certain clinical conditions such as altered vessel properties, use of venous grafts in arterial bypass, or coronary angioplasty and subsequent stent placement, mechanical stimuli can reach supraphysiological levels. Specifically in angioplasty and stenting, the vessel is dilated to a multiple of its original diameter in a matter of seconds, thus acutely stretching the endothelium. As complications of these interventions, endothelial denudation and impaired endothelial repair lead to inflammation, platelet activation, and smooth muscle cell proliferation, resulting in neointimal hyperplasia, restenosis, and adverse clinical outcomes. Thus, improved understanding of the rupture properties of endothelial monolayers is of importance for the improvement of clinical outcome.

We recently investigated the behavior of endothelial monolayers when exposed to acute stretch as a result of uniaxial tensile loading with lateral contraction of their substrate up to magnitudes of 87%, comparing the response of young and aged cells (1). We revealed that that aged cells were more susceptible to stretch-induced damage, characterized by intercellular and intracellular void formation, which increased with the level of deformation. Under in-vivo conditions, however, the load state can be highly heterogenous. In the case of coronary angioplasty, for example, the placement of the stent leads to states of stretch that vary locally in magnitude and directionality. Thus, the kinematic configurations assessed based on uniaxial tensile loading do not yield sufficient information to characterize stretch induced damage in endothelial monolayers in clinically relevant cases. We therefore extended the analysis to include both equibiaxial and uniaxial (i.e. no deformation in the direction perpendicular to the loading axis) stretch conditions. The experiments indicated clear differences in the amount of damage, quantified as the area of voids formed within the monolayer depending on the loading conditions.

In order to rationalize the observations, we aimed at identifying a kinematic variable which could characterize void formation for all three kinematic states considered in the experiments. Attempts based on the maximum principal stretch or the area stretch did not yield satisfactory results. To fill this gap, we developed a computational model of endothelial monolayer deformation and damage. The model aims at representing the extensibility of intracellular cytoskeletal structures as well as intercellular connections, with consideration of corresponding failure conditions. Moreover, as the cells bind to their substrate via protein complexes called focal adhesions, through which the deformation of the substrate is transmitted to the cells, representation of these links, their density and failure properties is an important aspect of the analysis. To this end, we created a discrete network model of a single endothelial cell's actin cytoskeleton, linked with elements representative of nucleus, cellular membrane, and focal adhesions. After calibrating the model of a single cell to experimental data from traction force microscopy (2), we were able to capture the endothelial cell's contractile behavior on unstretched substrates as well as the local stiffening caused by a contracting cell on a soft substrate subjected to equibiaxial stretch (3). We then extended the model to represent a monolayer through connection of many of the single-cell models by incorporation of cell-cell junctions. This allowed us to create endothelial monolayer models consisting of hundreds of cells with subcellular cytoskeletal resolution.

Because the single endothelial cell discrete network representation consists of thousands of intracellular connections, the setup and simulation of a mechanical boundary value problem of endothelial monolayers consisting of hundreds of cells is computationally demanding. Additionally, simulation of sub-isostatic networks (4) as well as implementation of the breaking of connections within the network pose further challenges to the solver. Conventional numerical techniques such as finite element modelling are ill-equipped for this kind of problem. Since solvers used in molecular dynamics are designed to handle such conditions, we implemented our mechanical boundary value problem in the Largescale Atomic/Molecular

Massively Parallel Simulator (LAMMPS). Inspired by the representation of covalent bonds in LAMMPS, we designed custom bond potentials to define the required mechanical behavior of the cytoskeletal components. These potentials exhibit a stretch-dependent bilinear material law with different moduli under tension and compression, respectively, as well as a stretch-dependent bond-failure criterion. The boundary value problems were solved by minimizing the potential energy by means of the Fast Inertial Relaxation Engine (FIRE).
The distribution of bond-failure properties of the intercellular connections in the computational model was determined such that good agreement was achieved with the experiments in terms of void area for the different amounts of applied stretch. This also led to sound agreement in terms of the void morphology, i.e. the endothelial damage patterns observed in the experiments. By means of the model we could confirm a correlation between the amount of void area and the total elastic energy stored in the different cytoskeletal elements. Moreover, using a hyperelastic model, the latter was expressed in terms of a strain-energy density function dependent on the isotropic strain invariants representative of the kinematic boundary conditions, so that the experimental void formation could be related to these invariants of macroscopic substrate strain. These results allow to predict the expected void area in endothelial monolayers for any arbitrary kinematic state of their substrate, thus creating a tool for estimating the expected damage during angioplasty and stenting. The model further allows us to analyze the influence of each cytoskeletal component on void formation, and thus provides a basis for biochemically modifying the properties of endothelial cells to increase their stretching resistance, or to reduce endothelial damage through an optimized application of vascular devices.

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Linking the microstructure of human middle cerebral arteries to their mechanical behavior

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Speaker: Demeersseman Nele. **Wednesday**. Start time: **15:10**. Room: Roseraie 3 LVL3. Link to abstract.

Introduction

In silico models of the cerebrovascular tree are valuable tools for advancing treatments of diseases like stroke (1). However, their reliability depends on how accurately they replicate the mechanical behavior of cerebral blood vessels. While models such as the Gasser-Ogden-Holzapfel model effectively represent arterial mechanics, their calibration is hindered by the limited data on cerebral arteries, which differ structurally from the more extensively studied large elastic extracranial arteries (2). This study aims to fill this gap by investigating the microstructure of human middle cerebral arteries and linking it to their mechanical behavior.

Materials and methods

Human middle cerebral artery tissue was obtained from six donors within 24 hours postmortem in collaboration with the Dublin Brain Bank (Royal College of Surgeons, Dublin, Ireland). From these arteries, 32 2 mm thick ring samples were excised, and their mechanical properties were characterized through ring-extension testing in a prior investigation. This testing resulted in stress-strain curves from which mechanical properties such as linear stiffness in the elastin- and collagen-dominant regions, failure stress, and x-intercept strain were derived.

To investigate potential microstructural links to the observed mechanical behavior, a histological analysis was conducted on 7 μm-thick cross-sections stained with Hematoxylin and Eosin (H&E), Verhoeff's elastin, and Picrosirius red. Next, imaging was performed using a Leica Aperio AT2 system for the H&E and Verhoeff's elastin-stained sections, whereas the Picrosirius red-stained sections were imaged using an Olympus BX41 microscope under brightfield and polarized light (0◦ and 45◦).

For each stain, qualitative and semi-quantitative analyses were performed on three sections per sample. Medial thickness and internal elastic lamina thickness were measured at 10 points in H&E- and Verhoeff's elastin-stained sections, respectively, and normalized to the total radial thickness of the section to account for size differences. Smooth muscle cell fraction was approximated from H&E images by dividing the hematoxylin-stained area by the total medial area, using QuPath. Collagen fraction was quantified from Picrosirius red-stained sections using a custom MATLAB script. To estimate the collagen content, polarized light images at 0◦ and 45◦ were combined, as each angle captures different fiber orientations (3). The resulting composite image was used alongside the brightfield image to delineate the media-adventitia border, enabling separate collagen fraction calculations for the media and adventitia. Finally, pixel intensities, which are proportional to collagen content (3), were normalized to the maximum observed intensity (assumed to represent 100% collagen) and averaged across the tissue segment of interest to calculate the collagen fraction. Unbalanced two-way ANOVA was used to evaluate the effects of cardiovascular disease and sample location (proximal M1 vs. distal M2 segment of the artery) on the histological features.

The relationship between histological and mechanical properties was evaluated by examining the correlation between elastin-dominant region stiffness and normalized internal elastic lamina thickness, as well as between the collagen-dominant region stiffness and collagen fraction.

Results and discussion

Histological analysis showed that middle cerebral arteries share structural similarities with other arteries, including the characteristic three-layer organization (intima, media, adventitia) and the presence of collagen, elastin, and smooth muscle cells. However, distinct differences were observed when compared to large elastic extracranial arteries, such as the aorta. Consistent with prior reports (2), the external

elastic lamina was absent in cerebral artery samples, though increased elastin fiber content was observed in the region where the external elastic lamina would typically be found. Additionally, although the semi-quantitative analyses are still ongoing, the qualitative analysis already revealed that the media of the cerebral arteries contains fewer elastin fibers and has a higher smooth muscle cell content than large elastic extracranial arteries. These findings align with the functional demands of cerebral arteries, which prioritize precise blood flow regulation over the elastic recoil required by large elastic arteries to buffer pulsatile flow (4). It should be noted that some extracranial arteries, such as the radial artery, share a similar role in blood flow regulation and exhibit a structure more similar to cerebral arteries. Therefore, the broad term "extracranial arteries", frequently used in the literature when comparing cerebral arteries to large elastic extracranial arteries, can be misleading. A clear distinction should be made between muscular and elastic arteries.

Although the semi-quantitative analyses are still ongoing, preliminary results, along with the qualitative analysis, suggest a relationship between the histological features and the mechanical properties. Donors with cardiovascular disease (n=3) appeared to have lower elastin content and exhibited reduced normalized internal elastic lamina thickness (median: 2.33 %, IQR: 2.21–2.61 %) compared to donors without cardiovascular disease (n=3) (median: 3.10 %, IQR: 2.34–3.42 %). These histological differences align with the earlier obtained mechanical findings, where unbalanced two-way ANOVA tests revealed significantly lower x-intercept strain ($p=4.92\times10^{-5}$) and higher elastin-dominant region stiffness (p=0.0097) in arteries from donors with cardiovascular disease. Additionally, initial findings indicated a higher overall collagen fraction in M1 segment samples (n=19) compared to M2 segment samples (n=13). This corresponds with the mechanical results which showed a significantly higher collagen-dominant region stiffness (p=0.038) and failure stress (p=0.002) for M1 segment samples.

In conclusion, the microstructure of cerebral arteries seems to affect their mechanical behavior, emphasizing the need for microstructurally-informed constitutive models for in silico simulations. Although multiple models like this exist for large elastic extracranial arteries, they often overlook the complexity of smooth muscle cells as elastin and collagen are seen as the main tissue constituents. Taking into account the higher smooth muscle cell content in cerebral arteries, a model with a more accurate description of these cells might be necessary. By developing a microstructurally-informed model for cerebral arteries, it will become possible to model the entire cerebrovascular tree with vessel-size-specific tissue compositions. It has been suggested that including this vessel-size specificity is essential to accurately capture the complex relationship between blood pressure and blood flow in the brain (4). Therefore, a microstructurally-informed model, calibrated using data from this study and future studies on smaller cerebral arteries, is expected to improve the accuracy of in silico models of the cerebrovascular tree, ultimately advancing research into diseases like stroke.

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Acknowledgments

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Regional micro- and macro-structural properties of the aortic wall in ascending thoracic aortic aneurysms

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Speaker: Ghorbani Omid. Invited. **Wednesday**. Start time: **15:30**. Room: Roseraie 3 LVL3. Link to abstract.

Objectives. Ascending thoracic aortic aneurysms (ATAAs), defined by permanent enlargement of weakened aortic walls in the ascending thoracic aorta, exert region-specific effects on the aortic wall. Understanding these biomechanical variations is critical for developing risk criteria based on the material properties of the aortic wall. Previous studies mainly focused on limited cohorts (1). Patients with bicuspid aortic valve (BAV) are at a higher risk of developing ATAA, typically 10–15 years earlier than patients with tricuspid aortic valve, highlighting the significant impact on the incidence and progression of thoracic aneurysms (2). The current study investigates these effects in a cohort consisting primarily of BAV patients.

Method. Samples were collected from 10 ATAA patients and 3 healthy cadavers and sectioned into six regional specimens (_~15 × 15 mm2): three from the major curvature (proximal to distal), one from the minor curvature, and two from the anterior and posterior regions. The specimens maintained their orientation to ensure circumferential (C) and longitudinal (L) alignment. Each specimen was subjected to quasi-static biaxial stretching at varying ratios (λlong:λcirc = {1:1, 1:0.5, 1:1.25, 1:0.75, 1:2}) with a linear rate of 1.5 mm/min. Planar deformation was assessed using planar digital image correlation at 2 Hz. After biaxial testing, the specimens were chemically fixed, dehydrated, and optically cleared. Collagen and elastin fiber distributions were imaged using two-photon excitation in a Leica confocal microscope with a scanned area of 465 × 465 μm2 at a resolution of 4.85 pixel/μm using line averaging to improve the signal-to-noise ratio. Z-stack images in the radial direction (R) were acquired in the C-L plane along with a single-depth image in the C-R plane to analyze fiber alignment with the circumference.

Results and Discussion. Fiber dispersion was quantified using von Mises distributions and combined with biaxial stress-strain data to create a multiscale material model of the aortic wall. The model is based on the fiber-reinforced strain-energy function of Holzapfel et al. (3) incorporating two dominant collagen fiber families in the C-L plane. High dispersion elastin fibers were modeled as part of the isotropic matrix to avoid overfitting.
Specimens from the main curvature (proximal, middle, distal) exhibited isotropic mechanical behavior. In contrast, regions on the minor curvature, anterior, and posterior showed anisotropic behavior with increased stiffness in the circumferential direction. These findings correspond to the observed collagen fiber patterns, where they were highly dispersed along the major curvature. In contrast, in other regions, collagens in the media reinforced the aortic wall circumferentially, while adventitial fibers showed dispersed and multi-directional patterns.

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A constitutive law for the tensile and compressive behaviour of fibrin networks applied to the simulation of aspiration thrombectomy

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Speaker: Bein Snee Kila. **Wednesday**. Start time: **15:50**. Room: Roseraie 3 LVL3. Link to abstract.

Traditional models for fibre-reinforced soft tissues assume that fibres are only active in tension (1-4). In such models it is assumed that wavy fibres, such as collagen, will buckle when shortened and therefore cannot support compressive stress. However, compression-tension experiments of pure fibrin blood clots, as retrieved from acute ischemic stroke patients, suggest that fibrin can support both tensile and compressive stress (5, 6). Therefore, the current study focuses on the development of a model in which fibre shortening results in the development of compressive axial fibre stress.
Published constitutive laws for fibres in soft tissues include exponential strain-stiffening (1, 2), and bilinear strain-stiffening models (4). Firstly, we demonstrate that the simple extension of existing fibre formulations to the shortening/compressive regime results in unphysical softening during high levels of applied compression. We propose a novel fibre constitutive law which prevents such softening in compression (compression-tension fibre (CTF) model). This allows us to model pure fibrin networks without the need to add an artificial isotropic matrix component.

In order to simulate a fibrin clot, we construct a network of discrete fibres in which the mechanical behaviour of each fibre is described by our novel constitutive law. The fibre model is implemented in Abaqus/Standard using a user defined subroutine (UMAT). Converged results were achieved with 1741 fibre segments. Computed results reveal that our discrete fibre network with a bilinear CTF formulation can replicate experimental compression and tension data for pure fibrin platelet contracted blood clot analogues.

Additionally, we use this novel material model to simulate the aspiration of a fibrin clot into a thrombectomy catheter, with an applied suction pressure of 80 kPa. This simulation correctly predicts the corking of the clot at the tip of the catheter as validated by bench-top aspiration tests of platelet-contracted fibrin clot analogues. The simulation further reveals regions of shortened fibres where the clot is compressed against the catheter wall, in addition to regions of fibres in tension in the centre of the clot. This new physically-based constitutive formulation provides new insights into fibrin clot biomechanical behaviour that can be incorporated into the design of thrombectomy devices.

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BLOOD PRESSURE AND FLOW CONTROL DURING ASPIRATION THROMBECTOMY INCREASES THE LIKELIHOOD OF CLOT RETRIEVAL SUCCESS

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Speaker: Glynn Aoife. Invited. **Wednesday**. Start time: **16:10**. Room: Roseraie 3 LVL3. Link to abstract.

Aspiration thrombectomy is an established method of clot removal in acute ischemic stroke (1). Advancements in catheter technology have resulted in the advent of newer generation 8Fr, balloon guide catheters (BGCs) and superbore catheters (SBCs), that can be used to deliver 6Fr large bore catheters (LBCs) to perform clot retrieval. In comparison to conventional 8Fr guide catheters (CGCs), placed in the internal carotid artery (ICA), BGCs achieve proximal flow control via inflation of a balloon in the ICA (2). SBCs, designed for intracranial use, offer local flow and pressure control, as they can be navigated to distal vascular regions (1,2). Little research has been completed to-date comparing these systems, their impact on pressure and flow, and likelihood of clot retrieval success. Thus, the aim of this work was to assess these technologies in vitro. We hypothesize that control of blood pressure and flow during clot retrieval will increase the likelihood of retrieval success. This study will provide critical insights into the clinical use of these emerging technologies.

To evaluate the systems in clinically challenging environments two distinct in vitro anatomical models were used. Five aspiration devices were investigated. Devices were used as per manufacturer's instructions by two interventional neuroradiologists. Two groups of thrombus analogues: cohesive and friable, were prepared with ovine blood (4). Analogues were used to create an occlusion in the M1 Middle Cerebral Artery (MCA). To simulate the clinical use of the devices, tracking to the target location and clot retrieval performance were evaluated. Five replicates were completed per device. Physiological blood pressure and flow were simulated and monitored throughout the experiment at defined time points: prior to device introduction, following device placement and during and after device use. Aspiration was applied through the LBCs via a 60cc syringe.

The SBC system significantly reduced the flow through the MCA during device tracking in comparison to the CGC & BGC systems ($p < 0.001$). The influence of the BGC in anatomical models with varying arrangements of the Circle of Willis (CoW) was recorded. Inflation of the BGC was not significant in Model 1, due to its possession of a complete CoW, resulting in collateral flow supplying the MCA. The BGC and SBC systems had the highest rates of clot retrieval success, indicated by the higher values of flow restored through the MCA ($p < 0.001$).

The presented results demonstrate the importance of pressure and flow control on clot retrieval success. The CGC system had limited flow control in the M1, and this translated to reduced flow restoration through the vessel. In comparison the BGC and SBC systems, which offer proximal and local control, had significantly higher rates of flow restoration. In one case the SBC, could not be tracked to the MCA to complete clot retrieval. This was attributed to a unique design feature of the device. The greatest challenge with the use of SBCs is their ability to track to distal vascular locations. This research suggests in cases where a SBC system is unable to track to the target location, proximal flow control with a BGC may provide equivalent results, however, the anatomical arrangement of the CoW should be considered. These results illustrate the importance of pressure and flow control during aspiration to maximize the likelihood of retrieval success. This research may influence device selection clinically and can be used to innovate the next generation of aspiration thrombectomy devices.

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Insights into aortic remodeling in type B aortic dissection using patient-specific fluid-structure interaction simulations

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Speaker: Rolf-Pissarczyk Malte. Invited. **Wednesday**. Start time: **16:45**. Room: Roseraie 3 LVL3. Link to abstract.

Aortic dissection, a life-threatening condition, arises from the sudden creation of a parallel flow channel within the delaminated aortic wall, known as the false lumen (1). In its chronic phase, the primary drivers of late complications are the degeneration and dilatation of the false lumen. The complex interplay between hemodynamics and microstructural remodeling, which leads to extensive anatomical remodeling over the course of years, is not yet fully understood.

This study (2) examines the progression of a patient's aortic dissection, captured by surveillance imaging with CT angiography from pre-dissection to the chronic phase over a total period of seven years. We applied monolithically coupled fluid-structure interaction models with tissue prestress, external tissue support, and an anisotropic tissue model to identify potential growth-related hemodynamic markers. In the aortic wall domain, we independently assigned thickness and material properties to each functional tissue layer. In vitro 4D-flow MR imaging (3) and the patient's blood pressure were used to inform the boundary conditions.

Quantitative measurements during routine clinical care showed that aortic dilatation was most significant distal to the left subclavian artery, reaching 6 cm in the chronic phase. Simulations resulted in a flow jet velocity through the entry tear that peaked in the subacute phase and successively decreased in the chronic phase, corresponding to an increased entry tear size. Flow jet impingement on the false lumen resulted in a localized increase in pressure and wall shear stress in the subacute and chronic phases. These hemodynamic changes appear to be the main drivers of aortic growth and morphological changes. Despite moderate overall flap movement, in-plane displacement increased as disease progressed, which was associated with an overall increase in aortic diameter. In fact, additional simulations with a significant reduction in flap stiffness during the subacute phase resulted in increased flap motion up to 9.5 mm. Although these results are based on a single patient, they suggest a strong relationship between hemodynamics and aortic growth.

BIVENTRICULAR HEART MODEL WITH NOVEL PSEUDO-FLUID DOMAINS AND THERMODYNAMICALLY-MOTIVATED GROWTH & REMODELING

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Speaker: Senthil Darshan. **Wednesday**. Start time: **17:05**. Room: Roseraie 3 LVL3. Link to abstract.

A common flaw in existing finite element (FE) models of the heart is the unphysical specification of pressure or volume boundary conditions on the myocardium wall to represent the effect of the ventricle. Changes in the pressure and volume of blood in the ventricle cavity result from active contractility of the myocardium. Therefore, ventricle pressure and volume should be computed model outputs rather than prescribed boundary conditions. To overcome this deficiency without resorting to computationally expensive fluid-structure interaction (FSI) approaches, we propose a novel "pseudo-fluid" framework for highly efficient patient-specific biventricular heart simulations.

We process MRI images of healthy human hearts using a custom workflow to automatically create a 3D patient-specific biventricular mesh with distinct myocardium and "pseudo-fluid" domains representing blood in each ventricular cavity. Our constitutive law for myocardial tissue includes active contractility of cardiac myocytes (1) in addition to passive anisotropic hyperelastic behaviour of collagen and elastin in the ECM (2). Spatial distributions of cell and collagen fibre orientations throughout the myocardium are generated using the Laplace-Dirichlet Rule-Based algorithm (3). In the ventricle cavities our novel "pseudo-fluid" approach is implemented using a custom user-defined material subroutine to determine ventricle volume and pressure changes in response to the actively contracting myocardium. During systole, pressure and volume changes in each ventricle are governed by a bespoke Windkessel-type formulation that incorporates aortic and pulmonary compliance, in addition to the peripheral resistance. This novel approach allows for the simulation of a single cardiac cycle in 30 minutes, 3-4 orders of magnitude faster than traditional FSI heart models (4,5), while accurately capturing key pressure-volume relationships in multi-cycle simulations of inferior vena cava occlusion (6).

We integrate a novel thermodynamically-based growth and remodelling formulation to predict the development of eccentric and concentric hypertrophy. Tissue remodelling is driven by a deviation of the free energy of cardiac myocytes from a homeostatic free energy. Cell free energy is based on active contractility of sarcomeres, in addition to strain energy of the passive components of the cell and the ECM. Eccentric hypertrophy results from in-series addition of sarcomeres as a result of excessive stretching of the ventricle during the filling phase, whereas concentric hypertrophy results from in-parallel addition of sarcomeres due to increased resistance to cardiac output (7). This thermodynamically-based approach represents a significant advance on previous phenomenological stress or strain-based growth algorithms.

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EXPERIMENTAL AND NUMERICAL STUDY OF AORTIC GROWTH AND REMODELING UNDER GESTATIONAL HYPOBARIC HYPOXIA

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Speaker: Navarrete Alvaro. Invited. **Wednesday**. Start time: **17:25**. Room: Roseraie 3 LVL3. Link to abstract.

Cardiovascular diseases are one of the main causes of death and morbidity worldwide (1). However, their pathogenesis and consequences are not fully understood, particularly regarding potential changes in structural and functional properties of the arterial wall (2). It is known that the arterial wall can modify its shape, structure, and properties in the face of external perturbations such as aging, vascular diseases, and surgical interventions. These changes are triggered with the goal of maintaining a state of mechanical homeostasis.
This kind of alteration is commonly studied within the context of growth and remodeling (G&R) phenomena, which is closely related to the production, removal or degradation of microconstituents of the arterial wall. Such alterations may be reflected in variation in mass and alteration of the mechanical properties of the vascular tissue.

One notable condition associated with alterations in the external environment that may have implications at the physiological level is high-altitude hypobaric hypoxia (HH). This phenomenon is defined by a reduction in oxygen partial pressure in comparison to normal conditions (normoxia). Its clinical significance is evident in organisms inhabiting highlands at an altitude of 2500 meters above sea level (3).

To investigate these effects, a coupled experimental-numerical study was conducted with the objective of determining the long-term impact of gestational exposure to hypobaric hypoxia on the thoracic aorta. To this end, the experimental groups utilize one-year-old guinea pigs as animal model. One group of animals was subjected to hypoxic hypobaric conditions during gestation, corresponding to a partial pressure of oxygen equivalent to 4600 meters above sea level. A second (control) group of animals was subjected to normoxic normobaric conditions.

Several ex-vivo biomechanical tests, including planar biaxial tensile, axial stretch and ring opening, were conducted on the thoracic aortas of animals studied. Concurrently, histological measurements were performed to determine the composition of the main load-bearing components of the artery wall. The data obtained from these experiments was used to calibrate a mechanobiological G&R model formulated by Latorre et al. (2020) (4).

The G&R model adopted considers a constrained mixture model approach (G&R-CMM) (5) to take into account the distinctive properties of each constituent and assumes mechanobiological equilibrium to describe the long-term, stationary state of the grown tissue. This condition is precisely suited to the experimental data available, as one year of age corresponds to a stage of adulthood in the cardiovascular development of guinea pigs.

The main findings illustrate the long-term impact of HH exposure during gestation, as evidenced by biomechanical parameters, residual deformation, and microstructural composition. The G&R-CMM model characterization provides insight into the mechanobiological phenomena and mechanisms governing G&R on aortic tissue under gestational hypoxic hypobaric conditions.

Acknowledgements

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Global and Local Mechanics of the Aortic Media Under Radial Extension

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Speaker: Sherifova Selda. Invited. **Thursday**. Start time: **10:00**. Room: Roseraie 3 LVL3. Link to abstract.

Radial tensile strength of the aorta may be significantly reduced due to pathological conditions that predispose patients to dissection – one of the most devastating complications of thoracic aortic disease. The mechanical behavior of arteries under such loading has rarely been investigated. We compare how the global and local mechanical response of the aortic media differs between dissected human and healthy porcine aorta using optical coherence tomography (OCT) and digital volume correlation (DVC).
Porcine ascending aortas and human ascending aortas were obtained from a local slaughterhouse and the donors undergoing surgery, respectively. Prior to preparing 5×5 mm (circumferential×axial) specimens, adventitia was removed from the porcine aortas, and the outer layer of the dissection was removed from the human aortas, with the aim of leaving intima and media intact in both sample types. Specimens were then mounted on the holders using cyanoacrylate adhesive with the circumferential-radial plane facing the OCT camera. After the glue was allowed to harden for 10 mins, the test chamber was filled with 0.9% PBS and the specimen was allowed to rehydrate for 10 mins. Subsequently, a 4×1×1.6 mm (radial × circumferential × axial) volume was imaged with OCT. After 5 preconditioning cycles, radial displacement was applied in 100μm increments until failure and the volume was imaged immediately after each increment while force was recorded. DVC was then applied to the volumetric images using DaVis 8.4 (LaVision) to obtain the displacement fields, and Green-Lagrange strain fields were derived using a custom Matlab code. Additional specimens were collected next to the mechanical testing specimens and optically cleared for investigations with multiphoton microscopy.
The loading curves initially showed a plateau, then the stress increased continuously to failure with the subsequent loading steps. Dissected tissues failed at lower loads, and voids that merged into larger defects appeared before the peak force during the initial loading steps. DVC revealed complex deformations and early strain localizations. Healthy porcine aortas can withstand significant radial stretches, likely caused by sucking up fluid. Large radial stretches also lead to induce localization effects and ultimately to mechanical damage, which, like GAG pools, can play an important role in triggering a dissection. Ongoing microstructural investigations will provide information about the influence of pathological structural changes on the global response and the local deformations.

In Vivo Validation of a 4D Ultrasound Strain Imaging Approach for the Identification of Patient Specific Anisotropic Elastic Material Properties of Abdominal Aortic Aneurysm

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Speaker: Blase Christopher. Invited. **Thursday**. Start time: **10:20**. Room: Roseraie 3 LVL3. Link to abstract.

Introduction:
Biomechanical computational models should be largely patient-specific to provide deeper insight into the pathophysiology of abdominal aortic aneurysms (AAA) and to be relevant for future clinical diagnostics. The identification of individual material properties is of central importance, but they are usually unknown and difficult to determine in vivo. Time resolved 3D ultrasound combined with speckle tracking (4D-US) is a non-invasive imaging technique that provides full-field information of heterogeneous aortic wall strain distributions in vivo. These strains are cyclic strains with respect to diastole. We here present a substantial new development of an in vivo 4D-US strain imaging approach that was presented previously by our group. It identifies the parameters of a nonlinear and anisotropic material equation, while using only information that can be collected in vivo. For this approach we perform an in vivo validation using 6 AAA wall tissue samples harvested from two different patients.

Material and Methods:
Data of two AAA patients (AAA1 and AAA2) presented at the Clinics for Vascular Surgery of the University Hospital Frankfurt am Main were evaluated. 4D-US data was acquired by use of a commercial real-time 3D-echocardiography system, equipped with a 3D transthoracic probe. Diastolic and systolic blood pressures were acquired. After US imaging, in total 6 wall samples (3 longitudinal and 3 circumferential) were harvested from the two AAA patients during open aneurysm repair. All samples were mechanically tested using uniaxial tensile tests, deformations were recorded optically.
On the one hand, specimen deformations were determined from camera images and stress-stretch curves were calculated from wall thickness and recorded force values. The parameters for the anisotropic Holzapfel-Gasser-Ogden (HGO) material equation were identified by fitting to calculated stress-stretch curves of longitudinal and circumferential samples.
On the other hand, for each patient a finite element analysis model was created containing both vessel wall and intraluminal thrombus geometries, which could be segmented independently from the 4D-US images. Measured diastolic/systolic blood pressures were applied to the lumen surface, reduced axial forces were set to be zero. Upper and lower ends of the vessels were artificially lengthened to achieve more physiological boundary conditions: upper end was clamped and lower end could only move axially (only areas for which US data was available were analysed later). Our newly developed in vivo 4D-US strain imaging approach uses an evolutionary self-adaptive Differential Evolution (JADE) algorithm as optimization strategy. It iteratively calculates the material-dependent load-free geometry and, based on this, the diastolic and systolic geometries using diastolic and systolic blood pressures. Cyclic strains are then calculated with respect to diastole. Parameters for the HGO material equation are identified by minimising an error function that compares cyclic measured wall strains using 4D-US and the calculated cyclic model wall strains.
Results:
For AAA1, comparison of stress-stretch curves calculated using the identified parameters show mean absolute percentage errors (MAPE) in the range MAPE = 0.76-0.07%. For AAA2 MAPE values are in the range MAPE = 0.51%-17.83%.

Conclusion:
We successfully performed an in vivo validation of a new developed in vivo 4D-US strain imaging approach

for parameter identification. Results for AAA1 showed good agreement between 4D-US and uniaxial tensile tests. AAA2 had 2 longitudinal and 2 circumferential uniaxial specimens, each identifying the local wall behaviour. The 4D-US method identifies a global material behaviour. If an averaged material behaviour is calculated from the 2 longitudinal and 2 circumferential specimens, this stress-stretch curve agrees well with the stress-stretch curve of the 4D-US method identifying a global material behaviour.

Quantitative X-ray elastography of coronary arteries using flexural pulse waves

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Speaker: Gregoire Sibylle. **Thursday**. Start time: **10:40**. Room: Roseraie 3 LVL3. Link to abstract.

Dynamic elastography uses an imaging system to visualise the propagation of elastic waves, the speed of which is directly related to the elasticity felt by palpation. Very few studies have focused on X-ray elastography because of the technical challenges it poses: a planar image of an integration volume at a very slow sampling rate. We demonstrate that tracking a slow elastic wave guided along a one-dimensional structure is the solution. The recently discovered flexural pulse wave, which is naturally generated by heartbeats and propagates along arteries, is the perfect candidate for X-ray elastography. As it reflects the cardiovascular health of patients, arterial elasticity is a biomarker of high clinical interest. We first validate the method by measuring the elasticity in arteries phantom using X-Ray. We then move on to data obtained in vivo on coronary arteries during a routine angiography examination. During coronary angiography, a catheter is used to inject an X-ray contrast dye into the patient's aorta. X-rays are then taken as the dye spreads through the coronary arteries. It shows the movement of the coronary arteries for a few seconds and allows us to follow the natural flexural pulse waves. The obtained Young's moduli for two patients are E = 41 $\pm$ 29 kPa and E = 12 $\pm$ 9 kPa respectively. These preliminary results are expected to pave the way for X-ray elastography.

MODELING THE MECHANICAL INTERACTION OF SKIN AND ARTERIES WITH WEARABLE BLOOD PRESSURE SENSORS

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Speaker: Chakroune Mohamed. **Thursday**. Start time: **11:00**. Room: Roseraie 3 LVL3. Link to abstract.

Introduction

Hypertension (HT), the leading cause of cardiovascular morbidity, requires precise and continuous monitoring for effective management. Traditional methods relying on inflatable cuffs are limited by their intrusive nature and unsuitability for real-time tracking. Wearable devices, such as smartwatches, present a promising solution for non-invasive, continuous measurements. However, their reliability is compromised by complex technical challenges, including mechanical interactions between the sensor, subcutaneous tissues, and the underlying artery, as well as individual physiological variability. This study aims to develop a finite element method-based numerical model to analyze these interactions, providing insights that could eventually be integrated into algorithms. Here, we focus on modeling an artery located under skin layers and muscle to study pressure variations between the sensor and the skin during arterial pulsation.

Model

The model was built using COMSOL Multiphysics coupled with MATLAB for automating simulations and analyzing results. It relies on large strain analysis including hyperelastic behaviors to accurately reproduce the properties of biological tissues and the complex mechanical interactions with a pulsating artery. (1)(2)

The constitutive parameters for the material models used in this study were sourced from the literature. Tissue layers were modeled as follows: the dermis and epidermis were represented using a Neo-Hookean hyperelastic model (3). The hypodermis employed a five-parameter Mooney-Rivlin hyperelastic model (4). Muscle tissue was characterized as an Ogden-type hyperelastic material (5), and the tissues were stretched following the average physiological elongation of the skin at the forearm level.

The artery, situated within the muscle, was modeled using the Delfino (6) strain energy function, with an internal diameter of 1.42 mm and a wall thickness of 0.39 mm(7). Arterial blood pressure (80–120 mmHg) was simulated as a Gaussian pressure variation, representing the cardiac cycle (7).

The sensor applied pressure ranged from 0 to 140 mmHg in 1 mmHg increments, allowing the evaluation of tissue deformations and signal variations. Simulations conducted under steady-state conditions integrated large tissue deformations and arterial pressure cycles (1)(2).

Results

The hyperelastic properties of the tissue layers have a significant influence on pressure signal transmission and arterial deformations (5). Nonlinear models better captured these interactions, offering a detailed understanding of the underlying mechanisms.

By exploring the impact of these properties on tissue deformation, we found that maximum arterial deformation occurred when the transmural pressure was equal to zero, corresponding to a locally applied pressure of 65.3 mmHg. Under this condition, the detected signal variation was maximized. Beyond this threshold, the signal decreased, indicating a saturation of measurable deformations.

Continuing this analysis, the model succeeded in reproducing the signal inversion phenomenon observed clinically by PhotoPlethysmoGraphy (PPG) (9). This phenomenon, linked to interactions between the artery and surrounding tissues, was more pronounced when the artery was closer to the skin surface and when the pressure applied by the sensor was relatively low.

Conclusion

This study presents an advanced numerical model of interactions between a wearable sensor, subcuta-

neous tissues, and a pulsating artery. Key contributions include identifying an optimal applied pressure to maximize signal amplitude and help us to understand the signal inversion phenomena influenced by sensor location and tissue mechanical properties. These advancements will enable more accurate algorithms for continuous blood pressure monitoring, with significant implications for developing robust and reliable wearable devices.
Future steps include comparing numerical model results using physical phantoms, confirming the model's capability to reproduce experimentally observed phenomena. Additionally, factors such as interindividual variability and the impact of specific pathologies will be integrated, along with clinical validation on human subjects using ultrasound imaging to quantify tissue interactions in a patient-specific manner. This work bridges numerical modeling and clinical applications, paving the way for more effective wearable devices for cardiovascular monitoring.

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Biaxial biomechanical properties of ex vivo perfused human thoracic aortas with and without stents

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Speaker: Yusefi Masoud. Invited. **Thursday**. Start time: **11:20**. Room: Roseraie 3 LVL3. Link to abstract.

Patient-specific modeling of endovascular repair is critical to improve clinical decision-making and allow improved surgical outcomes (1,2). Reliable simulations require an accurate representation of arterial material properties, particularly in areas affected by medical interventions such as stent placement. This study examines the immediate mechanical changes in the thoracic aorta after stent deployment, focusing on the altered mechanical properties near the stent struts.
Twelve non-diseased thoracic aortas (age 38–81 years, 4 females and 8 males, mean age 62.6 $\pm$ 11.7 years) were obtained from Austrian donors via the Diagnostic and Research Institute of Pathology at the Medical University of Graz. Exclusion of obese donors minimized the variability associated with obesity. The Ethics Committee of the Medical University of Graz approved the use of human aortic specimens (32-451 ex19/20).

To reproduce the in vivo loading conditions of the aortic wall during TEVAR, a customized mock circulatory loop (MCL) that can simulate the human circulatory system was used (3). Before stenting, aortic specimens were subjected to preconditioning to ensure a repeatable mechanical response. TEVAR was then performed using a polyester thoracic stent graft (E-vita Thoracic 3G, JOTEC, Hechingen, Germany). After the intervention, the aorta was reattached to the MCL and perfused for eight hours to simulate continuous physiological loading. The aorta was then cut longitudinally and the stent graft was removed.

For the planar biaxial extension test, over 170 square tissue samples (10×10 mm) were prepared from areas with and without stents, avoiding regions with atherosclerosis and branching vessels. Tissue mechanics was captured using a biaxial tensile testing device in a PBS bath at 37$\circ$C. A stretch-controlled protocol with increments of 0.05 to rupture was used. Different stretch ratios between the longitudinal and circumferential directions (1:1, 1:0.75, 0.75:1, 1:0.5, 0.5:1) were used. At each stretch level, samples were subjected to four preconditioning cycles to achieve a consistent response, with the fifth cycle serving as the actual measurement.
We used the model proposed in (4), which included the contributions of the ground substance and symmetrically arranged collagen fiber families with non-symmetric dispersion The model accurately represented both stented and unstented samples, showing significant mechanical differences between them and highlighting the localized effect of stent placement on the artery wall. These findings improve our understanding of the biomechanical behavior of stented arteries and contribute to more accurate patient-specific models that may support better clinical decision making.

Linking microstructure with mechanical behavior on the thoracic aorta: a multiscale approach

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Speaker: Utrera Andres. Invited. **Thursday**. Start time: **11:40**. Room: Roseraie 3 LVL3. Link to abstract.

Biomechanical analysis of soft tissues has emerged as a significant objective in recent years. This discipline seeks to improve our understanding of tissue behavior in both clinical and pathological conditions by studying the correlation between healthy and diseased tissues through mechanical tests, typically associated with the measurement of stiffness.
In terms of mechanical strength, collagen is the main protein that confers stiffness to the tissue. The vessel's collagen structure is composed of bundles of collagen fibers that are arranged in a helical pattern around the vessel. Even so, the mechanical contribution of collagen does not start immediately with deformation. Instead, the wavy collagen fibers are continuously recruited as the tissue undergoes deformation, resulting in a highly non-linear stiffening behavior. Hyperelastic and non-linear macroscopic responses of the tissue are significantly affected by the spatial and waviness distribution of this protein chain (1).
The fiber-reinforced-like constitutive models have been extensively used to study the mechanical response of arterial tissue. Those models describe the overall response of the material as a contribution of an isotropic energy term, representing the extracellular matrix of the tissue, and the contribution of an anisotropic term accounting for the collagen contribution. The collagen contribution is usually modeled with an exponential term.
Even though these models can describe the overall macroscopic mechanical response, the material parameters do not correlate directly with the microstructure of the material, and the mechanical parameters can be difficult to interpret in terms of the microscopic characteristics. Furthermore, modern techniques, such as confocal imaging or second harmonic generation, can be used to measure microstructural changes in tissue samples under many conditions. Therefore, the gap between mathematical formulations and the mechanical and geometrical composition of the material should be addressed, to better understand the complex mechanobiological relationships between microstructure alterations and mechanical loading.
Multiscale analysis is a tool that allows the understanding of the individual contribution of mechanically relevant components to the macroscopic response of different materials using a representative volume element (RVE) (2). This RVE is constructed using simple constitutive relations for each mechanical constituent, where the macroscopic response is obtained as a homogenized value of the microscopic stresses. In the context of this investigation, an RVE is modeled as an isotropic hyperelastic ground material, representing the tissue extracellular matrix, and a set of unidimensional elements that account for the collagen fibers. The proposed constitutive model of each collagen fiber corresponds to a linear elastic model, with an offset to account for the recruitment stretch of each fiber. The exponential stiffening of the macroscopic stress is a result of the progressive recruitment of many fibers.
This research focuses on the mechanical behavior of the thoracic aorta in a wistar rat model. Through the use of confocal microscopy, the geometrical distribution of collagen orientation is measured, and the mechanical properties at a constituent level are obtained using other manuscript references. The implementation and verification of a multiscale analysis for aortic tissue is developed using the plugin framework of the FEBio software (3) and contrasted with planar biaxial data from experiments on this tissue.

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Determination of induced vascular damage by in vitro stenting

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Speaker: Sommer Gerhard. Keynote. **Thursday**. Start time: **14:15**. Room: Roseraie 3 LVL3. Link to abstract.

Restenosis remains the most challenging complication after coronary stent implantation (CSI) (1), where the degree of restenosis largely correlates with the severity of vascular injuries (2). To reduce the failure rate of such coronary artery interventions, scientists and manufacturers must develop 'safer' stents by significantly reducing the risk of vascular injury. In this study, we investigated the damage to coronary arteries caused by *in vitro* stenting, where the vascular damage is based on a biomechanical experiment that simulates the loading conditions of stenting *in vitro*.
Damage to porcine coronary arteries caused by *in vitro* CSI was examined at different structural levels using histological investigation, electron microscopy modalities, and collagen hybridizing peptides (CHPs). In a custom-built testing chamber, the *in vitro* loading condition during CSI was simulated by biaxially stretching squared porcine coronary artery samples while a stent-mimicking punch was pressed into the sample with defined loads and orientations. Electron microscopy investigations were used to investigate the structural alterations under different loading conditions of the coronary artery walls (unloaded vs biaxially loaded and punched). Histological stains applied to cross-sections of arterial tissue specimens were utilized to identify mechanical damage at the microstructural level. Moreover, the surface and cross section of the vessel were examined using scanning electron microscopy (SEM). Mechanically important components such as collagen, smooth muscle cells (SMCs) and proteoglycans (PGs) in the arterial layers were visualized using 3D-TEM (electron tomography). Finally, fluorescently labeled CHPs shed light on the molecular unfolding of collagen and provide insights into damage mechanisms that occur at the molecular level.
Light microscopy images of the stained histological sections revealed focal, prominent, longitudinally oriented vascular SMC bundles in the intima, accompanied by a duplicated internal elastic membrane. In the indentation-treated specimens, significant compression below the indentation mark, stretched-out nuclei on the lateral walls of the lesion, bulging at the lesion edges, and structural weaknesses in the intima and media within the lesion were observed. The SEM results showed that the surface at the punch ends was more damaged when the punch was oriented axially rather than circumferentially. Moreover, the endothelial layer beneath and near the indented punch was completely removed. The results further revealed that not only the intima but also the media were severely damaged. The functionality of SMCs around the punch is questionable due to the damage. Interestingly, collagen fibrils appear to be able to withstand the enormous mechanical stresses caused by the applied punch loads. The 2D TEM and electron tomography studies showed rearrangement, reorientation and clustering of PGs between collagen fibrils due to the high loadings of the punch. The reorientation and accumulation of PGs was more pronounced below the punch mark than to the side of the punch edges. Analysis of the CHP fluorescence data revealed mechanically induced damage at the molecular level, particularly in the intimal region lateral to the punch mark, which was aligned with elongated nuclei, instances of intimal tearing, and other observed structural weaknesses. Overall, these findings suggest that the functionality of arterial tissue is significantly affected by the applied indentation force. Functional alterations in stented arteries may ultimately lead to the development of restenosis.

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Acknowledgements

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COMPUTATIONAL SIMULATION OF RESPIRATION-INDUCED DEFORMATION OF RENAL ARTERIES IN AAA PATIENTS AFTER EVAR

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Speaker: Corvo Alessandra. Invited. **Thursday**. Start time: **14:55**. Room: Roseraie 3 LVL3. Link to abstract.

Introduction

During human respiration, the diaphragm contraction and relaxation induce renal artery displacement. Studies reporting cranio-caudal kidney motion show changes in curvature and branching angles associated with respiration (1), which for patients with an Abdominal Aortic Aneurysm (AAA) may affect hemodynamics and stent-graft placement. AAA is a pathological dilation of the lower section of the aorta. It is predominantly treated by endovascular aneurysm repair (EVAR), a minimally invasive intervention that consists of stent-graft (SG) insertion inside the aorta to restore the original aortic lumen, preventing blood flow from entering the AAA. Although numerical simulations of SG deployment in patient-specific cases of AAA have been performed extensively (2), only Tran et al. and Cheng et al. evaluated the respiration-induced changes in branch vessels for patients undergoing EVAR (3) (4).

The bending of the renal arteries can affect renal stenting and induce complications like stenosis and occlusions. However, no studies have numerically simulated renal artery movement due to breathing and its impact on SG deployment. Moreover, the choice of the SG length is a complex decision for surgeons; too short and it increases the risk of endoleaks, whereas too long and it increases the risk of occlusion. Therefore, it is essential to provide quantitative evidence to assist surgeons in choosing the optimal length. Furthermore, to have a complete perspective of the possible complications that may occur, even long-term after surgery, hemodynamics in the peripheral arteries needs to be monitored, with a particular focus on the renal arteries, to detect potential thrombogenic flow patterns. CFD studies can assess hemodynamic changes both post-operatively and over the respiratory cycle. Some CFD studies have demonstrated changes in renal artery flow post-EVAR. However, the actual post-operative peripheral stent-graft geometry was not simulated and they did not account for the impact of breathing. Consequently, the primary objective of this study is to address missing artery and stent-graft motion on the evaluation of changes in SGs deployment across three different stent-graft lengths for each artery. Additionally, the goal is to combine the outcomes of SG deployment simulations with CFD analyses of hemodynamic changes in the renal arteries, before and after EVAR, including motion throughout the respiratory cycle.

Methods

Two models from CT scans of the same AAA patient with acquisition in inspiration and expiration were segmented and meshed with 0.5 mm triangular shell elements. First, the breathing effect was numerically simulated in the pre-operative geometry, by applying a displacement at the distal extremities of the renal arteries, according to the kidney movements measured from the CT scans. The anisotropic Holzapfel-Gasser-Ogden model was used for the arteries. Then, a model of a peripheral SG was designed. 3-Point bending tests were carried out experimentally on SG samples and modeled numerically to characterize the SG mechanical properties. After the aortic SG insertion that followed the process described by Perrin et al. (5), peripheral SGs were collapsed into the catheter caliber, expanded with a balloon (modelled as a cylindrical shell), and released inside the renal arteries. To validate simulations of breathing-induced motion, vessel centerlines were extracted and compared to the variation in branching angle and maximum curvature from in vivo results reported in the literature (1). In order to validate the SG deployment simulations, the renal arteries' centerlines were extracted and compared with those of the lumen of the arteries from post-EVAR CT scans. Simulations were then repeated for longer and shorter SGs. To conduct CFD simulations, a velocity waveform was imposed at the inlet of the model (supra-celiac aorta). 2-element Windkessel boundary conditions were applied at the outlets, with the

simulation conducted over five cardiac cycles (5 s). To more accurately replicate the hemodynamics of the renal arteries, artery motion was implemented to achieve respiratory movement of the renal arteries throughout a 5-second cycle (12 breathes per minute).

Results

By implementing a numerical model of the 3-point bending test, it was possible to replicate in silico the mechanical properties of the graft observed experimentally, solving an inverse problem. Peripheral SG were deployed in the renal arteries of two patients with the same length and diameter as the devices used clinically by surgeons. By comparing the centerlines of the four renal arteries at the end of the simulation with the ones from post-EVAR CT scans, mean distances below the imposed threshold (3 mm) were found for all of the arteries (1.59 mm, 2.79 mm, 2.57 mm, 1.99 mm), confirming the accuracy of the simulations.

Further calculations of the branching angle of the arteries revealed that the presence of the peripheral stent-graft reduces renal artery movement during the respiratory cycle, resulting in reduced variation in the branching angle. This effect is further emphasized when a stent-graft longer than nominal length is deployed in the renal arteries.

Moreover, preliminary CFD simulation results indicate a decrease in renal artery flow during the inspiratory phase due to the morphological changes, and a reduction in wall shear stress in the regions proximal to the maximum curvature of the vessel during the expiration, compared to the inspiratory configuration.

Discussion

In summary, we simulated the bending behavior of renal stents for the first time and were able to predict their deformation during breathing. Renal stenting with different SG lengths has been explored in patient-specific models to understand the effect of SG lengths and patient variability. Preliminary CFD studies have been carried out to assess the hemodynamic changes over the respiratory cycle. Future work includes CFD simulations in post-EVAR geometries to evaluate the impact of the stent-grafts, combined with breathing, on blood flow.

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A finite-element Julia platform for solid-to-beam contact modelling in vascular biomechanics

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Speaker: Bisighini Beatrice. Invited. **Thursday**. Start time: **15:15**. Room: Roseraie 3 LVL3. Link to abstract.

Stent-based devices have become pivotal in the treatment of various peripheral and cerebrovascular diseases, including the use of stents for vessel support and stent retrievers for thrombectomy procedures. These devices, typically small cylindrical structures made of metal or polymer, are delivered into the vasculature via a catheter. Upon deployment, stents expand to prop open diseased vessels and restore blood flow, while stent retrievers are designed to capture and extract clots. However, the interaction between these devices and the vascular wall during deployment or retrieval can induce non-physiological stresses. Additionally, the significant displacements and geometric nonlinearities inherent to these processes make it difficult to predict the final device configuration or the treatment outcome. This unpredictability can lead to prolonged intervention times and potential complications. Therefore, there is a critical need for advanced computational algorithms that enable virtual planning of stent deployment and retrieval, delivering accurate simulations within clinically relevant timeframes.
Finite element models have been widely employed to simulate the intricate interactions between stent-based devices, arterial walls, and clots (1-3). These models offer valuable mechanical insights into the behaviour of these medical devices, facilitating the optimization of their designs to improve performance and durability (4). Additionally, patient-specific simulations, which incorporate individual anatomical geometries, are playing an increasingly prominent role in clinical decision-making by predicting both short- and long-term treatment outcomes (5).

In finite element simulations, 3D beam elements are commonly used to model stents due to their computational efficiency, while solid elements (e.g., tetrahedral or hexahedral) are typically reserved for detailed structural analyses (6,7). Arterial walls are represented using either shell (5) or solid (1) elements, depending on the level of complexity and the need to capture their multilayered architecture. Clots are typically modelled using solid tetrahedral elements (2), with material properties tailored to account for variations in their composition and mechanical behaviour.

Many prior studies on the subject rely on commercial software like Abaqus to perform these simulations. While commercial software offers reliability and ease of use, it comes with notable limitations. These include high licensing costs, thus typical restrictions on the number of licenses available, and limited flexibility for modifying the underlying computational formulations. Such constraints can limit the customization required for specialized applications and restrict the ability to run multiple simulations in parallel-an essential capability in machine learning.

In this context, this work proposes an efficient, open-source finite element framework for vascular biomechanics written completely in the Julia programming language. Julia was deemed a good candidate for the implementation because it provides an optimal balance between performance and usability, combining the computational speed of compiled languages with the interactivity of MATLAB and Python. This framework was developed leveraging existing formulation for solid mechanics (8) and our previous work on beam-to-surface contact mechanics (9). Specifically, we have recently reported an efficient 3D corotational formulation to simulate a beam-to-rigid surface contact. In contrast to total Lagrangian beam formulations, the motion of each element in this formulation is separated into a rigid body component and a small local deformation. Consequently, this approach yields a computationally efficient formulation by allowing us to model beam deformation via linear constitutive models while incorporating nonlinearities into the rigid body component. Specifically, this beam formulation was implemented within the Julia-package EndoBeams.jl, which has proved very fast, with computational times comparable with Abaqus, thanks to its specific finite element formulation and the very efficient implementation with parallel computing capabilities (10). For the vascular model, we relied on a 3D total Lagrangian implicit

finite element formulation of solid elements, which allows the simulation of hyperelastic solids.

In the current work, we built upon these advances to develop a fully implicit algorithm to couple the contact between solid elements and corotational beam elements. The contact was modelled using the master-slave approach described in (11). The framework was used to simulate stent deployment in deformable vessels and clot retrieval using stent retrievers. After detailing the formulation and implementation, we will present several examples to demonstrate the efficacy and robustness of the proposed algorithm.

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A fully parameterized 3D computational model of atherosclerotic arteries to simulate balloon angioplasty

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Speaker: Kwakman Sanne M. B.. Invited. **Thursday**. Start time: **15:35**. Room: Roseraie 3 LVL3. Link to abstract.

Atherosclerosis is one of the most common cardiovascular diseases, characterized by the gradual accumulation of atherosclerotic plaques in the arteries. This process begins with the infiltration of smooth muscle cells and leukocytes into the intima and contributes to the formation of a lipid-rich core separated from the vessel lumen by a fibrous cap. Balloon angioplasty is a common treatment to restore normal blood flow in coronary or peripheral arteries affected by atherosclerosis. A critical event during balloon deployment is a rupture at the plaque shoulder or at the top of the fibrous cap, depending on the oversizing of the balloon (1,2). The mechanical load that leads to rupture is strongly influenced by various factors, such as the geometrical extension of the fibrous cap, the lipid pool and calcifications.
Patient-specific models provide valuable insights; however, they are often limited in their ability to capture the wide variability in morphological features that influence the outcomes of balloon angioplasty. To fill this gap, we developed an efficient computational model of an atherosclerotic artery that includes various geometrical features: a healthy three-layered structure, the fibrotic media, the fibrous cap, the lipid pool, and calcifications of different sizes and locations. This three-dimensional (3D) parameterized computational model is designed to be easily adjustable to tissue- and region-specific mechanical properties to mimic various vessels such as coronary, iliac, and femoral arteries, as well as various stages of atherosclerosis. In the current study, we employed experimental data from several iliac arteries (3) and fitted these data to the anisotropic Gasser-Ogden-Holzapfel model (4). Numerous simulations of balloon angioplasty have been performed in which the morphology of the atherosclerotic artery was altered by varying the dimensions of the lipid pool, calcifications, and fibrous cap. The aim of these simulations is to gain deeper insights into the possible causes of damage and plaque rupture during balloon angioplasty under different morphological conditions.

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Numerical analysis of stent geometry and deployment technique on arterial wall adaptation

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Speaker: Lisac Ana. Invited. **Thursday**. Start time: **15:55**. Room: Roseraie 3 LVL3. Link to abstract.

Atherosclerosis is characterized as plaque buildup on the inner wall of the artery, and its treatment involves the deployment of a meshed tube known as a stent. Stent deployment expands the narrowed arterial lumen, allowing blood to flow unobstructed. However, it simultaneously increases stress within the arterial wall, which can lead to damage, thrombus formation, or in-stent restenosis (re-narrowing of the artery). The stress induced by stent deployment triggers growth and remodeling processes within the arterial wall. Stress levels depend, among other factors, on the stent's geometry and deployment technique used.
Stents are generally made of metal and traditionally have a cylindrical shape due to the manufacturing process, and their geometry does not conform to the natural curvature of an artery. Metallic stents are usually expanded using a balloon, which deforms the metal beyond its elastic limit. Most modern carotid artery stents are made from nickel-titanium alloy. This material can elastically recover from significant strain caused by stress-induced deformation, allowing self-expanding deployment method (1). However, the metallic, thrombogenic stent surface increases the risk of stent thrombosis, which can lead to myocardial infarction or even cardiac death (2).

On the other hand, a promising alternative to traditional stents are polymer-based stents, which can be produced using additive manufacturing techniques such as 3D printing. This approach enables the creation of patient-specific stents tailored to follow the unique curvature of a patient specific individual arteries (3). These stents can be made from shape memory polymers (SMPs), advanced materials that can revert from a temporary, deformed state to their original, permanent shape when activated by an external stimulus, making SMP stents suitable for self-expanding deployment. Triggers for shape recovery include heat, hydration, magnetic fields, or light. Additionally, SMP stents have been shown to reduce the risk of restenosis (4).

Numerical analysis is a valuable tool for studying the effects of stent deployment on arteries. Soft tissues can be modeled using growth and remodeling (G&R) framework and this approach has greatly advanced our understanding of the biochemical and biomechanical processes and has improved predictions of disease progression over time (5).

This study simulates stent deployment and the adaptation of the carotid artery to the stent implantation, incorporating a growth and remodeling model for the arterial wall. Various stent geometries and deployment techniques are analyzed and compared. Simulations are carried out to study the effects of standard cylindrical stents versus curved designs, as well as balloon deployment versus self-expansion methods. For all scenarios, the impact on arterial stresses and the production of arterial wall constituents-key factors influencing the occurrence of in-stent restenosis-is evaluated. Additionally, the adequacy of stent expansion is assessed.

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Simultaneous Structural Damage and Calcification Dramatically Reduces Porcine Pericardium Durability

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Speaker: Guerin Luke. Invited. **Friday**. Start time: **10:00**. Room: Roseraie 3 LVL3. Link to abstract.

Introduction

Aortic stenosis (AS) is characterised by the narrowing and stiffening of the aortic valve, which restricts blood flow from the heart to the rest of the body. Severe AS is common and life-threatening condition, affecting 1.48% of individuals aged 55 and older, with a four-year mortality rate of 44.9% if left untreated (1,2). Minimally invasive treatment for AS involves the implantation of a bioprosthetic valve with porcine or bovine pericardium leaflets. These leaflets eventually succumb to failure due to regurgitation or stenosis, caused by calcification and structural damage (3). The relationship between these two durability-limiting processes is debated. Current commercial anti-calcification treatments utilise protective chemistry alone, ignoring leaflet mechanics and treating calcification as independent from structural damage. The aim of this work is to investigate and establish the relationship between calcification and structural damage of porcine pericardium (PP), and to identify screenable tissue features which minimise both factors.

Materials and methods

Commercial grade PP was screened for its collagen fibre architecture using small angle light scattering (SALS) and separated into highly aligned (HA) and highly dispersed (HD) groups based on average fibre alignment across each sample. HA tissue is highly anisotropic, with high stiffness along the dominant collagen fibre orientation, whilst HD tissue is isotropic. Tissue was loaded in an in-vitro calcification solution using a bi-directional bulge inflation rig for 30 million cycles. Each cycle is composed of an upwards and downwards bulge at a pressure amplitude of 150 mmHg and a frequency of 3 Hz (4). Structural damage and calcification were quantified at 0, 5, 10, 20, and 30 million cycles using digital image correlation and μCT imaging, respectively. Calcification volume was quantified using ORS Dragonfly software, and calcification distribution in the region of highest stress and bending was isolated using MATLAB. Samples were assessed for rupture every 1 million cycles and were replaced with a PP blank if rupture was identified. Calcified and damaged samples were compared to uncalcified PP loaded in the same conditions.

Results

By 30 million cycles, 16 samples ruptured in PP exposed to simultaneous calcification and structural damage. Fibre architecture of the tissue influenced its durability, with HA PP rupturing at a faster rate than HD PP when exposed to calcification and structural damage. No ruptures were observed in PP with the same loading conditions which were not exposed to calcification, nor were differences between HA and HD tissue observed. Rupture did not always occur at the most calcified region of the samples, but instead appeared to be co-located with radially oriented collagen fibres.

Discussion

The results of this study suggest that calcification and structural damage are synergistic factors dramatically affecting bioprosthetic valve leaflet durability. This is evidenced by the high number of ruptures when PP is simultaneously calcified and loaded for 30 millions cycles and none when only cyclic loading is present. While the overall presence of calcification leads to rupture, calcification and failure site are not always co-located. Instead, collagen fibre orientation appears to determine the failure site. Overall collagen fibre architecture of PP influences the likelihood of failure when exposed to damage and calcification, with HA samples failing at a faster rate during the study. The findings suggest that high collagen fibre alignment in PP bioprosthetic valve leaflets could lead to premature device failure if not aligned to support the dominant loading direction. Future work will investigate the influence of spatially varying

collagen fibre architecture and calcification distribution on PP stresses and strains using finite element analysis.

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Mechanics of the calcium movement inside cardiac myocytes and the effect on contractility

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Speaker: Lai Choi-Hong. **Friday**. Start time: **10:20**. Room: Roseraie 3 LVL3. Link to abstract.

A computational model is constructed to study the mechanics of the calcium movement inside cardiac myocytes. The governing PDE model, closely resembling the physiological model, is based on the calcium-induced calcium release mechanism coupled with a time dependent vibration model representing the actin-myosin interaction and the force development in the sliding filaments. Constitutive equations relating primitive variables of the mechanism are used to formulate the problem. Suitable methods are used to gain information of the mathematical/physiological parameters whereas open-source data are used to retrieve these parameters to match the physics.
Two different systems are to be examined in this paper, one with buffers and dye to emulate in vitro calcium behaviour and the other without buffers and dye to emulate in vivo contraction behaviour as reported in the literature. The mathematical model used in the calcium-induced calcium release mechanism follows closely the physiological description as seen in the literature. Both deterministic and stochastic cases are examined. The stochastic case examined is realised by putting a stochastic mechanism into the model to activate release of calcium from Calcium Release Units.

Finally, a 2D curvilinear domain of size and shape resembling a typical cardio myocyte is used to demonstrate the contraction features. Computational results match all experimental results as reported in the literature. Machine learning techniques are also included in the work. The computational model is able to provide reliable information about contractility of cardio myocytes.

An in-silico framework for design and optimisation of 3D-printed bioinspired polymer heart valve leaflets

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Speaker: Hughes Celia. Invited. **Friday**. Start time: **10:40**. Room: Roseraie 3 LVL3. Link to abstract.

Introduction

Aortic stenosis (AS) affects 4% of people over 70 and has a 50% chance of mortality within 2 years when left untreated (1,2). Prosthetic heart valves used to treat AS have significant drawbacks such as the need for lifelong anticoagulant therapy or premature failure within 25 years (3). Bioinspired polymer valves have the potential to remove these drawbacks; however, to fully embrace these into future treatment we need a directed approach to design and optimise these devices. In this research, we present a novel framework for the development and optimisation of 3D-printed, bioinspired polymer leaflets using finite element (FE) modelling. Informed by imaging and mechanical characterisation of native porcine aortic leaflets in our previous work (4), this provides a novel preclinical design tool to inform material selection and optimise leaflet structure for different valve leaflet shapes and varying clinical cases.

Materials and methods

A FE-based valve model inspired by the ACURATE neo2™ Aortic Valve (Boston Scientific, Massachusetts, USA) was developed to represent silicone-based polymer leaflets with a polycaprolactone (PCL) bioinspired fibre reinforcement structure made using melt electrowriting (MEW), as described previously (5). A design of experiments (DOE) approach was taken to determine the optimal combination of key structural features: fibre spacing (0.5, 1, 1.5, and 2 mm), fibre layers (2, 5, 8, and 10), and overall leaflet thickness (0.2, 0.3, 0.4, and 0.5 mm). Performance outputs were average valve opening area (OA) across key points of the cardiac cycle, maximum valve OA, time to maximum opening, and leaflet stress and strain. Using the determined best combination, a fibre reorientation algorithm adapted from Creane, et al. (6) was applied to further improve the leaflets' mechanical response. This reorients the two families of fibres according to the max and mid principal strain directions to maximise load bearing capacity. Two different methods were employed for fibre remodelling: aligning the fibres symmetrically about the direction of max principal strain based on the ratio of max to mid principal strain (as described in (6)), and aligning family 1 along the direction of max principal strain while family 2 is oriented along the mid principal strain direction.

Results

Development of the FE model allowed for extensive assessment and improvement of the bioinspired, fibre-reinforced polymer leaflet. The DOE enabled us to identify the optimum combination of leaflet structural features based on material response and valve opening behaviour: fibre spacing of 0.5 mm, 2 MEW layers, and 0.3 mm thick. This combination gave the most effective leaflet in terms of opening area across the cycle, while also minimising leaflet stress and strain. Using the fibre reorientation algorithm on this leaflet further improved the material response. Both remodelling methods reduced the average principal strain across the leaflet compared to the original bioinspired design, from 17.4 to 12.2% for method 1 and 14.3% in method 2. This reduction in leaflet stain could potentially lead to extended leaflet lifetimes.

Discussion

This study established a novel FE-based framework to design, develop, and assess 3D-printed, fibre-reinforced polymer leaflets based on native aortic leaflets. This methodology can now be utilised to design heart valves for patient-specific anatomies with varying disease states. Overall, this tool will enable effective development of bioinspired polymer heart valves that can outperform current commercial devices and improve patient outcomes.

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Characterization of the active response of carotid arteries measured by pressure myography.

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Speaker: Álvarez-Carrasco Fabián. Invited. **Friday**. Start time: **11:00**. Room: Roseraie 3 LVL3. Link to abstract.

The biomechanical analysis of arteries represents a fundamental area of research to understand their behavior under physiological and pathological conditions. The carotid arteries, major vessels supplying blood to the brain, are critical for hemodynamic regulation and metabolic exchange to brain tissue. Their central role in the cardiovascular system makes them an ideal model to explore mechanobiological phenomena in both normal and pathological conditions (1).
This work analyzes carotid arteries extracted from rats raised under normal conditions and subjected to hypobaric hypoxia, aiming to identify differences in their active contractile response. These arteries exhibit biomechanical characteristics, including highly anisotropic walls with an organized extracellular matrix that supports both continuous and pulsatile pressures (2). Therefore, the contractile properties of smooth muscle in the carotids play an essential role in regulating cerebral blood flow, highlighting the importance of studying their active response under chemical and mechanical stimuli.
The pressure myography used allows the evaluation of the active response of the carotid arteries under controlled conditions, simulating both physiological and pathological pressure ranges. Measurements were taken under both static and pulsatile pressures to reflect the complexity of hemodynamic conditions. The arteries were exposed to a Krebs Ringer physiological solution enriched with KCl to induce smooth muscle contraction, providing a direct view of how hypobaric hypoxia affects the active contractile response and arterial stiffness (3).
The chemical-mechanical model developed by Murtada has been used to describe the contractile behavior of the carotid arteries in isometric activation studies (4). This model combines interactions between the cellular components of smooth muscle and the passive properties of the extracellular matrix. The fitting process is carried out using a non-linear least squares method applying finite element simulations, achieving a representation of arterial behavior in both experimental groups.
The study emphasizes the relevance of the active response in carotid arteries as a model for understanding vascular adaptations to hypoxic conditions. In low oxygen pressure situations, such as those found at high altitudes, the carotids undergo structural remodeling that can alter their mechanical and functional properties. This has direct implications for the regulation of cerebral blood flow and the predisposition to cerebrovascular diseases. The integration of experimental tools, such as pressure myography, and theoretical models, such as Murtada's chemical-mechanical model, enables a comprehensive approach to the complex mechanobiological phenomena that govern the behavior of these arteries.

Acknowledgements
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On the Impact of Residual Strains in the Stress Analysis of Patient-Specific Atherosclerotic Carotid Vessels: Predictions Based on the Homogenous Stress Hypothesis

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Speaker: Alessandro Mastrofini. Invited. **Friday**. Start time: **11:20**. Room: Roseraie 3 LVL3. Link to abstract.

The identification of carotid atherosclerotic lesion at risk for plaque rupture, eventually resulting in cerebral embolism and stroke is of paramount clinical importance. High stress in the fibrous plaque cap has been proposed as risk factor. However, amongst others, residual strains influence said stress predictions, but quantitative and qualitative implications of residual strains in this context are not well explored. We therefore propose a multiplicative kinematics-based Growth and Remodeling (G&R) framework to predict residual strains from homogenizing tissue stress and then investigate its implication on plaque stress. Carotid vessel morphology of four patients was reconstructed from clinical Compute Tomography-Angiography (CT-A) images and equipped with heterogeneous tissue constitutive properties assigned through a histology-based artificial intelligence image segmentation tool. As compared to a purely elastic analysis and depending on patient- specific morphology and tissue distributions, the incorporation of residual strains reduced the maximum wall stress by up to 30% and resulted in a fundamentally different distribution of stress across the atherosclerotic wall. Regardless residual strains homogenized tissue stresses, the fibrous plaque cap may persistently be exposed to spots of high stress. In conclusion, the incorporation of residual strains in biomechanical studies of atherosclerotic carotids may be important for a reliable assessment of fibrous plaque cap stress.

MS2.4 - Mechanics of Mineralized Tissues

Organisers: Hanna Isaksson (Lund University), Christian Hellmich (TU Wien) and Rémy Gauthier (MATEIS)

A Multiscale Ultrastructural, Chemical and Mechanical Investigation of the Musk Ox (Ovibus Moschatus) Horn

Genna Monahan (1), Coppens Frederik (2), Foucher Corentin (3), Schwiedrzik Jakob (3), Dehm Gerhard (1), Ramachandramoorthy Rajaprakash (1)

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Speaker: Genna Monahan. **Thursday**. Start time: **10:00**. Room: Rhône 3A LVL1. Link to abstract.

Male musk oxen, weighing up to 400 kg, engage in head-to-head collisions at speeds up to 50 km/hr during mating season, surviving repeated impacts over their lifetimes. This makes them a compelling subject for studying natural impact mitigation mechanisms. This research investigates the musk ox horn's microstructural and compositional changes at varying scales using a combination of complementary techniques including optical microscopy, backscattering electron microscopy (BSEM), micro-computed tomography (μCT), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD). Here, a detailed multisale structural investigation of a sample taken from the primary impact zone (Fig.1(a)) of the musk-ox skull, is presented. It features four distinct regions: the impact surface, impact region, interface, and wave-like region (WLR) (Fig.1(a)), resembling structures in mantis shrimp (1). Here we show the musk ox horn's ultrastructure is similar to that of rhino horn and hooves, whereby hollow pores (known as tubules) are surrounded by circular rings of lamellae and separated by some intertubular material, similar to osteons in human cortical bone which may help manage crack propagation. (2-4). The large musk ox tubules are surrounded by smaller, open and closed tubules, this configuration may allow the horn to deform and absorb energy during collisions. Large tubules were demarcated by white lines resembling cement lines in bones, potentially deflecting or arresting microcracks (Fig.1(b)). The interface marks a transition to the organised, layered WLR, where major wave peaks are seen in the white vertical lines, interconnected by smaller wave structures. EDS analysis of all layers showed an elemental composition indicative of keratin (carbon, oxygen and sulfur) (5). Finally, compositional differences identified between the impact region and the WLR will be presented, along with their correlation to varying mechanical properties identified using nanoindentation stiffness and hardness measurements.

Ex vivo analysis of pressure and streaming potential in bone explants during loading: development of a new experimental protocol

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Speaker: Gauthier Rémy. **Thursday**. Start time: **10:20**. Room: Rhône 3A LVL1. Link to abstract.

Introduction

Bone remodelling is known to be driven through biomechanics. Mechanobiological mechanisms operating in bone architecture are based on the circulation of fluids within bone multiscale porous network. During loading, pressure gradients arise in bone porosity due to matrix deformation. It is assumed that the osteocytes, bone cells orchestrating the biology of bone remodelling, are able to sense the shift in fluids velocity and pressure induced by such poroelastic behaviour1. Fluid hence acts as the intermediate transmitting the mechanical information from the organ to the cell's scale. Understanding how fluid behaves during loading thus appears essential to better handle bone remodelling and further develop suitable bone regenerative strategies.

To that end, it is important to focus on bone porous network that represents the fluids pathway. In the current study, we will focus on two different pores scales: the vascular and the lacuno-canalicular networks. The vascular porosity is the largest porosity within bone tissue. It corresponds to the 100 μm cylindrical pores observed within cortical bone2 and to the large pores of spongy bone3. This porosity is filled with the blood vessels, the bone marrow, and different cells involved in bone resorption and formation. At a lower scale, the submicrometric lacuno-canalicular porosity tightly trapped within bone mineralized matrix hosts the interconnected osteocytes network4, bone mechanosensitive cells. These two porous networks are involved in fluid behaviour during loading. But due to their different size, their influence on osteocytes mechanical stimulation is different. Distinguishing these two types of porosity during load-induced fluid behaviour is hence of great interest.

While fluid relaxation during loading is associated with both the vascular and lacuno-canalicular porosities, it is assumed that the development of streaming potential is mainly due to fluid circulation within the lacuno-canalicular network5. Because bone surface is negatively charged, an outer counter-ions diffuse layer is formed at the pores wall. During load-induced fluid flow, this charged layer is advected inducing the generation of streaming potentials. Due to a high specific surface ($>$ 20,000 mm2.mm-3) compared to the vascular network ($<$ 100 mm2.mm-3 in cortical bone), these potentials are generally attributed to the fluid circulation within the lacuno-canalicular network. Measuring these potentials will provide insights on fluid flow within this lacuno-canalicular porosity. The objective of the current study is thus to develop an experimental protocol allowing to measure both the fluid relaxation and streaming potentials within bone explant under loading.

Materials & methods

Bone samples: Cylindrical bone samples (10 mm in diameter and height) were harvested from bovine femoral condyle, femoral head, and tibial plateau obtained from the butcher. Samples (n=14) were scanned through micro-computed tomography (voxel size = 10 μm) in order to calculated their bone volume fraction (BVTV in %). An Otsu automatic threshold was applied in order to segment the bone from the vascular porosities. BVTV was calculated as the ratio between the volume of segmented bone over the total volume of the sample.

Experimental set up: In parallel, an experimental device was developed allowing to apply a fluid pressure within a bone explant while measuring both the outlet relaxation pressure and the potential difference developed within the sample. Briefly, the device is made of a polycarbonate Hassler cell, designed to prevent leakage from the bone sample surface during pressurization. To that end, the cylindrical bone sample is wrapped into a polymeric soft sleeve subjected to a hydrostatic pressure (5 bar) to hold it against the sample and prevent fluid to flow out from bone porosity. The bone sample is then in a confined configuration. A fluid pressure will be applied using a pressure controller (OB1 MK3, Elveflow,

France) while the outlet pressure is measured using a pressure sensor with a 4-mbar sensitivity (MPS 3, Elveflow, France). The potential difference was measured using home-made Ag/AgCl electrodes. Silver wires were coated with AgCl for 2 min in a FeCl3 bath (50 mM) and placed within a 3D printed electrode filled with KCl (3.5 M) that can be integrated within the hydraulic circuit. The potential developed during loading was measured using a potentiostat (Interface 1000, Gamry, USA) in open circuit potential configuration.

Samples pressurization: The samples were immerged in a saline solution at least the night before the experimentation. A step loading pressure (ranging from 0 to 1000 mbar) was applied at the top of the cylindric sample. A 1000 mbar pressure was maintained for 15 s and then released for 15 s. The resulting pressure and potential relaxation curves were processed by fitting a stretched exponential.

Results:
The samples BVTV ranged from 23.8 to 88.6% (mean = 55.8% and median=55.8%). The outlet pressure time characteristics ranged from 0.11 to 0.77 s (mean = 0.33 s and median = 0.25 s). A significant correlation was found between BVTV and the pressure characteristic time (ρ(Spearman) = 0.82, p-value = 0.0005). The streaming potential's characteristic time was several times higher than the pressure characteristic time. However, in the current version of the experimental set up, the reproducibility for the streaming potential measurement remains poor. Further improvements in the home-made Ag/AgCl electrodes need to be achieved.

In conclusion, a new experimental device has been developed allowing to measure fluid-related parameters during bone explant bone loading, distinguishing the vascular and lacuno-canalicular networks. In the future, such set up could be used to perform mechanobiological experimental while monitoring bone fluid behaviour.

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Impact of Hydroxyapatite Morphology on the Fracture Behavior of Lamellar Bone: A Phase-Field Modeling Approach

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Speaker: Alijani Hamid. **Thursday**. Start time: **10:40**. Room: Rhône 3A LVL1. Link to abstract.

Lamellar bone, the basic building block of bone, exhibits a remarkable combination of stiffness and toughness, which emerges from the interaction of hydroxyapatite (HA) polycrystals and organic phases. While many computational studies have explored the effective properties of lamellar bone, they often model HA either as platelets (1) or grains (2) without fully investigating the implications of these morphologies on fracture behavior. This study employs a phase-field damage modeling approach within a 2D finite element framework to evaluate the influence of HA morphology and size on the fracture properties of lamellar bone. Two Representative Volume Element (RVE) configurations were analyzed: one with platelet-based minerals (100–200 nm) and another with granular-based minerals (10–15 nm). Both configurations incorporated mineralized collagen fibrils (MCFs) modeled as anisotropic elastic materials with a diameter of 50 nm and a physiological volume fraction of 50%, and their interactions with HA were mediated by non-collagenous proteins using a semi-cohesive fracture profile. The platelet-based configuration demonstrated superior mechanical performance in terms of stiffness, strength, and toughness, with MCFs acting as effective crack propagation barriers. In contrast, granular configurations exhibited lower fracture resistance due to their lower aspect ratio. The study further revealed that higher mineral aspect ratios in the loading direction enhance stiffness and load-bearing capacity, leading to increased tissue strength.

Microstructure influence on the local mechanical properties of human trabecular bone: insights for biomimetic scaffold for bone repair

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Speaker: Xiong Zhuang. **Thursday**. Start time: **11:00**. Room: Rhône 3A LVL1. Link to abstract.

Background

Bone tissue is a highly dynamic tissue that undergoes remodeling throughout life and has the capacity for self-healing. However, this capacity becomes limited when bone lesions are extensive. One promising strategy for bone repair is to associate mimetic bone scaffolds, bone progenitor cells and soluble factors to create an environment suitable for the cells to proliferate and differentiate. Scaffolds are hence the essential component as they provide support for the cells and promote vessel and nerve growth. Bone allografts extracted from human donors are promising scaffolds. These scaffolds provide both the chemical and biochemical environment, and also local mechanical properties felt by the bone cells. In fact, trabecular bone porosity is well known to be an important determinant of macroscopic mechanical properties such as the apparent Young's modulus and permeability. On the contrary, the relationship between trabecular bone microarchitecture and mechanical conditions at the microscopic scale, i.e., the trabeculae level is still poorly understood. This information is essential for designing biomimetic scaffolds that provide a suitable environment for cells to resembles the in vivo environment.

Materials and methods

Twenty-nine trabecular bone allografts harvested from human femoral heads obtained from a tissue bank were included in the present study. These samples were devitalized and defatted, and cut into cylindrical shapes with a diameter of 6.9 mm and a height of 10 mm. X-ray computed tomography were used to obtain the 3D images and a representative cylindrical volume was chosen for each sample to reconstruct the 3D numerical model and to calculate the microarchitectural parameters such as bone volume fraction and degree of anisotropy. Finite element analysis (FEA) and computational fluid dynamics (CFD), respectively were used to determine the trabecular mechanical response and the wall shear stress, respectively. The correlation between the microarchitectural parameters and the mechanical properties at both apparent and local scales were investigated.

Results

From the FEA results, it was found out that the apparent Young's modulus is linearly correlated with the porosity of the scaffold; however, the average axial strain, the average axial stress and the average strain energy density were more correlated with the plate-and-rod composition, determined by the ellipsoid factor (EF), and the degree of anisotropy (DA) of the trabecular structure. A new parameter DAEF was obtained from these two parameters that can well predict the micromechanical properties. From the CFD results, it was found out that the permeability and the average wall shear stress of the scaffold were well predicted by the porosity of the scaffold. The results also show that surface curvature plays a significant role in wall shear stress on a local scale.

Conclusion

Studying their relationship between the microarchitecture of scaffolds and the local mechanical properties of human trabecular bone will help the design of 3D synthetic substitutes. In the present study, a new parameter DAEF derived from the plate-and-rod composition and the degree of anisotropy can well predict the mechanical properties under compression. On the other hand, the surface curvature will influence the level of local wall shear stress under fluid flow while the porosity determine the average wall shear stress level at macroscopic scale. As a result, these microarchitectural parameters need to be taken into account for future biomimetic scaffold design for bone repair, in order to recreate a mechanical environment suitable for the cells to proliferate and differentiate.

Acknowledgement
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Understanding cold-water coral strength: Molecular interactions and scaling simulations

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Speaker: Krämer Konrad . **Thursday**. Start time: **11:20**. Room: Rhône 3A LVL1. Link to abstract.

1. Introduction

Cold-water coral reefs provide essential services to marine ecosystems. However, they face significant threats by ocean acidification, rising temperatures, or deoxygenation. Their ecosystem services are enabled through formation of powerful and efficient material architectures making up a mineralised skeleton. Cold-water corals form these mineralised skeletons in extreme environments that are characterized by low temperatures, high pressures, and limited resources. They form a material architecture that uses aragonite ($CaCO_3$) as crystalline building block (1). While aragonite single crystals exhibit very high stiffness and strength (1-7), polycrystalline material they form in a tightly controlled biofabrication process exhibits a much lower but still exceptional strength – up to ten times stronger than concrete (1). Interestingly this strength is retained even when skeletons are synthesised in adverse oceanic conditions while stiffness is not and it is currently unclear why this is the case (1). The change in mechanical properties along the length scales of the material architecture implies a structure-property relationship that may provide answers why strength is maintained.

Interfaces, i.e., surfaces where aragonite grains interact with each other or with proteins, have been identified as critical failure points in the material architecture (1). However, how these interfaces moderate the structure-property relationship is unclear and difficult to assess experimentally. Therefore, the aim of this study was to investigate these interfaces to understand its role in the structure-property relationship of the polycrystalline skeletal material. To do so our objectives were: (i) explore the interactions between aragonite crystals and organic proteins; (ii) integrate coral acid-rich proteins (CARPs) to model crystal-protein interfaces and analyse their effect on mechanical properties; (iii) employ multiscale coarse-graining techniques to simulate larger material compartments

2. Methods

We use molecular dynamics (MD) simulations to investigate crystal-protein interaction. We refine existing interatomic potentials for aragonite (8) to improve modelling accuracy using GULP (9) for parameter optimisation. We incorporated a representation of CARPs, such as Lustrin A (1L3Q) (10) and aragonite protein-7 (2JYP) (11) to represent crystal-protein interfaces and analyse their effect on mechanical properties. Using these refined potentials, we simulate interfaces between aragonite and proteins, incorporating structures prepared with CHARMM-GUI (12) for seamless integration into MD simulations in LAMMPS (13). CARPs are relaxed, equilibrated and shaped via steered MD before being interfaced with aragonite This approach allows us to accurately capture the behaviour of these interfaces, providing insights into the role of organic components in coral structures.

Another factor contributing to reduced mechanical properties is intracrystalline porosity. We introduce nanoporosity (1-2 nm) using a custom Python script that preserves electroneutrality. Porosity levels up to 3.5% to 4% are tested, representing the maximum levels permitted by Coulombic interactions.

To address the limitations of MD, we use multiscale coarse-graining (MSCG) (14). The method maps groups of atoms to single beads, simplifying complex systems while retaining essential interactions. Interaction potentials are fitted using force-matching techniques. To bridge the gap between molecular-scale simulations and experimentally observed mechanical properties, we aim to eventually scale up our models to simulate the behaviour of entire coral skeletons. Thus, the data obtained at smaller scale is to be used as input for coarser-scale simulations.

3. Results

Single crystals of aragonite simulated using MD with refined potentials demonstrate good agreement with both experimental and previous simulation results on stiffness tensors, showing deviations within 10% (1). Additionally, investigations into twin interfaces reveal that crystal-crystal misorientation does not significantly reduce mechanical strength, indicating that twin boundaries are stable structures, in contrast to low-angle grain boundaries (15). Furthermore, the introduction of CARPs at the interface significantly

diminishes strength, with tensile testing revealing a reduction to approximately 700 MPa compared to the 4-6 GPa typically observed in single crystals, highlighting the influence of organic-inorganic interactions. Lastly, simulations suggest that nanopores minimally impact mechanical properties, particularly when compared to the effects of larger intercrystalline pores observed experimentally.

4. Discussion

We here investigated the interfaces in the polycrystalline skeletal material used by cold-water corals to form their skeleton. By combining refined MD simulations with multiscale coarse-graining, we revealed mechanisms behind the length scale dependent mechanical properties of coral skeletons. We demonstrate that interfaces, particularly crystal-protein interactions, are key to understanding the change in mechanical properties along the material architecture. Our research may help to challenge existing experimental data on the mechanical properties of polycrystalline coral skeletons (1) and help to uncover the structure-property relationship of this material architecture. This, in turn, may be useful for the biomimetic design of new materials.

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Bone Fracture Prediction: From Experimental Determination of Material Properties to Phase Field Model Implementation

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Speaker: Maxime Levy. **Thursday**. Start time: **11:40**. Room: Rhône 3A LVL1. Link to abstract.

Bone fracture prediction by CT-based finite element analysis based on maximum principal strain criterion can predict fracture initiation load within 80% accuracy (conservative prediction) (1). It cannot predict the crack path which may also be of interest for clinical application.
Phase Field Models (PFMs) may improve bone fracture predictions (2), however, PFM predictions are highly influenced by the heterogeneous critical Energy Release Rate (ERR) , critical ultimate stress and Young modulus of the bone.

To improve fracture initiation and crack path predictions in human long bones by PFM we apply numerical-experimental methods to determine the material properties of bone tissue so to be used in conjunction with CT-based FEA. We firstly focus on the femoral cortex and failure in transverse direction (perpendicular to osteons).

Human fresh frozen femurs were CT-scanned to obtain bone density along the femur, then sliced to create three point bending specimens in which crack like defects were inserted. These specimens were then micro-CT scanned before loaded to fracture.

Using standards designed for metals and concrete, we computed the critical Stress Intensity Factor ( ) through a three-point bending test setup combined with Digital Image Correlation (DIC). This allowed us to establish a qCT-based correlation for , which was validated using PFM and FEA. Additionally, fracture experiments on unnotched bone specimens were conducted to estimate the critical strain through DIC measurements and the results were compared with data available in the literature.
Preliminary FE results are presented to investigate the influence of the newly computed material properties on the fracture loads of human humeri and femurs.

A mathematical model for predicting the elastic properties of cortical bone using algorithm-generated images

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Speaker: Zhiyu Wang. **Thursday**. Start time: **14:15**. Room: Rhône 3A LVL1. Link to abstract.

With the increasing elderly population, osteoporosis has become one of the major factors affecting health. In order to provide precise diagnosis and treatment, quickly predicting the mechanical properties of bones in the elderly is crucial. However, traditional methods for evaluating bone strength typically rely on cumbersome mechanical experiments and macroscopic assessment methods, which often fail to consider the impact of microstructural features and cannot provide rapid evaluations. To address these shortcomings, this study proposes a model for rapid prediction of cortical bone mechanical properties based on an algorithm that generates effective bone cross-sections. Specifically, this paper introduces a novel parameter, the planar elliptical eccentricity , to better reveal the geometric characteristics of cortical bone cross-sections. Additionally, a model combining multi-objective optimization and depth-first search algorithms is proposed, which efficiently generates cortical bone-like cross-sections. Through parameters such as the osteons distribution density, the area ratio between osteons and Haversian canals, and eccentricity, the model accurately and comprehensively represents the hierarchical structure of cortical bone. This method overcomes the limitation of scarce cortical bone cross-sectional images, providing rich data support for subsequent mechanical analysis. In terms of mechanical analysis, finite element analysis is performed using ABAQUS, which calculates the dimensions of the representative volume element (RVE) of cortical bone and the macroscopic equivalent Young's modulus, thereby enabling the rapid assessment of cortical bone mechanical properties. This study demonstrates that the microstructural parameters of cortical bone, particularly the distribution density of bone units, the area ratio of bone units to Haversian canals, and the eccentricity , are key factors influencing the elastic modulus of cortical bone. Further analysis reveals a significant quantitative relationship between , and . and a fitting equation is derived within a certain range. The findings of this study provide new insights for predicting the mechanical properties of cortical bone in the elderly, with significant clinical implications. In the future, further optimization and application of this method could provide a scientific basis for the elderly diagnosis of osteoporosis.

An IGA approach to flexoelectricity-induced remodelling in cortical bone

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Speaker: Menzel Andreas. **Thursday**. Start time: **14:35**. Room: Rhône 3A LVL1. Link to abstract.

Flexoelectricity, which couples electric polarisation with strain gradients, was found to be present in cortical bone and to take a key role within the bone remodelling. In this regard, experiments showed that flexoelectricity can induce osteocyte apoptosis in mechanically stimulated bones, (1), which is a starting point for targeted bone remodelling. This effect is most relevant on small scales due to the size-dependency intrinsic to felxoelectricity. Conceptually speaking, strain gradients in the vicinity of micro cracks in cortical bone induce an electric field that, if sufficiently large, results in osteocyte apoptosis. A related computational model has been proposed, see (2,3), which is the basis for this contribution.
To cover higher gradient contributions as occurring in the resulting set of field equations to be solved, an isogeometric analysis is employed within the computational setting, (4), since the NURBS basis functions used satisfy the required continuity properties. In addition to the flexoelectric electro-mechanical coupling, a coupling to chemical fields is included so that the behaviour of different bone cells and biochemical signals, which drive the remodelling process, can be modelled. Specific types of bone cells considered are osteocytes, osteoclasts and osteoblasts. Moreover, signalling is performed by different types of messenger substances. All these bone cells and chemical substances are included via additional field variables, respectively diffusion type balance equations. A representative initial boundary value problem is discussed, which mimics healing of a micro crack in a small sample of cortical bone.

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HIERARCHICAL ELASTOPLASTICITY OF CORTICAL BONE:OBSERVATIONS, MATHEMATICAL MODELING, VALIDATION

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Speaker: Hellmich Christian. **Thursday**. Start time: **14:55**. Room: Rhône 3A LVL1. Link to abstract.

While the mechanical failure of bone is classically associated with the formation of microcracks, with sizes ranging from 50 to 300 microns, a variety of experiments and computations, including solid-state nuclear magnetic resonance tests,molecular dynamics simulations, and mechanical tests on cuboidally or cylindrically shaped micropillars of bone extracellular matrix, have evidenced that the nanoscale source for material degradation and bone strength appears to be of plastic and ductile nature, coming from mutual dissipative sliding of hydrated hydroxyapatite mineral crystals within the extracellular bone matrix.We here quantify the macroscopic strength effects of this nanoscale source, through a six-step hierarchical elastoplastic micromechanics model:A non-associated Mohr-Coulomb plasticity model is adopted for the description of plastic events arising right at the nanolevel of the hydrated mineral crystals found within the ultrastructure of bone. The latter is first integrated in a fashion inspired by the so-called return-mapping algorithm which was popularized in nonlinear Finite Element analysis, and then combined with a hierarchical concentration-influence tensor concept, yielding elasticity and strength values throughout the entire hierarchical organization of bone. Finally, the six-step homogenization scheme is carefully validated against a broad selection of biochemical and biomechanical experiments.

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Modeling and simulation of the coupling between trabecular bone adaptation and microdamage repair though remodeling

Adachi Taiji (1), Muto Tsuyoshi (1), Kim Young Kwan (1)

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Speaker: Adachi Taiji. **Thursday**. Start time: **15:15**. Room: Rhône 3A LVL1. Link to abstract.

Physical exercise maintains and improves bone structure and its strength, whereas excessive exercise leads to the accumulation of microdamage in the mineralized bone matrix, which in turn decreases bone strength and increases fracture risk. In this complex phenomenon, the coupled adaptation and microdamage repair are regulated by mechanosensory osteocytes embedded in the bone matrix through bone remodeling activities of osteoclasts and osteoblasts. To better understand this complex mechanobiological coupling in bone, by using an in silico experimental platform based on a voxel finite element method (1, 2), we performed remodeling simulations on the osteoporotic trabecular bone cube, which was reproduced under reduced physiological loading conditions, under various mechanical loadings. The spatiotemporal dynamics of coupled bone adaptation and microdamage repair were studied, and quantitative and qualitative changes in trabecular bone structure were evaluated. In addition, potential clinical applications of this simulation platform will be discussed, including methods to predict the impact of the combined effects of exercise and drugs in the treatment of osteoporosis.

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Phase-field modelling of damage evolution in cortical bone

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1 - Lund University (Sweden)

Speaker: Carlsson Jenny. **Thursday**. Start time: **15:35**. Room: Rhône 3A LVL1. Link to abstract.

With ageing, bone becomes stiffer and more brittle, leading to an increased risk of fracture. The changes in properties can be attributed to changes in bone composition and microstructure. Computational models can be used to elucidate the links between fracture behaviour and microstructure. Moreover, computational models are useful because experimental determination of mechanical properties of the different tissues in the bone microstructure is difficult. With computational models, it is possible to investigate the fracture behaviour of normal and ageing bone, as well as the role of the microstructure in the fracture process. Models relying on cohesive criteria e.g. the cohesive zone method and the extended finite element method have been used extensively in this regard. More recently, phase-field models have been introduced for this purpose. However, as no validation studies have been published, it remains unclear to what extent classical phase-field methods accurately represent bone. In this contribution, we evaluate the predictive performance of a classical phase-field finite element model in comparison with experiments performed by Gustafsson et al. (2024).
A phase-field finite element model of bovine cortical bone with a resolved osteonal microstructure consisting of osteons, matrix and cement line was used. A set of material parameters was estimated using a design-of-experiments approach in which all six parameters (three moduli and three critical energy release rates) were varied according to a Box-Behnken design to create response surfaces for peak force, tortuosity and toughness. From the response surfaces, the parameter set that minimised the error with respect to experimental results from single-edge notched bending (SENB) of bovine bone and subsequent imaging of the crack path (Gustafsson et al., 2024) was identified as the best fit.

The model was then validated using new specimen geometries in comparison with data from corresponding SENB experiments (Gustafsson et al., 2024). It was found that phase-field models in their classical form predict peak load, toughness and final crack path with reasonable accuracy. However, the force versus crack mouth opening displacement (CMOD) response was not well captured. Being based on linear-elastic fracture mechanics, the phase field models predicted brittle failure. On the other hand, SENB experiments performed on bovine cortical bone showed both an initial, gradual damage evolution, resulting in a non-linear response, and a ductile post-peak behaviour with increasing toughness as the crack length increases.

The observations imply that the material locally undergoes non-elastic deformation and that the size of this plastic or bridging zone (i.e. the characteristic length) is significant compared to other dimensions of the specimen. The cohesive-zone phase-field formulation of Wu and Nguyen (2018) implemented by Navidtehrani et al. (2021) accurately predicts failure of both notched and unnotched specimens also when the characteristic length is non-negligible. When the cohesive-zone phase-field model was implemented in the bovine cortical bone geometries, considerably better agreement was obtained between the experimental and predicted force vs. CMOD curves. The present contribution investigates the predicted damage development and crack path in comparison to post-fracture CT scans of the experimental cortical bone specimens. As the findings indicate that fracture in healthy bone is ductile or quasi-brittle, care should be taken when applying classical, brittle phase-field methods to bone.

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Ultrasound stimulation of bone cells: 3D finite-element model of acoustic streaming around osteocytes.

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Speaker: Allegre Lucille or Baron Cécile. **Thursday**. Start time: **15:55**. Room: Rhône 3A LVL1. Link to abstract.

Introduction

Ultrasound (US) stimulation of bone remodeling remains an open question as the underlying mechanisms involved are still poorly understood. Among the possible hypotheses, the propagation of ultrasonic waves (US) in bone tissue could generate acoustic streaming (AS) resulting in fluid shear stress exerted on the wall of osteocytes known as the mechanosensitive conductors of bone remodeling. Osteocytes are dendritic cells surrounded by a viscous pericellular fluid (PCF), ubiquituous in the bone extra-cellular matrix (ECM) forming a complex micrometric 3D network called the lacuno-canalicular network (LCN). This paper investigates the interaction of US with the osteocyte dendrite (OD) confined in a canaliculus, as it is considered as the most mechanosensitive part of the cell. The aim is to explore the relevance of taking into account the irregular 3D shapes of the canaliculus and dendrite in terms of mechanical sollicitations induced by US stimulation.

Material & Methods

From images (FIB-SEM imaging "slice and view" in BSE mode (Gianuzzi 2004), FEI Helios NanoLab 660, pixel size 16.78 × 16.78 × 20 nm3), a realistic 3D geometry of a canaliculus of rabbit cortical bone is reconstructed and implemented in the Finite-Element software Comsol Multiphysics (v. 6.2). The geometry of the dendrite inside the canaliculus (not accessible by imaging) is deduced from the canaliculus wall geometry.

The acoustic properties of the cell dendrite and of the PCF are similar to those of water, except that the viscosity of the PCF is supposed to be 10 times higher than water dynamic viscosity (μwater=0.65.10-3 Pa.s).

To mimic the US stimulation od bone cells inside the LCN, a first order oscillating velocity **U1** is imposed along the ECM/PCF interface under the form of a harmonic acoustic wave at frequency f of 1 MHz with an amplitude of displacement d0 propagating in the US propagation direction: $\mathbf{U1}(f) = i2\pi f d0 \mathbf{ex}$.

The acoustic streaming is a second-order (non-linear) acoustic effect which results in a steady flow. In order to investigate the acoustic streaming induced by US stimulation inside the PCF, we need to solve the second-order Navier-Stokes equations obtained by the perturbation method.

In Comsol Multiphysics, the Thermoviscous Acoustics module (in frequency domain) is used to resolve the first order acoustic field which provides the source term for the second order equation implemented in the Laminar Flow module.

From the acoustic streaming velocity (time-averaged second-order term) thus obtained, the resulting wall shear stress (WSS) applied at the PCF/process interface is calculated.

Results & Discussion

The WSS is plotted along the interface PCF/OD. The values are compared to those obtained for idealized 3D-geometries (annular tube) deduced from the realistic one and to the results obtained in 2D cross-sections as previously presented in (Baron 2023).

We investigate how canaliculus and dendrite geometries could have an influence on the US-induced PCF flow. Finally, the quantification of the WSS induced by acoustic streaming is questioned in regard of stress levels that can trigger a biological response (Weinbaum 1994).

Keywords*:* acoustic streaming; wall shear stress, osteocyte; mechanotransduction; FE model; FIB-SEM.

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A Quasi-Brittle Fracture Mechanics Model for Assessing Treatment Effects in Human Cortical Bone

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Speaker: Gallaway Glynn. **Friday**. Start time: **10:00**. Room: Rhône 3A LVL1. Link to abstract.

Fragility fractures are increasingly common, yet efficacy of treatments often remains low. Most treatments address bone quantity, yet changes to bone quantity do not necessarily result in a corresponding change to fracture risk. To better understand fragility fractures, there is a need to improve fundamental understanding of bone fracture mechanics.
Ex-vivo treatment of bone with the FDA-approved compound Raloxifene provides a testbed to study fracture in the context of bone quality treatments. Bone fracture mechanics commonly employ linear elastic fracture mechanics (LEFM) stress-intensity factors or J-integral calculation. Large fracture process zones (FPZs) have been observed in bone, violating LEFM and restricting the J-integral. We hypothesize that quasi-brittle fracture mechanics (QBFM) can be used to assess changes in the fracture properties of bone with treatment.

Cadaveric human femur tissue is obtained and sectioned into 12 prismatic bars (4 mm x 4 mm x 24 mm) with a nominal 2 mm notch. Osteon diameters (On.Dm) were determined. Beams are randomly assigned to 2 treatment groups; 6 beams are treated with a Raloxifene solution (RAL), and 6 beams are treated with a control solution (VEH). Four-point bend fracture experiments are conducted in-situ a 3D X-ray microscope (Zeiss XRADIA) with a physiological bath. FPZ size is measured directly from 3D images. Quasi-brittle fracture mechanics methods with a size-scaling law are used to obtain intrinsic material properties: a true tissue fracture toughness and an associated material characteristic length scale.

RAL treatment is found to significantly increase the FPZ size compared to VEH. Such an increase in FPZ size is found to be associated with differences in micro-crack deflection processes during the formation of the FPZ. LEFM fracture toughness with the initial crack length does not distinguish RAL and VEH. QBFM fracture toughness with the effective crack length differs between RAL and VEH, with RAL possessing higher fracture toughness. Tissue intrinsic fracture toughness for RAL is found to be 36% higher than that for VEH, while in intrinsic length scale for fracture for RAL is 86% higher than for VEH. Intrinsic length scales are found to relate to bone microstructure lengths as expressed by the osteon diameter: 14.0 On.Dm (RAL) and 6.3 On.Dm (VEH).
Quasi-brittle fracture analysis of bone is necessary to understand treatment effects across length scales. Treatments to reduce bone fracture risk should consider and evaluate effects of fracture, microdamage, and microstructure properties.

Computational evaluation of geometrical and physical skull growth for craniosynostosis treatment via finite element analysis

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1 - University of Galway (Ireland)

Speaker: Vafaeefar Mahtab. **Friday**. Start time: **10:20**. Room: Rhône 3A LVL1. Link to abstract.

INTRODUCTION

Craniosynostosis, a condition where cranial sutures fuse prematurely, affects about 1 in 2,000 infants, leading to abnormal head shapes and facial features (1, 2). Current treatments involve invasive surgeries to relieve brain pressure of the closed suture on the brain, such as removing fused sutures, reshaping bones, or spring-assisted cranioplasty. The synchronized growth of the brain and skull, the biomechanics of this process remains poorly understood, with limited studies addressing this gap through biomechanical and mechanobiological environment. This study aims to develop a finite element (FE) framework to simulate mechano-regulated calvarial growth within the first year of life for healthy and synostosis skull, exploring physical and geometrical constraints influence cranial development.

MATERIALS AND METHODS

The skull geometry was approximated as an ellipsoid, with a cephalic index of 78, including 6 regions of bone (frontal, parietal and occipital bones), and suture tissue. The brain tissue, or intercranial volume (ICV) was modelled as a solid section, with the same index, offset from the skull geometry. The z-direction was constrained, as well as planar constraint on the skull elements on the bottom z-face. Bone and suture material behaviour were assumed to be linear elastic, undergoing a bulk bone formation scenario, to account for the change of mechanical properties of bone and suture during growth. Ultimate Young's moduli for bone and suture tissue were 3,000 MPa and 230 MPa (3), respectively, and a Poisson's ratio of 0.3. Brain was considered as a Neo-Hookean hyperelastic material. Skull and brain are in normal and tangential frictional contact. Growth algorithms were applied on through field equations of kinematics, constitutive behaviour, mechanical equilibrium and growth kinetics. The brain grows isotopically with a growth rate of $\lambda_$brain. The bone and sutures undergo anisotropic mechanobiological growth, driven by applied deformation from brain, beyond an activation stretch for each tissue. Different growth schemes and rates are accommodated to different tissues, using UMAT subroutine into the finite element (FE) model. The algorithm is validated for a healthy case skull growth first and further used for recreating craniosynostosis conditions. Dysmorphologies due to synostosis conditions were quantitatively studied by calculating the cephalic index (CI) for the deformed skulls. Sensitivity analysis were also performed to account for the effects of individual model parameters on the results.

RESULTS

According to the results of the simulations, the algorithm predicted healthy skull growth, whereby the model predicted a volume increase by a factor of 2, within one year of age. Subsequent skull dimensions resulted in CI of 77.73% and in the range of a healthy skull shape (4). Using the growth model, individual growth contributions of sutures were captured, and the mechanical interactions between model elements were revealed. Craniosynostosis models and subsequent developed dysmorphologies were predicted during the 12-month growth process. The normalised deformation of each synostosis case described how the skull has changed in comparison to its original shape. The dysmorphologies in craniosynostosis cases were in close agreement with clinical data. The algorithm was capable of predicting the overall shape of the dysmorphologies with a maximum error of 12% for the metopic craniosynostosis case. The results show that the growth algorithm on the FE model is capable of predicting the overall malformed skull shape in individual craniosynostosis cases.

DISCUSSION

This study developed a mechanically driven model of skull growth that captures the geometry of the skull within the first year of age. Compared to previous models, the parallel growth of intercranial volume and skull was considered as a gradual process over the long term of growth, rather than a sequential growth. Unlike most studies that use constant pressure on the skull, this method allows comparing different re-

constructions at one point in development using a parallel growth algorithm in three tissues, where the volumetric growth of the ICV works as the driving force for the overlying skull growth, in an element strain-based feedback loop. Another contribution of the model is that it can predict the dysmorphologies due to craniosynostosis cases. The resulting geometries for healthy and craniosynostosis cases showed good agreement with clinical observations, in terms of cephalic indices as well as remarkable qualitative consistency in skull shape. The model is potential to predict useful data towards more accurate planning for the surgical intervention in terms of location, time of intervention, as well as correction techniques.

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Fibrillar-level mechanics of the healthy and aged bone-cartilage unit

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Speaker: Gupta Himadri Shikhar. **Friday**. Start time: **10:40**. Room: Rhône 3A LVL1. Link to abstract.

The bone-cartilage interface at the ends of long bones is essential for distributing physiological loads across articulating joints, and facilitating smooth, pain-free joint movement (1). Structural and mechanical degradation of this bone-cartilage unit (BCU) is a key factor in developing osteoarthritis, affecting over 500 million individuals globally. Despite its biomedical and mechanobiological importance, the *in situ* structural deformation of the collagen-based extracellular matrix (ECM) within the BCU has been difficult to quantify due to the small length-scale of the deforming units (mainly Type II collagen fibrils $<$ 100 nm in diameter and proteoglycans along with water) and the graded, hierarchical structure of the ECM across the BCU, from the superficial (surface) layer to the underlying subchondral bone.

This study introduces a 3D synchrotron-based small-angle X-ray modelling and spatially correlative mechano-imaging approach to measure nanoscale fibrillar deformation across the intact BCU under biomechanical loading. Synchrotron small-angle X-ray scattering can detect the fibrillar-level strains, reorientation and intrafibrillar molecular organisation of the collagen fibrillar network, and when combined with compressive loading and high-brilliance synchrotron radiation, enables microscale maps of the fibrillar-level scattering to be determined. However, the anisotropic, graded structure of the scattering fibrils makes interpretation of the scattering signal complex. Here, we developed 3D fibre-symmetric models of the scattering from the fibrils to link the measured scattering to intrinsic fibrillar structural parameters, like the axial tropocollagen stagger (D-period, linked to pre-strain), fibril orientation, diameter and axial strain heterogeneity. Using this approach, we identified previously hidden deformation mechanisms within the semicrystalline collagen fibril network (2,3), which are spatially graded across the BCU. These include shifts in fibril crystallinity, pre-strain, lateral compression, axial contraction, and molecular disordering (2). In the superficial cartilage layer, collagen fibrils exhibit heightened molecular disorder. Progressing deeper toward the bone interface, fibrils transition from reorientation-driven strain at the microscale to molecular kinking strain. Simultaneously, fibrils undergo greater lateral compression than axial contraction, likely due to intrafibrillar water expulsion under load. The mineralized cartilage and bone closest to the interface with articular cartilage exhibits compressive deformation, but on going deeper into the subchondral bone, the fibril strain reduces. Further, the trabecular bone under the BCU shows a much lower pre-strain than the articular cartilage and the mineralized interface.

Age-related cross-linking of the BCU, simulated using *in vitro* glycation using ribose, further alters these mechanics by reducing fibril pre-strain, increasing fibril diameter, and diminishing the nanofibrous network's resilience by lowering fibril deformability. These findings significantly enhance our understanding of the nanoscale mechanobiology of the bone-cartilage interface and open pathways for targeted biomarkers and therapeutic interventions.

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The role of inflammation on subchondral bone adaptation in post-traumatic osteoarthritis

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Speaker: Gustafsson Anna. **Friday**. Start time: **11:00**. Room: Rhône 3A LVL1. Link to abstract.

Inflammation is believed to play a key role in osteoarthritis (OA). However, the etiology is still largely unknown. In this study we focus on post-traumatic OA, where OA is triggered by a joint injury. What is interesting from a modeling perspective is that the starting point is well defined, i.e. the time of the injury. Data from PTOA animal models (Goetz et al., 2015) show an acute inflammatory response in the joint at the time of injury, which slowly subsides to moderate levels of chronic inflammation. The aim of this study was to evaluate possible effects of such an inflammatory response on the subchondral bone over time using a mechanobiological computational framework. This is important as changes in the subchondral bone typically occur before the degeneration of cartilage, which suggests that subchondral bone may be key for the onset and early development of the disease.
Typical subchondral bone development in OA follows the following pattern: In early OA, there is increased remodeling resulting in thinning of the subchondral bone plate. In later stages of OA, the thickness of the subchondral bone plate instead increases and the deep articular cartilage calcifies, resulting in a thick calcified unit composed of bone and calcified cartilage. In addition, the trabecular bone volume increases while the tissue mineral density decreases.

In this study, we want to evaluate different mechanobiological mechanisms in order to predict these changes. In particular, we are interested in the following mechanisms, and the combination of them:

a) Inflammation drives bone resorption (Epsley et al., 2021).

b) Inflammation affects bone formation, resulting in decreased mineralization and tissue stiffness (Walsh et al., 2009).

c) TGFβ promotes abnormal bone formation (Hu et al., 2021).

d) Inflammation and TGFβ together promote calcification of articular cartilage (Thielen et al., 2023).

To do this, we use a well-established framework for bone remodeling (Huskies et al., 2000), which was later extended to include both calcified and articular cartilage (Cox et al., 2011). The basic idea is that osteocytes are mechanosensitive and produce a stimulus proportional to the strain energy density that regulates bone formation. Bone resorption occurs randomly at bone surfaces according to defined resorption rates. We combine the remodeling framework with a diffusion model describing the mass transport of inflammatory cytokines (e.g., IL-1b) and TGFβ. In this way, we can use the local concentrations of IL-1b and TGFβ as additional stimuli for bone remodeling. Inflammation is assumed to originate from the synovial fluid, where the concentration decreases over time. TGFβ is stored in the bone matrix and released locally as bone is resorbed. Both bone remodeling and mass transport are implemented in Abaqus and we solve the problems iteratively under daily loading conditions using a square 2D grid (7.5x7.5 mm2) including articular cartilage, calcified cartilage and subchondral bone. First, remodeling is simulated under healthy conditions to predict an initial bone structure in equilibrium, and then mechanisms a)-d) are introduced individually or in combination to simulate the progression of OA.

Preliminary data show that bone formation is sensitive to both loading conditions, load magnitude and tissue stiffness, with lower stiffness resulting in thicker bone structures. When inflammation-driven resorption is included, the models predict the initial thinning of the subchondral bone plate. The combination of inflammation and TGFβ also predicts articular cartilage calcification similar to patterns seen experimentally. Current work is focused on the combination and timing of different mechanisms to elucidate the mechanisms driving the alteration of subchondral bone in OA.

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Ultrasound Spectroscopy of Cortical Bone: Insights from In-Silico Modeling to In-Vivo Detection of Fragility Fractures

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Speaker: Raum Kay. **Friday**. Start time: **11:20**. Room: Rhône 3A LVL1. Link to abstract.

Cortical ultrasound spectroscopy (CortBS) offers a non-ionizing method for assessing viscoelastic properties and intracortical pore morphology, showing promise in detecting fragility fractures. This study integrates in-silico modeling and in-vivo evaluation to establish the sensitivity of ultrasound metrics to cortical bone properties and their utility in fracture discrimination.
In-silico simulations using a finite-difference time-domain (FDTD) model analyzed cortical bone with varying pore morphologies and tissue absorption (αabs). A heterogeneous pore size distribution (Ct.PoDm.D) was modeled through an erosion procedure, which gradually increased pore sizes from the outer to the inner bone boundaries. While material properties remained constant (c11=c22=23.7 GPa, c12=9.5 GPa, c66=6.6 GPa, ρ=1.93 kg/m^3), thickness, αabs, and Ct.PoDm.D were varied. Results demonstrated distinct shapes and amplitudes of backscatter and attenuation coefficients BSC(f) and α(f) with respect to pore density, morphology and tissue absorption, reflection bone deteriorations caused by reduced turnover, unbalanced remodeling and viscoelastic matrix alterations (Fig. 1).

Building on these insights, an in-vivo study evaluated 177 participants (144 women and 33 men, aged 30–86 years). DXA scans were performed at the lumbar spine and femoral sites, while CortBS measurements were performed at the anteromedial tibia midshaft. Multivariate analyses examined the effects of gender, age, and anthropometric factors, while partial least squares discriminant analysis (PLS-DA) compared fracture detection performance. CortBS scores, influenced by age, sex, and fracture status, demonstrated superior fracture discrimination for vertebral and non-vertebral fractures compared to DXA (AUC: 0.68–0.74 for CortBS vs. 0.60–0.63 for DXA).
CortBS reflects gender-specific alterations in cortical pore morphology and viscoelastic properties, providing a robust tool for assessing fracture risk in both women and men. The in-silico findings underscore the sensitivity of ultrasound metrics to pore morphology and viscoelastic matrix properties, offering a foundation for interpreting in-vivo results and advancing the understanding of bone quality and fracture risk with respect to ageing and bone pathologies.

Determining the Patient-Specific Anisotropy by cQCT in Vivo

Gebert Johannes (1) (2)

1 - University of Stuttgart (Germany), 2 - High-Performance Computing Center Stuttgart (HLRS) (Germany)

Speaker: Gebert Johannes. **Friday**. Start time: **11:40**. Room: Rhône 3A LVL1. Link to abstract.

Motivation

Human cancellous bone is a patient-specific, load-bearing tissue. Considerations of the spongious tissue's patient-specific mechanical characteristics promise to enable better fracture risk predictions, the design of patient-specific implants, and other applications.

However, trabeculae require about 0.015mm voxel spacing for their detailed structural representation. Computed tomography (CT) images of such spatial resolutions require radiation exposures that are prohibitive for use in vivo. Consequently, exact patient-specific quantifications of the spongiosa's mechanical behavior are unavailable a priori, e.g., before the patient undergoes surgery.

Following is a new method and its validation for computing patient-specific elasticities based on clinical quantitative computed tomography (cQCT).

Approach and Validation

Spongious tissues consist of marrow and trabeculae, a heterogeneous, non-repetitive structure. Rodney Hill proposed a general and exact description of two phases. Rietbergen et al. developed this idea into the "direct mechanics assessment of elastic symmetries and properties of trabecular bone architecture." Ralf Schneider implemented this direct mechanics approach for use on high-performance computers. The author developed a modified version of this software during the research. For microfocus computed tomography (μCT) scans, we rely on binary segmentation to extract the trabecular structure. The software decomposes the image into seamless, grid-parallel cuboid volume elements (VEs) of edge lengths 0.6mm, 1.2mm, 2.4mm, or 4.8mm, for which we compute effective stiffness matrices. These matrices represent the 3-dimensional, equidistant 4th-rank tensor field of mechanical elasticities of the bone. We then reorient these grid-parallel, 6x6 effective stiffness matrices to characterize the orthotropic symmetries best. The results of this process chain constitute the ground truth of this abstract.

This research aims to compute patient-specific anisotropies in vivo based on cQCT with a voxel spacing of 0.173x0.173x0.6mm. In collaboration with Peter Helwig and with the confirmation of the ethical review board, we collected and published samples of human femoral heads of patients undergoing surgery for THAs. Jan-Peter Schenkengel and his colleagues at the hospital Heidenheim scanned the femoral head with a cQCT scanner and an in vivo protocol. Additionally, we scanned the bone sample with a μCT scanner at a voxel spacing of 0.015mm.

We define the high-resolution μCT scans as the ground truth of this research. The clinical CT scan is reoriented in silico to spatially register exactly with the μCT scan of the identical bone sample.

The μCT based computations of mechanical elasticities rely on a binary segmentation of the voxel image. For cCT images, instead, we apply a direct voxel conversion based on Hounsfield values to the clinical scans. We assume that the CT attenuation depicted in the voxels of the CT scan is the superposition of the attenuation of all structural bone features contained in the respective voxel. Hence, applying a reasonable radiodensity-elasticity relationship from the literature allows us to assign mechanical properties to all voxels in a cCT image. Now, we can compute a direct mechanics assessment of the clinical image. The spatially registered cCT and μCT scans allow for comparing the anisotropies in vivo to the ground truth.

Results and Conclusions

Correlations of the spatially registered μCT to cCT comparison of the orthotropic effective stiffness give a coefficient of determination of r^2 $\geq$ 0.893. Eight of nine parameters have an r^2 greater than 0.9 for this representative VE edge length of 2.4mm with all parameter slopes around m $\approx$ 1, small intercepts b, and a p-value $<$ 0.001. Such correlations hold despite several probable inaccuracies, which implies even higher correlations in future research.

Outlook

Probable inaccuracies are identified and can be accounted for in further research, enabling even more detailed representations of elasticities in vivo. Once these improvements are confirmed, we investigate many different bone samples. In addition, we aim to validate the method based on the opportunistic use of cQCT images that will be collected from tissues in vivo.

MS2.5 - Mechanics of Biomaterials: from implant to Tissue Engineering

Organisers: Giulia Luraghi (Polimi), Diana Massai (Polito), Jérôme Chevalier (MATEIS), Jérôme Molimar (Ecole des Mines de Saint-Etienne), Svein Keliven (KTH Stockholm), Michael Gilchrist (University college of Dublin) and Philippe Beillas (University Gustave Eiffel)

Development of a variable locking angle implant for treating of Pauwels type III femoral neck fractures and mandibular angle fractures

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1 - Faculty of Mechanical Engineering and Naval Architecture [Zagreb] (Croatia), 2 - Klinički bolnički centar Sestre milosrdnice (Croatia)

Speaker: Adamović Petra. **Thursday**. Start time: **10:00**. Room: Rhône 3B LVL1. Link to abstract.

Introduction: Pauwels type III fractures are generally associated with the verticality of transcervical high-energy hip fractures in younger individuals. They occur in approximately 3.6% of total body fractures and 57% of hip fractures and are the leading cause of hospitalization in elderly patients. On the other hand, young adults with femoral neck fractures are considered for hospitalization if they are younger than 65–70 years and they tend to have fewer femoral neck fractures than elderly with osteoporosis. Young adults tend to have more vertically oriented distal neck or basicervical fractures from high-energy mechanisms (commonly car or motorbike accidents). Locking plates are considered as a favourable treatment option for bone injuries and healing due to their strong biomechanical properties. Nowadays, a fair amount of locking system designs are available, but their mechanical properties and features are not entirely sufficient for the challenges the patients find themselves in. The purpose of this study is threefold. First, to both computationally and experimentally validate a novel screw locking system containing a plate and a screw by comparing it to another state-of-the-art locking system. Secondary purpose is to apply the said system in an environment of a fractured mandible to test the system in a bony environment. The last and ultimate goal of the system is to re-develop it to extend its functionality further; to compare the biomechanical stability of a standard inverted triangle configuration for treating Pauwels type III femoral neck fractures with newly proposed x-crossed screw configurations, which are the new addition to the patented locking system. When treating femoral neck fractures in both young and old individuals, artificial femoral head replacement surgery is typically not advised. Multiple screws, or a sliding hip screw with or without an antirotation screw are the most often used methods for treating vertical femoral neck fractures. So, a perfect locking system should be able to anchor itself in a healthy as well as in an osteoporotic bone, simultaneously being able to remove itself without causing any additional damage to the surrounding biological tissues. The screw's geometry, size, position, and length are the most important factors affecting the structural performance of internal fixation implants; nevertheless, the question of determining the ideal medical implant in order to guide clinical practice still exists between the surgeons.

Methods: The novel locking system was drawn in a SolidWorks software. FEA based simulations made in Abaqus were used to determine the mechanical properties of the novel locking system and the standard one prior to experimental tests. The systems containing a plate, and a screw were locked in the plate holes at 0○, 10○, 15○, and 20○. Cyclic bending tests and push-out tests were performed in order to determine the stiffness and push-out forces of both locking systems. A patent application was written afterwards. For testing the locking systems in the cyclic tests, a plate with four holes, 1 mm thickness, and 18 mm in length in a combination with 2.4 mm screw was used. For each sample, 5000 load cycles was conducted with a frequency of 1.4 Hz. Then, the newly designed locking system was reshaped and implemented in mandibular angle fracture. FEA simulations were made to check the biomechanical properties of the novel locking system in a new environment, simultaneously comparing it with a standard locking system for such fractures. For the femoral neck fracture problem, a left, 4th generation composite Sawbones® femur was scanned using computed tomography and later imported into Materialise Mimics software to segment the trabecular and cortical bone. The same artificial and identical bones are going to be used in later studies, in biomechanical experiments. Finally, the locking system was re-designed in SolidWorks for the osteosynthesis purpose of Pauwels type III femoral neck fractures and was later subjected to new FAE simulations, also with a comparison with a commonly used femoral neck fracture osteosynthesis method. In all of the FEA simulations, a mesh of tetrahedral elements of the second order (C3D10) was used on the models. The size of the elements was chosen based on the convergence test of the displacement results. Also, all of the materials were assumed to be homogeneous and isotropic.

Results: The novel locking system showed greater stiffness by 17.3% at the deflection angle of 20◦ in cyclic tests, with lower values for other deflection angles in comparison with a similar locking system. The push-out test performance of the control locking system was somewhat superior according to the results. Same trends were displayed in simulations of a fractured mandible angle environment, while comparing the new system to the standard one. The patent application was approved, but just for the mechanism of the locking system. Considering the placement of the screws in the plate, FEA simulations for the osteosynthesis of the femoral neck fracture showed that an x-crossed-right assembly provides biomechanical stability for Pauwels type III femoral neck fractures in terms of maximum von Mises stresses and femoral head displacement. However, it falls short in ensuring full stability for maximum relative neck fracture displacement.

Conclusion: Greater stiffness of the new locking system in cyclic loading tests, together with polyaxiality of the new locking screw, could lead to easier application and improved biomechanical stability of the mandible angle fractures. More importantly, the system demonstrated its potential to be used in different human fractures such as high degree femoral neck fractures.

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Mechanical target for bone implant optimization based on numerical homogenization

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Speaker: Vasta Marcello. **Thursday**. Start time: **10:20**. Room: Rhône 3B LVL1. Link to abstract.

Microstructurally architected materials have recently received a significant boost due to advent of new manufacturing techniques. Despite these functionally graded materials, such as graded lattice, are now widely employed in many fields of engineering: in bioengineering they play the role of artificial substitutes mimicking the real architecture of some biological tissues; their effectiveness for prosthetic implants, especially orthopedic and dental ones, is crucially affected from the accuracy level of their biological functions understanding, as much as from the choice of the optimization target. In recent studies the mechanical response of several kinds of Triply Periodic Minimal Surfaces (TPMS) is investigated in the limit of their manufacturability, due to their structural efficiency (1), or density-based topology optimization of homogenized lattice structures in a patient-specific hip endoprothesis is performed (2).

The goal of the present study is to provide a more reliable mechanical optimization target to mitigate the stress shielding experienced by the prosthesis-bone system due to the mismatch in the compliance properties between the bone and implant materials. The stress jump at the prothesis- bone system interface progressively impairs the stress resistance of the implant, since the surrounding extant bone tends to decrease in thickness, adversely affecting implant longevity and effectiveness.

The applied methodology is driven by a set of data acquired through micro Computed Tomography images (μCT) over a serie of human hip bone samples. We performed a statistical analysis, extrapolating the probability density functions (PDF) of a set of fundamental geometrical features: beyond the sole volume fraction of the bone tissue, we get information on the trabecular thickness distribution, and on the anisotropy of the trabecular architecture as well. In particular, from the binary images of μCT dataset the volume fraction is estimated as the ratio between the dimension of the bone tissue islands and the overall sample; the trabecular thickness is estimated by a direct interpolation through the superposition of ellipsoidal domains over the tissue islands; while the anisotropy is evaluated by using the Mean Intercepts Length (MIL) method (3,4). The statistical behavior of the aforementioned geometrical features are integrated in a computational study getting a continuum equivalent of the resected bone before the implantation. Due to high computational costs associated with stochastic computational homogenization, it is shown that the highly complex bone material with random microstructure can be replaced by a simplified ergodic model. The numerical homogenization techniques used to describe composites with random structures are several: from the stochastic collocation method to polynomial chaos, up to Monte Carlo methods and Stochastic Finite Elements (SFEM). The latter ones are the most widely used for this kind of composites (5,6).

The homogenized continuum equivalent allows to compute the minimal stress jump achievable, with the accuracy level provided by the geometrical features accounted in the model, at the prothesis-bone system interface. The stress jump is computed performing FEM analysis over the implant for different load conditions. The future perspective of this work opens up to an inverse problem formulation where the continuum equivalent material would be the mechanical target of a density-based topological optimization study on a regular periodic graded lattice, such as TPMs.

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Evaluation of the feasibility of 3D-printed Ti-6Al-4V assembled bone plates

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Speaker: Revol Laura. **Thursday**. Start time: **10:40**. Room: Rhône 3B LVL1. Link to abstract.

1. Introduction

Patient specific guides and bone plates for the correction of antebrachial angular limb deformities significantly improve the accuracy of the surgery, reduce operating time and accelerate recovery(1)(2). These personalised solutions are mainly produced using additive manufacturing (AM) methods due to the freedom of geometric complexity. However, their high cost, due to significant design preparation and production expenses, limits their use in clinical practice(3).
To optimize the preparation process, we propose to combine these solutions with a newly modular system, usable both as surgical guide and for stabilisation during bone healing. This new system is made of two patient-specific plates and an additional assembly device (realised with two clips), which joins the plates and realigns bone fragments. However, compared to a monobloc plate, the assembly system reduces the bending properties4 and potentially alters the implant fatigue life, which is a critical factor, as the most common mode of implant failure is due to cyclic fatigue 5. Over a 3-month healing period on average, authors consider that a dog loads its implant between 100.000 and 250.000 cycles(5)(6).
The aim of this study was to evaluate the mechanical performance of this new modular system under both static and cyclic loading conditions, thereby providing insights into its potential applications in clinical settings. As the fatigue properties of AM bone plates are known to be lower than those of conventional method (CM) bone plates(7), the study will compare both manufacturing methods

2. Method

2.1 Modular system definition and fabrication

Modular systems were compared to reference monobloc plates (without assembly system). Both have identical dimensions (100x10x3.5 mm3), with the only distinction being the assembly mechanism in the modular plates. All reference plates and modular systems were produced with Ti-6Al-4V ELI using either CM or AM. CM parts were internally milled with a Haas OM2 machine (FEMTO-ST). AM parts were printed using selective laser melting (SLM) process on SLM®500 and had a post heat treatment (2h at 800∘C under Argon).

2.2 Mechanical testing

Mechanical testing consisted of quasi-static and cyclic fatigue four points bending tests using an electrodynamic machine (ElectroPuls E1000) and following the standard ASTM F382-17(8). The maximal deflection was recorded using an optic sensor (Opto NCDT). The maximal deflection was recorded using an optic sensor (Opto NCDT). The quasi-static tests were performed on 6 samples of each group at a rate of 0.1mm/s to 10mm of maximal deflection. The bending properties were computed following the ASTM F382-17. The cyclic tests were performed on 1 CM sample and 4 AM samples of each group at 25% of the maximal load before plastic domain (cycles: 30.5-305N at 5Hz). Each test was conducted to reach 1 million cycles: the number of cycles was recorded at failure if it occurs before the end of the fatigue test. Fretting wear and fracture were observed using x-ray tomography and numerical microscope.

3. Results and discussion

All AM reference plates failed before reaching 10mm of deflection, unlike of the CM reference plates. However, their mean static bending properties are close, with less than 5% of difference, which contrasts with findings from other studies regarding strengh(5)(7)(9):
- Stiffness: 342±4N/mm (CM) and 327±3N/mm (AM)
- Strength: 1215±13N (CM) and 1225±17N (AM)

Modular systems have a lower bending stiffness and strength in comparison with reference plates for both fabrications methods, which could be beneficial for the stress shielding effect (4). Their mean bending properties show some differences:

- Stiffness: 227±5N/mm (CM) and 204±2N/mm (AM)
- Strength: 991±154N (CM) and 1012±88N (AM)

The cyclic tests show better fatigue performance for CM than AM parts. All CM samples (reference plates and modular systems) have reached 1M (i.e. 1.000.000) cycles. The results for AM process differ:
- Reference plates: Two samples reached 1M and two samples fractured before 200.000 cycles
- Modular systems: One sample reached 400.000 cycles with fracture outside of the assembly system while three samples fractured around 800.000 cycles with breaks within the assembly system.

This suggests that, prior to assembly system, the inherent porosity and surface roughness of AM parts have the most significant impact on their cyclic life. Although AM cyclic tests revealed variability, modular systems using AM could survive 250.000 cycles without failure.

Therefore, the use of AM assembled bone plate seems feasible, especially considering that surface post-treatments that was done can significantly improve the cyclic life(7). Additional samples will undergo fatigue testing to perform a statistical analysis. Further biomechanical testing is required to confirm the suitability of this modular system for clinical use.

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Trabecular-Like Structure based on Triply Periodic Minimal Surfaces 3D-Printed by low-cost LCD-Printing via two-stage curing.

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Speaker: Claude Joris. **Thursday**. Start time: **11:00**. Room: Rhône 3B LVL1. Link to abstract.

Bone scaffolds based on Triply Periodic Minimal Surfaces (TPMS) represent a cutting-edge approach to creating structures with properties that significantly promote osteointegration. The use of TPMS geometry allows researchers to precisely manipulate parameters such as relative porosity, pore size, and pore shape, all of which influence the mechanical properties of the scaffold and the rate of bone healing. These scaffolds also have the benefits of an interconnected porous network, which is a critical feature for bone regeneration and for additive manufacturing. TPMS scaffolds also enable the generation and control of architectural gradients, including variations in relative density and TPMS geometry. This feature is a major asset for modeling both cortical and trabecular bone in the same scaffold. Cortical bone, with its high density and mechanical strength, contrasts with trabecular bone, which is more porous and flexible. Using data from CT-scans, cortical and trabecular regions can be identified based on mean Bone Mineral Density (BMD) and morphological parameters. This gradient design can effectively replicate the natural structure of bone, optimizing both mechanical stability and biological compatibility. Various 3D printing methods can be used to produce TPMS-based scaffolds, including Stereolithography (SLA), Fused Deposition Modeling (FDM) or Electron Beam Melting (EBM). However, these techniques are often expensive and limited in resolution, constraining the potential for designing really small pore sizes and geometries that can be obtained with TPMS structures. The emergence of consumer-grade Digital Light Processing (DLP) and Liquid Crystal Display (LCD) 3D printers offers a cost-effective alternative. These printers can achieve higher resolutions compared to FDM and EBM and similar resolution to SLA. However, post-curing the printed parts with UV light is a crucial step for ensuring complete polymerization but shows one major flaw. UV penetration depth is limited due to its short wavelength, leading to inhomogeneous polymerization within the scaffold and uncontrolled mechanical properties, especially in its inner regions. In order to address this limitation, a novel low-cost two-stage curing method has been developed. The initial stage of polymerization occurs during the 3D printing process, with the application of UV light. The photoinitiators present in the commercial resin, when irradiated with 405 nm light, generate free radicals which initiate the polymerization of each layer in accordance with the desired geometry. Following the printing process, the scaffold is cleaned in an isopropanol bath in order to remove any unpolymerized resin.The second stage consist of thermal polymerization. In this approach, thermal initiators, such as azobisisobutyronitrile (AIBN), are incorporated into the resin prior to printing. Using a 1% by mass concentration of AIBN, the scaffold is thermally treated at 80∘C for 24 hours. This process releases additional free radicals, which facilitate the completion of the polymerization process in a uniform manner across the structure.

A series of tests were conducted to evaluate the homogeneity of the polymerization and mechanical properties of the 3D-printed scaffolds. The test samples were 3D-printed encapsulated within TPMS cubes of varying relative densities in order to analyze the properties within the scaffold. The samples were subjected to three-point bending tests and nanoindentation experiments, while Fourier-transform infrared (FT-IR) spectroscopy was employed to evaluate the degree of polymerization along the depth of penetration within the structure. The results were compared between samples with and without the addition of AIBN and those subjected to conventional UV post-curing.

The findings demonstrate that the two-stage curing process achieves a homogeneous polymerization rate and consistent mechanical properties throughout the structure. This outcome is unattainable with traditional UV post-curing methods alone, which often result in non-uniform properties due to incomplete inner polymerization. The use of ceramic particle-loaded resins enables the further tailoring of the mechanical properties of the scaffolds. For instance, the incorporation of ceramic particles enables the scaffold's compressive Young's modulus to approach that of cortical bone. This adaptability ensures that the cortical regions of the scaffold, which exhibit higher density and stiffness, can provide the requisite

mechanical strength. Concurrently, the trabecular regions, which exhibit a lower density and greater porosity, retain the desired elasticity and permeability for cell infiltration and nutrient transport.
Bone scaffolds based on TPMS geometries represent a transformative step in biomaterials engineering. Their ability to precisely mimic the structural and mechanical characteristics of natural bone enhances their potential for osteointegration and effective bone regeneration. By integrating ceramic-loaded resins and gradient density designs, TPMS scaffolds can provide customized solutions that meet the diverse mechanical and biological demands of bone repair. The development of a cost-effective two-stage curing process using consumer-grade 3D printers marks a significant advance, addressing previous challenges associated with incomplete polymerization and high production costs.

Investigating the Bone-Implant Interface Using Quantitative Ultrasound: A Numerical Approach

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1 - CNRS (France), 2 - Univ Paris Est Creteil (France)

Speaker: Moisan Baptiste. **Thursday**. Start time: **11:20**. Room: Rhône 3B LVL1. Link to abstract.

Introduction

The success rate of endosseous implants depends on their long-term stability, which relies on the osseointegration process, *i.e.* the creation of a bone-implant interface (BII). Such stability is determined by the quantity and the biomechanical properties (structure, composition and material properties) of bone tissues located around the implant surface. The temporal and spatial evolution of these biomechanical properties are not fully understood yet, and there is a need to develop techniques to assess them. For instance, Quantitative Ultrasound (QUS) is a nondestructive method sensitive to the mechanical properties of bone tissue. Recently, the interactions of ultrasonic waves with the BII have been shown to reflect the Bone Implant Contact (BIC) ratio (1). Nonetheless, the QUS *ex vivo* measurements performed with standardized implants immersed in water emphasized the difficulty to locally analyze osseointegration phenomena, because of i) limitations in controlling the bone distribution at the BII and ii) the relatively poor lateral resolution of QUS methods (around 1 mm). This study therefore aims to numerically replicate the experiment performed in (1) in order to improve our understanding of the interactions of ultrasonic waves with the BII in a controlled environment.

Methods

Specimens

We used an already existing standardized coin-shaped titanium implant model intended for animal experimentation with a planar BII (1-2), adapted for studying ultrasonic reflection phenomena at the BII. A Teflon ring around the implant creates a few hundred micrometers thick bone chamber in order to isolate newly-formed bone. After 12 weeks of healing in rabbit cortical bone, 8 implants were extracted and imaged with neutron tomography, to map the 3D bone spatial distribution close to the implant (2). A reference BIC ratio was calculated from the first layer of bone in immediate contact with the titanium implant. The resulting 3D images are used as propagation domain in the numerical wave propagation model.

Elastic wave propagation model

The wave propagation model is decomposed into two coupled simulation domains. On the one hand, the wave propagation across the water path between the transducer and the implant is achieved using a semi-analytical model based on Green's functions. On the other hand, the wave propagation across the bone-implant system is carried out by solving the elastodynamics equations using an open-source finite-difference time-domain (FDTD) simulation software (3), by considering a 3D staggered grid where specific material properties are assigned to each voxel based on the neutron tomography maps. This coupled model is composed of three sequential steps described as follows:

- Semi-analytical emission and forward propagation of the focused pulse through the water domain, which delivers a pressure field.
- FDTD simulations: the pressure field from the previous step is used as input for the simulation of the interactions of the focused wave with the BII. After propagation of the elastic waves in the bone-implant system, an output pressure field is recorded.
- The backpropagation of the output pressure field from step 2 is calculated semi-analytically to reconstruct the acoustic response at the transducer location.

QUS maps

By spatially moving the transducer location in the plane parallel to the implant, we can reconstruct a 2D map of the maximum amplitude of the wave reflected at the BII for each of the 8 specimens. The post-processing of the map allows reducing the influence of the Teflon ring, thereby highlighting the bone

distribution at the BII.

Results
The observed local decrease of the amplitude received between a non-osseointregated implant (before surgical insertion), and an implant harvested after 12 weeks of healing time is strongly correlated with the local bone quantity at the BII from the neutron microtomographic data. Non-osseointegrated areas of the BII and high concentration of mineralized tissues can then be straightforwardly discriminated. The averaged amplitudes of the 2D maps consistently decrease with the reference BIC ratio of the samples, leading to a coefficient of determination R^2=0.71 ($p < 0.01$), in accordance with the experimental results reported in (1).

Conclusion
The proposed coupled wave propagation model presents several advantages to address such complex configuration: i) it prevents numerical dispersion that would otherwise hinder such simulations if using numerical tools only and ii) it drastically reduces the computational burden thanks to the two semi-analytical steps. The present numerical approach underlines the sensitivity of the QUS technique to both bone quantity and spatial distribution at the BII from 3D high-resolution data, thereby confirming previously observed experimental evidence. Future works will aim to provide further insights into the correlation of the resulting QUS maps with the experimental data, by applying advanced signal processing techniques, such as spectral analysis or colocalization methods, to the acoustic response of the BII.

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Exploring the mechanical complexity of the interface between gray and white matter in the brain

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Speaker: Khalaj Mina. **Thursday**. Start time: **14:15**. Room: Rhône 3B LVL1. Link to abstract.

Diffuse axonal injury is one of the most common causes of morbidity after traumatic brain injury (TBI). Due to its significant differences in composition and mechanical properties, it is often localized at the junction between gray and white matter in the brain. White matter is generally stiffer and more viscous than gray matter and responds less quickly to mechanical strains, making the interface particularly vulnerable to shear forces and inhomogeneous deformation under dynamic loading conditions (1, 2). Computational models predict the highest acceleration and shear forces at this interface, highlighting its critical role in injury mechanisms (3). Microstructural studies also show that alterations in the transition zone correlate with post-concussive symptoms and adverse long-term outcomes, highlighting their potential as biomarkers for mild TBI (4). Despite its importance, the biomechanical properties of this interface are still poorly understood.
To address this gap, we conducted an extensive experimental investigation of gray matter, white matter, and the transition zone. Using cubic tissue samples subjected to different shear loading protocols, we assessed and compared the nonlinearity, hysteresis, and peak stress responses of the regions. Shear loading to failure also allowed us to evaluate the rupture strength and failure characteristics. Using digital image correlation, local strain distributions were visualized and fracture points were precisely identified. Our investigation provides new insights into how this interface behaves under dynamic loading conditions, a crucial aspect for the development and calibration of brain tissue TBI models.

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Identifying constitutive parameters for the axon and matrix: A Finite Element and Neural Network Approach

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Speaker: Majdolhosseini Maryam. **Thursday**. Start time: **14:35**. Room: Rhône 3B LVL1. Link to abstract.

Diffuse axonal injury is a common brain trauma affecting the axons in the white matter. The micro-mechanical environment endured by the axon is directly relevant to the surrounding matrix. Finite element (FE) models are used to study axonal behaviour under injury conditions at cellular and tissue levels. While most FE models focus on isolated axons, many models study axons embedded in the tissue. However, these models use material properties for the matrix derived from small-strain experiments or neglect the viscoelastic properties of the matrix, limiting the model's applicability at the high-strain regime that is more relevant to injury. This study investigates the mechanical behaviour of axons and their surrounding brain matrix under high strains (up to 30%) and high strain rates (up to 30/s). Axonal properties were derived from experimental data on the stretching of isolated axons, and the matrix properties were estimated indirectly from experimental data on the brain tissue under multiple loading modes (i.e., tension, compression and shear) using inverse parameter identification that combined FE and neural network approach. First, around 350 FE simulations were run, changing the matrix material properties. The properties were selected randomly in a chosen window using Latin hypercube sampling. Based on the FE simulation results, a neural network (NN) model was trained to predict the effect of matrix properties on brain tissue behaviour, namely, stress-strain curves. Then, optimization methods were used to predict the best matrix properties that match experimental observations. The final model was validated using FE simulations, confirming the reliability of the identified matrix properties. The calculated shear modulus of the axon is approximately 10 kPa, with relaxation modulus ranging from 6.5 to 10 kPa. The optimum shear modulus of the matrix was estimated to be 0.85 kPa, with relaxation moduli below 1 kPa. The FE validation simulations aligned well with the experimental data, with a mean absolute error of 53.7 Pa, demonstrating the model's effectiveness. This approach provides a reliable framework for characterizing composite materials with missing properties. Moreover, the material properties derived in this study can be used in future simulations and models of axonal injury.

Biomechanical and biological characterization of brain tissue-inspired hydrogels: Focus on porous material properties for tissue engineering applications

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Speaker: Kainz Manuel P.. **Thursday**. Start time: **14:55**. Room: Rhône 3B LVL1. Link to abstract.

Soft biomaterials intended for implants or soft tissue engineering must meet a number of properties to ensure compatibility with host tissues. The mechanical match between biomaterial and host tissue is crucial to avoid adverse reactions and prevent rejection of the material or device, especially in ultrasoft tissues such as the human brain (1). In addition to stiffness, the most important properties include microstructure-dependent permeability and porosity, which are crucial for effective integration. In addition, biocompatibility needs to be thoroughly assessed, either with animal models for implants or with relevant cell types for tissue engineering purposes.
This work presents a series of hydrogels that mimic brain tissue (2), produced through sterile processes, focusing on their microstructural, mechanical and biocompatibility properties. Two new experimental approaches have been developed to specifically study the behavior of porous materials, targeting the effective porosity and fluid permeability that are fundamental to fluid and nutrient exchange in soft tissue engineering applications. Mechanical characterization was conducted using a combination of cyclic compression-tension experiments and consolidation, while biointegration was assessed by pull-off tests after five days of incubation in a chick *'ex ovo'* chorioallantoic membrane (CAM) model.

Histological analysis of cryosectioned samples revealed notable interactions at the hydrogel-membrane interface, including ectoderm alterations and cell infiltration into the hydrogels. Softer hydrogels, characterized by less dense polymer networks, promoted enhanced biointegration, which was strongly correlated with their lower stiffness and higher porosity. The biocompatibility of the materials was also confirmed by cytotoxicity assays and by culture of multiple cell types representative of soft tissue.

Our findings suggest that hydrogels with tailored mechanical and porous properties are promising candidates for implant substrates, coatings, and tissue engineering scaffolds (3). The strong correlation between material stiffness, porosity and biointegrability underscores the importance of designing biomaterials that correspond as closely as possible to the physiological conditions of the target tissue.

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Methodology for Comparing Viscoelastic and Poroelastic Properties of GelMA Hydrogels at the Cellular Scale

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Speaker: Tosini Marta. **Thursday**. Start time: **15:15**. Room: Rhône 3B LVL1. Link to abstract.

Introduction

Cell behavior is significantly dependent on the mechanical properties of the microenvironment, which can regulate mechanotransduction pathways essential for adhesion, migration, differentiation, and tissue development in general(1). Some pathways are also involved in pathophysiological processes, highlighting the importance of controlling mechanical properties when developing materials aimed at mimicking extracellular matrices of healthy or diseased tissues.

While research has primarily focused on the elastic properties of tissues, it is increasingly recognized that soft biological materials exhibit significant time-dependent mechanical behaviors (2), categorized as either poroelastic (i.e. fluid flow through a porous matrix driven by pore size and physical stimuli) or viscoelastic (i.e., combined effects of elastic and viscous properties, which dictate both immediate and time-dependent responses).Variations in viscoelastic properties often correlate with disease progression, while poroelastic effects stem from water content in biological tissues (3). The overall mechanical response in biological tissues is determined by micro-scale interactions involving the cytoskeleton and extracellular matrix (ECM) biopolymers, influenced by their molecular compositions, microstructures, and hydration levels. The viscoelastic model captures the mechanical behavior arising from intrinsic material properties like polymer relaxation and deformation. The poroelastic model integrated the behavior of the solid matrix and fluid flow within porous materials, offering insights into tissue hydration and permeability, linked to porosity, hence the material microstructure(4). Additionally, the poroelastic model leads to the direct extraction of material parameters that function as physical constants linked to the material's microstructure, while traditional high order linear viscoelastic analysis, which usually relies on empirical fitting parameters that could be more challenging to interpret(5).

Therefore, accurately characterizing the time-dependent behaviors of materials at the cellular scale is essential for supporting the investigation of the mechanotransduction pathways and related cellular responses. In literature, various materials and substrates have been developed to study and influence cell behavior through tailored mechanical properties. Hydrogels, made of cross-linked polymer networks that absorb and retain water, have emerged as promising materials for replicating cellular microenvironments, due to their high versatility in controlling their mechanical properties such as stiffness(6). Despite these advancements, the complete investigation of hydrogels' time-dependent properties requires further exploration, underscoring the need for robust characterization methodologies. Among the various techniques used to evaluate elastic and time-dependent properties, nanoindentation stands out as a powerful tool for its capability to assess localized mechanical properties, which are particularly relevant for soft tissues such as biological tissues or biomaterials(7).However, standardized nanoindentation protocols and data analysis methods are missing.

This study introduces a novel methodological approach for quantitatively analyzing and comparing the time-dependent load relaxation responses of hydrogels at the cell-length scale using nanoindentation. The ultimate goal was to aid in identifying specific hydrogel compositions that can replicate the properties of defined biological tissues, such as healthy and pathological pulmonary or epithelial tissues. In detail, stress-relaxation nanoindentation tests were conducted on different compositions of gelatin-methacryloyl (GelMA) hydrogels, characterized by different concentrations (7.5%, 10%, 12.5%) and methacrylation degrees (classified as Medium, High, Very High). The proposed methodological approach effectively identified key parameters essential for understanding the mechanical behavior of each sample, enabling meaningful quantitative comparisons of their viscoelastic and poroelastic properties.

Materials and methods

Sample preparation

To validate the method proposed for characterizing the viscoelastic properties, nine different compositions of GelMA hydrogels were tested. GelMA was synthesized following the protocol reported by Van Der Bulcke et al.(8), adopted in previous studies. In detail, gelatin (10 g) was dissolved in 100 mL of warm Dulbecco's phosphate buffer saline (DPBS), then methacrylic anhydride (MA, Sigma) was slowly added in different amounts (4 ml, 8 ml, and 20 ml) to achieve the desired methacrylation degree. The mixture was diluted and dialyzed to remove unreacted components and stored at -80∘C before lyophilization. Prior to testing, GelMA was dissolved at different weight/volume concentrations (7.5%, 10%, 12.5%) in complete culture medium, pre-mixed with a photoinitiator (Lithium phenyl-2,4,6-trimethylbenzoylphosphinate) at a concentration of 2.5 mg/mL. The solution was injected into a PDMS mold and exposed to a fibre lamp at 405 nm for 5 min for the photo crosslinking reaction. Samples were stored in an incubator at 37∘C and analyzed the day after preparation.

Experimental procedure

Nanoindentation tests were conducted using the Piuma nanoindenter (Optics 11 Life). Depending on the selection of the cantilever stiffness (kc) and the tip radius (R), it is possible to test samples with different mechanical properties. Spherical probes with nominal radius R = 25 μm and cantilever stiffness kc = 0.5 N/m were used. The indentation tests were performed under indentation control (I-mode) with a prescribed indentation depth δ = 2000 nm to record the load (P) decay over time. Ideally, such depth should be reached impulsively (δ (t = 0) $\not\equiv$ δmax ; P(t = 0) $\not\equiv$ Pmax), but due to practical limitations of the experiment, a finite ramp time of 1 s was used. Then, the probe was kept at the same δ for 6 s to record the relaxation response of the material. In fact, stress relaxation tests consist of three phases: (i) the loading phase, during which the probe touches the sample and the set δ is reached; (ii) the holding phase, lasting for us 6 s; and the (iii) unloading phase, when the probe is retracted from the sample. Three batches were tested for each sample type, with 30 to 50 indentations performed per batch, resulting in approximately 120 indentations per sample. All tests were conducted in wet conditions (PBS) at 37∘C to mimic the physiological environmental conditions.

Theoretical remarks

To obtain the mechanical properties from the nanoindentation data, the Hertz model (9) was selected for the analysis. The model was applied to the initial loading phase of the nanoindentation curve, within the elastic limit. It defines the relationship between load (P) and indentation depth (δ) using effective modulus (Eeff), which depends on material properties such as Poisson's ratio and Young's modulus.

For the viscoelastic characterization, the generalized Maxwell model was selected(2,10,11). It consists of a spring connected in parallel to a number n of units, each consisting of a spring in series with a dashpot. Mathematically, this model is described by Prony exponential series, and it describes load relaxation over time. Parameters derived from fitting the Prony series, such as relaxation times (τ_k) and load decay (p_k), enable calculation of shear modulus (G). The shear modulus at maximum load (G_0) and equilibrium ($G\infty$) can be derived and the entity of their difference is an indication of the viscoelastic nature of the analyzed samples.

Hu et al.'s model(12) was selected for the poroelastic properties analysis. The final equation used to fitting the data that represents the load decay presents two parameters to optimize and derive: the drained poisson ratio νd and the time constant tPE. These values enable the determination of poroelastic properties like the diffusivity coefficient D and the intrinsic permability k. The diffusivity coefficient D is evaluated as: D = $a2$/tPE where a is the maximum contact radius, linked to the set indentation depth δ and the scale of the experiment itself. In fact, the intrinsic permeability k depends on D, and it was obtained as follows: k = Dμ(1-2vd)/2G0(1-vd) where μ is the solvent viscosity set equal to 10-3 Pa·s. G0 was calculated from the Hertz model using the maximum load P0.

Data analysis

For the fitting procedure, a genetic algorithm (GA) (13) optimization was implemented using Matlab software R2023a. The key equation was normalized with respect to the maximum load (Pmax) to simplify calculations, introducing four parameters for optimization: two material parameters (p1, p2) and two time constants (τ1, τ2) for each indentation curve. The process began with an initial population of random and heuristic parameter sets to minimize the risk of local minima and confined the search to physically meaningful ranges determined by preliminary simulations.

Each experimental curve was used as input for the GA, generating 15 solutions per curve. The mean of these solutions provided a representative set of parameters for each curve, then the global parameters for each sample were calculated as an average of all the indentation curves parameters obtained per sample. This approach ensured robust fitting of the viscoelastic and poroelastic models to the nanoindentation data while accounting for variability. The performance of the proposed models was evaluated using the coefficient of determination (R^2), where only solutions with $R^2 > 95\%$ were considered acceptable. Here, R2 = 1–SSres/SStot, with SSres and SStot representing the residual and total variance, respectively. Statistical analysis of nanoindentation data was conducted using non-parametric Kruskal-Wallis test on software Prism. Differences were considered significant for $p < 0.05$.

Results and discussion
Elastic modulus
The global elastic properties (Eeff) obtained by applying the Hertz model assuring an R2 > 95% in the fitting procedure are listed below as mean values with standard deviation (kPa):

GelMA 7.5%:

- **M:** 0.9 ± 0.4
- **H:** 2.0 ± 1.1
- **VH:** 3.2 ± 1.6

GelMA 10%:

- **M:** 4.7 ± 1.1
- **H:** 5.3 ± 1.5
- **VH:** 7.1 ± 3.0

GelMA 12.5%:

- **M:** 12.1 ± 9.0
- **H:** 28.9 ± 11.0
- **VH:** 48.0 ± 9.4

The analyzed indentation curves used to derive these values were approximately 115 per sample. For the three concentrations of GelMA analyzed (7.5%, 10%, 12.5%), as the degree of methacrylation increased, the Eeff value also tended to increase. Moreover, Eeff values increased when the GelMA concentration raised: the highest Eeff average value was found for GelMA VH 12.5%, while the lowest Eeff average value was related to GelMA M 7.5%. The characterization of GelMA at various concentrations and degrees of methacrylation has demonstrated the suitability of GelMA to be tuned for obtaining Young's moduli between 0.5 kPa and 57 kPa, approximately. Therefore, a specific composition of GelMa can be used to mimic different biological tissues. For instance, healthy lung tissue typically exhibits an elastic modulus of 0.5-3 kPa while pathological lung tissue presents a modulus of 10-20 kPa(14,15). Both conditions could be represented by specific GelMA compositions analyzed in this study. The ability to tailor the mechanical characteristics of GelMA and measure them in a reliable way enables the selection of a GelMA composition that is most suitable for replicating the mechanical properties of the desired tissue type.

Time dependent behavior
Viscoelastic model
Nanoindentation tests assessed stress-relaxation behavior in nine different compositions of GelMAa hydrogels using a n =2 term Prony series. Experimental data closely matched the fitted curves (R2 > 95%) obtained through the previously described model, highlighting its reliability. The derived parameters were two material parameters (p1, p2) and two time parameters (t1, t2) for each indentation curve. The fitting parameters obtained from the indentations performed in the three batches were then averaged to obtain the global parameters for each sample type, which describe the trend of their relaxation behavior. A comparison of the time parameters associated with the two exponential terms of the Prony series reveals that t1, the time parameter associated with the first term of the series, is an order of magnitude smaller than t2, the time parameter of the second term. This indicates that the first term decays more rapidly

than the second one. Thus, the series is represented by two terms that have distinct meanings, as the first approximates the behavior of instantaneous relaxation, while the second captures the material's long-term response.
A quantitative comparison of sample behaviors involved analyzing the instantaneous and equilibrium shear moduli (G0 and G∞). The results are provided below showing the average value for each sample in kPa. The number of curves analyzed is variable for each sample type, ranging from 30 to 100 indentation curves.

GelMA 7.5%

- **M**: G0 = 0.3 ± 0.1 | G∞ = 0.2 ± 0.1
- **H**: G0 = 0.6 ± 0.2 | G∞ = 0.5 ± 0.1
- **VH**: G0 = 0.8 ± 0.3 | G∞ = 0.7 ± 0.2

GelMA 10%

- **M**: G0 = 1.4 ± 0.3 | G∞ = 1.3 ± 0.3
- **H**: G0 = 1.6 ± 0.4 | G∞ = 1.4 ± 0.4
- **VH**: G0 = 2.3 ± 1.0 | G∞ = 2.0 ± 1.0

GelMA 12.5%

- **M**: G0 = 3.0 ± 2.5 | G∞ = 2.7 ± 2.4
- **H**: G0 = 7.6 ± 4.0 | G∞ = 6.7 ± 3.6
- **VH**: G0 = 16.0 ± 2.8 | G∞ = 14.1 ± 2.6

sing degree of methacrylation (M,H,VH) but also with the increasing concentration (7.5%, 10%, 12.5%) of GelMA analyzed, spanning values ranging from approximately 0.20 kPa to 19 kPa. Furthermore, G∞ is always lower than G0, indicating that all samples are characterized by a more or less pronounced relaxation, which indicates their degree of viscoelasticity. In fact, the percentage decrease between G0 and G∞ ranges from 7 to 13 % depending on the sample.

Poroelastic model
The poroelastic properties characterization allows to evaluate the drained passion ratio vd, the time parameter tpe, the effective diffusivity constant D and the intrinsic permeability k for each sample.
The drained poisson ratio is a parameter that varies between 0 and 0.5.The obtained values are very similar to each other, ranging from 0.35 to 0.43. The constant tPE obtained was in the order of a few seconds for all analyzed samples, a decrease is observed with increasing concentration. The effective diffusivity constant D was found to be in the order of 10-11 m2/s for all samples, a decreasing trend with increasing methacrylation degree can be observed. The mean of the global values of the intrinsic permeability k (obtained by averaging the results of the three performed batches), expressed in m2, for each degree of methacrylation at various concentrations are reported below:

GelMA 7.5%

- **M**: $4.1 \pm 3.6 \times 10^{-17}$
- **H**: $1.6 \pm 1.9 \times 10^{-17}$
- **VH**: $1.2 \pm 0.8 \times 10^{-17}$

GelMA 10%

- **M**: $3.0 \pm 0.9 \times 10^{-18}$
- **H**: $4.4 \pm 4.4 \times 10^{-18}$
- **VH**: $3.2 \pm 3.5 \times 10^{-18}$

GelMA 12.5%

- **M**: $3.4 \pm 2.7 \times 10^{-18}$
- **H**: $1.3 \pm 1.2 \times 10^{-18}$
- **VH**: $4.8 \pm 3.0 \times 10^{-19}$

The results show that intrinsic permeability tends to decrease with increasing degree of methacrylation. Also, k tends to decrease with increasing GelMA concentration for each degree of methacrylation, confirming that higher values are associated with softer samples while lower values are associated with stiffer samples. In fact, this aligns with the previous observation that both Young's modulus and shear modulus tend to increase as GelMA concentration rises. The exception occurs with the M 10% and M 12.5% concentrations, that seem to exhibit a slightly higher k value, although still very close to each other. In the case of VH samples, there is a notable difference among the three concentrations of more than an order of magnitude.
Intrinsic permeability is closely tied to pore size ($\xi \propto \sqrt{k}$) but does not indicate the number of pores, which explains why νd (drained Poisson's ratio) does not always correlate consistently with k. In poroelastic models, *vd* reflects the degree of relaxation, where greater relaxation suggests increased fluid migration. Higher intrinsic permeability is associated with larger pores, enabling more fluid movement. However, when stiffer samples show more relaxation and lower *vd* compared to softer ones, this likely reflects a higher density of smaller pores.
Our results lie in agreement with Miri AK et al.(16), investigating how hydraulic permeability in GelMA hydrogels varies with concentration, methacrylation degree, and UV exposure. Their intrinsic permeability values, related to the hydraulic permeability, range from 10-17 m2 to 10-15 m2. The magnitude difference lies in the scale difference used for the probe radius in the two studies: the first is 10-3 m while in our case 10-5 m. Similarly, Strange et al. (17) reported 10-17 m2 to 10-15 m2 using larger probes.

Conclusions
Understanding the time-dependent mechanical behavior of materials that replicate native tissues is vital in mechanobiology and tissue engineering. This study presents a novel methodological approach, based on nanoindentation tests, to extract mechanical parameters that define elastic, viscoelastic, and poroelastic properties of soft hydrogels and potentially soft biological tissues.
For overcoming the lack of standardized testing protocols for soft materials, here we developed and used a new protocol that enabled a consistent mechanical analysis of GelMA samples. Elastic, viscoelastic, and poroelastic properties were determined through various models. The Hertz model revealed a wide elastic modulus range (0.5–57 kPa), demonstrating GelMA's suitability for mimicking the ECM properties of the investigated tissues.Using a viscoelastic model, the stress–relaxation curves indicated that for all the samples, a holding period of 6 s was sufficient for reaching a complete relaxation of the stresses stored during the instantaneous loading phase at the cell-length scale. The relaxation moduli (G0 and G∞) were calculated in a consistent way, offering insights into sample relaxation behavior. Poroelastic analysis provided additional information, revealing that the intrinsic permeability k was higher in softer GelMA samples, ranging from $4.82 \cdot$ 10-19 to $4.06 \cdot$ 10-17 m2.
In conclusion, nanoindentation proved to be a powerful tool for characterizing the mechanical properties of the samples, offering significant potential for advancements tissue engineering and regenerative medicine. By linking material properties to biological responses, this approach facilitates the design of scaffolds that closely replicate the mechanical and structural attributes of native tissues. Moreover, it emphasizes the importance of enhancing reproducibility and reliability in mechanical assessments, fostering progress in both tissue engineering and the study of pathological processes.

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Exploration of neo-formed tissue using combining reactive poromechanics with computational cellular biology

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Speaker: Swider Pascal. **Thursday**. Start time: **15:35**. Room: Rhône 3B LVL1. Link to abstract.

1 - Objectives

Mechanobiology is focusing on how physical stimuli contribute to cell mechanotransduction, i.e the biochemical cell response due to a mechanical signal. Indeed, cell-cell and cell-matrix interactions might play a significant role into space and time evolution of extracellular matrix and beyond, to tissue and organ homeostasis or pathology. The same is true for understanding how biomaterials or cell seeded scaffolds work, whether they are designed for laboratory purposes or for in-vivo implantations. The interstitial flow can be considered as a stimulus for cells. However, advective properties of porous material are of particular interest when exploring in-situ response and interactions with host zone in biological environment. Cells population shows active migrations influenced by gradient growth-factors and capabilities to differentiate and produce extra-cellular matrix in presence of mechanical stimuli. Growth factors show diffusive properties in interstitial flow and matrix. These events are also conditioned by source terms such as vascularization bringing cells and nutrients among with growth factors. One of the key challenges is to predict extracellular matrix formation at the pore scale and beyond, as well as its evolution in space and time under biochemical and mechanical stimuli.

We hypothesized that the framework combining computational cell biology and reactive poromechanics to address this challenge. We have also provided a unique in vivo validation using a canine experimental model10 of implant healing. Among biophysical and clinical relevant output, the proposed methodology explained healing heterogeneity and stress-shielding frequently encountered and problematic in clinical arthroplasty.

2 - Materials and Methods

Poroelasticity define an effective medium formed of phases, namely the porous and deformable extra cellular matrix and the fluid fraction also representing the medium porosity. Continuity equations for darcean flow, i.e low filtration velocities, involved effective permeability associated with substrate porosity. Balance momentum due to loadings established combination of effective stress and fluid. Governing equations involved Lamé coefficients, namely elasticity properties and fluid pressure gradients.

Cell populations were governed by advection-diffusion-reaction equations involving random motility, and active migrations, namely chemotactic migrations due to growth factors gradients influenced by fluid convection, and haptotactic migration due to evolution of local surface properties of extra-cellular matrix. Because of proliferation and extracellular matrix fabrication poromechanical response and cell populations responses were combined in space and time.

3 - Results

Governing equations were applied to the prediction of periprosthetic implant healing. Transport properties, namely diffusion coefficients, porosity and permeability as far as elastic properties of neo-formed tissue were explored as far as responses of osteoblastic phase and endothelial phase describing the neovascularization of the site. The role of transforming angiogenic factors and anabolic growth factors were considered. Theoretical and numerical results were compared to experimental studies in an animal model using segmented histological results.

4 - Conclusion

The combination of convective, diffusive and reactive effects nourished a wave front migration of extracellular matrix from the host bone to the implant but also from the implant to the host bone because of bioactive coating. The initial conditions were playing a major role and the model predicted a signifi-

cant influence of cyclic implant motion on tissue formation. Concentrations of mineralized tissue at the implant at the implant surface and drill-hole similar to stress-shielding in the host bone were very well predicted by the model. Indeed, cell active migrations associated with mechanical strain are underlying crucial mechanisms playing reverse role in tissue formation.

A hitchhiker's guide to size effects in metamaterial implants.

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Speaker: Veluvali Meghashyam. **Friday**. Start time: **10:00**. Room: Rhône 3B LVL1. Link to abstract.

Metamaterial implants – rationally designed cellular bone-reconstruction devices – have recently emerged as promising alternatives to common clinical solid implants (1,2). While researchers can nowadays design personalized implants replicating patient's morphology (3), these bulky metal structures suffer from mechanical failure occurring mainly due to stress shielding - a mismatch in the mechanical properties of an implant and adjacent bones that leads to a loss in bone density followed by loosening of the implant. In contrast, the mechanical properties of metamaterial implants can be tuned to bone-like behavior that promises to minimize implant failure (4). For this, the solid parts of a metal implant are replaced with a porous microstructure optimally distributed for applied muscular-driven loads (1).
The dimensions of a metamaterial implant can however be very limited, to ensure the implant's fit that leads to size effects – the dependence of the mechanical properties of a metamaterial on the number of constitutive building blocks (unit cells) under different types of loading. It occurs if the characteristic lengths of an implant and unit cells are comparable and results in the failure of classical approximation techniques, e.g. first-order homogenization, to provide adequate approximations for the mechanical behavior (5).
In this study, we propose a procedure to estimate and model size effects through full-scale and effective medium FE simulations. We exemplified our findings by analyzing auxetic, beam-type, and surface-type unit cells under all relevant loading conditions and identified that size effects occur in every structure containing less than 5 unit cells. These findings were confirmed in full-scale experimental tests on additively manufactured polymer prototypes. To properly capture the size effects within an effective continuum, we applied a higher-grade continuum theory which allowed us to develop a toolkit for efficiently modeling and optimizing different types of metamaterial implants. The outcomes of our study are especially relevant for implants with intrinsically limited dimensions, including mandibular, cranial, and pelvis implants (3, 6).

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Rate-dependent Deformation and Fracture of a Thermoplastic Elastomer Tissue Surrogate

Chen Yao (1), Ding Jow (1)

1 - Washington State University (United States)

Speaker: Ding Jow. **Friday**. Start time: **10:20**. Room: Rhône 3B LVL1. Link to abstract.

Characterizing and modeling the mechanical behavior of tissue-like materials are essential for various biomedical applications. In addition to deformation-related properties such as strength and ductility, fracture toughness is a critical material property as it reflects a tissue's ability to resist defects and fractures. Experimental techniques commonly used to measure the fracture toughness of soft materials include the trouser tear test, the pure shear test, and similar methods. Fracture toughness, or the critical energy release rate, is typically calculated using rate-independent nonlinear elasticity analyses.
For the trouser test, the critical energy release rate is given by:

J = 2(L)(F)/(B) - 2W(strain)(H), (1)

where L is the stretch ratio, F is the critical force at the initiation of the crack growth, W is a hyperelastic strain energy function of strain, B and H represent the sample width and height, respectively. In practice, the strain energy stored in the branched sections of the sample, where tensile force is applied, is often ignored, yielding a simplified expression:

J = 2(F)/(B). (2)

For the pure shear test, J is given by

J=2W(strain)(H). (3)

Although these equations are grounded in rate-independent strain energy functions, they are often applied to materials exhibiting rate-dependent fracture behavior, where fracture toughness varies with crack velocity or loading rate. This rate dependence arises from the rate-sensitive critical values of F, L, or strain at the initiation of crack growth, which serve as inputs to evaluate the rate-independent strain energy functions. However, for rate-dependent materials, the strain energy function is expected to depend not only on strain but also on strain rate. This raises important questions about the role of rate-dependent strain energy functions in fracture toughness measurements, motivating the present study.

A recent investigation (1) explored the deformation behavior of a synthetic SEBS gel (styrene-ethylene-butylene-styrene), a widely used tissue surrogate, under uniaxial compression across a broad range of strain rates. The material exhibited highly nonlinear and rate-dependent mechanical behavior. Based on these observations, a visco-hyperelastic model was developed, extending Ogden's hyperelastic framework to incorporate rate sensitivity. This model, using a rate-dependent strain energy function, W(strain, strain rate), effectively captured the material's essential characteristics.

Building on this model, the current study investigates the influence of rate-dependent strain energy functions on fracture toughness measurements. Both trouser tear and pure shear tests were performed to assess the impact of rate dependence across test configurations and to cross-validate results. The same SEBS gel from (1) was tested at strain rates ranging from 0.001/s to 0.1/s. Complementary tensile tests were conducted to validate the model's predictions for tension loading. Within this strain rate range, the material exhibited increased strength and toughness with increased strain rate.

Fracture test results were analyzed using both rate-independent and rate-dependent strain energy functions. For the pure shear configuration, rate-independent analysis, Equation (3), underestimated fracture toughness, while for the trouser tear configuration, Equation (1) overestimated toughness. Notably, the simplified analysis based solely on the critical force, Equation (2), reasonably approximated the rate-dependent analysis within the studied strain rate range. Incorporating rate-dependent strain energy functions proved essential for achieving consistent fracture toughness measurements across different test

configurations.

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An in vitro Blood Loop to Assess Catheter Thrombogenicity at High Shear Rates

Raphaelle Dodart (1), Ku David N. (1)

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Speaker: Raphaelle Dodart or Ku David N.. **Friday**. Start time: **10:40**. Room: Rhône 3B LVL1. Link to abstract.

The development of reliable *in vitro* test methods for evaluating thrombogenicity is important for the development of blood-contacting devices. For arterial catheters, blood flow will be high around the device, likely leading to high shear rates. Existing tests primarily assess thrombogenicity of materials at low shear rates, either in static conditions or low flow loops. However, thrombus formation on some materials may form by Shear-Induced Platelet Aggregation (SIPA) within minutes under high shear rates. In this study, we developed and validated a blood loop circuit for thrombogenicity testing under high shear conditions using fresh, whole human blood. The *in vitro* thrombogenicity results were compared to an FDA approved protocol for *in vivo* testing of arterial catheters for thrombogenicity using a swine model as a blinded study. Thrombogenicity was visually assessed using a modified Non-Anticoagulated Venous Implant/ Anticoagulated Venous Implant (NAVI/AVI) scoring scheme of the catheters, tubing and arteries. The amount of thrombus formation developed on the catheters or within the tubing after one hour by the *in vitro* circuit was the same as in the *in vivo* arteries in swine. Consistency between these results substantiates the suitability of employing an *in vitro* blood loop circuit for thrombogenicity of arterial catheters subject to high shear that is comparable to costly, terminal porcine studies.

Piezoelectric Composite Sensors for Artificial Arteries: Toward Realistic Simulation of Vascular Mechanics

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Speaker: Missaoui Tasnim or Morelle Xavier. **Friday**. Start time: **11:00**. Room: Rhône 3B LVL1. Link to abstract.

Flexible sensors have gained significant interest in the biomedical field due to their potential for application in medical diagnostics, human health monitoring, and artificial organ systems (1, 2). Their unique ability to adapt to complex geometries and respond to dynamic mechanical stimuli offers a critical tool for accurately monitoring and replicating physiological conditions. This feature is crucial in medical simulation and therapeutic devices, where precise detection of mechanical deformations contributes significantly in understanding organ function and optimizing medical device performances.
In this context, this study aims to develop piezoelectric flexible sensors made of silicone matrix (polydimethylsiloxane, PDMS) filled with ceramic particles (Barium Titanate, BaTiO3). The obtained piezoelectric composites are engineered to be integrated into an experimental vascular network model, allowing advanced monitoring of mechanical deformations in artificial arteries designed with unfilled silicone matrix (3). Combining the inherent flexibility of silicone with the piezoelectric response of ceramic fillers, these sensors are expected to enhance the detection of mechanical deformations within artificial arteries as well as the additional stress applied by the deployment of a medical device, such as vascular stents.

To achieve an optimized piezoelectric sensitivity and still be able to maintain a mechanical behavior comparable to that of human arteries, several processing parameters were investigated. These include the ceramic filler content, the configuration of particles (random or oriented), and the curing conditions (temperature and duration) (4). This investigation revealed that processing parameters significantly influence the composite's mechanical properties, with the incorporation of $BaTiO_3$ notably enhancing the piezoelectric performance yet substantially altering the material's mechanical response. For the unfilled silicone matrix, modifying the curing temperature and duration enabled tailoring its mechanical behavior to mimic the trend of non linear elasticity of human arteries, characterized by a transition from a supersoft behavior at low strain to a superstiff behavior at higher strain. These findings underscore the crucial role of filler content, particle orientation and curing conditions in modulating the overall performance of the composite and in achieving application-specific properties.

Furthermore, ongoing cyclic tensile tests are being conducted to assess the durability and reliability of the sensor under repeated deformation cycles, simulating physiological conditions. These tests will provide crucial data for optimizing the integration of sensors within the vascular simulator, ensuring their long-term performance.

In regard to the incorporation of the sensor within the simulator, tests are being first carried out on flat silicone substrates to evaluate sensor performance and adhesion. The piezoelectric and mechanical responses under cyclic deformation of the sensor-substrate assembly are also being investigated. After these preliminary tests, the sensors will be adapted for integration onto a tubular model that more closely replicates the geometry of a human artery. This progression is crucial for developing a realistic vascular simulator capable of accurately mimicking physiological conditions.

These findings provide valuable insights into the fundamental mechanisms that govern the mechanical and piezoelectric behavior of silicone/ceramic composites, offering a pathway to tailoring their properties to mimic closely the mechanical characteristics of arterial tissues. This approach aims to upgrade the vascular simulator, improving the testing and validation of medical devices in a controlled environment.

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TOPIC: Continuum Mechanics

MS3.1 - Homogenisation and Continuum Strategies for Multiphase Materials

Organisers: Carole Nadot-Martin (P', ISAE ENSMA), Pedro Ponte Castaneda (University of Pennsylvania), Martin Idiart (Universidad Nacional de La Plata) and Issam Doghri (UC Louvain)

Internal variables and statistics of the viscous strain field in linear viscoelastic particulate composites

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Speaker: Masson Renaud. Keynote. **Tuesday**. Start time: **16:35**. Room: Rhône 1 LVL1. Link to abstract.

Here we consider a composite material made of an inclusion phase dispersed in a matrix. For moderate fractions of the volume fraction of inclusions and non-ageing linear viscoelastic behaviour of the phases, the correspondence principle associated with the Hashin-Shtrikman model are used to estimate the Laplace transforms of the effective creep and relaxation functions of the composite as well as the phase averages of the stress field. In the isotropic case and if the relaxation functions of the phases display a discrete spectrum (Maxwell model here), exact expressions of the macroscopic behaviour (macroscopic free and effective energies) as well as the time evolutions of the averages and fluctuations per phase of the stress field have been established from a finite number of macroscopic internal variables (see (1)).
To elucidate the general link between these macroscopic internal variables and the microscopic field of internal variables (viscous strain), the correspondence principle is used to express the Laplace transform of the viscous strain field as a function of the macroscopic loading. In the isotropic case and for Maxwellian phases, the results mentioned above can be used to express the phase averages of the viscous field as a function of the poles associated with the microstructure and those of the phase relaxation functions. This yields general relations between the macroscopic internal variables and the phase-averaged viscous strain field.

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Thermodynamic potentials for viscoelastic composites with simple constituent rheologies

Idiart Martín (1)

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Speaker: Idiart Martín. **Tuesday**. Start time: **17:15**. Room: Rhône 1 LVL1. Link to abstract.

The viscoelastic response of composite media is the result of intricate interactions between elastic and viscous deformation processes operating within the different constitutive phases. A key consequence of such interactions is that microscopic constitutive descriptions based on finite sets of internal variables give rise to macroscopic constitutive descriptions with an infinity of internal variables. This seemingly ineludible feature of multiscale inelasticity has hindered the development of a mean-field thermodynamic theory of viscoelastic composites that correlates macroscopic and microscopic energetics in a rational and practical manner on a par with existing mean-field thermodynamic theories of purely elastic and purely viscous composites. Knowledge of such correlations is required, for instance, to adequately quantify the contribution of microscopic viscous dissipation to heating during any thermomechanical process. Mean-field thermodynamic potentials are derived in this work by resorting to variational approximations. Efforts to do so are not new. Central to the present effort, however, is the recognition that any viscous deformation field —which does not necessarily comply with any differential constraints— can be additively decomposed into an irrotational field and a solenoidal field —which do comply with differential constraints— in such a way that variational approximations available for elastic potentials become applicative to viscoelastic potentials. The variational approximations already available for random elastic media prove then instrumental. Attention is restricted to composites with ellipsoidal microstructural randomness and with constituents exhibiting Maxwellian or Kelvinian rheologies. The resulting thermodynamic potentials simultaneously i) conform to the two-potential formalism with a finite number of effective internal variables with explicit physical meaning, ii) comply with the convexity required by the generalized standard model, iii) can be expected to comply in a certain sense with elementary bounds, iv) predict the expected purely elastic and purely viscous regimes, v) can improve on decoupled descriptions of viscoelastic transitions, vi) can be realizable under certain circumstances, and vii) are amenable to including nonlinearly viscous effects. Specific approximations of the Hashin-Shtrikman and the Self-Consistent types are worked out in detail. Intraphase statistics of the stress field up to second order are also provided. Finally, extensions to nonlinear material behavior are discussed. It is anticipated that results and procedures reported in this work will bear relevance to open questions in the viscoelasticity theory of composite media.

Direct time-incremental homogenization models for elasto-viscoplastic composites based on second moments of stresses

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Speaker: Berbenni Stephane. **Tuesday**. Start time: **17:35**. Room: Rhône 1 LVL1. Link to abstract.

A direct time-incremental homogenization model for two-phase non linear elasto-viscoplastic materials was recently proposed in (1), using the linear viscoelastic ellipsoidal inhomogeneity problem obtained in the real time domain. The extension to non-linear behavior based on a "modified secant" formulation (1,2) or a "modified affine" formulation (3), is first shown with this model, involving the second moment of stresses to obtain the linear comparison composite (LCC) properties. Hence, the both "modified secant" and "modified affine" viscoplastic compliances are considered for the matrix phase. The effective behavior as well as the evolution laws of the averaged strains and stresses per phase are directly solved in the time domain, without the need of Laplace-Carson transforms. The estimates provided by the present homogenization model are compared to full-field calculations of (2,4) for two-phase non linear particulate composites constituted of an isotropic elastoviscoplastic matrix phase and isotropic elastic particles, and, for radial and non-radial loadings. In a second part, the Translated Fields (TF) homogenization method, which was initially developed for classic secant (5) and affine (6) formulations (with first moments of stresses), is here extended to account for the second moments of stresses through both "modified secant" and "modified affine" formulations. Applications to two-phase fiber-reinforced/weakened elasto-viscoplastic composites are proposed, and comparisons between the different estimates are discussed.

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Modelling of elastic-viscoplastic composites by the additive Mori-Tanaka scheme based on a modified tangent linearization

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1 - Institute of Fundamental Technological Research (Warsaw Poland)

Speaker: Kowalczyk-Gajewska Katarzyna. **Tuesday**. Start time: **17:55**. Room: Rhône 1 LVL1. Link to abstract.

When phases have non-linear elasto-viscoplastic behaviour, mean-field modelling based on the Eshelby inclusion problem presents certain challenges. One challenge is the long-term memory effect, which results from presence of time derivatives of different orders in the local constitutive response. The additive interaction law is one potential solution to this issue (1). Due to its appealing simplicity associated with fairly good accuracy, the model is well suited to be employed as a material model in large scale finite element calculations (2). However, while alternative variational approaches take into account the second moments of stresses and strains, this mean field approach based on the additive interaction law typically just adopts the mean values of stress and strain fields in each phase. It is clear that methods developed in (2) by taking account of stress fluctuation within the phases enhance model predictions. On the other hand, the variational homogenization framework is not efficient for non-proportional loadings and large-scale finite element due to their complexity. Therefore, in this work, we propose to include second moments in homogenisation models based on the additive interaction law.
The current study discusses how to formulate the additive Mori-Tanaka model of two-phase elastic-viscoplastic material by including the second moments of stresses (3). Following (5), the Hill-Mandel's lemma is adopted to capture the evolution law of second moments of stresses. With these modifications, a modified tangent linearization of the viscoplastic law is suggested. The outcomes of the model are compared with full-field fast Fourier transform numerical calculations of (4). In order to demonstrate the model accuracy, predictions are compared to those of other models accounting for stress fluctuations found in the literature (5). These benchmarks show that the improved tangent linearization performs well for both monotonic and non-monotonic loading responses.

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Prediction of local field statistics using an incremental mean-field homogenization scheme for high-concentration composites

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1 - Sorbonne Université (France), 2 - Sorbonne Université (France)

Speaker: Bourdier Éléonore. **Tuesday**. Start time: **18:15**. Room: Rhône 1 LVL1. Link to abstract.

To predict the non-linear behavior of composites using mean-field homogenization methods, it is necessary to estimate local field statistics (1). In the case of composites with a high concentration of inclusions, the differential scheme in its incremental form has already proved its worth. Our aim is to define local field statistics within the framework of this incremental method.
General expressions of the first and second-order moments of the intraphase strain fields have been derived for multiphase elastic composites. The main challenge in this work was to account for the successive homogenization steps inherent to the incremental process. For first-order moments, the localization tensors for each phase were achieved by reconstruction by integrating all the homogenization steps. For second-order moments, the approach is based on the application of the chain derivation rule throughout the process, making it possible to express the derivatives of the final effective properties as a function of the initial properties of the phases.

On the one hand, this approach has been validated by comparison with Zimmerman's analytical solution for isotropic porous media (2). On the other hand, additional applications were carried out on microstructures presenting phases with pronounced contrasts and a wide range of volume fractions. These results were then compared with those of other linear homogenization schemes, such as the Mori-Tanaka (3) and Lielens schemes (4), as well as with full-field simulations. These comparisons confirm the relevance of this scheme in the context of highly inclusionary media.

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Influence of strain hardening and elasticity upon transformation plasticity of metals and alloys

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1 - Institut Jean Le Rond d'Alembert (France)

Speaker: Leblond Jean-Baptiste. **Wednesday**. Start time: **10:00**. Room: Rhône 1 LVL1. Link to abstract.

Some recent theoretical works were devoted to Greenwood and Johnson's mechanism of transformation plasticity of metals and alloys, that is, the anomalous increase of plastic deformability during solid-solid transformations. These works used the powerful kinematic approach of the classical theory of limit-analysis, assuming the sole weaker mother-phase to be plastic. The theory is based, by construction, on the hypothesis of absence of strain hardening and elasticity - it thus applies to *rigid-ideal-plastic* materials only. The models derived on this basis were found, on average, to yield acceptable predictions, as evidenced through comparisons with the results of both experiments and micromechanical numerical simulations of Greenwood and Johnson's mechanism.
However, at the temperatures at which transformation plasticity occurs in practice, the hypothesis of ideal plasticity is questionable. Moreover, micromechanical numerical simulations have evidenced a notable effect of elasticity in the daughter-phase, at least in the case of growing nuclei of this phase of elongated shape (as encountered in laminated plates). Theoretical models are therefore prone to improvements pertaining to the effects of both strain hardening and elasticity.

In the present work, we propose to account for the effect of (isotropic) strain hardening by adapting a trick used by Gurson when developing his famous model for porous ductile materials. This trick consists in replacing the true medium with a heterogeneous distribution of hardening through some " equivalent " medium with a uniform hardening ; this " equivalent " hardening being determined by assuming the plastic dissipations in the true and equivalent media to be equal. Comparisons of the predictions of the model thus defined with results of some new micromechanical numerical simulations of Greenwood-Johnson's mechanism evidence a nice agreement, provided some correction is introduced into the model to account for the strong nonlinearity of hardening at the onset of plasticity.
We also propose to model the effect of elasticity by assuming the daughter-phase to now be elastic instead of rigid ; elasticity being still disregarded in the (essentially plastic) mother-phase. This amounts, in the homogenization-based derivation of the model, to modifying the boundary conditions on the plastically deforming RVE of mother-phase. Comparisons of model predictions and results of micromechanical simulations evidence a reasonable agreement, except for relatively high stresses applied and nuclei of daughter-phase of highly elongated shape. The reasons for the discrepancy are discussed.

A variational approach to boundary effects in higher-order homogenization

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Speaker: Thbaut Manon. **Wednesday**. Start time: **10:20**. Room: Rhône 1 LVL1. Link to abstract.

From an engineering point of view, it is convenient to describe composite materials using homogeneous effective properties. When the microstructure is periodic, asymptotic homogenization is particularly well suited for this aim. Classical homogenization corresponds to the dominant order model and yields an effective standard Cauchy medium. At next orders, we can derive additional corrections that depend on the successive strain gradients. These corrections are typically of interest to capture size-effects appearing for microstructures with contrasted stiffness properties.

However, these higher-order models present two major limitations. First, the corrections produced by homogenization can handle size-effects that occur in the bulk region, but are not suited to the analysis of the boundaries. In fact, they miss significant boundary effects which can ruin the quality of the predictions. Secondly, these higher-order models present several mathematical inconsistencies, including non-positive strain-gradient stiffnesses. As a result, the effective energy is not necessarily positive and any equilibrium solution is unstable with respect to short-scale oscillations. To handle these two limitations simultaneously, we elaborate a new homogenization procedure that includes boundary effects. By contrast with usual approaches, in our procedure the homogenization is carried at the energy level, rather than on the strong form of the equilibrium. Besides, the positivity of the resulting energy is guaranteed by an original truncation method (1).

As an example, we consider a 2D laminate that is invariant in the direction perpendicular to the fibers. The resulting effective energy contains a bulk term that is positive, plus a boundary term that accounts for the energy generated by the boundary effects. The effective stiffness on boundary is computed numerically, by combining solutions of elementary 2D elastic problems formulated on a semi-infinite strip. We show that, by contrast with usual asymptotic homogenization, this higher-order model is able to capture size-effects occurring in the interior domain, as well as near the boundaries.

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On modeling size-dependent strain gradient elastic adhesively bonded joints

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Speaker: Serpilli Michele. **Wednesday**. Start time: **10:40**. Room: Rhône 1 LVL1. Link to abstract.

As a bonded structure scales down to the microscale, the role of the adhesive joint becomes more relevant concerning the overall performance of the microdevice. At the small scale, the microstructural and size-dependent properties of thin adhesive start to play a key role in the mechanical response of the layered assembly (1). The present work focuses on the derivation of a soft imperfect interface law in a composite, constituted by two solids, separated by a thin adhesive layer in the framework of linear strain gradient elasticity. The model is obtained by means of an asymptotic analysis. The contact laws, expressed in terms of the jumps and means values of the displacements, normal derivatives of the displacements, represent a formal generalization of the soft elastic interface conditions (2). The present study reveals the stiffening behaviors of layered structures and size-dependent phenomena, typical of microscale structures (3). Two benchmark problems are investigated through their closed-form solutions: i) a simply-supported laminated beam with soft core subjected to a uniform distributed load; ii) a mode 2-type loading configuration of a layered axially deformable beam. Size effects and non-local phenomena, due to high strain concentrations, are highlighted.

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On Nitsche's method for higher-order boundary conditions in coupled gradient-elastic Cahn-Hilliard problems

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Speaker: Kranzosch Ole. **Wednesday**. Start time: **11:00**. Room: Rhône 1 LVL1. Link to abstract.

In the present contribution, we consider a coupled mechano-diffusion problem in the framework of Mindlin's strain gradient elasticity and Cahn-Hilliard diffusion models. This augments the modeling capabilities by incorporating elasticity-related length scales reflecting microstructural effects at the continuum level.
The higher-order boundary value problem of the coupled gradient elastic-diffusion model is formulated in a variational form within a proper Sobolev space setting. Conforming Galerkin 2D discretizations for numerical results are obtained via an isogeometric approach and implemented in Matlab.

The method implements the so-called generalized-α method for integrating the diffusion equation in time. Moreover, the time stepping procedure is paired together with an adaptive time step size to allow for stable and accurate results even for long time simulations and greatly varying time scales which are characteristic for Cahn-Hilliard models.

One drawback of the spline based finite element method arises when dealing with higher order boundary conditions that appear for the Cahn-Hilliard diffusion equation and in the theory of gradient elasticity. A strong imposition of boundary conditions cannot be easily achieved for the general case. To deal with this problem a weak imposition is achieved by utilizing Nitsche's method which has gained popularity in recent years and shares close relation with discontinuous Galerkin methods. Its advantage compared to other penalty-based approaches for weakly imposing boundary conditions lies in its easy adaptivity and desirable properties such as resulting in linear systems that avoid ill-conditioning.
In our work, we first consider a 1D problem and verify the implementation and method by comparing the results obtained to a finite-difference method. After that, some two-dimensional examples are investigated to evaluate the performance of the proposed boundary treatment. Finally, we study an example of diffusional coarsening in solders and analyze the size effects in phase separation problems by extending the model towards the strain gradient elasticity framework.

Lippmann-Schwinger spectra, composite materials eigenstates and their role in computational homogenization

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Speaker: Bellis Cédric. Keynote. **Wednesday**. Start time: **14:30**. Room: Rhône 1 LVL1. Link to abstract.

When considering the homogenization of heterogeneous materials, one has to solve for the local fields in a representative volume element subjected to a uniform loading. This defines a cell problem, which can take the form of local equations or of an equivalent volume integral equation. When the composite material considered is made of constituents with linear behaviors, such an integral equation reduces to the so-called Lippmann-Schwinger equation. Establishing such a formulation relies on the introduction of a linear, and in most cases also uniform, comparison medium with its companion Green's function. In the case of periodic composites, this type of formulation has provided the foundation for the fast Fourier transform-based numerical method developed in (1) to compute the effective properties of linear and non-linear composites. This has opened the door to a breadth of successful developments since.
Theoretical results were also obtained using variational principles and volume integral formulations, in particular to establish bounds on the homogenized properties. In addition, the analytic properties of the effective tensor of the composite as a function of the parameters of its constituents have been the subject of a number of studies, initiated with (2, 3, 4) for dielectric composites. In the specific case of two-component materials, it is shown that the effective properties can be represented as an integral of a rational function of the material contrast between phases. This formulation turns out to be a Stieltjes integral representation associated with the spectral measure of the linear integral operator featured in the Lippmann-Schwinger formulation of the homogenization problem. Describing the spectrum of this operator and its associated eigenvectors, also referred to as eigenstates of the composite as in (5), is thus key for understanding the expression of the effective properties as functions of the composite micro-geometry and constituent parameters.

To bridge the gap between the generic computational methods on the one hand and the theoretical homogenization results for two-phase composites on the other hand, the perspective adopted in the present study is that the introduction of the comparison medium amounts to a preconditioning of the original cell problem. In the context of solving partial differential equations, preconditioning is a well-known method, see e.g. (6). It is then crucial to analyze the spectral properties of the preconditioned operator as the performances of iterative solution schemes, such as the conjugate gradient or fixed-point iterations, depend on them, a study that is carried out for example in (7) for second-order differential operators relevant to the problems considered here. This makes it possible to find an optimal preconditioner, i.e., in the present context, an optimal comparison medium.

In the context of computational homogenization methods and to connect with the known theoretical results, the overall objective of the present study is to shed some light on the implications of the preconditioning strategy by the introduction of the comparison medium and, in the linear case, on the role of the spectral properties of the integral operator of the Lippmann-Schwinger equation in computing the solution to the cell problem and thus the effective properties of a given composite. The results presented hereinafter are intended to be formulated in a framework as general as possible, encompassing in particular the conductivity and elasticity cases.

The homogenization problem is presented first in a variational setting for generic composite materials, potentially governed by a non-quadratic energy density. The introduction of the comparison medium is made through the definition of an energetic inner product. This naturally leads to the identification of the gradient of the energy functional as a preconditioned version of the original cell problem governing the local fields. Iterative solutions methods are then studied, starting with steepest descent, which we

connect to fixed-point iterations, revisiting the convergence criteria conventionally adopted. Although a formulation using the unknown potential (or displacement) field is adopted in this study, the link is made with the gradient (or strain) based formulations that are widely used in the applications. This analysis is then particularized to the case of linear composites, so as to obtain the well-known Lippmann-Schwinger integral equation. The featured linear operator, which is bounded and self-adjoint, is then analyzed with bounds on its eigenvalues and a description, in the conductivity setting, of the associated eigenvectors, referred to as eigenstates of the composite. Then, we will focus on the role of the spectral properties of the operator considered, namely how the solution to the cell problem and the effective properties are expressed in terms of the eigenvalues and eigenvectors in the case of multiple phase composites. These developments are then particularized to two-component materials. This analysis conducted in an infinite-dimensional functional setting is then transposed in the context of numerical methods, with a suitable discretization scheme. A matrix formulation of the eigenvalue problem is investigated in connection with the conventional tools of FFT-based homogenization methods. Finally, some numerical results will be presented and discussed for a set of synthetic microstructures. Some numerical spectra will be described together with the associated eigenstates, highlighting in particular the very small portion of the spectrum that actually plays a role in computing the solution to the homogenization problem.

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Quasiperiodic composites: homogenization and spectral properties

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Speaker: Cherkaev Elena. **Wednesday**. Start time: **15:10**. Room: Rhône 1 LVL1. Link to abstract.

From quasicrystalline alloys to twisted bilayer graphene, materials with a quasiperiodic structure exhibit unusual properties that drastically differ from those with periodic structures. A key feature of quasicrystalline microgeometry is a long-range order in the absence of periodicity. Quasiperiodic geometries can be modeled using the cut-and-projection method that restricts or projects a periodic function in a higher dimensional space to a lower dimensional subspace cut at an irrational projection angle. Homogenized equations for the effective behavior of a quasiperiodic composite can be derived by cutting and projecting a periodic function in a higher dimensional space. Using equations for the local problem in the higher dimensional space established in the homogenization process, we develop the Stieltjes analytic representation of the effective properties of quasiperiodic materials; this representation determines the spectral characteristics of fields in quasicrystalline composites and used to derive bounds for the effective properties. This is a joint work with Niklas Wellander and Sebastien Guenneau.

Efficient Wavelet-FFT-Approaches for Multiscale Problems

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Speaker: Kaiser Tobias. **Wednesday**. Start time: **15:30**. Room: Rhône 1 LVL1. Link to abstract.

The predictive capability of computational multiscale methods relies on detailed representations of the underlying microstructure and on sophisticated material models for the microscale constituents. However, with the increasing physical complexity of the cell problem, the computational complexity also keeps increasing. This necessitates the development of tailored solution approaches that leverage the specific structure of the cell problem, with FFT-based spectral methods emerging as some of the most promising options.
In this work, we address a key drawback of state-of-the-art FFT-based solution approaches: their reliance on regular structured grids. To overcome this, we make use of the intrinsic hierarchy and built-in adaptivity of wavelets. By representing the governing fields in a wavelet basis and by using wavelet transforms, higher-order stress approximations are successively derived within a nested set of approximation spaces. This enables the detection and accurate resolution of localized features while (at the same time) significantly reducing the number of material model evaluations. Since the computational overhead of the wavelet transform scales linearly in the number of voxels, and since the additional per-voxel operations are negligible compared to the cost of typical material model evaluations, a substantial gain in computational efficiency is achieved.

This is demonstrated through a detailed study of representative boundary value problems in one- and two-dimensional settings, where we use a wavelet-enhanced version of the classic Moulinec-Suquet basic scheme as a starting point. In particular, we show that the numerical grid in the hybrid wavelet-FFT approach naturally adapts to the solution profile based on a predefined refinement tolerance and report a 95%-reduction in the number of material model evaluations.

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Simplifying FFT-based computational homogenization with automatic differentiation

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Speaker: Pundir Mohit. **Wednesday**. Start time: **15:50**. Room: Rhône 1 LVL1. Link to abstract.

In the field of solid mechanics, Fast-Fourier Transform (FFT) techniques (1) are extensively employed to solve intricate homogenization problems. However, current FFT-based methods face challenges that limit their applicability to complex mechanical problems. These challenges include the manual implementation of constitutive laws and the use of computationally expensive and complex algorithms to couple microscale mechanisms to macroscale material behavior. Here, we explore the application of automatic differentiation (AD) (2) in the context of an FFT-based framework to address and alleviate these challenges, thereby simplifying computational homogenization.

In this study, we show how AD allows the straightforward computation of stresses and tangent operators directly from the energy density functional, which makes FFT-based methods more accessible for complex hyperelastic materials.We show that AD's ability to perform differentiation across complex tensor manipulations, FFT processes, conditional loops, and Newton-Krylov solvers facilitates the calculation of tangent operators for materials where local stiffness cannot be derived from strain energy density, such as elastoplastic materials, or when an close-form expression does not exist, as in computational homogenization. We apply AD-enhanced FFT-based framework to multiscale problems and show how AD eases the computation of homogenized stiffness tensors, a significant computational bottleneck in multiscale problems.

Our results demonstrate that using AD in conjunction with an FFT-based approach is extremely advantageous. This combination decreases the reliance on explicit expressions of stresses and tangent operators while preserving accuracy and computational efficiency. Moreover, it significantly streamlines the process of computational homogenization for complex solid mechanics problems.

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Multiscale analysis of the anisotropy induced by defects in LPBF additive manufacturing using coarse graining homogenisation techniques

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Speaker: Gautier Lilou. **Wednesday**. Start time: **16:10**. Room: Rhône 1 LVL1. Link to abstract.

Additive manufacturing techniques have garnered significant interest in various industrial applications due to their potential for design optimisation, cost reduction, and shortened lead times. Among these techniques, Laser Powder Bed Fusion (LPBF) stands out for its ability to produce components of relatively small size with complex designs and satisfying material properties. Especially, it enables geometries that are unachievable with traditional manufacturing processes (1). These features are also relevant in the nuclear industry and particularly in nuclear fuel assemblies where components needs to provide high performances in restricted spaces (2).
The LPBF process uses a laser to melt and fuse metallic powder particles spread in a powder bed. The component is formed incrementally, as a new layer of powder is added after each pass of the laser. Despite its benefits, this technique also presents a specific defectology characterised by the type and quantity of pores, their spatial distribution and the potential interactions between them. It can be strongly influenced by the numerous manufacturing parameters, including for example the powder characteristics, the laser path and any complex interactions between these factors. In particular, a strong correlation can be observed between the lasing strategy used and the location of defects, revealing signature patterns (3).

The criticality of these voids with respect to the mechanical behaviour of LPBF components has yet to be fully established.

Previous works already showed the detrimental nature of larger voids (4) and highlighted the significant influence of the spatial distribution of defects (5). However, these studies usually focus only on spherical pores and rarely investigate the interaction between different types of voids. Besides, the anisotropy induced by the observed specific patterns remains undercharacterised. These limitations motivate the need for suitable numerical methods that can effectively simulate the behaviour of explicitly modelled complex pore populations. Simulations on images appear as a suitable approach to overcome the complex and significant meshing work usually required. Some authors also discussed scenarios where the defect size approaches the structure scale (6). This is particularly noteworthy for the thin designs enabled by LPBF and raises the question of the validity of the scale separation hypothesis in homogenisation. Moreover, since pore populations are highly diverse and the components typically fine, the existence or the appropriate size of a Representative Volume Element (RVE) remains uncertain.

In this work, we study the anisotropy induced by the particular spatial organisation of complex defect populations and investigate the existence of a homogenised RVE for such materials.

We address this question by performing high-fidelity multigrid elastic simulations on synthetic images representing a given distribution of pores (7). Elastic computations are conducted using six independent loading cases to evaluate the elasticity tensor. Coarse graining (CG) techniques are used to perform exact homogenisation of the domain at multiple scales (8). In this approach, the mesoscopic variables are computed from the convolution of microscopic variables with a kernel, while enforcing mechanical conservation laws at both scales. As a result, the method provides homogenised property fields across all elements without the need of a RVE. It is also worth noting that no assumptions are made regarding the material's behaviour. The convolution linearity ensures the elastic results remain independent after the homogenisation. Therefore, the elasticity tensor can be evaluated at multiple mesoscopic scales. The local anisotropy degree of the material is then determined by analysing the number of independent eigenvalues of the elasticity tensor and the corresponding eigenspaces (9).

Therefore, CG techniques allow for establishing correlations between the microscopic defect distribu-

tions and the resulting elastic properties at different scales. These findings highlight which defects should be accounted for, depending on the observation scale considered. Furthermore, the analysis of the variability of the homogenised elastic properties at different scales enables conclusions regarding the existence or size of a RVE and its degree of anisotropy. In the absence of a RVE, this method still automatically provides the equivalent heterogeneous material at the macroscopic scale for a given pore population.

Currently, the approach shows promising results in capturing anisotropic behaviours induced by voids at mesoscopic scales for relatively simple cases. Future work will focus on investigating the existence or size of a RVE and applying the same scheme to more complex defect populations. The validity of the scale separation hypothesis should also be examined. This can be achieved by evaluating the homogenised properties on real thin structures under actual loading conditions.

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Homogenization based modelling of electroactive porous metamaterials with nonlinear effects

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Speaker: Rohan Eduard. **Wednesday**. Start time: **16:45**. Room: Rhône 1 LVL1. Link to abstract.

We consider electroactive porous metamaterials which can serve for fluid transport, or shape morphing due to the pore inflation effect. The conference paper is devoted to the homogenization based modelling of periodic structures accounting for nonlinearities arising with moderate deformations which require to respect equilibria satisfied in deformed configurations. The micromodel describes the fluid-structure interaction in periodic porous structures with electroactive elements, such as the piezoelectric, or flexoelectric segments controlable by external electric circuits. Such microstructures can induce the fluid flow due to the peristaltic deformation which is generated by the piezoelectric, or flexoelectric actuators. The cell problems (at the micro-level) provide characteristic responses of the microstructures with respect to macroscopic strains, fluid pressure and electric potentials. The homogenized model is derived under the small deformation assumption. However, the nonlinearity associated with deforming configuration is respected by deformation-dependent homogenized coefficients of the hypoelastic constitutive law and all other effective (homogenized) material parameters evaluated using the characteristic responses of the microstructure. To reduce the computational efficiency, the sensitivity analysis of the homogenized coefficients with respect to deformation induced by the macroscopic quantities is employed (1). This enables to avoid the two-scale tight coupling of the macro- and microproblems otherwise needed in nonlinear problems using the "FE^2" method. The paper summarizes our recent theoretical results: piezoelectric effective properties generated by weakly flexoelectric microstructures, controlable weakly piezoelectric microstructures, and inflatable microstructures equipped with automatic, or controlled valves, and the unilateral selfcontact in deforming porosities (2). All the effective material models are derived using the asymptotic homogenization applied to incremental formulations. The models are implemented in the SfePy finite element code (sfepy.org)

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Homogenisation of Viscoplastic Properties in Porous Polycrystals Using FFT-Based Methods: Application to the Snow-Firn-Ice Transition

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Speaker: Védrine Louis. **Wednesday**. Start time: **17:05**. Room: Rhône 1 LVL1. Link to abstract.

Porous polycrystals include manufactured materials such as metal powders, metallic foams, and polycrystalline nuclear fuels, as well as natural materials like snow. These materials are often subjected to slow loading near their melting point, which involves viscoplastic deformation. Knowledge of their viscoplastic behaviour is thus essential for many applications such as metallic manufacturing, hot forming, or for understanding snow settlement under natural conditions. However, their microstructures can vary widely, significantly influencing mechanical responses. Systematic relationships between the microstructure of highly porous polycrystals and their viscoplastic behaviour remain rarely detailed in the literature. In this study, snow is used as a model material, represented as a collection of ice monocrystals sintered together. Ice is characterized by a strong viscoplastic anisotropy, with distinct stress exponents for soft and hard slip systems. This framework allows for investigating how microstructure influences homogenized viscoplastic behaviour.

The study focuses on the transition between two regimes: (i) in highly porous materials when crystal and pore sizes are comparable, the crystals act as isolated monocrystals; and (2) in denser materials, or when a grain is composed of several crystals, the neighbouring grains constrain the crystal behaviour. To explore this transition, numerical full-field simulations were conducted. Three-dimensional synthetic porous structures were simulated using a crystal plasticity model combined with a Fast Fourier Transform-based numerical solver, designed to handle high material property contrasts.
The numerical experiments led to the development of a homogenized model. Through asymptotic analysis, we demonstrated that a homogenized stress exponent can be defined over a wide range of stresses, even when crystal-scale exponents differ. The influence of microstructural patterns, specifically the solid fraction and intercrystalline surface area, on macroscopic viscosity and stress exponent was then investigated. Our results show that crystal-scale deformation mechanisms are strongly affected by confinement from surrounding grains, which constrains dislocation activity. For dense polycrystals, the stress exponent aligns with the hard system's behaviour. In porous polycrystals, the stress exponent varies between soft and hard system values, depending on their relative activities. By applying this new stress exponent parameterization, we reinterpreted experimental data on snow and firn. This work represents an essential step toward a unified model of porous polycrystal viscoplasticity.

Stress-driven FFT-Galerkin formulation for nucleus evolution in ferroelectric materials

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1 - Mechanics and Materials Laboratory, ETH Zürich (Switzerland), 2 - James Watt School of Engineering, University of Glasgow (United Kingdom)

Speaker: Cheng Hsu-Cheng. **Wednesday**. Start time: **17:25**. Room: Rhône 1 LVL1. Link to abstract.

The macroscopic properties of ferroelectric materials, such as their dielectric and piezoelectric constants and ferroelectric hysteresis, depend strongly on the nucleation and growth of ferroelectric domains and the associated motion of domain walls. Therefore, it is crucial to understand the motion of domain walls, in particular in the early phases of domain nucleus growth, which is the focus of this contribution. We present a new stress-driven FFT-Galerkin homogenization scheme, which is combined with a level-set method to study the long-term nucleus evolution. We discuss the benefits of the stress-driven formulation, such as imposing average stress conditions, and the unified form of the regularized driving force. Using this framework, we demonstrate the topological changes in the nucleus for different ferroelectric materials subjected to an applied average stress (thus mimicking experiments). Our simulations show the evolution, which cannot be captured by classical phase-field models due to the difficulties associated with the diffuse interface and associated interface energy, nor by analytical sharp-interface models that assume a self-similar motion. We present the new framework and demonstrate its suitability and performance in a series of benchmark simulations on domain nuclei in barium and lead zirconate titanate.

Machine learning-boosted nonlinear homogenization

Tannous Mikhael Ghnatios Chady (1), Castelnau Olivier (2), Ponte Castaneda Pedro (3), Chinesta Francisco

1 - École Nationale Supérieure des Arts et Métiers (France), 2 - Laboratoire Procédés et Ingénierie en Mécanique et Matériaux (France), 3 - Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania (United States)

Speaker: Tannous Mikhael. **Wednesday**. Start time: **17:45**. Room: Rhône 1 LVL1. Link to abstract.

Previous research has established nonlinear homogenization as an efficient technique for deriving macroscopic constitutive relations and field statistics in heterogeneous (i.e. composite) materials. This method involves optimal linearization of the nonlinear composite, resulting in a best linear comparison composite that shares identical microstructure and field statistics with the nonlinear material. However, the computational time associated with this method increases as the fidelity of the material representation improves, limiting its practical implementation in commercial finite element software for large-scale structural calculations in which a Representative Volume Element must be considered at each integration point. To overcome this limitation without sacrificing precision or efficiency, machine learning can be employed to develop a digital twin of the homogenization-based constitutive law. This approach enables realtime prediction of macroscopic material behavior while maintaining accuracy. The effectiveness of this approach has been demonstrated for twophase composites with nonlinear power-law constitutive relations, and it has been successfully extended to model the complex three-dimensional behavior of viscoplastic polycrystals. In the latter case, a significant reduction in computational time has been achieved without compromising the precision of nonlinear homogenization method outputs.

Data-driven simulations from multiphase material databases augmented by active learning

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Speaker: Platzer Auriane. **Wednesday**. Start time: **18:05**. Room: Rhône 1 LVL1. Link to abstract.

To overcome well-known drawbacks of classical phenomenological constitutive modeling of complex heterogeneous materials, a popular approach is the so-called computational homogenization (CH). In this full-field homogenization tool, the spatial arrangement and constitutive behaviors of the constituents in a representative volume element (RVE) are finely described, in order to derive an average mechanical response. A popular computational implementation, called FE2, encompasses two-level finite element numerical models, which circumvent the macroscopic constitutive modeling process (Feyel, 1999). However it quickly leads to prohibitive computational costs, even for problems with a modest number of degrees of freedom. A popular strategy in the literature to alleviate such computational burden is to use machine learning-based surrogate constitutive models (Matouš et al., 2017; Peng et al., 2021; Su et al., 2022) but this clashes with the original intention of bypassing the need for a macroscopic constitutive model. Conversely, the so-called (model-free) data-driven computation mechanics (DDCM) paradigm (Kirchdoerfer & Ortiz, 2016) proposes the direct integration of "experimental data", completely bypassing the need for explicit constitutive laws. The main goal of this work is to show how the DDCM approach can be used in synergy with CH to avoid fully-coupled multi-scale computations. A naive approach to using multi-scale constitutive behavior along with DDCM is the offline construction of a database via CH by assuming some sampling of the strain-space (Karapiperis et al., 2020; Xu et al., 2020). This approach is limited since the region of the strain-space covered during a simulation is problem-dependent. Instead, in the present work, we propose to bridge DDCM and CH into a semi-supervised machine learning tool using the Active Learning (AL) framework. Following AL jargon, CH is considered as the *oracle* responsible for labeling data: it provides the label "homogenized stress" for a given strain. The objective of this work is then twofold: (i) to provide valuable evaluations of the strain worth labeling from a boosted DDCM algorithm to the CH oracle in order to (ii) build a material database on-the-fly from carefully selected microscopic evaluations. We show through meaningful numerical examples that the proposed framework results in significant computational savings if compared to standard FE2 (Rocha et al., 2024). In addition, we discuss the relevance of the computed data points and how "rich" a database should or can be to properly represent the macroscopic material behavior.

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Methods in Applied Mechanics and Engineering, *363*, 112893. https://doi.org/10.1016/j.cma.2020.112893

Implementations of homogenized behaviours in structural codes: examples and on-going efforts on extending the MFront code generator

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1 - CEA, DES/IRESNE/DEC (France)

Speaker: Martin Antoine. **Wednesday**. Start time: **18:25**. Room: Rhône 1 LVL1. Link to abstract.

So-called "mean-field homogenization" (MFH) theories, often providing closed-form expressions for the effective properties of heterogeneous materials, have been continuously developed for more than 50 years. Yet, MFH is not commonly used in engineering studies at the structural scale for several reasons. On the one hand, implementation of behaviours resulting from MFH theories is complex and generally inefficient at the structural scale: explicit schemes are preferred for the sake of simplicity but have high local integration costs (at every Gauss's point) and do not provide a consistent tangent operator, leading to poor convergence rate at the structural scale.
This contribution presents an on-going effort to:

- develop efficient implicit algorithms for behaviours resulting from MFH theories
- extend the *TFEL/Material* library and the *MFront* code generator in the hope to make such behaviours easier to implement and available in many academic and commercial solvers.

The first point will be illustrated by an implicit scheme based on the static condensation of the equations resulting from the Berveiller-Zaoui scheme proposed in *Helfer et al.* This algorithm is extended in various ways, including support for behaviours with internal states, Cailletaud's beta-rule, etc. Based on the work of the members of the AnoHonA project, extensions to more general schemes will be discussed.
The second point will be illustrated by exposing some facilities introduced in MFront code generator that simplify the implementation of behaviours resulting from MFH theories.

The authors acknowledge the ANR – France (French National Research Agency) for its financial support of the AnoHonA project number AAPG2023.

The accelerated adaptive Eyre-Milton scheme for infinitely contrasted heterogeneous materials. Application to homogenization and damage problems.

Sab Karam (1), Dolbeau Martin Bleyer Jérémy

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Speaker: Sab Karam. Keynote. **Thursday**. Start time: **10:00**. Room: Rhône 1 LVL1. Link to abstract.

Sab et al. (2024) have recently proposed an FFT-based iterative algorithm, termed Adaptive Eyre–Milton (AEM), for solving the Lippmann-Schwinger equation in the context of periodic homogenization of infinitely double contrasted linear elastic composites (heterogeneous materials with linear constitutive laws that contain both pores and rigid inclusions). They have demonstrated the unconditional linear convergence of this scheme, regardless of initialization and the chosen reference material. However, numerical simulations have shown that the rate of convergence of AEM strongly depends on the chosen reference material. In Dolbeau et al. (2024), the authors introduced a new version of the AEM scheme where the reference material is updated iteratively, resulting in a fast and versatile scheme, termed Accelerated Adaptive Eyre–Milton (A2EM).
We will present the A2EM scheme and examine the possibility of extending its application to standard nonlinear problems using the finite element method, for example the well-known phase-field damage problem.

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An incremental variational approach and computational homogenization for composites with evolving damage

Ben-el-barguia Ghita (1), Dartois Sophie (1), Lahellec Noel (2), Kondo Djimedo (1)

1 - Sorbonne Université (France), 2 - Aix Marseille Université (France)

Speaker: Dartois Sophie. **Thursday**. Start time: **10:40**. Room: Rhône 1 LVL1. Link to abstract.

Various brittle matrix composites experience damage mechanisms caused by the initiation and growth of microcracks under mechanical loadings. This damage results in a softening effective response, ultimately culminating in failure. The main objective of the present study is to establish a mean-field homogenization model for composites with elasto-damageable constituents, by relying on the incremental variational procedure developed so far for elasto(visco)plastic composites. To achieve this, the Effective Internal Variable (EIV) method initially proposed by Lahellec and Suquet (1) is adopted (see also (2) & (3)).
Based on the variational principle proposed by (4) and the EIV method, a time discretization of the corresponding equations is proposed and a condensed incremental potential J(x,ϵ,d), which involve the free energy and the dissipation potential for the damageable constituents, is introduced. This enables the application of Ponte-Castañeda's homogenization variational procedure for non-linear behaviors described by means of a single potential (see (5)). A linearization of the elasto-damageable behavior is then performed leading to an approximation of J by J_0, the latter being the condensed potential of a linear comparison composite (LCC) with per-phase uniform parameters. An optimization with respect to the parameters introduced in J_0 provides in the end the final estimate of the effective condensed incremental potential. The macroscopic behavior can eventually be determined using a linear homogenization scheme; Hashin-Shtrikman bounds are here chosen.

The developed incremental variational procedure is then applied to composites composed of linear elastic spherical particles isotropically distributed in a damageable matrix. Thanks to a numerical solving of the developed model, an in-depth analysis of damage and deformation fields statistics, including phase averages, second moments, and field fluctuations can additionally be carried out (available in (6)).

The model is further extended by including positive hardening concurrent with damage progression. To this aim a new dissipation potential is proposed leading to a form of J_0 in which damage threshold is affine with damage level.

Performances of the model are illustrated by comparing its predictions for various loads to Finite Element (FE) full-field simulations carried out using a regularized gradient damage model (so-called "phase-field" model, see for instance (7)). A satisfactory agreement between the theoretical model and the FE simulations in terms of macroscopic behavior is first observed. At the scale of constituents, the predictions of the model for the local behavior and stress fluctuations in the matrix are also close to the FE ones. Estimations of the local behavior in the inclusion provided by the model are yet only in a qualitative agreement with the FE ones. At last, as far as damage is concerned, the evolution of d in the model demonstrates a good agreement with the spatial average of the same quantity in FE simulations even though the model equations imply a more progressive and diffuse evolution of damage within the matrix than what the damage patterns of full-field simulations predicts.

In conclusion, a homogenization model able to predict the effective response of elasto-damageable composites was proposed and first validations (by means of Finite Element computations) were provided. Current research efforts are directed toward exploring elastoplastic composites with evolving damage.

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Mean-field micromechanical incremental approaches for brittle damage in particulate microstructures under monotonic loading

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Speaker: Garajeu Mihail. **Thursday**. Start time: **11:00**. Room: Rhône 1 LVL1. Link to abstract.

In this work, two mean-field micromechanical approaches are proposed to determine the effective behaviour of a particulate microstructure where damage occurs in matrix phase. The local behaviour of the phases is derived in the framework of generalised standard materials proposed by P. Germain et al. (1983) and the effective behaviour is obtained by defining an incremental potential in the spirit of N. Lahellec and P. Suquet (2007}, made up of two potentials: the free energy and the dissipation, given in this work by E. Lorentz and S. Andrieux (2003) .

In the first incremental approach, presented in V. Gauthier et al. (2023), the variational formulation is developed by considering in the damaged phase two sub-phases characterised by two damage states at the beginning of each time step. This approach leads to the definition of an elastic nonlinear problem at each time increment but, due to the damage evolution, the corresponding nonlinear potential is non convex. Next, this elastic nonlinear problem is regularised by introducing a linear comparison composite whose features are optimised by taking inspiration from the Full Optimised Second Order approach of P. Ponte-Castañeda (2016). However, the reduction of the number of degrees of freedom of the problem is realised by considering an isotropic linear comparison medium.

The second incremental approach uses a linear comparison medium made by brittle elastic phases, by considering in each time step a quadratic incremental potential depending on both the strain and the damage fields. The inner and outer stationary conditions lead to a system of equations that characterises the effective behaviour and gives fields statistics. Moreover, these equations also provide an uniform damage field in the damaged phase, in each time step. The value of the damage depends on the average of the relaxed stored elastic energy.

The abilities of the proposed approaches are assessed through a particular case. The composite is made up of two elastic phases : the matrix and the inclusions. The inclusions are subjected to a monotonous increasing swelling while the boundary of the RVE is stress free. For this problem, the resulting solutions are given by closed-form expressions. These analytical developments are then used to obtain the effective response of the composite whose dependency on physical parameters (volume fraction of inclusions, toughness of the matrix, elastic contrast...) is then analysed and compared with the results of full fields calculations.

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A closed-form homogenization model for composites made of an elasto-damageable matrix reinforced by rigid particles and for structural computations.

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Speaker: Auslender François. **Thursday**. Start time: **11:20**. Room: Rhône 1 LVL1. Link to abstract.

The present study relies on the elastic damage model derived from nonlinear homogenization by Ben-El-Barguia et al in (1). By specifiying it to composites made of spherical rigid particles in an elasto-damageable matrix, we show that the effective constitutive law of such composites fully comply with the generalized standard material framework and can be described by closed-form expressions for both the macroscopic free energy and the effective dissipation potential. This allows to explicitly analyze the influence of the particles volume fraction on the macroscopic behavior of the composite.
Owing to the above results, the closed-form elasto-damageable model is implemented in a Finite-Element Fenics software in order to analyze the response of different structures made of the considered composite. In order to avoid mesh dependency of the structural responses, predicted by local damage models, a nonlocal extension of the model is proposed following a variational gradient damage approach as in (2,3) and its implementation via an alternate minimization algorithm.

We then carry out structural calculations by means of Fenics on different structures corresponding to an 1-dimensional bar submitted to a tensile stress, a traction of a plate reinforced by a circular rigid particle and a L-shape 2D structure. On the whole, the results exhibit the same following trends for the three structures. An analysis of the fracture paths shows that an increase in the volume fraction promotes both the damage and the fracture propagations, which start and end earlier in time, without changing the final geometry of the fracture path. We also performed an analysis of the influence of the volume fraction on the dissipated energies of the whole structure and found the same conclusions than those derived for the fracture paths. Moreover, the value of the final dissipated energy of the whole structure, i.e. that for which the final fracture path is reached, decreases as function of the concentration.

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The structure tensor field obtained by homogenization with the covariogram

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Speaker: Nait-Ali Azdine. **Thursday**. Start time: **11:40**. Room: Rhône 1 LVL1. Link to abstract.

The study of multi-phase materials such as fiber-reinforced composites, porous structures, and polycrystalline aggregates is essential for understanding and predicting their mechanical and physical behavior. These materials exhibit a high degree of complexity due to their heterogeneity, and the interplay of various phases at the microstructural level governs their macroscopic properties. The primary objective of this research is to characterize the damage behavior of such multi-phase materials by leveraging the intricate details of their microstructure. To achieve this, a non-local variational framework is utilized, offering a sophisticated approach that substitutes traditional characteristic lengths with microstructure-specific descriptions.
The non-local variational framework provides a robust mathematical foundation for modeling the damage behavior of heterogeneous materials. Traditional models often rely on a characteristic length scale to account for non-local interactions, such as the size of a representative volume element (RVE) or the scale of microstructural features. However, this approach can oversimplify the inherent complexity of multi-phase materials. Instead, the proposed framework incorporates a detailed microstructural description tailored to the specific material under study. This shift allows for a more accurate representation of the material's behavior, particularly in cases where microstructural details such as phase distribution, orientation, and connectivity significantly influence damage mechanisms.

One of the standout features of this framework is its ability to conduct computations on "morphologically equivalent" (ME) materials. These ME materials serve as substitutes for high-resolution tomography images, offering a computationally efficient alternative that still preserves the essential microstructural characteristics. By bypassing the need for direct tomography data, this approach simplifies the meshing process, reducing computational overhead while maintaining fidelity to the material's inherent structure. The microstructural description, therefore, becomes the cornerstone of the model, enabling accurate simulations and predictions of material behavior under various loading conditions.

Central to this framework are two powerful tools: the covariogram and the structure tensor field (STF). These tools facilitate the quantitative characterization of the microstructure, enabling the extraction of key parameters and features that define the heterogeneous medium.

The covariogram, also known as geometrical covariance, is a statistical measure that describes the spatial distribution of features within a heterogeneous medium. It captures essential information about the microstructure, including parameters such as:
- Volume Fraction (Vf): The proportion of different phases within the material, which influences overall material properties such as stiffness, strength, and thermal conductivity.
- Inclusion Size: The size of distinct inclusions or phases within the microstructure, which affects the material's mechanical response and damage evolution.
- Repulsion Length (lrep): A measure of the spatial arrangement and interaction of inclusions, indicating the degree of clustering or dispersion within the microstructure.
- Integral Range (A): The distance beyond which the covariogram no longer provides additional statistical information, reflecting the scale of heterogeneity in the material.

These parameters collectively define the material's microstructural landscape, providing a comprehensive description that informs the computational model.

The covariogram also serves as a basis for extracting the material's explicit morphology. By analyzing the inertia matrix derived from the covariogram, researchers can determine the shape and orientation of features within the microstructure. This analysis yields the structure tensor (ST), a mathematical representation that encapsulates the morphological characteristics of the material. The structure tensor

plays a critical role in the reproduction of ME materials, as it enables the accurate replication of the material's microstructural features in computational simulations.

The structure tensor field (STF) extends the concept of the structure tensor to a spatially resolved representation, providing a localized description of the material's microstructure. By computing the structure tensor at each point within the medium, the STF captures variations in morphology and orientation across the material. This localized approach is essential for modeling damage behavior, as it accounts for the heterogeneity and anisotropy of the microstructure.

The STF provides two primary descriptors of the local microstructure:

1. Local Orientation:
Represented by the eigenvector associated with the largest eigenvalue of the structure tensor, the local orientation indicates the predominant directionality of features within the microstructure. This information is critical for understanding anisotropic behavior and directional dependence of material properties.

2. Local Texture:
Quantified using the "coherence factor," a ratio derived from the eigenvalues of the structure tensor. In a two-dimensional context, the coherence factor is given by the formula:

Coherence Factor= (lambda_1 - lambda_2)/ (lambda_1 + lambda_2)

where lambda_1 and lambda_2 are the eigenvalues of the structure tensor. The coherence factor provides a measure of the degree of alignment or isotropy in the local microstructure, with higher values indicating greater anisotropy.

The integration of the covariogram and STF into the non-local variational framework has significant implications for the study of multi-phase materials. By providing a detailed and localized description of the microstructure, this approach enables the development of accurate damage models that account for the material's inherent heterogeneity and anisotropy.

One of the key applications of this framework is the generation of morphologically equivalent (ME) materials. These computational models replicate the essential features of the original material's microstructure, allowing for efficient simulations without the need for direct tomography data. This capability is particularly valuable in cases where experimental data is limited or where high-resolution imaging is impractical.

The use of ME materials also simplifies the meshing process, as the microstructural description provides a clear and detailed representation of the material's features. This streamlined approach reduces the computational resources required for simulations, enabling the study of complex materials and loading scenarios with greater efficiency.

The detailed microstructural characterization provided by the covariogram and STF supports the development of advanced damage models. By incorporating local orientation and texture information, these models can capture the anisotropic and heterogeneous nature of damage evolution in multi-phase materials. This leads to more accurate predictions of failure mechanisms and improved insights into material performance.

While the proposed framework offers significant advantages, several challenges and areas for further research remain. For instance, the accurate determination of covariogram parameters and the computation of the structure tensor field require robust algorithms and high-quality data. Additionally, extending the framework to three-dimensional microstructures introduces additional complexity, particularly in terms of computational requirements and data processing.

Despite these challenges, the potential applications of this framework are vast. From the design of novel composite materials to the optimization of existing structures, the ability to accurately model and predict the behavior of multi-phase materials opens up new possibilities for innovation in materials science and engineering.

Conclusion

The characterization of multi-phase materials through microstructural analysis represents a critical step toward understanding and optimizing their behavior. By leveraging the detailed information provided by tools such as the covariogram and structure tensor field, the proposed non-local variational framework offers a powerful approach for modeling damage mechanisms in heterogeneous materials. The use of morphologically equivalent materials and the emphasis on microstructure-specific descriptions ensure computational efficiency without sacrificing accuracy. As this framework continues to evolve, it holds promise for advancing our ability to design and engineer materials with tailored properties for a wide range of applications.

Time and space multiscale modeling of the high cycle fatigue of thermoplastic polymer solids and structures

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Speaker: Doghri Issam. **Thursday**. Start time: **14:15**. Room: Rhône 1 LVL1. Link to abstract.

The prediction of the high cycle fatigue (HCF) of solids and structures made of thermoplastic polymers faces a double challenge because those materials continue to dissipate energy and exhibit a frequency dependent response even under large numbers of cycles. On the one hand classical simplified methods based on linear elasticity are not applicable, and on the other hand direct structural analyses are so computationally prohibitive that they are not possible in practice. We propose a so-called hybrid formulation, which is theoretically sound, experimentally motivated and computationally efficient. The microstructure is viewed as being made of a viscoelastic (VE) matrix phase with small concentrations of process-induced pores and viscoelastic-viscoplastic (VEVP) weak spots, which have no visible influence on the structural response but are responsible eventually for fatigue failure. The structure is first computed as being VE, using a formulation enabling to compute accurate strain and stress fields at a very reduced cost, which is also independent of the number of cycles. Next, the full VEVP solution at any points of interest is computed with a time homogenization formulation which uses fast and slow time scales and asymptotic time expansions to compute complete solutions at extremely limited cost. The space homogenization of the heterogeneous microstructures is performed via an incremental-secant mean-field homogenization model. HCF is thus modeled via a combined time and space multiscale formulation. The number of cycles to failure at the macroscale is predicted when microscale damage in the weak spots reaches a critical value. Predictions of the hybrid formulation are compared against full reference solutions and their accuracy verifed. Numerical simulations for one million cycles are presented and the low computational cost of the hybrid formulation illustrated. First comparisons of HCF predictions against experimental results are presented.

Effective response of a nonlinear differential laminate assemblage

Willot François (1)

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Speaker: Willot François. **Thursday**. Start time: **14:35**. Room: Rhône 1 LVL1. Link to abstract.

We derive closed-form expressions for the effective conductivity of a class of powerlaw "differential" laminates in arbitrary dimension, studied in a previous work (Idiart and Ponte Castañeda 2013). Emphasis is put on the weakly and strongly nonlinear regimes, and on the asymptotic behavior of such composites in the "dilute limit" of a vanishingly small volume fraction of one of the two phases. In the strongly nonlinear limit, we examine the behavior of these solutions as the partial derivative equations loose ellipticity. We provide a geometric interpretation of our results in terms of field localization. We examine the behavior of the solutions at increasing dimensions and whether they could represent bounds. Finally, we discuss implications to the mechanics of composites.

On power scaling laws dictating the mechanics of porous materials

Rege Ameya (1)

1 - University of Twente (Netherlands)

Speaker: Rege Ameya. **Thursday**. Start time: **14:55**. Room: Rhône 1 LVL1. Link to abstract.

The mechanical, thermal, and acoustic properties of porous materials exhibit a power law relationship with their density or solid fraction. Thus, it is generally assumed that density is the critical parameter dictating the properties in the case of open-porous cellular materials. The Gibson and Ashby open-cell foam model derives a quadratic relation between the Young modulus and density for the case of such open-porous cellular materials (1). This relationship is validated against several foam-like materials. However, many novel materials such as aerogels or porous graphene demonstrate scaling exponents around 3.0 or 3.5. To design such materials for tailired applications, it becomes imperative to understand the origins of this unusually high scaling exponents. Thus, the effect of pore-size distributions, pore-wall morphology and the network connectivity of the solid material through the porous space is computationally investigated. The results demonstrate that the unusually high scaling exponents emerge from the network connectivity of the material (2). This aspect will be further explored.
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Some applications of a variationally consistent multi-scale model for microstructures displaying voids on boundary

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Speaker: Rocha Felipe. **Thursday**. Start time: **15:15**. Room: Rhône 1 LVL1. Link to abstract.

Materials displaying microstructures with random porous distribution are found in a myriad of ways in nature and engineering applications: foams, bones, reservoirs, architectured materials with defects, etc. Minimally constrained multiscale models (Reuss-like for solid mechanics) losses the well-posedness when voids reach the boundary in a non-periodic fashion (situation which the convenient periodic boundary conditions cannot be applied). Generally, only linear boundary models (Voigt-like) can be straightforwardly applied in such cases, notwithstanding the well-known drawback of overstimation of effective stiffness. Hence, we investigate a novel multiscale mechanical formulation based on a proper formulation of a generalised minimally constrained multi-scale model that remedies this issue for general combination of solid and void parts on the boundary, as recently proposed in (1). The Method of Multiscale Virtual Power serves as the foundation for developing the proposed model, with particular focus on reformulating the gradient homogenisation formula (6). This reformulation leads to the development of not only a novel Minimally Constrained Kinematical Multiscale Model but also inspires a broader family of multiscale models suited for practical scenarios. The key ingredient is the introduction of an averaged boundary normal vector modifying the point-wise normal appearing in the non-local kinematical constraints arising in fibre networks (2). Although special attention is given to the classical first-order theory of solid mechanics at continua, the present method can be straightforwardly adapted ot other applications, including strain-gradient of architected materials with defects (4), homogenisation of fibres networks (2) and fluid saturated porous media (5). Implementations aspects of such generalised kinematical constraint will be discussed in the context of FEniCSx-based opensource implementation (3). Several numerical examples demonstrating the potentialities of such method are also addressed.

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Asymptotic homogenization of rough elastic surface

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Speaker: Singh Vivek. **Thursday**. Start time: **15:35**. Room: Rhône 1 LVL1. Link to abstract.

Consider an elastic medium, which consists of a periodic arrangement of heterogenities on a surface. Such geometry has been explored for applications in acoustics and electromagnetics using the interface homogenization method. The elastic application of such configuration needs to be studied in detail. The bottleneck with the study of such complex configuration is the requirement of large computational resource for capturing the rapid variation of the displacement field in the complex microstructural region using an extremely fine mesh. The present study deals with the homogenization of a thin elastic rough surface, thereby resolving the related computational issue. The study considers a linear elastic material and the homogenization model is based on the matched asymptotic expansion technique. The actual problem consists of a material block with rough surface consisting of periodic arrangement of voids/defects (having periodicity p) and the surface is subjected to mixed boundary condition. When the void/defect periodicity at the surface is much smaller than the macroscopic length L ($p << L$), we get an effective problem with an effective boundary condition at the bottom. The homogenization model is validated by comparison with results from the full-field finite element simulations.

Acoustic/elastic Willis media and their dynamic homogenization

Hu Gengkai (1)

1 - School of Aerospace Engineering, Beijing Institute of Technology (5 South Zhongguancun Street, Haidian District, Beijing China)

Speaker: Hu Gengkai. **Thursday**. Start time: **15:55**. Room: Rhône 1 LVL1. Link to abstract.

Elastic (or acoustic) Willis medium refers to a generalized medium with coupling between stress and particle velocity, momentum and strain, similar to bianisotropic materials for electromagnetic waves. The Willis coupling coefficient is mainly originated from asymmetric (local), or non-local interaction of material microstructure or active materials. The special coupling relationship endows Willis media stronger wave control capabilities, but their microstructure design still faces huge challenges. The talk will introduce relevant progress. First, for a two-dimensional spring-mass system, I will explain how to customize the elastic local Willis coupling coefficients through unit cell design, and validate the design through examining asymmetric reflections unique for Willis materials. Then I will present a nonlocal dynamic homogenization scheme based on the multiple scattering method for acoustic metamaterials, two types of acoustic interface waves are predicted and verified through experiments.

Twinning and pneumatic actuation in porous elastomers

Ponte Castaneda Pedro (1), Caulfield Peter J. (1)

1 - Mechanical Engineering and Applied Mechanics, University of Pennsylvania (United States)

Speaker: Caulfield Peter J.. **Friday**. Start time: **10:00**. Room: Rhône 1 LVL1. Link to abstract.

It is known that constitutive models for the large-deformation response of porous elastomers can develop "macroscopic" instabilities as a consequence of loss of strong ellipticity. Indeed, constitutive models obtained by homogenization methods for porous elastomers with periodic and random microstructures can lose strong ellipticity under appropriate loading conditions. For periodic microstructures, it has been shown theoretically, and verified experimentally and numerically, that "microscopic" instabilities consisting in solutions that are periodic on ensembles of unit cells tend to occur before the long-wavelength "macroscopic" instabilities that are captured by the loss of strong ellipticity of the homogenized response. But what about the response of porous elastomers with random microstructures? In this case, microscopic instabilities can be excluded, and the question then arises as to what happens after the onset of a macroscopic instability. Building on earlier work for reinforced elastomers, it is shown here that porous elastomers can undergo twinning after the onset of a macroscopic instability. For this purpose, use is made of a generalized Maxwell-type construction arising from the theory of relaxation and applied to linear comparison variational homogenization estimates for a certain class of two-dimensional porous elastomers consisting of aligned cylindrical pores in a rubber matrix subjected to plane strain loadings. It is shown that such porous elastomers recover Legendre-Hadamard stability by twinning after the onset of a macroscopic instability. Interestingly, the porous elastomers behave like elastic fluids in the twinned region, losing their ability to support shear stresses. Corresponding homogenization estimates for the macroscopic response when the pores are subjected to an externally applied pressure are also obtained and the implications for actuation purposes discussed.

Buckling mechanisms in reticulated structures.

Antczak Stanislas (1), Boutin Claude (1), Rallu Antoine (1)

1 - LTDS (France)

Speaker: Antczak Stanislas. **Friday**. Start time: **10:20**. Room: Rhône 1 LVL1. Link to abstract.

This paper deals with the buckling of periodic reticulated structures formed by rigidly connected beams. Using the Moreau and Caillerie (1998) method of homogenization of discrete periodic media, the aim is to establish analytical models that allow us to identify the global, localized or distributed nature of the buckling and the associated critical loads. Following a pre-critical incremental approach (as in Triantafyllidis and Schnaidt, 1993), the procedure consists of (i) pre-integrating the equilibria of each beam in its deformed configuration under the axial load that it supports, then (ii) expressing the equilibria at the nodes, leading to a discrete (finite-difference) formulation parameterized by the load(s). Under the assumption of scale separation between the characteristic length of the buckling mode and the size of the elementary cell, different equivalent continuous media asymptotic models are thus derived, according to the contrasts between the stiffnesses of the elements. To determine the critical loading, the boundary conditions applied to the real finite-dimensional structure must be expressed in a form compatible with the equivalent model, so that the macroscopic description is well-posed. Solving the resulting eigenvalue problem allows us to predict the nature of the buckling, as well as its shape and critical load. These developments have been implemented for ladder beam structures, subjected to normal and moment loads. The analytical results obtained by this method are in good agreement with those obtained by full finite element calculations.

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The role of fiber plasticity on the onset of macroscopic instabilities in soft biological composites

Agoras Michalis (1), Fontenele Fernanda (2), Bouklas Nikolaos (2)

1 - University of Thessaly [Volos] (Greece), 2 - Cornell University [Ithaca] (United States)

Speaker: Agoras Michalis. **Friday**. Start time: **10:40**. Room: Rhône 1 LVL1. Link to abstract.

The main objective of this work is to shed light on the role of fiber plasticity on the onset of macroscopic instabilities in soft biological materials. For simplicity, we restrict our analysis on a class of two-phase laminates which are regarded as 2-D approximations of the actual fiber-reinforced composites of interest. We first develop a general homogenization framework, allowing for finite elastic and plastic strains in the constituent phases of the laminate, as well as for arbitrary 3-D loading conditions. This framework is then used to study the onset of long-wavelength instabilities in these composites, as captured by the loos of ellipticity (LOE) of their homogenized or macroscopic behavior. Attention is focused on plane-strain loading conditions on a plane perpendicular to the layers. For the special case of uniaxial loading along the direction of the layers, it is shown that the condition for macroscopic LOE simplifies considerably and admits the interpretation that, just like hyperelastic laminates, elastoplastic laminates loose macroscopic ellipticity when their incremental strength in shear transverse to the layers vanishes for the first time. The effect of fiber plasticity is modeled by taking the elastically stiffer phase (fibers) to exhibit elastoplastic behavior and the other phase (matrix) to be a purely elastic solid. A detailed study of the macroscopic behavior of these laminates is carried out for the case of non-monotonic loading conditions along the fiber direction, consisting of an initial tensile loading stage, followed by unloading to the macroscopically unstressed state, and a final compressive loading stage. Fiber plasticity is found to have a softening effect on the transverse shear modulus of the laminate under increasing loading and a hardening effect under decreasing loading, whereas elasticity has the opposite effects. Thus, the effects of local elastic and plastic deformations compete with each other at every stage of the deformation where both mechanisms are active, and whether or not the laminate will ultimately loose macroscopic ellipticity depends crucially on the relative strengths of these effects. It is found that macroscopic LOE may occur under positive (extensive) macroscopic strains along the fiber direction, during the compressive loading stage. It is also found that macroscopic LOE may take place under either purely elastic or elastoplastic incremental deformations, depending on the maximum strain applied during tension, the volume fraction and local material properties of the constituent phases.

Homogenization method applied to the mechanical behavior of the active zone of a Proton Exchange Membrane Fuel Cell

Mons-quendo Fabien (1), Kawka Sébastien (1), Blachot Jean-françois (1), Poirot-crouvezier Jean-philippe (1), Carral Christophe (2), Mele Patrice (2)

1 - Univ. Grenoble Alpes, CEA, Liten, DEHT (France), 2 - Laboratoire d'Electrochimie et de Physico-chimie des Matériaux et des Interfaces (France)

Speaker: Mons-Quendo Fabien. **Friday**. Start time: **11:00**. Room: Rhône 1 LVL1. Link to abstract.

Proton Exchange Membrane Fuel Cells (PEMFC) consist of a stack of cells. A sealing zone is located at the periphery of the cell, while the electrochemical reaction occurs at the center of the cell. This latter is referred as the "active zone"; the cell consists of an assembly of two components: the BiPolar Plates (BPPs) are used to facilitate the flow of the reactants to the Membrane Electrode Assembly (MEA). The MEA consists of a porous media, called the Gas Diffusion Layer, a Catalyst Layer and a Proton Exchange Membrane (PEM). The cells are then clamped together using End Plates (EP). This process is essential and must provide sufficient clamping pressure to seal the device with optimal compression of the active zone (1).
The components have disparate thickness scales, ranging from a few micrometers for the catalysts layers to tens of centimeters for the stack. To improve PEMFC performance, it is necessary to understand the associated complex mechanical behavior that occurs from the land/channel pattern through the entire device during the clamping process and operation. Numerical simulation using the finite element method is an effective tool to achieve this objective. In the literature, there are numerous 2D models to understand the impact of the assembly pressure on the MEA (2). However, only a limited number of studies have focused on the spatial stress heterogeneities resulting from clamping (3). The main challenge in simulating the whole stack is to reduce the computational time. In fact, this patterned compression generates a significant number of contact. Moreover the mechanical behavior of the porous media is highly nonlinear, with irreversible strain under cyclic compression (4), and the difference in thickness between all components generates a considerable number of degrees of freedom. Therefore, a homogenization method was chosen in this study to limit the computation time while maintaining high accuracy of macroscale calculations. It also provides information on the stress and strain levels on a smaller scale (5).

This study proposes an original approach to homogenize the mechanical behavior of the active zone, by integrating the non-linear and irreversible behavior of the GDL. The homogenized model is then compared with experimental data. Finally, it is implemented in a stack model to demonstrate the importance of clamping process control on system performance by identifying the zones where the heterogeneities occur during operation.

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Microvia homogenised behavior for the mechanical modelling of PCB with embedded components

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Speaker: Dailland Flora. **Friday**. Start time: **11:20**. Room: Rhône 1 LVL1. Link to abstract.

The transition to "all-electric" is leading to a growing demand for power electronics. In order to include more components in an ever-smaller volume, the embedding of active components in the core volumes of printed circuit boards (PCBs) appears to be a suitable solution (Huesgen 2022) (Bouarroudj 2023). There are various technologies for embedding components, such as chip-on cavity technology (R. Aschenbrenner 2000), chip-on-substrate technology (Tao-Chih Chang 2015) or double-side-microvias (Huesgen 2022). The interconnection in these technologies is usually ensured by microvias (John H. Lau 2000) which provides good electrical and thermal contact between PCB and component. However, incorporating a ceramic chip (Silicon or Silicon Carbide) inside the printed circuit board can lead to new failure mechanisms occuring during the thermal cycle or when the device is active (Young Todd 2000) (Maarten Cauwe 2022). The interface response between the chip and the microvia needs particular attention (Birch 2009) (Li-Na Ji 2010).
In the present work, the embedded chip is connected by multiple microvias while classical SMT (Surface Mounted Technology) used solder paste. A centimetre-sized chip can accommodate several hundred of microvias. Numerical modelling of such a structure using finite element method (FEM) is unrealistic because of the extremely time-consuming nature of meshing operation and calculations. Then we propose to replace the microvia structure and the FR4 material in its neighbourhood by its homogenised thermomechanical response (W. Kpobie 2014).

Lots of homogenisation methods exist in literature for heterogeneous materials containing ellipsoidal inclusions (Eshelby 1957) (Hill 1963) (Mori et Tanaka 1973). The microvia geometry is complex, so no analytical solution is available for the microvia shape. Then a numerical study is compulsory. In the present work, the Representative Volume Element (RVE) is referred to as the elementary pattern of a periodic medium describing the chip interconnexion method. The periodicity of the medium is reproduced from the RVE using Periodic Boundary Conditions (PBC). After calculation, the elastic response of the microvia structure is found to be orthotropic.

The homogenised mechanical response of the microvia is next implemented in finite element model of different configurations facing thermal cycles from -55∘C to 125∘C. Simulations where the microvia is geometrically represented are carried out at the same time. Average quantities (stress and strain) at the level of the RVE are compared between the two configurations to validate the homogeneous model.

Predictive capabilities of the present work are illustrated for two classical configurations in the PCB industry. First a grid of 9 microvias connected to a component made of silicon is subjected to thermal cycles. It is found that adopting the homogenised response for eight microvias does not change much the mean stress and strain faced by the central microvia. In the second case, three stacked microvias are considered. Once again, the overall response for each level of microvias is well reproduced.

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MS3.2 - Material Instabilities

Organisers: Odd Sture Hopperstad (NTNU, Norway) and Henryk Petryk (IPPT Pan)

Material instability in ductile multiphase materials – a computational micromechanics study

Peerlings Ron (1), Rezazadeh Vahid (1), Geers Marc (1)

1 - Eindhoven University of Technology (Netherlands)

Speaker: Peerlings Ron. Keynote. **Tuesday**. Start time: **16:35**. Room: Saint Clair 4 LVL2. Link to abstract.

Man-made materials tend to be either strong or ductile. Many applications, however, require strength and ductility. Materials producers attempt to meet these conflicting requirements by developing materials with microstructures which consist of two or more phases — often hard but brittle particles embedded in a soft and ductile matrix. Whereas multiphase microstructures show promising properties, the full potential of this concept to have 'the best of both' cannot yet be exploited because of an incomplete understanding of their failure properties. Given their intrinsically complex microstructure, the failure mechanisms of multiphase materials are also complex. Microcracks and microvoids may be nucleated in the hard or soft phase, or at their interface. They subsequently show a tendency to propagate and coalesce via the soft phase, ultimately resulting in the initiation of a macroscopic crack. All of these stages have been observed to depend heavily on the properties of the phases, their volume fractions and their morphology — as well as on the precise, local loading conditions.
The objective our study is to provide some clarity in this overwhelming picture of competing, heavily interdependent candidate mechanisms and paradoxical experimental observations.

We approach the problem at an abstract level, using a highly idealised micromechanical model which includes only the key features of the microstructure, including the key microstructural failure mechanisms. The model assumes the phases to be randomly distributed in a square grid and defines two competing failure mechanisms – one for each phase. Its simplicity serves multiple purposes, as it (i) greatly facilitates the interpretation of results, (ii) allows one to run many (hundreds of) realisations, thus generating statistically meaningful datasets, and (iii) enables a wide range of parameter variations, in order to study the influence of the parameters of the system on the outcome of the competition. Despite its simplicity, the model captures, and helps to explain, the trends predicted by much more complex models as well as observations made in experiments.
Specific questions which we aim to answer in this study are: (i) How do pre-existing defects affect the strength and ductility of multiphase materials? (ii) What determines the outcome of the competition between global and local ductility? (iii) How does formability of these materials depend on stress state – in particular on stress triaxiality and Lode angle?

Multiple necking in an expanding metal ring: polycrystal plasticity approach and texture influence

Dequiedt Jean-lin (1) (2)

1 - CEA, DAM, DIF (France), 2 - LMCE (France)

Speaker: Dequiedt Jean-Lin. Invited. **Tuesday**. Start time: **17:15**. Room: Saint Clair 4 LVL2. Link to abstract.

The onset of plastic strain localization in a metal ring under dynamic expansion in the form of multiple necking is classically analyzed at the macroscopic scale as a consequence of the development of unstable perturbation modes of the structure. However, the polycrystalline material microstructure influences the necking process since the inherently heterogeneous deformation at the mesoscale, due to the difference of grain orientations, initiates the development of instability modes. Simulations of stretching copper rods mimicking a piece of an expanding ring is performed with a crystal plasticity finite element code in which a Voronoï tessellation algorithm reproduce the grain structure. A Teodosiu type constitutive law taking dislocation densities as internal state variables rules single crystal behavior and the evolution of critical shear stresses is governed by the slip system interaction matrix identified by Madec and Kubin (2017). For an initial isotropic texture and a prescribed mean grain size, the variability of neck locations and amplitudes can be significant between different grain sets. On the contrary, a pronounced texture, which reduces grain orientation heterogeneity, modifies the neck development in terms of timescale and usually yields more regularly spaced neck positions. Another interest of crystal plasticity simulation is to model in-grain slip activity in highly deformed necks that may drive their subsequent failure. In such grains, lattice rotation is significant and the set of activated systems continuously evolve leading to non-monotonous increase of critical shear stresses before saturation by dynamic recovery.

Incorporating strain localization into porous plasticity modelling of ductile failure in aluminium alloys: a combined experimental and numerical study

Espeseth Vetle (1), Morin David (2), Børvik Tore (3), Hopperstad Odd Sture (2)

1 - Multiconsult (Norway), 2 - Norwegian University of Science and Technology (NTNU), Faculty of Engineering, Department of Structural Engineering, Structural Impact Laboratory (Norway), 3 - Norwegian University of Science and Technology (NTNU), Faculty of Engineering, Department of Structural Engineering, Structural Impact Laboratory (SIMLab, NTNU) (Norway)

Speaker: Morin David. Invited. **Tuesday**. Start time: **17:35**. Room: Saint Clair 4 LVL2. Link to abstract.

In this study we investigated, both experimentally and numerically, the ductile tearing of aluminium plates made of the 6016 alloy in three different tempers (T4, T6 and T7). The three alloys were characterized by means of notched tension specimens as well as single edge notched specimens under quasi-static loading conditions. Those experiments were simulated with an enriched Gurson-Tvergaard-Needleman model to describe the plastic flow and ductile failure of the investigated alloys. To incorporate strain localization into the constitutive model, two approaches were employed to trigger accelerated void growth: in-situ bifurcation analysis and a material softening criterion. Both methods demonstrated good agreement with experimental observations, effectively capturing failure initiation and crack propagation.

Observation and simulation of the Portevin-Le Chatelier effect at the grain scale in a polycristalline Nickel based superalloy

Billon Florian (1) (2) (3), Renollet Yves (3), Barres Quentin (3), Vattré Aurélien (3), Zambelli Sylvain (2), Al Kotob Moubine (2), Mazière Matthieu (1), Forest Samuel (1)

1 - Mines Paris - PSL (École nationale supérieure des mines de Paris) (France), 2 - Safran Aircraft Engines, Division Mécanique des Matériaux (France), 3 - ONERA (France)

Speaker: Billon Florian. **Tuesday**. Start time: **17:55**. Room: Saint Clair 4 LVL2. Link to abstract.

The Portevin-Le Chatelier (PLC) effect is a plastic instability phenomenon characterised by a fluctuating evolution of the flow stress, the formation of plastic strain rate localisation bands within the specimen, and a negative strain rate sensitivity during tensile tests. These manifestations occur within specific temperature and strain rate ranges due to dynamic strain ageing (DSA), which arise from the dynamic interaction between mobile dislocations and diffusing solute atoms. The microscopic origin of this effect and its macroscopic consequences are now well understood, and models are available to simulate the jerky flow using finite element simulations (1), (2). Nevertheless, the investigation of the PLC effect at an intermediate scale, such as the polycrystalline aggregate, remains less explored. In particular the emergence of plastic localisation in the grains and the impact of the PLC effect on the local mechanical behaviour require further investigation. Consequently, the present study aims to provide both experimental observations and modelling of the PLC effect in a nickel based superalloy, in this case an Inconel 718, within the framework of crystal plasticity.
In-situ scanning electron microscopy (SEM) experiments were conducted to observe the PLC effect in polycrystalline aggregates. These experiments capture the intermittency of plastic deformation, along with pronounced heterogeneities and strain localisation patterns at this scale. These observations highlight the critical role of microstructural interactions in the emergence of the PLC effect. To complement these experimental insights, a finite element crystal plasticity model was built to simulate the mechanical behaviour of the polycrystalline aggregates. This model builds on the classical crystal plasticity framework by incorporating the Kubin-Estrin-McCormick (KEMC) model, which accounts for the influence of dynamic strain ageing in the isotropic hardening rule (3). The simulations reproduce key features of the PLC effect, such as deformation intermittency and localised plasticity.

By combining experiments with advanced modeling, this work offers new insights into the mechanisms driving the PLC effect and provides valuable tools for understanding its implications on material behavior.

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Strain localization in thermo-viscoplastic materials

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1 - Indian Institute of Technology Madras (India)

Speaker: Tripathy Alok. **Tuesday**. Start time: **18:15**. Room: Saint Clair 4 LVL2. Link to abstract.

Experimental studies in the literature have often reported formation of strain localization bands, driven by plastic instability, prior to fracture in ductile materials. The onset of localization depends on various factors such as the loading conditions, specimen geometry, strain hardening, strain rate sensitivity and softening due to damage growth and/or adiabatic heating. The critical strain at the onset of localization provides an accurate estimate of the ductility of the material. Analytical models have been developed to predict the critical strain in the quasi-static rate-independent limit (1), under isothermal conditions, using the loss of ellipticity criterion for the equilibrium equations. However, in the rate-dependent case, the equilibrium equations do not lose ellipticity for elastically stiff materials.

Several authors have used a linear perturbation stability analysis to predict the onset of strain localization in rate sensitive materials under dynamic loading conditions. Strain localization occurs when the growth rate of the applied perturbation is large compared to the rate of change of the field quantities. The calculation of the perturbation growth rate is, however, a computationally expensive process and hence not suitable for implementation in finite element codes for fracture simulations. In our work, a close form localization criterion is derived assuming a general form for the plastic potential, that can be specialized to several practical material models. The derived criterion is shown to reproduce several known results from the literature as special cases.

The fracture mechanism in ductile materials involves the nucleation, growth and coalescence of microvoids. However, localization analyses performed using the widely used Gurson model (2) leads to predictions of unrealistically large failure strains under general loading conditions. This can be attributed to the assumption of dilute porosity in the Gurson model, which ignores the strong interactions between neighboring voids that manifest at finite porosities. Here, a recently developed model of 'inhomogeneous' yielding at the micro-scale of the voids (3), accounting for internal necking and shearing of the inter-void ligaments, is used to perform the strain localization analysis. The predictions of the resulting failure criterion are compared against periodic unit cell model simulations of ductile failure by void growth under proportional loading conditions. The analytical results are found to be in good agreement with the cell model simulations for varying strain rates, strain hardening, strain rate sensitivity and thermal softening exponents. The developed criterion is implemented as a user defined failure criterion in the finite element code, Abaqus. Fracture simulations for notched bars subjected to quasi-static & dynamic loading, ballistic penetration and machining are compared against available experimental data in the literature.

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Wrinkling and Creasing in Crystalline Metals under Bending

Kyriakides Stelios (1), Haley Jake A.

1 - University of Texas at Austin [Austin] (United States)

Speaker: Kyriakides Stelios. Keynote. **Wednesday**. Start time: **10:00**. Room: Saint Clair 4 LVL2. Link to abstract.

Creasing first reported by Gent (1999) in elastomers under bending has been extensively studied and widely predicted numerically for elastomeric materials. This presentation uses experiments and numerical simulations to show that creasing is a mode of failure for metal alloys as well. The creasing was observed in the concertina folds of axially crushed aluminum 6061-T6 tubes. As is well known, the folding can lead to tensile fracture and tearing. However, it has been observed that concurrently the compressed sides of the folds tend to develop wrinkles that lead to cleft-like features. Careful microscopic examination showed that, as the bending in the folds increases, the amplitude of the wrinkles increases and they evolve into folds, creases, and dangerous sharp discontinuities. Metallographic examination of axial sections of axisymmetric concertina folds of several tubes revealed that the surface wrinkles encompass several grains, which deform and conform to the imposed local geometric changes. This implies that this surface instability is mainly governed by continuum level kinematics. The grain deformation conforms to the growth of the wrinkles, to the subsequent folds, and to the early stages of creasing that follows. As the creases deepen and develop into clefts, the highly deformed microstructure appears to interact more strongly with these surface features.

The events observed in the experiments were simulated using an axisymmetric finite element analysis of the concertina folding in a tube under axial compression. An independently calibrated non-quadratic anisotropic constitutive model is used to model the elastic-plastic behavior of the material. The analysis simulates successfully the development of several concertina folds in the model tube. Special attention is paid to the evolution of surface instabilities on the intrados of one of the folds, which was discretized with a sufficiently fine mesh. Instability was primed by the introduction of measured surface roughness to the inner surface of this fold. As the local compressive strain reaches a level of about 50%, surface wrinkles develop, and as the local bending increases, their amplitude grows. With additional bending, the wrinkles evolve into local folds and creases that resemble surface features observed in the experiments. The presentation will use details of the experiments and the microscopic evaluation of the surface wrinkles, clefts, and creases to motivate the numerical modeling performed, and will discuss the sensitivity of the surface instabilities on model parameters.

Interaction of instabilities and functional degradation in shape memory alloys: a macroscopic modeling study

Rezaee Hajidehi Mohsen (1), Ryś Maciej (1) (2)

1 - Institute of Fundamental Technological Research (Poland), 2 - National Centre for Nuclear Research [Otwock] (Poland)

Speaker: Rezaee Hajidehi Mohsen. **Wednesday**. Start time: **10:40**. Room: Saint Clair 4 LVL2. Link to abstract.

Instabilities play a crucial role in stress-induced martensitic transformations in polycrystalline shape memory alloys (SMAs). Under tension-dominated loading, instabilities often manifest as localized martensite bands, which, with continued loading, evolve into patterned interfaces that separate the austenite and martensite domains. The localized martensitic transformation is inherently a multiscale phenomenon that appears at both the micro (grain) and macro (specimen) levels. At each level, pronounced strain incompatibilities are induced within the interface regions, which, in turn, give rise to large local stresses. Microscopically, localized interfaces are known to be the main source of microstructural defects, such as dislocations and locked-in martensite (1). On the other hand, macroscopic localization can accelerate the degradation of the functional properties and significantly impact the functional/structural fatigue behavior under cyclic loading (2). In this work, we aim to elucidate the interplay between macroscopic strain localization (structural-level inhomogeneities) and the functional degradation of SMAs. To this end, a macroscopic model of functional fatigue is developed, integrating two key capabilities: the ability to capture the functional degradation, which is incorporated into the materials' constitutive relations, and the ability to capture transformation localization, which is incorporated by adopting a softening-like response combined with the enhancement of the free energy function with gradient terms. The phenomenon of return-point memory observed during the subloop deformation of a partially-transformed NiTi specimen is a clear manifestation of the structure-material (localization-fatigue) interaction and is analyzed as an illustrating example (3). Subsequently, the analysis is extended to explore the low-cycle fatigue behavior of NiTi tubes characterized by cyclic localized transformation.

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The effect of microstructural inertia on plastic localization and void growth in porous solids

Hosseini Navab (1), Virazels Thomas (1), Jacques Nicolas (2), Rodríguez-martinez José A. (1)

1 - University Carlos III of Madrid (Spain), 2 - ENSTA Bretagne (France)

Speaker: Rodríguez-Martinez José A.. Invited. **Wednesday**. Start time: **11:00**. Room: Saint Clair 4 LVL2. Link to abstract.

This paper investigates the impact of microinertia on plastic localization, void growth, and coalescence in ductile porous materials subjected to high strain rates. For that purpose, we have performed finite element calculations on a flat double-notched specimen subjected to dynamic plane strain tension. The simulations employ three distinct approaches to model the mechanical behavior of the porous aggregate: (1) discrete voids within a matrix material governed by von Mises plasticity; (2) homogenized porosity represented using standard quasi-static Gurson-Tvergaard plasticity; and (3) homogenized porosity described with Gurson-Tvergaard plasticity extended by Molinari and Mercier (2001) to account for microinertia effects. The porous microstructures used in the simulations are representative of additive manufactured metals, featuring initial void volume fractions varying between 0.5% and 4%, and pore diameters ranging from 30 μm to 150 μm (Marvi-Mashhadi et al., 2021; Nieto-Fuentes et al., 2023). The applied tensile velocities ranged from 100 m/s to 1000 m/s, producing strain rates between 105 s–1 and 106 s–1, and stress triaxiality values spanning from 4 to 30. The simulations with discrete voids validate the calculations performed using homogenized porosity and microinertia effects, demonstrating that higher strain rates and larger pore sizes lead to slower void growth and a delayed, regularized plastic localization. Conversely, the standard Gurson-Tvergaard model shows notable mesh sensitivity and fails to describe the influence of the loading rate on plastic localization. Ultimately, the comparison between finite element models with discrete voids and those with homogenized porosity illustrates the stabilizing effects of porous microstructure and multiscale inertia on dynamic plastic flow, while also highlighting the strengths of the constitutive model introduced by Molinari and Mercier (2001) for simulating engineering problems involving porous ductile materials subjected to high-velocity impacts.

Yield surface modeling for failure prediction in turbine disk applications

Barrot Elodie (1) (2) (3), Feld-payet Sylvia (3), Forest Samuel (1), Rose Tonya (2), Al Kotob Moubine (4), Zambelli Sylvain (4)

1 - Centre des Matériaux Mines Paris, PSL University CNRS UMR7633 (France), 2 - Safran Tech, Failure Analysis and Multiscale Engineering (France), 3 - DMAS, ONERA, Paris Saclay University, F-92322 Châtillon (France), 4 - Safran Aircraft Engines, Division Mécanique des Matériaux (France)

Speaker: Barrot Elodie. **Wednesday**. Start time: **11:20**. Room: Saint Clair 4 LVL2. Link to abstract.

The plasticity criterion has been shown to strongly influence the global behavior of a rotating aeronautical turbine disk and its expected burst speed (1). Moreover, yield surfaces can evolve very rapidly with plastic strain. Their accurate knowledge is thus essential to accurately predict the behavior of a part subjected to multiaxial loading such as the turbine disk. Three characteristics of the yield locus have to be modeled: the center's movement (kinematic hardening), the size change (isotropic hardening) and a modification of its overall shape (distortional hardening). Furthermore, the material's failure is characterized by local ductile fracture and it has been shown previously that the curvature of the yield surface strongly influences the strain localization (2). Thus, this work aims to precisely reproduce the subsequent yield surfaces in order to predict accurately the failure of the turbine disk.

In this study, the shrinkage of the yield surface of a nickel-based superalloy after tensile loading has been demonstrated experimentally. Firstly, loading-unloading experiments with plasticity threshold detection on an axisymmetrical sample were conducted in order to investigate the material's hardening in the tensile direction and fine-tune the plasticity detection technique. Then, the subsequent yield surfaces were obtained through axial-torsional loading on a thin-walled tubular sample for various pre-strains from small to finite deformation. The subsequent yield surfaces exhibits an egg-shaped distortion, strong kinematic hardening and a very fast reduction in size. A cross-effect was also visible with a size reduction in the direction perpendicular to the loading direction.

Two material behavior laws have been identified on test results and used in this study. One model uses Hosford's macroscopic phenomenological plasticity criterion whereas the second model is an homogenized polycrystalline model. The use of polycrystalline plasticity models enables the numerical reproduction of yield surface distortion effects observed experimentally for all loading paths thanks to the model's proximity to the physical mechanisms at the origin of the plasticity. The prediction of the local field's redistribution of these models was then studied through the comparison between experimental fields measured via digital image correlation techniques on a flat notched specimen and finite element analysis results carried out with the Zset software.

Finally, the prediction of the strain localization obtained through the application of the loss of ellipticity criterion to finite element simulation results has been compared to experimental failure for both samples and the turbine disk. Special attention was paid to the effect of corner formation on the yield surface.

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On the criteria for material instability in rate-independent plasticity

Petryk Henryk (1), Kursa Michal (1)

1 - Institute of Fundamental Technological Research, Polish Academy of Sciences (IPPT PAN), Warsaw, Poland (Poland)

Speaker: Petryk Henryk. Invited. **Wednesday**. Start time: **14:30**. Room: Saint Clair 4 LVL2. Link to abstract.

In solving rate-independent plasticity problems at finite deformation, there is an inherent difficulty related to the non-uniqueness of incremental solutions and the instability of a deformation path. Of particular interest is the material instability, which manifests itself in deformation patterns and microstructure formation, regardless of external loading conditions. In rate-independent crystal plasticity, this phenomenon generally occurs when the effective hardening moduli matrix is indefinite due to cross-hardening of the slip systems greater than their self-hardening. The commonly used criterion of ellipticity loss has limited application because it is based on the assumed linearized relationship between the stress and strain rates and thus excluding unloading. In contrast, the analysis here also covers the onset of a laminate deformation pattern corresponding to different unloading modes in dfferent bands.
Material instability can also be understood in a thermodynamic sense and investigated using the Lyapunov direct method. To eliminate the influence of external loading conditions, displacements at the boundary of a deforming material element can be considered undisturbed. Then, in a quasi-static isothermal deformation process, the total internal energy increment of the thermodynamic system can be decomposed into the sum of the free energy and dissipation increments. It depends not only on the incremental displacement field, but also on the fields of other incremental variables, such as plastic multipliers or the increment of internal variables. The circumstances under which the energy increment satisfies the Lyapunov conditions for stability or instability are specified and discussed. If multiple solutions exist, which is common in rate-independent plasticity, then incremental energy minimization or quasi-minimization can be used to automatically select among them in simulations, in the potential case or non-potential case, respectively.
The effectiveness of this procedure is illustrated by the examples of large deformation of an fcc metal crystal. Along the stable solution paths, the number of simultaneously active slip systems never exceeded five. In uniaxial tension in a high-symmetry orientation, as opposed to rate-dependent models, only single or double slip activity is predicted due to the instability of the fully symmetric strain path.

Deformation patterns in finite strain crystal plasticity

Scherer Jean-michel (1)

1 - Centre des Matériaux (France)

Speaker: Scherer Jean-Michel. **Wednesday**. Start time: **14:50**. Room: Saint Clair 4 LVL2. Link to abstract.

It has been known since at least Piercy et al. (1955) (1), that the interaction between dislocations gliding on different slip systems can lead to "patchy slip" (2). This phenomenon is characterized by the segregation of plastic deformation in regions of single slip with little or no overlap between each region. Mathematically, this behaviour can be modeled by accounting for strong latent hardening effects in the crystal plasticity constitutive equations (3). Ortiz and Repetto (1999) (4) reviewed the occurrence of patchy slip in experiments and proposed a methodology to predict the onset of this phenomenon based on nonconvex energy minimization. They showed that the formation of patches follows a lamination process. The authors then drew a link between this deformation mechanism and the emergence of dislocation structures. Recently, Dequiedt et al. (2015) (5), Wang et al. (2018) (6) and Ryś et al (2024) (7) have shown the occurrence of patchy slip in single crystal plasticity simulations. Viscoplastic and rate-independent crystal plasticity models were considered in these studies and both were shown to induce formation of single slip patterns provided that the rate-dependence is sufficiently weak. To this day, regularization of the size of single slip regions predicted in these simulations is still missing in the literature. In addition, the occurence or absence of patchy slip in 2D and 3D polycrystal simulations is still an open question.
We revisit the plane strain cases investigated by Ryś et al. (7) in the context of finite strains. A crystal viscoplasticity model based on dislocation densities evolutions is implemented in a finite element software. First, we show the emergence of single slip deformation patterns. We demonstrate that these patterns are indeed associated to dislocation structures similar to cells and labyrinths. The sensitivity of deformation microstructures to numerical parameters such as mesh size, finite element type and integration scheme is discussed. We then extend the simulations to 3D single crystal specimens loaded along the highly symmetric (001) direction. The crystal plasticity model is then extended to strain gradient plasticity in order to regularize the size of single slip regions and associated dislocation structures. Finally, we discuss the occurence of patchy slip in 2D and 3D polycrystal simulations.

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Finite Element Modeling of Deformation Bands in Single-Crystal Plasticity at Small Strain

Ryś Maciej (1), Kursa Michał (1), Petryk Henryk (1)

1 - Institute of Fundamental Technological Research (Poland)

Speaker: Ryś Maciej. **Wednesday**. Start time: **15:10**. Room: Saint Clair 4 LVL2. Link to abstract.

The non-uniqueness of solutions in rate-independent crystal plasticity represents a fundamental challenge in modeling plastic deformation. A key difficulty arises at the material point level, where the determination of active slip systems is complicated by the indefiniteness of the slip-system interaction matrix. A computational framework based on incremental energy minimization provides an effective approach to resolving this ambiguity, yielding solutions that capture the underlying physical mechanisms without relying on artificial regularization techniques.
In this work, we investigate the spontaneous formation of deformation bands in plastically deforming single-crystal metals. Incremental energy is formulated at the Gauss-point level, and a trust-region algorithm is employed to minimize the non-convex energy functional and identify the increments of active slip systems, which are not predefined. The analysis is conducted within the small-strain crystal plasticity framework.

Our study reveals that, under specific conditions, the material develops a characteristic laminate structure, often referred to as a zig-zag pattern. Finite element simulations under plane-strain conditions demonstrate the spontaneous emergence of deformation bands, highlighting the critical role of the yield-vertex effect. These simulations capture the alternating deformation patterns caused by latent hardening, providing direct numerical evidence of this phenomenon. Notably, the algorithm avoids any reliance on predefined band structures or explicit lamination, ensuring that the observed banding arises naturally from the governing equations and imposed boundary conditions.

References

Ryś M., Kursa M., Petryk H., (2024) Spontaneous emergence of deformation bands in single-crystal plasticity simulations at small strain, *Computational Mechanics*.

Investigating ductile failure through strain localisation under non-proportional load paths

Kristoffersen Martin (1) (2), Morin David (1), Børvik Tore (1), Hopperstad Odd Sture (1)

1 - Norwegian University of Science and Technology (Norway), 2 - Multiconsult AS (Norway)

Speaker: Kristoffersen Martin. Invited. **Wednesday**. Start time: **15:30**. Room: Saint Clair 4 LVL2. Link to abstract.

Understanding and predicting ductile failure mechanisms under complex loading conditions is important for advancing the design and reliability of engineering structures. This study explores the onset of strain localisation in ductile materials subjected to non-proportional load paths using the imperfection version of strain localisation theory. A computational framework utilising results from finite element analyses was developed assuming a planar, porous imperfection band within a homogeneous solid, focusing on void nucleation, growth, and coalescence as primary drivers of ductile failure. Given a suitable and well calibrated plasticity model, the framework's parameters were determined using a single uniaxial tension test and finite element simulations thereof, achieving satisfactory accuracy in predicting experimentally observed macroscopic fracture strains from notched tension and compression-tension tests. The approach was further applied to a pipe denting problem involving large deformations and complex loading paths, demonstrating its potential for broader applications. The localisation analysis framework offers a robust post-processing tool for finite element analyses utilised in the design of materials and structures subjected to extreme loading scenarios.

Modeling and analysis of shear banding in metallic glasses

Kamasamudram Vasudevan (1), Moes Nicolas (1), Pardoen Thomas (1)

1 - Université Catholique de Louvain (Belgium)

Speaker: Kamasamudram Vasudevan. **Wednesday**. Start time: **15:50**. Room: Saint Clair 4 LVL2. Link to abstract.

The inelastic behavior of metallic glasses depends on various factors such as temperature, strain rate, composition, specimen size, etc. These materials typically exhibit a macroscopically elastic-perfectly plastic behavior, with the deformation characteristics ranging from a homogeneous state at smaller strain rates to intensely localized shear banding at higher strain rates. Various studies also demonstrate a size-dependent macroscopic response, where the yield-strength and the strain to fracture depend on the specimen size. Their behavior is also known to be pressure sensitive. Thus, there has been a considerable effort towards developing models and modeling methods that effectively describe the behavior of these materials ranging from Molecular Dynamics, Kinetic Monte Carlo (KMC) methods (with rates described by Transition state theory), and Continuum models (with associative and non-associative flow rules and a possibly pressure-dependent yield function, a visco-plastic type flow rule, a gradient-enhanced model to address size effects).
The KMC methods use the rates computed from the Transition state theory to describe the inelastic behavior of the material. A sequence of random numbers are used to determine the plastic strain and the time increment at the current step, which together with equilibrium, and boundary conditions are used to evolve the system in time. However, the KMC methods exhibit time step dependency in early simulation phases. Also, many realizations of the simulations are necessary to obtain a statistically significant behavior of the system, which in turn is computationally expensive. On the other hand, the continuum methods use a constitutive model that (deterministically) describe the behavior of the material. Thus, an average behavior of the system can be directly obtained by integrating the constitutive model while enforcing the equilibrium conditions. The aim of this study is to examine the convergence of the KMC method towards the continuum methods in the limit of increasing system size.
Also, intense shear banding and the accompanied strain localization are treated by using gradient-enhanced models or by strain localization elements, where these elements are inserted between the bulk elements. In the latter technique, the thickness of shear bands are taken as a material parameter. The current study also analyzes and compares the behavior of the gradient enhanced (diffuse) models and the strain-localization (sharp) models.

Mechanical instabilities in metallic glasses: a statistical nanoindentation approach

Pomes Silvia (1), Adachi Nozomu (2), Wakeda Masato (1), Ohmura Takahito (1) (3)

1 - National Institute for Materials Science (Japan), 2 - Department of Mechanical Engineering [Toyohashi Univ of Technology] (Japan), 3 - Department of Materials Science and Engineering, Faculty of Engineering, Kyushu University, Fukuoka (Japan)

Speaker: Pomes Silvia. **Wednesday**. Start time: **16:10**. Room: Saint Clair 4 LVL2. Link to abstract.

Bulk metallic glasses (BMGs) are highly promising materials for structural applications due to their exceptional strength and high elastic limits. However, their potential is limited by instabilities in their mechanical behavior under applied loads, often leading to sudden failure due to the formation of shear bands. This study employs a statistical approach to explore the fundamental physical dynamics governing deformation at the elemental level and the temperature-dependent properties, based on over 100 tests per sample under varying structural and thermal conditions. Nanoindentation testing on a Zr-based BMG was used to measure key properties, such as hardness, while also providing insights into deformation behavior. The analysis of nanoindentation data revealed new insights into the deformation dynamics, including the identification of the first serration and a precursor event (1). Further investigations examined how the microstructure of BMGs in different structural states influenced these deformation events. Results indicated that precursor events are linked to unstable regions rather than influenced by the broader microstructure (2). The temperature dependence of mechanical performance, ranging from room temperature to the glass transition and crystallization temperatures, is also explored. BMGs exhibit softening behavior below the glass transition temperature and the activation energy for softening was found to be consistent across different structural states, supporting the idea of a localized mechanism driving deformation (3). These results provide a deeper understanding of the physical processes governing deformation and temperature-dependent properties of BMGs, which could guide their design and application in diverse contexts.

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FORMING LIMIT DIAGRAMS FOR PERFECT AND IMPERFECT SHEETS USING PLASTIC MODELS WITH TWO POROSITIES

Benallal Ahmed (1), Khan Imran (2), Benzerga Amine (3), Needleman Alan (4), Moussy Francois (5)

1 - Laboratoire de Mécanique Paris-Saclay (France), 2 - Reactor Safety Division, Bhabha Atomic Research Centre, Trombay, Mumbai-400085, India (India), 3 - Department of Aerospace Engineering and Department of Materials Science & Engineering Texas A&M University, College Station, TX 77843 USA (United States), 4 - Department of Materials Science & Engineering, Texas A&M University, College Station, TX 77843 USA (United States), 5 - French Iron and Steel Research Institute (IRSID), St Germain-en-Laye, France (United States)

Speaker: Benallal Ahmed. Invited. **Wednesday**. Start time: **16:45**. Room: Saint Clair 4 LVL2. Link to abstract.

Localised necking in biaxially stretched sheets is investigated using a rate independent porous plastic constitutive relation with two porosity parameters; one associated with the void volume fraction and the other associated with the weakening effect of void shape changes in shear dominated stress states. Imperfection localisation analysis is performed, where band imperfection triggers the onset of localised necking as defined by a loss of ellipticity of the governing equations in the band. This band imperfection is taken to be either an increase in initial void volume fraction or an increase in the volume fraction of void nucleating particles. Proportional straining plane stress calculations are carried out for ratios of imposed in-plane principal strain rates ranging from –1 (shear) to 1 (equal biaxial tension). The predicted forming limit curves are compared with predictions for a localised necking bifurcation of an elastic-plastic solid. In the bifurcation analysis, four regimes are observed in the forming limit diagram: (i) a shear softening dominated regime; (ii) a plastic properties dominated regime; (iii) a porosity induced localisation regime $0 \leq \rho \leq 0.4$; and (iv) a porosity induced failure regime (loss of load carrying capacity). In the imperfection localisation analysis, for negative values of the imposed strain ratio, except for near pure shear where the second porosity reduces the critical strains, the predicted critical localisation strains and the predicted critical localisation band orientations differ little from the corresponding critical values predicted by the bifurcation analysis. For biaxial tensile states the critical localisation strains are sensitive to the nature and magnitude of the imperfection. Besides, when void nucleation occurs over a very narrow range of strain or stress, void nucleation and the onset of localised necking can coincide.

3D Wrinkled Substrates for Soft Pressure Sensing: Maximizing Surface Area and Mechanical Resilience

Xiaoyi Chen (1)

1 - Beijing Normal University, Hong Kong Baptist University - United International College (China)

Speaker: Xiaoyi Chen. **Wednesday**. Start time: **17:05**. Room: Saint Clair 4 LVL2. Link to abstract.

This study explores the enhancement of surface area in three-dimensional wrinkles within multi-layered systems, with applications in soft pressure sensors. Embedding pressure sensors in a wrinkled substrate significantly increases their sensitivity and mechanical robustness. Despite these advantages, systematic investigations into methods for enlarging the wrinkle surface area in layered systems remain limited. Utilizing a morphoelastic plate theory framework, we analyze the formation and behavior of 3D wrinkles in fiber-reinforced multi-layered substrates. Both linear stability analysis and post-bifurcation analysis are conducted to comprehensively understand wrinkle development. Our research examines the influence of matrix and fiber properties on the wrinkle surface area, offering valuable insights for the design of ultra-sensitive and mechanically resilient pressure sensors.

A micromechanics-based damage model for prediction of sheet metal forming limits

Morey Krunal Namdeorao (1), Keralavarma Shyam (2)

1 - Indian Institute of Technology Madras (India), 2 - Indian Institute of Technology Madras (India)

Speaker: Morey Krunal Namdeorao. **Wednesday**. Start time: **17:25**. Room: Saint Clair 4 LVL2. Link to abstract.

The prediction of failure in sheet metals subjected to complex non-proportional loading paths during forming operations is a challenging, and technologically important, problem. Fracture in sheet metals subjected to biaxial plane stress loading generally occurs following localized necking in the thickness direction. The critical condition for the onset of localized necking depends on the loading path, and constitutive effects such as strain hardening, plastic anisotropy and the formation of vertices on the yield surface. In particular, plastic anisotropy can play a major role in case of sheet metals that develop well defined textures as a result of the rolling operations used in their manufacture. Phenomenological models of sheet metal failure based on the experimentally determined forming limit diagrams (FLD) under proportional loading are known to be inadequate under strongly non-proportional loading paths. Imperfection band approaches such as the widely used Marciniak and Kuczy'nski (1967) (MK) model are also limited in their predictive ability, since their predictions depend on arbitrary choices of preexisting imperfections in the material. The objective of the present work is to develop a criterion for localized necking in plastically anisotropic sheet metals using a ductile fracture model based on the micromechanics of void growth and coalescence. Classical ductile failure models such as the Gurson (1977) model are unable to predict necking in sheet metals at realistic strain levels due to the assumption of dilute porosities, which lead to prediction of a smooth yield surface and the normality flow rule. However, it is known from several micromechanical simulation studies that the interaction between voids at finite porosities has a significant influence on the effective yield behavior, leading to a transition from diffuse yielding to localized yielding of the inter-void ligaments within a porous representative volume element. The transition from diffuse to an inhomogeneous yielding at the micro-scale results in the formation of macroscopic yield vertices, which can potentially trigger necking instabilities in thin sheets. In the present study, yield criteria for plastically orthotropic materials of the Hill (1948) type, developed by Benzerga and Besson (2001) for diffuse yielding and Keralavarma and Chockalingam (2016) for inhomogeneous yielding, are combined using a multi-surface approach. The shapes of the effective yield surface predicted by the model are validated by comparison with quasi-exact numerical yield loci obtained using a finite elements based limit analysis procedure. A plasticity model based on the above yield criterion, specialized to the plane stress case, is used to predict their forming limits for sheet metals under proportional loading paths, using the plastic instability criterion of Stören and Rice (1975). It is shown that realistic shapes of the FLDs as a function of the plastic anisotropy parameters of the material are predicted using this approach, which does not require the assumption of a macro-scale imperfection band as in the MK model.

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Damage modeling in the swelling evaluation of the WWERs pressure vessel internals

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Speaker: Dubyk Yaroslav. **Wednesday**. Start time: **17:45**. Room: Saint Clair 4 LVL2. Link to abstract.

Long-term operation (LTO) of WWER-type nuclear power plants (NPPs) beyond their originally planned lifetime is critical in providing reliable low emissions power. In the aspects of pressure vessel internals (PVI) the main limiting factor is Irradiation induced swelling of the Core Baffle, which affects related PVI elements (pins, Core Barrel).
The reactor core baffle experiences heavy loadings of neutron and gamma irradiation, thus, the degradation of reactor internal material along with geometric distortion, called swelling, is quite severe. The computational model includes determination of the void swelling of an elementary volume of the Core Baffle material depending on the neutron fluence in dpa and temperature (based on heat rate assessment and compared to other swelling models, influence of the stress is accounted. Also, this degradation includes changes in the material microstructure and microchemistry and can lead to irradiation assisted stress corrosion cracking (IASCC).
The present study focuses on the damage modeling of PVI during the operational time. Due to the complex visco-plastic mechanism of Baffle deformation an attempt is made to use different damage mechanisms to estimate the lifetime of the components.

MS3.3 - Mechanics and Physics of Dense Granular Media: Experiments, Theory and Modelling

Organisers: Stéphanie Deboeuf (Institut Jean le Rond D'Alembert) and Nathalie M. Vriend (University of Colorado, Boulder)

Local strain fluctuations in granular media

Leopoldes Julien (1)

1 - Laboratoire Navier (France)

Speaker: Leopoldes Julien. Keynote. **Wednesday**. Start time: **10:00**. Room: Saint Clair 1 LVL2. Link to abstract.

Solids respond elastically to shear stress at low strain, then progressively yield and eventually fail. In the case of heterogeneous and discrete solid systems made of particles such as foams, emulsions, colloidal glasses or granular media, yielding at the macroscopic scale is well described by some constitutive laws such as Herschel-Buckley. However, the microscopic mechanisms involved in the elastic-to-plastic transition seem specific to a given system. In granular media, the local mechanisms at the source of elasto-plasticity are not clearly identified yet. In this context, it is useful to develop experimental methods able to resolve particle rearrangementsin the bulk of granular media. Here, we study a dense granular under oscillatory shear stress in the plastic regime. By combining optical tracking of the grains and correlation of multiply scattered ultrasound signals, we show that the strain at the scale of the grains is mainly diffusive. We obtain a consistent signature of plasticity in oscillatory shearing, dominated by the intensity of the anticorrelation between local strain cells that depend on the maximum applied strain and on the density of the packing through the available free volume.

An experimental study of creep in non-cohesive granular materials

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1 - Institut de Physique de Rennes (France)

Speaker: Gicquel Cécilia. **Wednesday**. Start time: **10:40**. Room: Saint Clair 1 LVL2. Link to abstract.

This work aims to contribute to the understanding of the origin of creep deformation in non-cohesive granular materials, that is, their response to a constant stress loading. We have performed biaxial tests on samples made of glass beads which diameter is comprised between 70 and 100 microns, used as an athermal amorphous model material. The use of such samples enables us to observe local deformation and rearrangement over time thanks to an interferometric method. Previous studies have demonstrated that when those samples are submitted to constant strain rate loading, the deformation localises in shear bands at a critical value of the stress. We have carried out stress-imposed experiments and report the observation of creep deformation in the sample. Three stages are observed: first the strain rate decreases as a power-law with an exponent close to one, then a stationary regime of variable duration is observed during which the strain rate stays approximately constant, finally an acceleration of the strain rate until the failure of the sample is observed. Our method of measurement allows us to observe and study the spatial distribution of the deformation during the different phases of the creep process. To the best of our knowledge it is the first time that the three stages of creep are observed in granular materials, especially the acceleration towards failure.

Influence of grain shape on grain rotation under Coble creep

Mortadi Saad (1), Delannay Laurent (1), Delannay Francis (1)

1 - iMMC-UCLouvain (Belgium)

Speaker: Mortadi Saad. **Wednesday**. Start time: **11:00**. Room: Saint Clair 1 LVL2. Link to abstract.

The objective of the present study is to gain some insight into the physics of Coble creep based on the observation and the modeling of the microscopic deformation field. Recent advancements in Electron Backscatter Diffraction (EBSD) and Digital Image Correlation (DIC) have indeed enabled detailed experimental investigations of grain shape evolution and lattice rotations in deformed polycrystalline materials (1).
At elevated temperatures and/or low deformation rates, the sliding of neighboring grains along their boundaries may be accommodated by atomic diffusion along GBs, while maintaining the grain interior rigid. Inspired from previous work (2), an original variational approach is developed to model Coble creep over periodic crystalline aggregates. The model simulates GB sliding and GB diffusion mechanisms while considering grains of varying shapes and sizes, and while testing different assumptions about the threshold shear stress allowing GB sliding. It is demonstrated that the predicted macroscopic viscosity and the grain rotation rates tend to reproduce experimental trends.

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A hemivariational granular-chain model with elasticity, damage and impenetrability constraints

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Speaker: Tran C. Anthony. **Wednesday**. Start time: **11:20**. Room: Saint Clair 1 LVL2. Link to abstract.

A granular-chain model is proposed taking into account damageable elastic links between the grains, as well as impenetrability conditions represented by inequality constraints. The modelling approach is hemivariational: it is formulated as a variational inequality based on virtual powers defined on the set of admissible kinematics. This approach is adapted from recent research efforts in formulating hemivariational models for elasticity, damage and plasticity in granular materials. More specifically, the presented work is developed within the framework of a recent masonry model (see for example Tran & Barchiesi 2023), and intended as an intermediate step to homogenising said model.
The modelling approach used in the presented work is an extension of the one in Tran et al. 2024: time-dependence is taken into account (although the model remains quasi-static), and inequality constraints have been added to account for the impenetrability of the grains. The solving process is illustrated analytically for undamaged evolutions, and numerically in damaged elasticity.

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Brittle-to-ductile transition in snow: a microstructural perspective

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Speaker: Chambon Guillaume. **Wednesday**. Start time: **11:40**. Room: Saint Clair 1 LVL2. Link to abstract.

Snow consists of bonded ice grains, air, and possibly liquid water. It can be regarded either as a porous ice skeleton or as a loose cohesive granular material. Furthermore, as this material generally exists on Earth close to its melting point, it is characterized by rapid thermodynamic evolutions (metamorphism, sintering) and exhibits a wide variety of microstructures. The mechanical behaviour of snow is strongly dependent on strain rate, with a transition from a ductile to a brittle deformation regime as the strain rate increases. At the microstructural scale, snow deformation involves a complex interplay between continuous deformation of the ice skeleton and granular rearrangements of the bonding network. We report here on specific mechanical experiments designed to better unravel the relationship between macroscopic deformation and microstructural evolution in snow, focusing on the brittle-to-ductile transition. Cylindrical snow samples were subjected to displacement-controlled oedometric compression tests over a wide range of strain rates, from 10^-6 to 10^-2 1/s. The tests were performed in situ in an X-ray computed microtomography (micro-CT) scanner installed in a cold room at a controlled temperature (-18.5∘C). Full 3D scans taken before, during, and after the experiments were analyzed to follow the evolution of several microstructural descriptors, such as the specific surface area and bond network metrics. 2D radiographs were also taken at a higher frequency to follow fast mechanisms using image correlation techniques. The stress response is characterized by a clear regime transition at a strain rate of about 10^-3 1/s. Micro-CT data show that this transition is associated with a change from an essentially diffuse to a localized deformation pattern. Above the transition, we observe the formation of compaction bands separating deformed and undeformed zones. The bands propagate back and forth in the samples. This pattern is associated with stick-slip-like fluctuations of the stress response, which are presumably the signature of sample-scale rupture events in the bands. Conversely, at low strain rates, the stress-strain curves are smooth. In this regime, snow deformation is controlled by intra-granular visco-plastic deformation and the creation of new bonds. Lastly, when the transition is approached, bursts of stress fluctuations are observed. Micro-CT data reveal that these events are associated with intermittent meso-scale localization patterns, which could be regarded as precursors to the compaction bands forming at higher strain rates.

Swelling granular media made of plant seeds: pressurisation and inverse silo effect

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Speaker: Marmottant Philippe. **Wednesday**. Start time: **14:30**. Room: Saint Clair 1 LVL2. Link to abstract.

Plants do not possess a heart to drive the circulations of their internal fluids, but rely on two mechanisms: osmotic pressure and evaporation. The osmotic effects lead to high turgor pressures, that are responsible for maintaining the shape of non-lignified plants.

Here we are interested in a specific aspect of fluid circulation in plants: the rehydration of dessicated seeds. In contact with water, seeds attract water through osmotic effects leading in a strong volume increase and possibly strong pressures. Plants seeds act as elements of peculiar type of granular media, not really studied in literature: swelling granular media. The main objective of this talk is to present the physics of imbibition of these plant granular media.

First we will show the temporal dynamics of imbibition of single seeds in water, using chickpeas because of their near spherical shapes. The volume increased by a factor three, and we model the dynamics of imbibition using two kinetic models: diffusion trough the volume and membrane limited regime.

Second we measured the forces exerted by seeds when they are hydrated and confined in spaces, such as in between two planes, in a tube or within a chamber with a piston. In an a chamber full of seeds, we could measure contact pressures as high as 8 bars in a chamber. In a vertical tube we observe an inverse Janssen effect, were the pressure increases very rapidly when entering deeper in the stack, exactly the opposite as the traditional Janssen effect.

Third we will generalize these findings with different types of plant seeds or artificial hydrogel materials. Finally, we aim at using this granular media as an autonomous media to exert pressures by sole imbibition reproducing the phenomenon of turgor pressure.

A dynamic Janssen effect

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1 - Mines Saint-Etienne, University of Lyon, CNRS, UMR 5307, Centre SPIN (France), 2 - Institut National des Sciences Appliquées de Lyon (France)

Speaker: Mollon Guilhem. **Wednesday**. Start time: **14:50**. Room: Saint Clair 1 LVL2. Link to abstract.

When granular materials are stored in a container, a part of the weight of the grains is reported to the container walls through arch-forming oblique force chains and wall friction. This effect, well-known in the storage industry, is called the Janssen effect and was discovered in 1895. It is more pronounced when the container gets taller compared to its horizontal dimensions, and can eventually lead to container failure if not properly accounted for. Its physics are nevertheless well-understood, and rely on a limited number of parameters, in addition to the container geometry: a so-called Janssen coefficient (defining the ratio between vertical and horizontal stress in the granular medium), and a wall-grain friction coefficient.
However, this theory is based on the assumptions of a granular material at rest and of a fixed container. There are situations, however, where these assumptions are no longer valid, for example in the case of pneumatic transport of grains in a pipe. In this communication, we investigate the consequences of a vertical (i.e. downwards or upwards) motion of the granular sample inside an infinitely tall vertical container, caused by the piston-like motion of its lower plate (the walls remaining fixed). We perform 2D DEM simulations and vary in a systematic way the friction coefficients (intergranular, and with the container walls), the quantity of granular matter, and the direction and the velocity of the vertical motion.

By doing so, we illustrate the complexity of this situation, by identifying several regimes adopted by the granular mass to accommodate these boundary conditions: wall-sliding, wall-rotation, stick-slip, convection, intermittence, fluidization, etc. We show that a Janssen-like formulation can be empirically retrieved based on these simulations, but with parameters that strongly depend on the regime and on the model parameters.
We will also discuss experimental observations of a millifluidic granular slug displacement in the light of the numerical simulations performed. Despite some strong differences between the numerical simulation of a two-dimensional granular material confined inbetween moving vertical walls, and the experimental displacement of a small volume of glass beads immersed in water in vertical millifluidic tube, strong analogies can be put in evidence. A transition in the granular slug displacement regime is observed when the speed increases. With the help of the numerical parameter study some interpretation of the experimental observation will be exposed.

Size segregation in confined granular shearing flows: a two-dimensional process

Caro Santiago (1) (2), Richard Patrick (1), Artoni Riccardo (1), Larcher Michele (2), Jenkins James

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Speaker: Caro Santiago. **Wednesday**. Start time: **15:10**. Room: Saint Clair 1 LVL2. Link to abstract.

Granular materials are important in many industrial and geophysical processes, but they are often a problem to handle as they are intrinsically polydisperse in size, leading to segregation when dense mixtures are sheared. While existing models can represent particle transport in simplified flow configurations, describing the interplay between collisional and gravitational segregation in more complex granular flows remains a challenge.
In this paper, we experimentally and numerically studied the coupling between size segregation and granular flow rheology in bidisperse mixtures of spheres that have the same density but different sizes. These mixtures are subjected to non-uniform shear rates and confining pressure, with systematic variations in mixture concentration and size ratio. The experiments are conducted in an annular shear cell with rotating bumpy bottom, while simulations are performed in a linear cell with a moving bottom base, using the open-source discrete element method (DEM) code LAMMPS. Additionally, we worked with an extension of kinetic theory for dense binary mixtures to predict the concentration and velocity profiles of the mixtures.

In experiments and simulations, a cell is initially filled with lower layers of large particles and upper layers of small particles, confined at the top by a bumpy wall, with a mass equal to the total mass of the mixture. In the experiments, the segregation process is filmed through transparent sidewalls, and the evolution of particle concentration in space and time is evaluated by means of post-processing image analysis. At the end of some experiments, grains are carefully removed by layers and then sieved to determine the particle concentration within the flow. In the simulations, we collect particle-level information, including instantaneous velocity, position, and normal and tangential inter-particle forces. This data is then filtered to obtain particles concentration in space and time, as well as other local parameters, such as granular temperature, packing fraction, coordination number and force chain network.
Both experiments and simulations demonstrated that vertical segregation fluxes are proportional to the size ratio between large and small particles, and the quantity of large particles within the mixture. It was observed that the segregation process takes place in two dimensions, not only in the vertical direction but also in the horizontal direction. The two dimensional nature of segregation was evident in the cross-section of the simulated cell, where small particles accumulate next to the sidewalls, displacing large particles toward the interior. These large grains form a persistent, dense core, preventing complete vertical segregation. Force chains were observed to extend along and across the flow, indicating enduring contacts. The presence of these force chains suggests that collisional models, such as kinetic theory, may not be adequate to describe deep and highly loaded granular flows.

A non-local model for stress, velocity, and packing fraction in a rotating drum: Theoretical, numerical and experimental approach for grains from convex to highly concave

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Speaker: Barés Jonathan. **Wednesday**. Start time: **15:30**. Room: Saint Clair 1 LVL2. Link to abstract.

In this presentation, we examine the influence of particle shape, ranging from spherical to highly concave, on steady granular flows within a rotating drum. This system provides a unique environment to study the transition from jamming at deeper layers to unjamming near the surface. We propose an analytical model to describe the granular behavior in the drum:
(i) First, we decompose the shear stress and resolve discrepancies between simulation data and theoretical predictions by establishing a link to the angle of repose.
(ii) Second, we extend the generalized Bagnold scaling, incorporating a non-local fluidity relation based on packing fraction. This allows us to model the correlation between shear stress, shear rate, and packing fraction. Additionally, we introduce a characteristic length scale that quantifies the effects of particle shape and drum speed.

The proposed model provides explicit functional forms for the profiles of key physical quantities, which are validated experimentally in a thin rotating drum and numerically in a two-dimensional drum. Our results show that the model accurately captures the velocity variation from the drum's base to the free surface. Furthermore, for different particle shapes and drum speeds, the characteristic length effectively describes the interplay between shear stress, shear rate, and packing fraction variation.

Crack propagation in wet granular medium

Dalbe Marie-julie (1), Vandenberghe Nicolas (1), Jodlowski Pierre (1)

1 - Institut de Recherche sur les Phénomènes Hors Equilibre (France)

Speaker: Dalbe Marie-Julie. Keynote. **Wednesday**. Start time: **16:45**. Room: Saint Clair 1 LVL2. Link to abstract.

Wet granular materials are able to sustain a tensile load thanks to the cohesion between grains induced by the capillary bridges. When an intruder is pushed in such a material, tensile cracks, like mode 1 cracks in solid materials, can appear. Such cracks are relevant in a variety of context (soil mechanics, powder compaction ...), but have not been studied extensively. We offer a solid mechanics perspective on the issue, focusing on the study of crack propagation within this type of matter to build a model able to predict fracture advancement.
We have designed a procedure to prepare a wet granular pile with a reproducible compaction. Using X-ray tomography, we show that for dense enough material, the overall compaction is homogeneous in our medium. We investigate the threshold compaction value needed to observe cracks, as well as the final crack pattern. Using 3D X-ray microtomography, we can measure the displacement fields, and show that crack nucleation is linked to dilation. We also measure the indentation force, and its dependence on compaction and cohesion level.
These experimental measurements allow us to develop a model to understand the stress-strain relation, and the appearance of cracks.

Numerical approach to crack initiation in irradiated nuclear fuel: brittle fracture assessment by comparison between coupled criterion and the cohesive zone model.

Rudasingwa Kimonyo Jean Paul (1), Doitrand Aurélien (2), Michel Bruno (3), Zacharie-aubrun Isabelle (4), Gatt Jean-marie (4)

1 - Centre de recherche du Commissariat à lÉnergie Atomique - CEA Cadarache (Saint Paul-lez-Durance, France) (France), 2 - Matériaux, ingénierie et sciences [Villeurbanne] (France), 3 - Centre de recherche du Commissariat à lÉnergie Atomique - CEA Cadarache (Saint Paul-lez-Durance, France) (France), 4 - Centre de recherche du Commissariat à lÉnergie Atomique - CEA Cadarache (Saint Paul-lez-Durance, France) (France)

Speaker: Rudasingwa Kimonyo Jean Paul. **Wednesday**. Start time: **17:25**. Room: Saint Clair 1 LVL2. Link to abstract.

This work aims to establish fracture criteria of a used nuclear fuel in storage conditions using finite element simulation in line with a linear elastic fracture mechanics (LEFM) framework *(1)(2)*. We propose a finite element multi-scale approach to model the behaviour of an irradiated fuel microstructure, with fracture induced by over pressurised bubbles. The fracture behaviour of brittle materials is deeply influenced by their microstructure and that needs thorough consideration for an accurate prediction of fracture properties. Irradiated fuels exhibit a very complex and heterogeneous structure, with restructured grains in high-burnup zones and pressurised bubbles with complex shapes located in the bulk or on grain boundaries *(3)*. In (4) and (5), they adopt fracture mechanics approach to study their behaviour in the first approximation, defining crack initiation loading of a lenticular bubble with a Griffith criterion *(1)*. While this approach tracks successfully the growth of pre-existing cracks or simple singular defects, it fails to account for crack initiation from an arbitrary geometry (6). To go beyond that limitation, we use the coupled criterion (7), (11), (12) to assess the initiation of a crack from a pressurised spherical bubble. On the other hand, cohesive zone models firstly introduced in *(8)* and *(9)*, enable the description of crack initiation and growth from any type of geometry using, along the cohesive element interfaces, a traction-separation law. The former and the latter approaches are both used *(10)* to assess the crack initiation loading for pressurised bubbles. The predictions of the critical pressure leading to failure are in agreement with both models as the conclusion that crack growth process is unstable. The workability of this approach is demonstrated through comparison with experimental data issued by micrometric cantilever bending tests.

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Fiber drag and conformation in 2D dense granular flow

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1 - Physique et mécanique des milieux hétérogènes (France), 2 - Institut de Physique de Rennes (France)

Speaker: Corbel Pierre-Yves. **Wednesday**. Start time: **17:45**. Room: Saint Clair 1 LVL2. Link to abstract.

From the locomotion of sandfish and plant root pull-out to the self-burying robots and soil strengthening through the incorporation of fibers, the interaction between a slender structure and a granular medium is commonly found in nature and engineering. Those problems pose multiple challenges: the non-local action of the granular medium, the slender structure's large deformations, and the couplings between the two. Therefore, this fluid-structure interaction is studied at the contact scale in 2D experiments to gain insight into the problem phenomenology. The main objective is to identify the different interaction regimes on a sinusoidal fiber fixed in space at one end, inside a quasi-static dense bidisperse granular flow. The sinusoidal fiber is an ideal representation of most shapes and permits to simplification of a complex structure to three parameters: a length, a wavelength, and an amplitude. As the fiber behaves as an elastica under a discrete heterogeneous pressure distribution, those geometric parameters vary during the tests. The experiment is designed to create either a granular domain with controlled pressure or controlled volume to get a complete picture of the different interaction regimes, with fiber shape conformation and drag force. The results of the present study will give new information on the anchoring dynamics of fibers in a granular medium.

Drag and lift forces when moving in a cohesive granular medium

Dumont Denis (1), Pouliquen Olivier (1)

1 - Laboratoire IUSTI UMR CNRS 7343 (France)

Speaker: Dumont Denis. **Wednesday**. Start time: **18:05**. Room: Saint Clair 1 LVL2. Link to abstract.

Studies on the forces acting on a moving object immersed in a dry granular medium have shown that strong differences exists with a classical newtonian fluid. The frictional rheology of granular media strongly alters the drag and lift forces. In particular, the drag force is proportional to the pressure exerted by the column of grains above the object, whereas the lift force is related to the pressure gradient and is positive even for a symmetrical object. By means of experiments and DEM simulations, we investigate how the introduction of cohesive forces between grains modifies the drag and lift forces. Experiments are carried out for two types of cohesive granular media: wet grains and sticky polymer coated grains. The measurements reveals that the drag is weakly impacted by the cohesion, whereas the lift is strongly diminished. DEM simulations highlight the key role played by the cohesion length in this observation.

Dynamics Model of a steerable drilling devices in Granular Medium

Zihao Yuan (1) (2), Zhao Haifeng Mu Ruinan Wang Ke

1 - Technology and Engineering Center for space Utilization, Chinese Academy of Sciences (China), 2 - University of Chinese Academy of Sciences (China)

Speaker: Zihao Yuan. **Wednesday**. Start time: **18:25**. Room: Saint Clair 1 LVL2. Link to abstract.

Inspired by locomotion of animals or insects, the robots are developed to crawl, swim and burrow in fluid-like granular medium by mimicking the mechanisms of inchworms, earthworms, wood wasps or gophers (1, 2). During the penetrating and locomotive process, the resistive force is produced along the interaction between the robotic body and granular substances. To construct the mathematical model of underground locomotion is the key to streamline the design and maneuver of the robots in the down-hole. There are several approaches to deal with such complex interactions of the drilling robot and soils (3-5). The predicting and implementation of locomotion in granular medium is still a challenging subject and opened problem to be investigated (6). A reduced-order model is a practical way to assistant the developing of complicated drilling device. This means is beneficial to both the early design phase as a trade-off study toolbox and mission decision-making stage as a core in building a physics-based digital twin (7). In this work, a predictive model of self-locomotive burrowing device is proposed to simulate the operating and controlling scenarios of an autonomous robot steering in granular medium. The mole-type burrowing robot is idealized as a rigid intruder steering in the granular block with thick stacks of sediments, which represents the stratigraphic profiles of geological structures.
The characteristic parameters are considered including the length, cross-section diameter and centroid of a cylindrical rod. A set of 3-DOF governing equations is derived to describe the kinematic states of a mole-like drilling robot. By introducing the resistive force theory, the interaction scheme between the locomotive body and granular medium is described. the resistive stiffnesses of the lunar regolith are idealized as three components: two compressive stiffnesses of $k1$ in the x-direction and $k2$ in the y -direction, and one torsional stiffness, Gr. These three terms of stiffnesses are defined as the characteristics of different layered formations corresponding to a vertical depth. The Lagrangian equations for this problem are obtained as the following ordinary differential equations (ODEs). The trajectory and kinematics of locomotion is predicted numerically with the implementation of Runge-Kutta method. To obtain the values of thrust, P and lateral force, F by following the specified trajectory, the proportional-derivate (PD) control method coupled with ODEs dynamic equations (PD-ODEs) is proposed and implemented. The calculation is conducted in the local coordinate system fixed in the robotic body. Thus, the events of generalized forces Q are formulated in a new way QPD and the dynamic model of directional drilling conducted with the PD controller.

Considering the actual condition of the layered structure of regolith, a depth-dependent stiffness can provide the high-fidelity prediction to simulate a practical robot–soil interaction for deep locomotion in granular medium. The effective stiffnesses are introduced as and along the local coordinated system attached to the robot body. And the torsional stiffness, , can be easily calculated based on the variables of a, b, , and . The effective stiffnesses are decomposed in forward, lateral and deflectional events, respectively. The computational results indicate that the higher curvature of trajectory produces a larger horizontal movement and higher value of F/P. For the high curvature case, the value of F/P and Rc/R snaps during the locomotion across the segments with different dogleg severities (DLSs). For the small curvature case, the shape of the wellbore becomes slender. This is because, under the relatively smaller DLS, the gradient of variation of the trace is actually smoother. Thus, the robot tends to adjust more easily under the path with a smaller DLS. The variation of Rc/R along the trajectory relates to the steerability, manipulation, and energy consumption of a robot. Accordingly, the value of F/P is increased with the rise in velocity. In the case of constant cruising speed, a high velocity could lead to a strong counteracting resistance, and therefore consume additional power to manipulate. The overburden and confining pressures in the layered soil are represented in the value of $k2/k1$. The higher stiffness ratios of $k2/k1$ leads to a slenderer wellbore geometry.

Overall, he proposed reduced-order model serves as a simplified tool to simulate the operating and controlling scenarios of an autonomous burrowing robot in the granular media, such as sand and soils.

It also provides intuitive inputs to plan the missions of a drilling robot to extract subsurface samples on earth or in an extraterrestrial planet.

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A DEM study of the damping properties in uniaxially loaded granular material mixtures

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Speaker: Avdić Sanel. **Thursday**. Start time: **10:00**. Room: Saint Clair 1 LVL2. Link to abstract.

Keywords: granular material, force chain, vibration damping, discrete element method

Particle damping technology is a widely used approach for vibration and noise reduction based on the use of various energy dissipation mechanisms in granular materials. In most cases, particle dampers do not have a load-bearing function and their use often leads to an increase in structural weight and indirect energy loss. It has been shown that by using so-called "force-chain based granular damping elements" it is possible to utilise the advantageous vibration damping properties of granular materials while maintaining a load-bearing capacity similar to that of bulk material (1–3).

Understanding the behaviour of these damping elements is challenging due to the numerous influencing parameters involved. In particular, the size of the granules is closely linked to many of these parameters and significantly affects both the load-bearing capacity and the damping performance of granular materials. Given that granular materials consist of collections of solid particles, analysing their behaviour at the grain scale is difficult to achieve experimentally. To address this challenge, the Discrete Element Method (DEM) (4), a numerical tool that allows detailed monitoring of particle interactions and behaviour under different loading conditions, has been employed. This study focuses on investigating the behaviour of granular material samples with various particle size distributions during uniaxial compression. An in-depth analysis of several parameters – including the volume ratio, the distribution of contact forces between particles, the evolution of the coordination number, and the load transmission - has been conducted. The relationships among these parameters and their influence on the load-bearing and vibration-damping capacities of the samples are discussed.

The results provide valuable insights into inter-particle interactions, which are a fundamental operating mechanism of force-chain based granular damping elements. In addition, the further development of such damping elements offers the possibility of using waste materials (such as plastic and rubber) and environmentally friendly alternatives (like sand), thereby reducing negative environmental impacts.

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Granular flows over obstacles using smooth and non-smooth discrete element methods

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Speaker: Oziol Mattéo. **Thursday**. Start time: **10:20**. Room: Saint Clair 1 LVL2. Link to abstract.

This study investigates the interaction between granular flows and obstacles, a critical topic for designing protective structures and mitigating natural disasters. Traditionally, researchers have used two types of discrete numerical methods to model granular flows in quasi-static (solid-like), dense inertial (liquid), or dilute (gas) states: smooth and non-smooth Discrete Element Method (DEM). In this study, we perform numerical simulations of a two-dimensional (2D) granular flow down an incline passing over an obstacle, with the help of both smooth and non-smooth DEMs.

The main objective is to validate a granular fluid model by applying both methods to the same geometry and examining key phenomena, such as the μ(I)–rheology, the formation of "dead zones" upstream of obstacles, and the forces exerted on these obstacles. Smooth and non-smooth DEM differ significantly in their definitions of contact laws. Smooth DEM requires explicit, differentiable contact laws and small time steps to maintain stability and accuracy, often relying on numerical damping. This method has been used by Faug et al. (1) to obtain results in the specific case we consider here. Non-smooth DEM, on the other hand, can use an implicit approach with piecewise functions for contact laws, allowing it to capture discontinuous interactions without the need for small time steps and damping. This method was used by Azéma & Radjaï (2) to decipher the different contributions to effective friction in the context of the μ(I)–rheology for tree-dimensional flows. Direct comparisons between these two methods are rare. Saint-Cyr et al. (3) proposed one for the quasi-static state but, to date, no comprehensive study has yet established the equivalence of results between them for a highly non-uniform flowing state, particularly for the case considered here when a granular flow impacts an obstacle.

After calibrating the mechanical parameters of the contact law, we examine the influence of time step size and numerical damping parameters specific to each method, providing insights into their sensitivity and stability. We use YADE (4) for smooth DEM and Siconos (5) for non-smooth DEM, with computational times being comparable (simulation of 25000 spheres over 3 seconds in 2D). Through these simulations, we compare the two approaches across various parameters, finding consistency in volume fraction, velocity profiles, and stress tensors.

Overall, this study aims to provide a detailed comparison of smooth and non-smooth DEMs, highlighting the strengths, limitations, and optimal application scenarios of each method in granular flow modeling. Finally, we discuss the validation of μ(I)–rheology using both smooth and non-smooth DEM, in zones far from the obstacle and near the obstacle. Around the obstacle, a dead zone forms upstream and co-exists with a fluid-like zone above, while a much more gaseous jet forms downstream: this complicated mechanism may raise questions about the validity of the μ(I)–rheology everywhere inside the bulk of the granular medium.

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Particles impact on granular media

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Speaker: Mahjoub-Bonnaire Provence. **Thursday**. Start time: **10:40**. Room: Saint Clair 1 LVL2. Link to abstract.

Grain transport by saltation is involved in numerous geophysical phenomena such as wind-blown sand, snow drift, aeolian soil erosion, dust emission, etc. Particle impacts on a granular bed trigger rebound and ejections processes, which can lead in certain conditions to a steady state of solid transport. The present work is dedicated to the analysis of the impact processes at the grain scale, with the objectives of inferring robust statistical laws and better understanding granular transport, accounting for the possible role played by adhesion between the grains. The study is based on numerical simulations with the DEM (Discrete Element Method). The numerical experiments consist in throwing a spherical particle on a granular packing with controlled velocity (Froude number between 0 and 200) and impact angle (between 10◦ and 90◦). The contact model (friction, cohesion) between the grains is varied to represent different types of granular materials (e.g., dry sand, wet sand, snow). We investigated the influence of incident parameters on the impact process, focusing on the incident particle rebound and on the number and energy of ejected particles. For non-cohesive granular beds, the simulations were compared to laboratory experiments. In particular, the restitution coefficient of the incident particles and the number of ejected particles were found in good agreement with experimental results. The simulations also give access to quantities that cannot be easily measured in the experiments. In particular, we analyzed the statistical relation between the number, the energy, the locations of the ejected particles and the impact velocity and angle. Preliminary results concerning cohesive granular beds will also be presented, considering contact laws representative of liquid (capillary) and solid cohesion processes. Effect of cohesion on the number of ejected particles, and energy dissipation processes within the cohesive granular beds, will be discussed. These detailed analyses allowed us to identify the physical processes associated with the ejection mechanisms and their relative influence for non-cohesive and cohesive materials.

MS3.4 - Mechanics and physics of fracture

Organisers: Véronique Lazarus (ENSTA Paris), Eric Bitzek (Max Planck Institute Dusseldorf) and Matteo Ciccoti (ESPCI, Paris)

Crack growth in mechanical metamaterials: random architectures, toughness and roughness

Bonamy Daniel (1), Montiel Antoine (1), Nguyen Thuy (2), Lienard Antoine (1), Derieux Thibaud (1), Chomat Laure (1), Rountree Cindy (1), Geertsen Valérie (3), Guenoun Patrick (3)

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Speaker: Bonamy Daniel. Keynote. **Monday**. Start time: **10:10**. Room: Rhône 2 LVL1. Link to abstract.

Linear elastic fracture mechanics provides a predictive theoretical framework for addressing fracture problems in a wide range of brittle materials such as glasses, polymers, ceramics, etc (1). On the other hand, its application to mechanical metamaterials made up of microbeams or microtubes arranged periodically to confer lightness and mechanical resistance to the structure remains more questionable. In particular, these discrete architectures lead to specific system-size dependencies that are a priori incompatible with standard LEFM (2, 3).
In this context, we have carried out a series of simulations and tensile fracture experiments on mechanical metamaterials with random architectures. In the presentation, we will see and discuss to what extent crack growth in these metamaterials differs from that observed in standard brittle materials in terms of crack roughness, fracture toughness, and the damage mechanisms involved.

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Steering Fracture in Metamaterials – Synergy of Plasticity and Fracture in Slender Beams

Gkougkousi Katerina (1), Kühner Paul (2), Kopecz-muller Caroline (1), Aragón Alejandro (3), Velikov Krassimir (1) (4), Coulais Corentin (1)

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Speaker: Gkougkousi Katerina. **Monday**. Start time: **10:50**. Room: Rhône 2 LVL1. Link to abstract.

Metamaterials have been of increasing interest in various applications fields, such as absorbing shocks or vibrations, as well as damage prevention. So far, they have been developed with a goal to increase toughness, reduce weight, increase durability of structures, all of them aiming at fracture prevention. While conventional fracture mechanics aims to prevent the initiation and propagation of cracks, a novel approach seeks to utilize the phenomenon of fracture in our favour, by steering fracture through exploiting the geometry of metamaterials. In this work, we aim to gain the opportunity to precisely control and steer the crack propagation route in compression, by taking advantage of controlling the metamaterials design and thus their mesh properties. Starting from a deeper understanding of crack propagation during compression, we investigate the mechanisms that determine the crack path in both brittle and ductile materials. Firstly, we compress beams of different slenderness, cross section shape, and materials, using a system of two displacement-controlled fixed grippers. We analyse with both a high-speed and a regular camera, and we look into the simultaneous effect of buckling and plasticity and its impact on the fracture propagation. For elasto-plastic materials, if the plastic regime is already reached when the fracture starts, the effective cross section area reduces during the crack propagation while the stiffness is considerably reduced, causing an unusual fracture response. By tuning this effect, designing more complex structures and applying our findings on fundamental beams to them, fracture propagation can be used as a design tool, instead of being dreaded and avoided. Our findings highlight the potential of intentionally directing fracture as a design tool, opening up new avenues for the design of safer, more efficient materials in applications where fracture control is critical, such as helmets and battery shells.

Structure property relationships in beetle wing joints

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Speaker: Aitzaz Ali. **Monday**. Start time: **11:10**. Room: Rhône 2 LVL1. Link to abstract.

Insect wings, particularly those of beetles, exhibit remarkable adaptations for flight and resilience, making them valuable for bioinspired engineering. This study investigates the fracture properties of wing joints in rhinoceros beetles (*Eupatorus gracilicornis*), highlighting the role of resilin, a flexible and elastic protein, under tensile and bending loads. Beetle wings are composed of a flexible membrane, veins, and joints, with the latter being critical in the folding process and mechanical performance of the wings. To evaluate joint strength and resilin contribution, mechanical tests were performed on hydrated and dried wings. Tensile tests using a micro-tensiometer and bending tests modelled as cantilever beams showed that dried wings fail at the resilin patch, which become brittle when dehydrated. This contrasts with the flexible and resilient properties of hydrated joints observed in nature. Fluorescence microscopy confirmed the presence of resilin at critical locations, leveraging its intrinsic self-fluorescent properties. Additionally, wing loading ratios for male and female beetles were calculated to relate joint strength to body mass. Results demonstrate a clear connection between resilin's hydration-dependent properties and joint durability, highlighting the adaptability of these structures under varying environmental conditions. The findings offer valuable insights into the design of bioinspired deployable wings for micro-robots, particularly in applications requiring lightweight, resilient composite structures capable of dynamic movement and folding. This research bridges biological understanding and engineering innovation, contributing to advancements in biomimetic technologies.

Fracture by Design of Topological Metamaterials

Chouzouris Matthaios (1), De Waal Leo (1), Dias Marcelo (1)

1 - School of Engineering, University of Edinburgh (United Kingdom)

Speaker: Chouzouris Matthaios. **Monday**. Start time: **11:30**. Room: Rhône 2 LVL1. Link to abstract.

Architecting mechanisms of damage in mechanical metamaterials, by translating the target effective mechanical response to structural features of the lattice, poses a complex inversion problem. Of these metamaterials, Maxwell lattices, which are on the verge of mechanical stability, offer significant potential for advanced functionality. As a result of their robust topological and geometry-dependent properties that dominate the stress activation, simplified considerations may be used to more precisely design the damage evolution. Using continuum representations of these lattices, we set up a framework that allows us to explicitly engineer the stress concentration around discontinuities. This in turn offers robust pathways to manipulate the mechanisms of damage and the fracture propagation.

Crack propagation in 2-dimensional architected material: the effects of inertia on fracture

Dantas Batista Raquel (1), Lingua Alessandra (1), Van Dokkum Jan (1), Pundir Mohit (1), Kammer David (1)

1 - Institute for Building Materials, ETH Zurich (Switzerland)

Speaker: Dantas Batista Raquel. Invited. **Monday**. Start time: **11:50**. Room: Rhône 2 LVL1. Link to abstract.

Architected materials have properties not common in homogeneous solid materials while being lightweight. These materials are engineered to achieve a target mechanical behavior by designing the geometry, which consists of connected struts. Despite the advances in additive manufacturing techniques, the engineering use of architected materials is limited as their fracture behavior is not well understood. We identify the complexity of fracture in discrete media as one reason why. The quasi-static approach to fracture is usually adopted in the study of metamaterial fracture. This approach shows that the fracture toughness scales with the relative density, and this scaling law changes with the topology (1,2), highlighting the geometry dependence on the fracture behavior of architected materials. Also, unlike a continuum, the crack advances by sequential breakage of struts, and the crack path is not necessarily continuous. However, the quasi-static approach neglects the effects of inertia on crack propagation, which plays an important role in brittle materials. To consider these effects, an analysis under the context of dynamic fracture mechanics is needed (3). It is known that inertial effects control the crack propagation in continua. Whether the inertial effects can or cannot be neglected in the fracture of architected materials remains an open question. The influence of different topologies and relative density in the fracture under dynamic conditions is unclear. In this presentation, we explore the fracture of architected materials in the context of dynamic fracture mechanics. We compare the crack propagation of two-dimensional architected materials by performing numerical analysis of pre-cracked triangular lattices modeled as beam networks in the quasi-static and dynamic load regimes. We assess the effect of inertia on crack path and fracture properties in architected materials and its influence on different relative densities.

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Anticracks as localized damage with volume loss: overview and new experimental insights

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Speaker: Hach Mathis. **Monday**. Start time: **13:40**. Room: Rhône 2 LVL1. Link to abstract.

The concept of anticracks is used to describe the localized damage under compression that is associated with negative mode-I stress intensity factors. Such localized damage can only appear and propagate within a material when a volume loss mechanism within the material exists. It has been shown that concepts of classical fracture mechanics can be applied to describe such phenomena.
Anticracks have been used to describe propagating volume loss phenomena in various domains. The concept was first formulated by Fletcher and Pollard (1981) to describe the behavior of localized compaction mechanisms in porous sedimentary rocks. In such cases, a local stress concentration leads to enhanced pressure dissolution and removal of minerals which leads to further localization of the stress fields and to planar extension of the compacted domain and movement of the stress singularity. Additionally, compaction bands in porous sandstones were analyzed and explained by this concept. Anticracks have also been used to describe the propagation of volume loss mechanisms occurring in phase changes of minerals under high hydrostatic pressure, which are associated with deep earthquakes. In snow mechanics, anticracks have been extensively studied in the context of dry-snow slab avalanches. Here, snow covers that contain highly porous weak layer exhibit a propagating collapse that extends below the slab and explains remote triggering of avalanches or the infamous whumpf-sound of instable slopes (Heierli et al., 2008). To analyze anticracks in snow covers extensive theoretical and experimental studies have been conducted, enabling the identification of fracture toughness values of anticracks under pure mode-I and mixed-mode loading conditions (Adam et al., 2024). In technical materials like highly porous foams or additively manufactured cellular structures the formation of anticracks has also been reported for negative mode-I loadings (Heierli et al., 2012; Shenhav and Sherman, 2019).

In contrast to these volume-loss damage mechanisms, the term anticrack has also been used to describe the singular stress field around rigid lamellar inclusions, which also exhibits a square root singularity. This concept has been used in micromechanics of composites with significant elastic contrasts.

In this work, we provide an overview of the concept of anticracks and compare anticrack models across various settings. We discuss the required extent of volume loss mechanisms, the associated time scales and the change of stiffness within the anticrack domain. The different applications of the anticrack concept imply different internal material mechanisms for lateral, planar propagation that are analyzed with respect to their brittle nature and energy dissipation mechanisms. The role of negative mode-I stress intensity factors in mixed-mode problems will also be addressed.

We show recent experimental findings on anticrack propagation in brittle highly-porous technical foams. Using microscope imaging and CT analysis we show the microstructural mechanisms associated with stable anticrack propagation in fracture mechanics specimens. Using digital image correlation, we provide insights into the elastic and inelastic strain fields in the vicinity of the anticracks. The results allow for an analysis of the energy dissipation during anticrack propagation.

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Path difference under monotonic and cyclic loading in anisotropic media

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1 - Institut des Sciences de la Mécanique et Applications Industrielles (France), 2 - Institut de Recherche en Génie Civil et Mécanique (France), 3 - Physics Department and Center for Interdisciplinary Research on Complex Systems, Northeastern University (United States)

Speaker: Zhai Xinyuan. Invited. **Monday**. Start time: **14:00**. Room: Rhône 2 LVL1. Link to abstract.

Additive manufacturing has garnered significant attention due to its flexibility in modeling and its capacity to easily design complex microstructures (1). Given that microstructure plays a crucial role in determining crack propagation paths (2), additive manufacturing has become increasingly relevant in the study of fracture mechanics. In this work, we used samples fabricated by Fused Deposition Modeling, which exhibit a strongly anisotropic behavior in fracture toughness while retaining isotropy in elasticity. This anisotropic behavior arises from employing the 'criss-cross' printing strategy as reported in (3). This strategy involved filling each layer with a selected infill angle or raster angle (angle of deposited material with respect to the notch), with successive layers arranged orthogonally.
By applying monotonic and cyclic loading, we observed notable differences in crack propagation paths between quasistatic and fatigue cracks. Under monotonic loading, cracks propagate along the direction of the raster angle (referred to as the 'weak plane'), consistent with predictions from the Generalized Maximum Energy Release Rate (GMERR) criterion. In contrast, fatigue cracks subjected to cyclic loading exhibit a distinctly different paths, following a straight path by KII = 0 in agreement with the Principle of Local Symmetry (PLS). A similar behavior has been observed in fatigue phase-field computational models with two-fold anisotropy (4), indicating that this path difference is a general phenomenon. Both experiments and numerical computations suggest that quasistatic crack paths are primarily dictated by the microstructure, while fatigue crack paths are influenced by the symmetry of the loading (5).

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Predicting Crack Paths Using 'Elastic Charges'

Szachter Oran (1), Siéfert Emmanuel (2), Adda-bedia Mokhtar (3), Moshe Michael (1), Sharon Eran (1)

1 - The Racah Institute of Physics, The Hebrew University of Jerusalem (Israel), 2 - Laboratoire Interdisciplinaire de Physique (France), 3 - Laboratoire de Physique de l'ENS Lyon (France)

Speaker: Szachter Oran. **Monday**. Start time: **14:20**. Room: Rhône 2 LVL1. Link to abstract.

Predicting crack trajectories remains a central challenge in theoretical fracture mechanics, primarily due to the non-local and history-dependent nature of crack propagation. In this study, we introduce a novel theoretical framework that represents cracks as distributions of elastic charges, which can be effectively approximated by charges localized at the crack tip. This framework captures the non-local nature of cracks while enabling a simplified, point-like description of crack dynamics akin to the treatment of particle motion in Newtonian mechanics.
We apply this framework to predict crack trajectories in two distinct scenarios. First, we analyze crack propagation in residually stressed flat sheets, using the framework to predict crack paths in elastomer sheets containing dislocations. Second, we extend our approach to tearing in thin sheets, incorporating mode III cracks, and apply it to the well-known "poster problem."
Our predictions demonstrate excellent agreement with experimental observations, highlighting the potential of this approach to advance our understanding of crack dynamics.

Quantifying the interplay amongst fracture, heterogeneities, plasticity and process zone

Anusuya Ponnusami Sathiskumar (1), Ani Allamaprabhu (1), Turteltaub Sergio (2)

1 - City, University of London (United Kingdom), 2 - Delft University of Technology (Netherlands)

Speaker: Anusuya Ponnusami Sathiskumar. **Monday**. Start time: **14:40**. Room: Rhône 2 LVL1. Link to abstract.

The physics of fracture in heterogeneous or composite materials is often linked with how cracks interact with the constituent phases (or inclusions). A matrix crack approaching a stiffer inclusion will experience a shielding effect (a reduction in the crack driving force), whereas an anti-shielding effect is experienced if the inclusion is softer (lower elastic modulus) than the matrix. Despite a long history of research into crack-inclusion interactions, there appears to be a very limited study on the interplay amongst physical processes and parameters such as plastic yielding, stiffness mismatch, and the evolution of fracture process zone in a composite material. The current research will address the gap by explicitly quantifying such interactions on the crack driving force. For this purpose, crack propagation in a simplified inclusion-matrix system is modeled using the eXtended Finite Element Method (XFEM) in the context of the cohesive zone approach. The crack driving force parameters associated with the elastic mismatch and the plastic yielding in inclusions are quantified using configurational force integrals. While the crack growth is governed by maximum principal stress, the crack direction is controlled using maximum energy dissipation criteria. Specific emphasis is placed on revealing the competing/synergistic effects of plasticity and stiffness mismatch in the presence of varied fracture process zone lengths. The results are qualitatively correlated with the strengthening and toughening mechanisms in composite materials, which, in turn, guide fracture-resistant microstructure design. The study provides insights into the gaps in understanding one of the fundamental interaction problems in fracture mechanics.

An anisotropic model for the multiscale analysis of short fiber reinforced polymers through Phase Field

Fajardo Lacave Angela (1) (2), Welschinger Fabian (1), De Lorenzis Laura (2)

1 - Robert Bosch GmbH (Germany), 2 - ETH Zuerich (Switzerland)

Speaker: Fajardo Lacave Angela. Invited. **Monday**. Start time: **15:00**. Room: Rhône 2 LVL1. Link to abstract.

Understanding and modeling the fracture mechanical behavior of short glass fiber reinforced polymers (SFRPs) is challenging: the strong heterogeneity induced by the manufacturing process causes a tight coupling of the material microstructure to the effective response on the component scale. Aiming to account for this microstructural complexity, fracture is approached using a multiscale approach.
Typically manufactured via injection moulding, SFRP components exhibit locally varying microstructural configurations e.g., fiber orientations, fiber volume contents, and fiber length distributions, which render fracture modelling a challenging task. To resolve the microstructure induced anisotropy and its relationship with the macroscopic material behavior, the well established isotropic phase field models of brittle fracture is extended towards the anisotropic case making use of the fiber orientation interpolation concept.To create the database, the anisotropic elastic coefficients are obtained from previously executed micromechanical simulations on realistic microstructures using the efficient microscopic solver FeelMath. At the simulation level, the local microstructure must be known in order to access the database: microstructural information stemming from either X-ray micro computed tomography or from injection moulding process simulation is mapped into the Abaqus mesh prior the execution of the macroscopic simulaiton. The performance of the simulation method is demonstrated by means of several numerical analyses and the predicion quality together with the limitations of the proposed method are demonstrated.
Therefore, an innovative approach is proposed using an offline training of a database plus a fiber interpolation concept to take into account the heterogeneity of the material. The approach is fully integrated into the seamless simulation chain for SFRPs ranging from the manufacturing process to the structure mechanical fracture analysis. The limitations of the approach stemming from the underlying assumptions are quantified and further development needs are identified.

Modelling of crack propagation in strongly anisotropic media using phase-field fracture and LEFM

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Speaker: Loiseau Flavien. **Monday**. Start time: **15:20**. Room: Rhône 2 LVL1. Link to abstract.

The study of crack propagation in anisotropic media is becoming increasingly important in structural mechanics. Additive manufacturing processes, in particular, are being investigated for their capacity to produce custom parts and their potential to repair structures (Ngo et al., 2018). Understanding and modeling their mechanical degradation is crucial to ensure the safe application of 3D-printed materials. However, knowledge of crack propagation modeling in these materials still needs to be completed. The microstructure of anisotropic materials induces anisotropy in their fracture toughness, complicating the modeling process. While some models can qualitatively represent crack propagation in such materials, only a few quantitative studies are currently available. Previous studies (Corre & Lazarus, 2021; Zhai, 2023) have demonstrated that strongly anisotropic phase-field fracture models can effectively capture crack propagation in anisotropic media. Building on this foundation, this work further evaluates the capabilities of strongly anisotropic phase-field fracture models. In particular, we aim to investigate more complex propagation problems, such as cases involving crack path bifurcation. Simulations will be compared against Linear Elastic Fracture Mechanics results, using the Generalization of the Maximum Energy Release Rate to anisotropic media.

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Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, *143*, 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012

Zhai, X. (2023). *Crack propagation in elastic media with anisotropic fracture toughness: Experiments and phase-field modeling.*

Supershear growth of tensile cracks enabled by geometric non-linearities

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Speaker: Kammer David. Keynote. **Monday**. Start time: **16:00**. Room: Rhône 2 LVL1. Link to abstract.

Linear elastic fracture mechanics (LEFM) theory has long postulated that the speed of crack growth is constrained by the Rayleigh wave speed. While numerous experimental and numerical studies have generally supported this prediction, some exceptions have raised questions about its validity and the underlying factors influencing dynamic crack behavior. In this work, we present new numerical results showing that tensile (mode I) cracks can surpass the Rayleigh wave speed and exhibit propagation at supershear velocities. The key to this finding lies in incorporating geometric non-linearities into the material model. While such non-linearities are inherent in most materials, their effects on dynamic fracture growth have been largely overlooked in previous work. Our results reveal that accounting for geometric non-linearities is sufficient to enable supershear crack propagation. In addition, we show that these non-linearities induce modifications in the crack-tip singularity, leading to unconventional crack-tip opening displacements, cohesive zone behavior, and altered energy flow dynamics toward the crack tip. These observations suggest that the elastic fields and energy budgeting in the vicinity of the crack tip of geometrically non-linear materials have a completely different behavior than that of linear elastic materials, which is commonly assumed in LEFM theory. Consequently, this provides a novel perspective on dynamic crack growth that challenges existing theoretical frameworks.

Geometrically Nonlinear Materials as a Framework for Nonlinear Elastic Fracture Mechanics

Adda-bedia Mokhtar (1)

1 - Laboratoire de Physique, Universite´ de Lyon (France)

Speaker: Adda-Bedia Mokhtar. Invited. **Monday**. Start time: **16:40**. Room: Rhône 2 LVL1. Link to abstract.

Linear elastic fracture mechanics theory (LEFM) predicts that the speed of crack growth is limited by the Rayleigh wave speed. Although many experimental observations and numerical simulations have supported this prediction, some exceptions have raised questions about its validity. The underlying reasons for these discrepancies and the precise limiting speed of dynamic cracks remain unknown. Here we lay the foundations of a theory of nonlinear elastic fracture mechanics (NLEFM) to demonstrate that tensile (mode_˜I) cracks can exceed the Rayleigh wave speed and propagate at supershear speeds. We show that taking into account geometric non-linearities, inherent in most materials, is sufficient to enable such propagation modes. These geometric non-linearities modify the crack-tip singularity, resulting in different crack-tip opening displacements, cohesive zone behavior, and energy flows towards the crack tip.

Brittle fracture and fatigue of unsteadily rotated structures

Yakir Gilad (1), Gutierrez-prieto Eduardo (1), Lazarus Veronique (2), Reis Pedro (1)

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Speaker: Yakir Gilad. **Monday**. Start time: **17:00**. Room: Rhône 2 LVL1. Link to abstract.

Nearly every machine built since the Industrial Revolution involves rotating components such as wheels, gears, fans, and turbines, which are so ubiquitous that they often go unnoticed. Regardless of their size and purpose, the dynamics of rotating systems can be described by a set of differential equations with respect to an observer or a frame of reference (FoR). A FoR can either be inertial (*i.e.* non-accelerating), implying that any object within it has a zero applied net force will move at a constant velocity, or non-inertial (i.e. accelerating). A non-inertial FoR produces what are known as fictitious (or pseudo) forces. More specifically, a rotating non-inertial FoR generates three fictitious forces: (*i*) *Coriolis*, (*ii*) *centrifugal*, and (*iii*) *Euler* forces. We examine the brittle fracture of a rotating structure subjected to these coupled fictitious forces. In this talk, we consider the following problem: What governs the brittle fracture of rotating pre-notched cantilevered beams? We introduce a pre-crack to a beam-like acrylic sample. The coupled centrifugal and Euler forces invoke the tensile opening mode (mode I) and, by choosing the beam configuration, either the in-plane shear mode (mode II) or the tearing mode (mode III). We conduct systematic experimental and finite element simulations to study the interaction of the coupled modes. We show that linear elastic fracture mechanics (LEFM) can predict the onset of crack propagation under certain loading conditions. Using the same apparatus, we also investigate the fatigue of a soft tissue-like hydrogel.

Macro Cleavage Energy to Micro Bond Breaking Mechanisms - Shorter is Tougher

Sherman Dov (1)

1 - Tel Aviv University (Israel)

Speaker: Sherman Dov. Invited. **Monday**. Start time: **17:20**. Room: Rhône 2 LVL1. Link to abstract.

The fracture of brittle solids is ultimately executed by atomistic-scale, discrete, and ultrafast bond-breaking mechanisms along the crack path. Here we show a new fracture behavior and properties of brittle materials, based on macroscopic fracture cleavage experiments of brittle crystals (cubic silicon, hexagonal lithium niobate, quartz) and amorphous (soda lime glass) specimens and atomistic-scale semi-empirical model for bond-breaking mechanisms along the curved crack front, to relate macro to micro in fracture.

Griffith's theory of brittle solids is based on a total energy balance at the equilibrium of slow fracture processes. He defined twice the free-surface energy density, 2γs under vacuum, or 2γscc under environmental assisted stress corrosion cracking (or in short 2γs(cc)) as the governing material property resisting crack initiation, known as the Griffith barrier. While full details of the experimental program are unavailable, Precrack lengths in the glassy tube specimens are over 0.25" (6.25 mm). Our fundamental query would be the fracture (or cleavage) energy in specimens with shorter precrack.

Following an extensive experimental program, we concluded that the Griffith barrier is only the lower bound of the cleavage energy, 2γs(cc). When short precracks are introduced, the cleavage energy increases.

In addition, we examined the Griffith's finding that a0 const , and concluded that it is not constant for shorter cracks. Surprisingly, our measure of long cracks starts at about 7 mm (or a0/W$>$ 0.17). In Griffith's paper, W is not reported.

We will introduce at first our extended approach to the macroscale evaluation of the critical Energy Release Rate (ERR), 0 and the effect of the derivative of the ERR, dG0(a0)/da. We then present our high- resolution fracture cleavage experiments of brittle specimens and their macroscale fracture properties. We then suggest an additional fracture mechanism we termed quasi-propagation, during which the cleavage energy is increased at short propagation length and at nearly zero speed. Only then, do we connect the macroscale and microscale in fracture.

Our experimental, theoretical, and numerical evaluations have yielded the following major findings:
1. The cleavage energy in brittle single crystal specimens yielded increasing cleavage energy, 0, for

decreasing precrack length, a0, up to 3 times the Griffith barrier. Short crack length is when a0/W$<$ 0.17.
2. The Griffith barrier of S(CC) is the lower bound for crack initiation energy and the lattice-trapping barrier

is the upper bound. Both are linearly dependent on .

3. While it is widely accepted that fracture processes include initiation and propagation, we indicate the existence of a third mechanism of a short propagation of several microns only at zero speed. It is spent to increase the cleavage energy from the Griffith barrier of 2γs (or 2γSCC) to that dictated by the energy flow to the crack front, It is also intended to change the bond-breaking mechanisms along the crack front from kink advance-dominated mechanisms to kink formation ones.

4. An important result of this investigation is that the strength of a material may increase significantly compared to Griffith's prediction, due to . For short precracks, this increase may be tens of percent, indicated by the following modified Griffith's strength of brittle materials (a0, the precrack length):

cr

0()E

Nonlinear elasticity in the coupled criterion : Influence on crack initiation and propagation

Doitrand Aurélien (1)

1 - Matériaux, ingénierie et science [Villeurbanne] (France)

Speaker: Doitrand Aurélien. **Monday**. Start time: **17:40**. Room: Rhône 2 LVL1. Link to abstract.

This work focuses on the influence of considering the nonlinear elasticity of the material to study crack initiation and propagation using the coupled criterion. Experimental observations of i) unstable crack initiation at a circular hole or at a V-notch and ii) stable crack propagation under opening mode combined with different T-stress levels show some limitations of linear elastic fracture mechanics in i) predicting crack initiation and ii) characterizing the material critical energy release rate or critical stress intensity factor. The application of the coupled criterion (1) considering the nonlinear elastic behaviour of the material is presented. First, we highlight how the consideration of the nonlinear elastic material behaviour improves the inverse identification of the material fracture properties based on a set of two crack initiation experiments, namely a plate with holes under tensile loading and TDCB specimens. We then discuss how the dependence of the apparent critical stress intensity factor on the T-stress level measured by Digital Image Correlation can be explained by the nonlinear material behaviour.

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The Fundamental Physics of the Onset of Frictional Motion: How do laboratory earthquakes nucleate?

Fineberg Jay (1), Gvirtzman Shahar (1), Kammer David (2), Adda-bedia Mokhtar (3)

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Speaker: Fineberg Jay. Keynote. **Tuesday**. Start time: **10:00**. Room: Rhône 2 LVL1. Link to abstract.

Recent experiments have demonstrated that rapid rupture fronts, akin to earthquakes, mediate the transition to frictional motion. Moreover, once these dynamic rupture fronts ("laboratory earthquakes") are created, their singular form, dynamics and arrest are well-described by fracture mechanics. Ruptures, however, need to be created within initially rough frictional interfaces, before they are able to propagate. This is the reason that "static friction coefficients" are not well-defined; frictional ruptures can nucleate for a wide range of applied forces. An important open question is, therefore, how the nucleation of rupture fronts actually takes place. We experimentally demonstrate that rupture front nucleation is prefaced by extremely slow, aseismic, nucleation fronts. These nucleation fronts, which are often self-similar, are *not* described by our current understanding of fracture mechanics. The nucleation fronts emerge from initially rough frictional interfaces at well-defined stress thresholds, evolve at characteristic velocity and time scales governed by stress levels, and propagate within a frictional interface to form the initial rupture from which fracture mechanics take over. We will briefly describe a new theoretical description of the nucleation process obtained by means of a nontrivial extension of fracture mechanics. This theory quantitatively describes all of the experimentally observed features of the extremely slow nucleation process and merges seamlessly with the accepted fracture mechanics description of rapid dynamic ruptures. In addition, this new theory provides a mechanical explanation for what are considered as slow 'creep' processes that often take place prior to fracture. These results are of fundamental importance to questions ranging from earthquake nucleation and prediction to processes governing material failure.

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The role of slow slip in triggering dynamic frictional ruptures

Faure Yohann (1), Bayart Elsa (2)

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Speaker: Bayart Elsa. Invited. **Tuesday**. Start time: **10:40**. Room: Rhône 2 LVL1. Link to abstract.

An earthquake occurs when a seismic fault suddenly slips, releasing stresses that have accumulated during tectonic movement. These stresses can also be released by slow slip events, which can be detected by monitoring crustal deformation. The role of slow slip events is critical because they influence the occurrence of earthquakes along a fault. However, the mechanisms by which slow slip affects earthquake initiation remain poorly understood.
A seismic event consists of the propagation of an interfacial rupture along a seismic fault, which can be described as a frictional interface. These ruptures, which break the microcontacts that form the interface and resist shear, have been shown to be pure shear (mode II) cracks (1). The question of how slow slip affects earthquake triggering is then related to the question of mode II crack initiation along a weak plane.

In a recent experimental study, we studied the case of laboratory fault, along which slow slip was induced by the presence of a heterogeneity in the composition of the interface, a granular inclusion. By measuring the response of the fault to shear and performing interfacial slip measurements and high-frequency strain measurements, we show that the slow-slip region acts as a nucleation center for seismic rupture, thereby increasing the frequency of earthquakes. The destabilization of the slow-slip region follows the same trends as a crack initiation criterion: the longer the slow slip patch, the earlier the destabilization into dynamic rupture and the more frequent the triggering of earthquake-like ruptures. Our work suggests that a fracture mechanics-based description may be used to predict the destabilization of a slowly slipping patch into a dynamic rupture. This provides further insight into how to account for fault complexity in models and improve understanding of the diversity of seismic fault behavior.

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The stick-break instability of extended fractures

Albertini Gabriele (1), Cochard Thomas Svetlizky Ilya Robert Viesca Weitz David

1 - University of Nottingham (United Kingdom)

Speaker: Albertini Gabriele. Invited. **Tuesday**. Start time: **11:00**. Room: Rhône 2 LVL1. Link to abstract.

Fractures can lead to catastrophic failure of materials. Although crack propagation in a two-dimensional plane is well understood, all cracks are extended in a three-dimensional (3D) space, through which they propagate. When cracks slowly move forward in a 3D brittle material, they do so in a discontinuous way with long pauses of no motion followed by rapid forward jumps. We call this a stick-break instability. These forward jumps are short-lived dynamic ruptures propagating perpendicular to the main direction of motion at velocities as high as the Rayleigh-wave speed. We study the crack propagation experimentally in a circular geometry that achieves an uninterrupted extended fracture front and use a fluid to control the loading conditions that determine the amplitude of the forward jump. We find that this amplitude correlates with the transverse velocity. Here we further investigate this observation with dynamic rupture simulations to shed light on the underlying mechanics. These results emphasize the importance of transverse dynamics in the forward propagation of extended fractures.

Energy balance of fluid driven frictional rupture in a fractured rock mass

Sarma Antareep Kumar (1), Lecampion Brice (1)

1 - Geo-Energy Lab, École Polytechnique Fédérale de Lausanne (EPFL) (Switzerland)

Speaker: Sarma Antareep Kumar. **Tuesday**. Start time: **11:20**. Room: Rhône 2 LVL1. Link to abstract.

Re-activation of pre-existing discontinuities in the form of fractures and faults can occur due to fluid pressurization at depth. The increase of fluid pressure can facilitate the propagation of slow frictional ruptures over considerable distances and can also trigger frictional instabilities. These can occur in response to either anthropogenic fluid injection (e.g. hydraulic stimulation) or via natural occurences (e.g. serpentine dehydration). Hydraulic stimulation, a commonly employed technique in various geo-energy applications, aims to enhance the permeability of rock formations by creating new fractures or reactivating the pre-existing ones with pressurised fluid injection. This process induce slip along existing fractures, resulting in a range of behaviors from stable, slow-slip events to more rapid, dynamic ruptures.
Recent studies have made significant strides in quantifying the mechanics of fluid-induced frictional slip in single-plane systems. For instance, Sáez and Lecampion (2024) identified four distinct slip regimes for a fluid-induced slip-weakening fault in 3D, progressing from quasi-static slip to nucleation, arrest, and ultimately a runaway dynamic rupture based on three dimensionless numbers that consist information on the in-situ stress state, injection strength and peak and residual friction coefficients (1) . These findings provide a clear understanding of how single-plane fractures respond to fluid pressure. However, the response of interconnected fracture networks, which is more representative of real-world subsurface conditions, to fluid injection remains poorly understood. The intricate stress interactions that arise between multiple fractures under fluid pressure introduce an additional level of complexity that existing theoretical and numerical models have yet to fully capture. Although some numerical studies have qualitatively explored the behavior of fracture networks subjected to fluid injection, detailed quantification of energy distribution and slip mechanics within these interconnected systems have not been investigated in detail (2).

In this study, we derive an energy balance of the hydro-mechanical system consisting of the fractured rock mass and the injected fluid. Our primary goal is to understand the overall energy budget, and notably quantify the partitioning of the energy dissipated in plastic slip along major and the surrounding minor fractures. Specifically, we evaluate whether the presence of additional smaller fractures leads to a shielding effect on major fractures-where stress interactions inhibit rupture propagation-or a promoting effect, where interactions facilitate rupture growth and energy transfer, as function of in-situ stress, statistical and material properties of the discrete fracture network, as well as injection conditions.

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Physics of Earthquake Cycles: An energy perspective

S. Bhat Harsha (1), Kheirdast Navid (1), Almakari Michelle (1), Villafuerte Carlos D. (2), Gupta Ankit (1)

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Speaker: S. Bhat Harsha. **Tuesday**. Start time: **11:40**. Room: Rhône 2 LVL1. Link to abstract.

Natural fault zones containing fractures/faults of various scales from millimeters to several kilometers, under tectonic loading show complex spatiotemporal stick-slip cycles which result in a broad spectrum of rupture velocity which corresponds to slow-slip earthquakes to major earthquakes. The competition between the frictional strength of faults against slip and the dissipation due to the damaged fault zone gives rise to such complex slip behavior. We developed a two-dimensional fault-zone seismic cycle model in which the main fault is surrounded by off-faults and sliding under the rate and state friction law, which can capture all the statistical scaling laws observed in natural faults.
Next, we formulate the energy budget for the seismic cycle and derive the energy relations in terms of observable energy quantities namely: Radiated energy, Potential energy change, and apparent fracture toughness of fault zone. We show that the observable part of energy quantities can be calculated just by deducing the accurate shear slip profiles on ruptures on faults in the model. Further by partitioning the energy quantities for the main fault and the off-fault contributions, and their interaction energy, we compare the underlying physical behavior of the damage zone around main faults during slow slip events and major earthquakes.

A Statistical and Multiscale Perspective on Solute Induced Embrittlement for Intergranular Fracture

Fernandez Miguel (1), Dingreville Remi (2), Spearot Douglas (1)

1 - University of Florida (United States), 2 - Sandia National Laboratories (United States)

Speaker: Spearot Douglas. Keynote. **Tuesday**. Start time: **14:15**. Room: Rhône 2 LVL1. Link to abstract.

Intergranular fracture is a common form of fracture in polycrystals and can be influenced by the presence of solutes (for alloying) and impurities at grain boundaries (GBs). One approach to assess the influence of solute segregation to a GB on intergranular fracture is via the calculation of an embrittling potency. Historically, studies have reported embrittling potency as a single, scalar value, assuming a single segregation site of importance at a GB and a particular cleavage plane. However, the topography of intergranular fracture surfaces is rarely known a priori. Thus, the objective of this work is to take a statistical ensemble approach to solute embrittling potency, where distributions of embrittling potencies are computed via atomistic simulations and such calculations motivate the use of local fracture property distributions in phase-field fracture simulations. Specifically, atomistic calculations are used to compute embrittling potency distributions for Cr segregation to GB sites at two Ni $<111>$ symmetric tilt grain boundaries. The average embrittling potency for a particular GB site, considering the ensemble of fracture permutations, is not equal to the embrittling potency computed using the lowest energy fracture path. Then, phase-field fracture simulations are performed where the local fracture toughness of a GB within a two-dimensional polycrystal is sampled from a distribution that depends on local solute composition and GB type. Assigning local properties to GBs stochastically influences the global stress-strain response of the polycrystal, the stress necessary for fracture initiation, and the fracture path, relative to the case where each GB has uniform fracture properties. The effect of different distribution widths for solute induced embrittlement is also explored.

Fracture toughness thickness dependence in thin SS316L sheets

Mohtadifar Negar (1), Colla Marie-stéphane (1), Azevedo Valentin (1), Jacques Pascal J. (1), Pardoen Thomas (1) (2)

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Speaker: Mohtadifar Negar. Invited. **Tuesday**. Start time: **14:55**. Room: Rhône 2 LVL1. Link to abstract.

The fracture toughness (FT) of thin ductile metallic plates is not an intrinsic property but varies with thickness, sometimes significantly. For metals with pronounced strain-hardening capacity and sufficiently large fracture strain, the FT of the sheet increases with thickness, reaches a peak, and then levels off to reach the well-defined plane strain value. However, the factors governing this thickness dependence and its potential for designing lighter, tougher thin-walled structures remain underexplored.
In this study, an experimental investigation is conducted on thin SS316L sheets of varying thicknesses to identify the key factors influencing FT. SS316L, with its high strain-hardening exponent, is expected to reach the FT peak at an approximate thickness of 10 mm. Double-edge notched tension (DENT) specimens with varying ligament lengths were tested. Some specimens were deformed to the point of fracture, while others were arrested after experiencing varying degrees of plastic strain. For specimens deformed to fracture, the essential work of fracture (EWF) methodology was applied to separate the contributions of necking and damage within the fracture process zone (FPZ) from the plastic work occurring in the diffuse plastic zone (DPZ). These contributions are further interpreted in the context of earlier models discussed in (1) and (2).

For the arrested specimens, the crack tip opening displacement (CTOD) method was utilized to assess fracture toughness at the initiation stage by using the Shih factor (3) and also relying on original 3D computed x-ray microtomography data. The results exhibit thickness-dependent trends consistent with the fracture toughness values derived from fully fractured tests, encompassing both initiation and propagation stages. The findings for SS316L are compared with those for SS304LN and literature data, providing deeper insights into the factors affecting fracture toughness and its peak behavior.

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Influence of Strain Hardening on Ductile Crack Growth under Small-Scale Yielding Plane Strain Conditions

Kaniadakis Antonio (1), Nguyen Van Dung (1) (2), Besson Jacques (3), Pardoen Thomas (1) (4)

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Speaker: Kaniadakis Antonio. Invited. **Tuesday**. Start time: **15:15**. Room: Rhône 2 LVL1. Link to abstract.

The influence of strain hardening on ductile crack growth is investigated using a small-scale yielding finite element approach under plane strain conditions, incorporating *J2* plasticity and an advanced non-local Gurson model (1). High strain hardening exponents (n up to 0.5) are explored, extending beyond classical studies to include materials such as stainless steels, TRIP-TWIP alloys, and high entropy alloys. *J2* plasticity simulations reveal the impact of higher n on the finite strain zone, the opening stress distribution, and the crack tip opening displacement, providing insight into how strain hardening influences fracture toughness. Subsequently, Gurson-based simulations are conducted for varying values of strain hardening and initial porosity, generating *JR* curves, tearing modulus, and crack initiation metrics, such as JIC and critical crack tip opening displacement. These simulations demonstrate an increase in fracture toughness with higher n. We will address the following questions: (i) Why does fracture toughness increase with n? (ii) What is the effect of very large n on fracture resistance indicators? (iii) What is the potential impact of developing metallic alloys with high strain hardening capacity? Additionally, we emphasize the need for fine-tuning the Gurson model for high strA&Min hardening exponents and establishing precise rules for mesh generation and initial crack opening to ensure accurate results.

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Investigating the effect of thickness on the fracture toughness of thin metallic sheets focusing on Al2050

Javangorouh Sara (1), Kaniadakis Antonio (1), Nguyen Van Dung (1) (2), Colla Marie-stéphane (1), Mohtadifar Negar (1), Noels Ludovic (2), Pardoen Thomas (1) (3)

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Speaker: Javangorouh Sara. Invited. **Tuesday**. Start time: **15:35**. Room: Rhône 2 LVL1. Link to abstract.

Fracture toughness is a critical parameter in material selection and structural design. For thin metallic sheets, fracture toughness is not solely an intrinsic material property but is also strongly influenced by sheet thickness. Previous studies have shown that fracture toughness increases with sheet thickness, reaching a peak at low thicknesses, and then decreases and stabilizes to a plateau in the plane-strain regime (1). However, the position and magnitude of this peak and the underlying mechanisms remain inadequately studied.

This study integrates both experimental and numerical approaches to address these gaps. The experimental investigations focus on aluminum alloy Al2050-T8, employing the Crack Tip Opening Displacement (CTOD) method on Double-Edge Notched Tension (DENT) specimens. A wide range of thicknesses is tested to accurately capture the influence of sheet thickness on fracture toughness and identify the critical peak.

On the numerical side, J2 elastoplastic simulations on both 2D and 3D frameworks are performed to establish reference solutions for the static case. Then simulations are performed using an advanced nonlocal Gurson–Tvergaard–Needleman (GTN) model, which incorporates mechanisms of void nucleation, growth, and coalescence. This model captures crack initiation and propagation in order to investigate the thickness-dependent trends in fracture toughness of thin sheets (2).

The study also investigates the role of strain hardening in influencing fracture toughness. While previous simulations relied on the Swift hardening law, this research implements the Kocks-Mecking strain hardening law, which accounts for four distinct hardening stages and is integrated into the GTN model to generate more realistic predictions.

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Liquid metal embrittlement: from application of global energetical criterium to crack initiation stress intensity factors

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Speaker: Auger Thierry. Invited. **Tuesday**. Start time: **15:55**. Room: Rhône 2 LVL1. Link to abstract.

Liquid metal embrittlement (LME) of an otherwise ductile material is an environmentally induced fracture phenomenon characterized by potentially high brittle crack propagation rate and deleterious effects on mechanical properties. LME also encompasses fracture induced by the grain boundary wetting (GBW) phenomenon. The phenomenology of these phenomenons is still not well understood, in particular neither for the prediction of sensible solid/liquid couples, nor to decipher a priori potential fracture modes or fracture toughness.
We will illustrate what energetical criterium based on AbInitio modelling of solid-liquid interfaces can bring to the phenomenology of LME in terms of the prediction for systems classification (GBW versus standard LME with a ductile to brittle transition induced by environmental adsorption). Via a sound calculation of the wettability parameter S representing the driving force for GBW, the predicted trend for several systems from pure elements to high entropy alloy will be presented and we show a good match with experiments. The fracture toughness in Fe based systems showing LME will be also shown to compare favorably with the predicted trends by an energetical Griffith approach based on the modelling of solid-liquid interfaces. Taking all these results together, this brings confidence that energetical criterium based on AbInitio modelling can be used in LME for predicting at least the LME sensitivity of various systems.
At last, we will report on the study at the atomic level by QM/MM approach to go one step beyond and predict crack initiation stress intensity factors in a copper LME system. A methodology for comparison with experiment will be presented that show how mechanical quantities of interest in fracture could be infered from AbInitio modelling.

Fracture behavior of brittle particulate composites consisting of a glass matrix and glass or ceramic particles

Rouxel Tanguy (1)

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Speaker: Rouxel Tanguy. Keynote. **Tuesday**. Start time: **16:35**. Room: Rhône 2 LVL1. Link to abstract.

In this presentation, we will illustrate the peculiarities of the fracture behavior of brittle particulate composites consisting of a glass matrix and glass or ceramic particles based on numerous examples of composites exhibiting innovative functional properties. We will focus in particular on the reinforcement mechanisms at the nano- and micro-scopic scales as well as on original functions obtained with particles presenting remarkable properties, such as mechanoluminescence, superabrasion, or crack-healing.

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Volume expansion vs cryosuction in frost-driven fracture: a look through numerical modeling

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Speaker: Chao Correas Arturo. Invited. **Tuesday**. Start time: **17:15**. Room: Rhône 2 LVL1. Link to abstract.

Exposing hydrogels to sufficiently low temperatures can cause the liquid imbued within to freeze into ice crystals. Far from innocuous, the presence of these internally growing solid inclusions compromises the hydrogel's structural integrity, ultimately having the potential to trigger fracture. Traditionally, the volume expansion that water undergoes upon freezing has been assumed to be the main culprit behind frost-driven fracture. This classical line of thought hypothesizes that this volume expansion has to be accommodated by the hydrogel's microstructure, hence causing it to stretch and eventually rupture. However, conclusive experimental evidence has showed that frost-driven fracture can also occur in wet solids imbued in liquids that contract upon freezing for instance, thus ruling out this physical process as the sole cause. Instead, another physical mechanism has recently arisen as a contender for causing frost-driven fracture: cryosuction. This concept stands for the migration of liquid water towards the ice front driven by a reduction of the liquid pressure therein. As such, cryosuction can potentially play a dual role in frost-driven fracture: (i) leading to cracking by desiccation, and (ii) allowing ice to build up within the internal crevices for as long as the supply of supercooled water holds. In this context, the present work leverages numerical models inspired by experimental evidence to weigh the contribution of these two mechanisms to the occurrence of frost-driven fracture in hydrogels. This is done through two different approaches. Firstly, a simplified hyper-elastic numerical model is used to assess the difference between the actual freezing experiments and the hydrogel deformation merely due to the experimentally documented presence of ice, hence providing an indirect quantification of the actual cryosuction-induced hydrogel desiccation around the ice-filled crack tip. Secondly, a hygro-mechanical numerical model of the hydrogel is set up to preliminarily describe the migration of water towards the ice-filled crack as it grows in time at different speeds. As in the previous model, the crack shape is directly extracted from the experimental observations, while the liquid pressure drop at the crack lips is derived from the ice-water thermodynamic equilibrium. This model provides detailed insights into how cryosuction draws water from the bulk as the ice-filled crack grows, and it helps interpret the experimentally observed size-dependency of the desiccation-affected region near the ice-filled cracks.

An in-situ study of ductile fracture using random porous metamaterials

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Speaker: Rocco Alessandro. **Tuesday**. Start time: **17:35**. Room: Rhône 2 LVL1. Link to abstract.

Ductile fracture is a common failure mechanism of metals and alloys. It consists of several stages, which involve the nucleation, growth and coalescence of microscopic voids within the metallic matrix. Over the years, intensive efforts have been made to study this complex fracture process and a variety of theoretical as well as numerical models have been formulated to describe these mechanisms. To assess the faithfulness of model predictions, multiscale experiments that allow for the identification of meaningful physical parameters are needed.
In the present work, *in-situ* tensile testing is combined with Finite-Element based Digital Volume Correlation (DVC) to study the mechanisms of ductile fracture at the mesoscale. In particular, the influence of void interaction on plastic localization and damage accumulation is investigated using a novel class of metamaterials in which cylindrical voids (with elliptical geometry) are randomly dispersed into a metallic matrix. Their arrangement and geometry are precisely-controlled from design to manufacturing, by combining a Random Sequential Absorption Algorithm (RSA) with Laser Powder Bed Fusion (L-PBF) additive manufacturing.
The results show that model materials of this type effectively display, in their tensile response, several features of ductile fracture of metals-albeit at the mesoscale. For example, it is found that experimental data for the average void growth agree well with the predictions of McClintock's micromechanical model, when void interactions are small. Conversely, voids grow significantly faster when large defects, such as cracks, are present within the matrix. Defects of this type are known to result from L-PBF manufacturing, and are shown to trigger plastic strain localization. To quantify their influence on the observed strain patterns, a Finite Element Model Updating (FEMU) technique is implemented using locally-damaged meshes, in which pre-existing defects are first identified (from the initial tomography) and removed from the nominal (defect-free) mesh.

The scatter in ductile fracture: Effect of material microstructure

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1 - Université Paris-Saclay, CEA, Service d'Étude des Matériaux Irradiés, 91191, Gif-sur-Yvette (France)

Speaker: Stchepinsky Anne-Constance. **Tuesday**. Start time: **17:55**. Room: Rhône 2 LVL1. Link to abstract.

Ductile fracture by nucleation, growth and coalescence of voids is one of the main types of fracture in metal alloys. Typically, the simulation of ductile fracture is based on homogenised models that assume scale separation where the grain size is very small compared to the specimen size, thus neglecting the effect of microstructure at this scale. However, the current trend towards miniaturisation of specimens and devices (e.g. heat exchangers (1)) means that these conditions no longer apply, as in these cases the grain size is comparable to that of the structure. In fact, it has been shown both experimentally and numerically (2, 3) that the microstructure of the material influences the fracture strain and stress, leading to a scattering of the ductile fracture properties. The objectives of this study are (1) to develop methods to quantitatively characterise the fracture property scatter associated with material microstructure both experimentally and numerically, and (2) to predict ductile fracture properties as a function of sample size. The experimental characterisation is based on two model materials: a 6061 aluminium and a 316L steel obtained by additive manufacturing (WAAM). An optimised heat treatment was applied to both materials to obtain a large grain size and a high density of transgranular inclusions promoting ductile fracture. Tensile tests were performed on homothetically notched flat specimens to quantify fracture stresses and strains as a function of specimen size. The average fracture strains increase with decreasing specimen size (number of grains at the notch) and with increasing dispersion, allowing an estimation of the typical number of grains required in the notch region above which deterministic behaviour is recovered. The experimental results are rationalised by performing numerical simulations taking into account the microstructure and using homogenised constitutive equations for porous single crystals. From a statistical point of view, the simulations, once calibrated, allow to recover the experimental trends for the effect of the sample size on the fracture properties. Finally, from a deterministic point of view, the comparison between the numerical results obtained by considering the exact microstructure of a given sample obtained by Diffraction Contrast Tomography (DCT) and the experimental results is discussed.

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The scatter in ductile fracture: Effect of void distribution

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Speaker: Hure Jérémy. **Tuesday**. Start time: **18:15**. Room: Rhône 2 LVL1. Link to abstract.

Ductile fracture by void growth to coalescence is one of the major failure modes of metal alloys. Voids nucleate from inclusions and/or second phase particles and then grow by plastic flow under mechanical loading. In most cases, scale separation applies, i.e. the distance between these voids is very small compared to the size of the structure, justifying the development and use of homogenized models for porous materials to simulate ductile fracture (1). However, in some cases, scale separation breaks down due to the miniaturization of the samples/devices or the fabrication process, e.g. additive manufacturing, or both (2). In this regime, the void distribution is important, as shown experimentally and numerically, leading to a scatter of ductile fracture properties such as fracture strain / stress. This scatter has been predicted by performing direct numerical simulations that take into account realistic void distributions (3). However, this approach is computationally intensive, especially when statistical information about the scatter is considered. Therefore, the aim of this study is to develop a model to predict the scatter of ductile fracture properties induced by void distributions. A 2D model is first developed, considering plane strain conditions for an isotropic von Mises material, for random void distributions under uniaxial loading. Limit analysis is used to provide semi-analytical estimates of the plastic dissipation/stress associated with the localization of plasticity between two voids, as a function of intervoid distance and angle. These estimates are validated and calibrated against reference finite element simulations. Graph theory is then used to find the minimum dissipation path, which is considered to be the expected localization path / fracture path. These predictions are again compared with reference finite element simulations. Very good agreement is obtained for the localization stress and localization path. The model is used to predict the scatter of ductile fracture properties as a function of porosity and void number, allowing the effect of void distributions on the mean and standard deviations of fracture stress/strain to be estimated. In particular, the number of voids above which scale separation is restored can be predicted, as well as the optimum void distribution - for a given porosity and void number - that maximizes fracture strain. In addition, the results of this model are compared with the predictions of a generative deep learning model inspired by (4), where the advantages and disadvantages of both approaches are discussed. Finally, extensions to the previous models are detailed, focusing on the 3D aspect and the interplay between material anisotropy and void distribution, and comparisons to experimental results are presented.

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Tensile crack propagation in disordered materials: geometrical nonlinearities, instabilities, and toughening

Lebihain Mathias (1), Sanner Antoine (2), Vasoya Manish Lazarus Veronique (3), Kondo Djimédo (4)

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Speaker: Lebihain Mathias. Keynote. **Wednesday**. Start time: **10:00**. Room: Rhône 2 LVL1. Link to abstract.

Over millions of years, Nature has evolved tough and strong biological materials through an intricate patterning of their microstructures across multiple scales. The principles underlying these multiscale reinforcement strategies have been successfully applied to create fracture-resistant bioinspired composites. However, modern challenges require optimizing the fracture properties of engineering materials based on constraints distinct from those found in Nature, such as environmental performance, fabrication process requirements, or resource availability. Nature's blueprints, which result from complex evolutionary processes, may not be adequate to address these new sets of constraints. This motivates the construction of a comprehensive homogenization theory for tensile fracture properties to swiftly screen the vast compositional space of hierarchical composites and design tougher materials.
Yet, the prediction of the macroscopic fracture resistance from a microstructural description of a heterogeneous material at multiple scales remains challenging. Traditional simulations methods based on the extended finite-element method or the variational (phase-field) approach of fracture often cannot describe failure processes from the scale of the heterogeneities up to the structural scale, due to limited numerical efficiency in 3D. Simulations based on the perturbation approach initiated by Rice (J. Appl. Mech, 1985) have provided valuable insights on the toughening of perfectly brittle materials by heterogeneities (Gao and Rice, J. Appl. Mech, 1989; Roux et al., Eur. J. Mech. Sol. A, 2003). They showcase unparalleled numerical efficiency, as they require only meshing of the 1D crack front to model 3D crack propagation. Yet, they build on a first-order expansion of the energy release rate with respect to the front deformation, and overlook the impact of geometrical nonlinearities arising from the front distortion. Higher-order theories are available (Leblond et al., JMPS, 2012; Lebihain et al., IJSS, 2023), but their practical implementation in a numerical code is still missing.

In this work, we use variational perturbation approach of linear elastic fracture mechanics (LEFM) to model coplanar crack propagation in heterogeneous media featuring spatial variations of fracture energy Gc. Equilibrium front positions are calculated by minimizing the sum of a potential energy, estimated asymptotically through the LEFM perturbation theory, and a dissipated energy, set by the fracture energy field. This approach, recently proposed by Sanner and Pastewka (JMPS, 2022), can seamlessly integrate geometrical nonlinearities of the crack front shape, while maintaining numerical efficiency thanks to the Fast Fourier Transform (FFT). Moreover, this energetic approach provides a well-established theoretical framework (Nguyen, JMPS, 1984) to describe the instability onset during crack propagation in disordered media.

By conducting thousands of simulations of coplanar crack propagation in brittle composites, we investigate the impact of the crack size and the heterogeneity contrast on the macroscopic fracture energy. We show that the presence of heterogeneities weakens the material with respect to its reference value for cracks smaller than the heterogeneity size, and a toughening for larger crack sizes (Lebihain et al., IJSS, 2023). This transition from weakening to toughening can be attributed to geometrical nonlinearities. When the crack front perimeter is smaller than the heterogeneity size, front deformations are carried by low frequency modes only. These low frequency modes generate an overall increase of energy release rate with respect to the undeformed configuration, leading to an apparent weakening of the material. As the crack grows, the presence of heterogeneities generate high frequency modes, whose contribution decreases the energy release rate and toughens the composite. Moreover, when the heterogeneity contrast increases, the crack does not propagate continuously but jumps from an equilibrium position to another. This transition from continuous to intermittent crack propagation, often referred to as the "weak"-to-"strong pinning" transition (Patinet et al., PRL, 2013), generates additional toughening of the material,

as the crack only visits the regions of high effective fracture energy.
Overall, we provide a comprehensive view of material toughening by heterogeneities for coplanar crack propagation, emphasizing on the role of geometrical nonlinearities and instabilities. Future works will focus on extending this framework to non-coplanar propagation, to account for the impact of surface/front roughening, and to cohesive failure, to capture size effects introduced by the presence of a finite process/damage zone.

Heterogeneity in dynamic fracture [1,2]

Kolvin Itamar (1), Adda-bedia Mokhtar (2)

1 - Georgia Institute of Technology [Atlanta] (United States), 2 - Laboratoire de Physique de l'ENS Lyon (France)

Speaker: Kolvin Itamar. Invited. **Wednesday**. Start time: **10:40**. Room: Rhône 2 LVL1. Link to abstract.

Rapid cracks are the cause of catastrophic mechanical failure. The continuum theory of cracks, Linear Elastic Fracture Mechanics (LEFM), successfully predicts the propagation of cracks along a straight line in homogeneous brittle solids (3-5). Even so, the dynamic fracture of heterogeneous materials is a conundrum. Cracks are 3D entities whose leading edge, the crack front, may locally move faster or slower when cutting through weak or tough regions. The upshot is that the overall energy cost of driving the crack becomes a function of its dynamics rather than a 'static' material property. Thus, a description of the crack front's time-evolving geometry is needed to predict whether heterogeneity makes a material tougher or weaker.
I will show how LEFM can be modified to encompass the dynamics of crack fronts. The pioneering works of Willis and Movchan (6) and Ramanathan and Fisher (7), provide a general scheme for calculating the elastic stresses near a moving crack front as a perturbation series in the crack front fluctuation. However, past efforts only provided explicit tractable expressions for the linear order. We expanded the theory to the second order and obtained the local energy release rate, or the elastic energy per unit area available for fracture, as a nonlinear functional of the front geometry and history. To predict the front dynamics, we locally balance the energy release rate with the energetic cost of fracture. We model the fracture energy as a product ofo a homogeneous part that depends on crack velocity and a heterogeneous part. Energy balance then yields a 1D nonlinear equation of motion for the crack front. A custom GPU-powered code allows us to solve the equation numerically over 2D meshes with up to _~4 million nodes.

The main result of our calculations is that heterogeneity may have a toughening or, surprisingly, a de-toughening effect. When the fracture energy weakly depends on crack velocity, the nonlinear coupling between the heterogeneous landscape and the front dynamics enhances the energy dissipation and decreases the overall crack speed. This effect is dominant when the crack is slow compared to the Raleigh wave speed, When the fracture energy strongly depends on crack velocity, the heterogeneity may decrease the dissipation and facilitate crack motion. This effect is strongest at intermediate crack speeds. I will show that insights from these solutions can be used to design toughness landscapes that create preferable crack propagation directions and discuss possible extensions of this work.

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Toughening effects of out-of-crack-path architected zones

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Speaker: Lazarus Veronique or Triclot Julie. **Wednesday**. Start time: **11:00**. Room: Rhône 2 LVL1. Link to abstract.

Architected materials have generated a lot of interest in the last two decades, both in the scientific community and the industry. This interest could be attributed to two main qualities: their high stiffness to weight ratio and their ability to display new behaviors. In this contribution, we aim to explore these new behaviors in the context of Linear Elastic Fracture Mechanics (LEFM). More specifically, we aim to analyze how the addition of architected zones adjacently to the crack path can remotely modify the crack propagation process.
This problem is address in the framework of quasi-static LEFM with both numerical and experimental approaches. Numerically, finite element simulations with a path-following algorithm are performed to show that the architected zones have a complex and significant effect. An interesting configuration is found where the addition of the architected zones has two toughening effects (1). The first one is a temporary increase of the crack propagation resistance due to stored strain energy in the zones. The second one is snap-back instability that leads to a higher energy dissipated by the crack propagation process.

Experimentally, 3D-printed Tapered Double Cantilever Beam (TDCB) samples are tested with Digital Image Correlation (DIC) monitoring. The results demonstrate the possibility to reproduce the theoretically found toughening effects.

This study establishes a new way of using architected materials to improve the mechanical performance of a structure while reducing its weight. It opens up prospects of shape optimization for practical purposes and eventually be able to finely tune the crack propagation response.

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Toward the determination of optimal initiation and propagation interfacial crack shape

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Speaker: Girard Hugo. **Wednesday**. Start time: **11:20**. Room: Rhône 2 LVL1. Link to abstract.

Multi-material interface problems are encountered in many industrial sectors as they often appear in assembled parts or heterogeneous materials. Additionally, structures made from these elements are nowadays increasingly employed, especially in aeronautic and aerospace applications, wherein composite materials are used primarily for weight reduction. In such materials, the fiber-matrix interface is a key aspect of global mechanical properties since it drives damage initiation and load transfer. It is therefore crucial to predict the fiber-matrix interface debonding in order to prevent or control the damage in composites.
Debonding initiation and propagation at the fiber-matrix interface of a single-fiber micro-composite loaded transversely is assessed using the Coupled Criterion (CC). The latter requires the crack path for its implementation. Among the possibilities to describe the potential crack shape, stress isocontour-based and energy-based shape solutions, corresponding respectively to the shapes maximizing either stress or energy conditions, can be employed. The stress isocontour-based shapes are numerically efficient because they can be derived from a single linear elastic calculation without releasing any nodes. However, this approach fails at describing the optimal CC solution when the solution is driven by the energy condition. This work aims to determine the optimal fiber-matrix debonding shapes. These determined shapes are then used to predict both crack initiation and propagation. Stress isocontour-based and energy-based shape solutions are compared. Both approaches yield different crack front topologies, with those based on the energy condition aligning more closely with experimental observations. Additionally, regardless of the interfacial fracture properties, the initiation loadings predicted by the CC using energy-based shapes are always favorable. Once the initiation debonding shape topology is assessed, further propagation is addressed by identifying the crack path that maximizes Griffith's criterion. The final debonding topology is then compared with experimental observations to validate the developed crack shape determination approach.

How Stress Biaxiality Controls Crack Morphology and Apparent Fracture Energy of Rocks

Guggisberg Antoine (1), Lebihain Mathias (2), Violay Marie (1)

1 - Ecole Polytechnique Fédérale de Lausanne-Laboratory for experimental rock mechanics (Switzerland), 2 - Laboratoire Navier (France)

Speaker: Guggisberg Antoine. Invited. **Wednesday**. Start time: **11:40**. Room: Rhône 2 LVL1. Link to abstract.

The emplacement of dikes and sills plays a crucial role in crustal mechanics. Notably, the parameter used to describe their resistance to propagation, fracture energy, is subject to controversial variations. Here, we show how different stress biaxiality levels experienced by dikes can directly affect the micromechanisms of crack propagation in rocks, consequently impacting fracture energy.
We performed tensile crack propagation experiments on Carrara marble under opposite stress biaxialities, measured by the T-stress. We chose the modified ring tests (MRT) and wedge splitting tests (WST) for their average T-stress values of -8.7 and 3.5 MPa, respectively. Their steady propagation allows for continuous monitoring of fracture energy using a compliance-based method. On post-mortem specimens, we extracted thin sections at the crack tip to acquire backscatter electron (BSE) and electron backscatter diffraction (EBSD) images using a scanning electron microscope.
These experiments reveal test-dependent fracture energy ranging from 20 to 35 J/m2 on MRT and 20 to 65 J/m2 on WST, depending on crack tip position. BSE and EBSD scans display straighter cracks traversing grains under negative T-stress (MRT). While under positive T-stress (WST), cracks stray and fork along grain boundaries to circumnavigate tougher heterogeneities, further devolving into fragmentation of the crack front. This yields a higher fracture energy that we attribute to front roughening and bridging mechanisms. The bridging toughening is gradual and increases with crack size, aligning with the growth of out-of-plane excursions adding tearing stresses (mode I + III) that promote these topological instabilities. This suggests a scale dependency of fracture energy in dikes and sills that also experience positive T-stress.

Configurational Mechanics-Based Study of Mixed-Mode Fracture in Soft Hydrogels

Santarossa Angel Agustin (1), Moreno-mateos Miguel (1), Steinmann Paul (1) (2)

1 - Lehrstuhl für Technische Mechanik, Friedrich-Alexander-Universität Erlangen-Nürnberg (Germany), 2 - Glasgow Computational Engineering Center, University of Glasgow (United Kingdom)

Speaker: Santarossa Angel Agustin. **Wednesday**. Start time: **14:30**. Room: Rhône 2 LVL1. Link to abstract.

When an initial fracture caused by uniaxial tension is subjected to mixed-mode loading, the crack front deviates from its original planar shape. Under mixed-mode I + III (the superposition of tension and out-of-plane shear), the crack front segments into an array of tilted facets. Unlike traditional approaches based on Linear Elastic Fracture Mechanics, this study explores cracks under mixed-mode I + III loading using configurational mechanics. The Configurational Force Method (1,2), implemented as a post processing algorithm in a Finite Element (FE) simulation, extends beyond the linear elastic assumptions of LEFM and offers a more general approach suited for capturing the complex interactions at the crack tip, particularly under mixed-mode loading and finite strains in soft materials.
We develop an idealized geometrical model of cracks subjected to tensile and out-of-plane shear stress, i.e., Échelon-like cracks, which replicates key features reported in earlier experiments-facet number, tilting angle, and shape-across different combinations of modes I and III. Using FE simulations, we analyze the configurational forces at the crack tip before crack onset, providing new insights into fracture mechanics in soft materials under complex mixed-mode loading, particularly unveiling the intricate interaction among tilted facets.

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Fracture of soft composites: modeling and experiments

Abu-qbeitah Suhib (1), Rudykh Stephan (1), Jabareen Mahmood (2), Volokh Konstantin (2)

1 - University of Galway (Ireland), 2 - Technion (Israel)

Speaker: Volokh Konstantin. **Wednesday**. Start time: **14:50**. Room: Rhône 2 LVL1. Link to abstract.

We present theory and simulations of fracture of soft staggered composites (1) based on the generalization and finite element implementation of the material sink approach (2). Results of the simulations are compared to experiments with 3D-printed soft composites (3,4). In addition, the experiments allow an assessment of the stress-based versus energy-based failure criteria (5). Results of the assessment are intriguing.

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Measuring in-situ 3D deformation of stepped cracks

Wei Xinyue (1), Kolinski John (2)

1 - EPFL (Switzerland), 2 - EPFL (Switzerland)

Speaker: Wei Xinyue. **Wednesday**. Start time: **15:10**. Room: Rhône 2 LVL1. Link to abstract.

The post-fracture surfaces of brittle solids commonly feature step-like structures. These step-like structures consists of discontinuous crack segments that are bridged by a thin material ligament. The ligament of material is the key topological feature that differentiates a "stepped crack" from a simple crack. What happens inside this material ligament? To probe this question requires in-situ 3D measurements of the deformation state near the crack steps. Here, we directly measure the in-situ kinematics at the tip of a stepped crack in 3D. Material displacements in the bulk of a brittle polyacrylamide hydrogel are measured by tracking the motion of embedded polystyrene particles. To obtain the kinematics in three dimensions, we scan a laser sheet through the sample and image the scattered intensity onto our camera sensor.The particle trajectories are used to calculate the local kinematic tensors, and thus to characterize the deformation in the ligament and the surroundings of the stepped crack. Our measurements of deformation state in stepped cracks may help to explain the propagation of the steps in a dynamic setting, and provide insights into out-of-plane brittle failure.

The fracture pattern of masonry dones: a shell-ring analogy

Michel Sebastien (1), Sipos Andras A. (2)

1 - TU Wien Institute of Mechanics and Mechatronics (Austria), 2 - Budapest University of Technology and Economics, Dept. Morphology and Geometric Modeling (Hungary)

Speaker: Michel Sebastien. Invited. **Wednesday**. Start time: **15:30**. Room: Rhône 2 LVL1. Link to abstract.

Studying the fracture of masonry domes has a long track record, and findings related to the crack evolution are of immediate interest in conservation or the design of new structures. The cracking of brittle shells became famous with the investigation of the St Peter Basilica dome by G. Poleni in the eighteenth century (1). In the second half of the twentieth century, the problem was revisited by J. Heyman (2) in the context of limit plastic analysis. Due to the low tensile strength of the material and the load-bearing mechanism of the cupola, the appearance of cracks produces a hoop-stress-free equilibrium state of the structure. Heyman also suggested that further investigation of the emergence of the pattern in the cupola would be of interest (2). In particular, we seek to determine the position and order of appearance of the meridional cracks and clarify how existing cracks affect the formation of further ones, creating the whole pattern. For this purpose, we focus on the canonical structural model of a hemispherical dome whose equator is constrained to deform in its plane and consider a quasi-static increase of the self-weight of the structure. Modeling the dome as a shell under Kirchhoff-Love hypotheses, we first show that the equations governing the displacement of the dome's middle surface within the equatorial plane can be interpreted as the equations governing the deformation of a planar elastic ring, loaded by an outward pointing inner pressure and constrained by springs, a problem already investigated (3). Relationships between the ring and the dome parameters are given and found to depend strongly on the imposed boundary conditions on the shell edge and the elastic response of the dome. These results should open new ways to assess the genesis of the pattern in domes. In particular, the proposed formulation allows some freedom in modeling the top part of the dome in the spirit of Poleni's work. Finally, we turn to a numerical parametric study of the cracking pattern appearance in rings. Assuming the material to be unilateral in compression, we rely on an energetic criterion according to Griffith's postulate. We find that the tangential to radial spring stiffness ratio is a crucial driver of pattern formation by controlling elaborate bifurcations that determine the emerging crack's position. Numerical experiments are proposed and compared with finite element simulations.

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Damage quantification of thin films on soft substrate

Singh Akash (1), Ciccotti Matteo (2), Santoprete Roberto (1), Creton Costantino (3), Luengo Gustavo S. (1)

1 - L'OREAL Research and Innovation, Aulnay sous Bois (France), 2 - Sciences et Ingénierie de la Matière Molle (UMR 7615) (France), 3 - Sciences et Ingénierie de la Matière Molle (UMR 7615) (France)

Speaker: Santoprete Roberto. Invited. **Wednesday**. Start time: **16:45**. Room: Rhône 2 LVL1. Link to abstract.

Thin films on soft substrates are a subject of interest in several applications such as cosmetics and flexible electronics (OLED). Understanding damage to the film or debonding from the substrate can be crucial for the functionality, aesthetics, and lifetime of such films. However, understanding remains limited due to the large deformation of the soft substrate compared to investigations for rigid substrates(1), evidence of mixed-mode interfacial fracture and sliding at the interface(2), and due to the inelastic behavior of the film. We show a robust methodology to characterize damage and adhesion and more generally, the durability of thin films on a soft substrate. Results can then be extended to different substrates. The method involves macroscopic mechanical measurements and simultaneous local optical imaging using camera and confocal microscopy to characterize the different features of the deformed film and the mechanisms by which thin coatings accumulate damage due to the stretching of the substrate. After extracting the local deformation field in both the film and at the interface (3) (using fluorescent markers embedded near the surface of the substrate), we derive suitable PIV algorithms to extract local deformation mismatches due to phenomena such as fracture, debonding, slippage and plasticity. Combining with energy modelling, these quantifications can be used to obtain the desired interfacial adhesion and cohesive energy of the film.

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Size Selection of Crack Front Defects in Soft Materials: Multiple Fracture-Plane Interactions and Intrinsic Length Scales

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1 - The Hebrew University of Jerusalem (Israel), 2 - Weizmann Institute of Science [Rehovot, Israël] (Israel)

Speaker: Wang Meng. Invited. **Wednesday**. Start time: **17:05**. Room: Rhône 2 LVL1. Link to abstract.

Failure of soft materials is mediated by the propagation of cracks which, in realistic 3D media, typically involves multiple coexisting fracture planes. Multiple fracture-plane interactions create poorly understood out-of-plane crack structures, such as step defects on tensile fracture surfaces. Steps form when a slowly moving crack front fragments into disconnected and overlapping segments, separated by a stabilizing distance. The stepped crack fronts leave, in their wake, step defects on the fracture surface. In this talk, we will show that the stabilizing distance of the steps depends linearly on both a nonlinear elastic length and a dissipation length, as demonstrated through numerous fracture experiments on various brittle hydrogels. Here, the nonlinear elastic length scales with the ratio of the crack velocity–dependent fracture energy to the material's shear modulus. Additionally, using the energy balance, we will explain why the steps are topologically stable along the crack front. These intrinsic length scales, which govern the fracture of soft materials, point the way to a fundamental understanding of multiple-crack interactions in 3D that lead to the formation of stable out-of-plane fracture structures.

Why cutting elastomers is easier than tearing?

Ciccotti Matteo (1), Zhao Donghao Cartier Alex Narita Tetsu Creton Costantino Lechanault Frederic

1 - Ecole Superieure de Physique et de Chimie Industrielles de la Ville de Paris (France)

Speaker: Zhao Donghao. Invited. **Wednesday**. Start time: **17:25**. Room: Rhône 2 LVL1. Link to abstract.

We all know that tearing tough soft solids such as rubbers, leather or meat can be quite difficult while cutting them with a sharp blade is much easier. Understanding why is crucial to optimize energy efficiency in material processing. By using samples labeled with mechanically sensitive fluorophores to investigate cutting and fracture behavior in PDMS elastomers we are able to quantify the extent of covalent bond scission resulting from cutting prestretched samples. Our findings reveal that stretch-induced cracks, as they occur in tearing, exhibit significant deformation, bond scission and blunting near the crack tip, requiring a higher fracture energy to propagate. In contrast, using sharp blades reduces the amount of stretching and blunting required for crack propagation, results in a lower fracture energy and producing sharp and clean fracture surfaces. The observed linear correlation between fracture energy and the number of broken chains per unit area, validated through mechanical testing and mechanochemical experiments, clarifies the relationship between pre-stretching, blunting, and the extent of molecular damage. These comprehesive insights demonstrate the key differences between fracture and cutting mechanics of soft materials, paving the way to optimize cutting processes for engineering applications.

Analysis of the relaxation time in subcritical rupture of heterogeneous materials

Braux Chloé (1)

1 - Institut Lumière Matière [Villeurbanne] (France)

Speaker: Braux Chloé. **Wednesday**. Start time: **17:45**. Room: Rhône 2 LVL1. Link to abstract.

Predicting subcritical rupture of heterogeneous materials is an important subject in physics of materials. Subcritical rupture happens when a material is loaded at a constant force below its ultimate tensile strength for a long time. This process ends with the ultimate failure that defines the lifetime of the sample, τc. The lifetime is a scattered and hard to predict parameter. If we stop maintaining the target force before the final rupture, we observe a relaxation of the force in the sample. This relaxation can be fitted using a visco-elastic rheological model (1) which predicts a logarithmic decay of the force with a characteristic time τ . The aim of our experiment is to measure the evolution of the relaxation time, τ , during the subcritical rupture process. For this purpose, we use paper samples held in a tensile stress apparatus controlling elongation and we impose a constant force with a feedback loop. In addition to this constant force, we apply tiny force steps to probe the relaxation locally. The time between two steps is proportional to the characteristic relaxation time. Experimentally, for paper samples, we observe that this time τ increases linearly, indicating a slowing down in the subcritical rupture dynamics, then fastly decreases at about 80% of the lifetime τc(2). This behavior can be qualitatively explained by the fiber bundle model (3) that describes the phenomenological rupture of a heterogeneous fibrous material. Considering the strain of our sample, we recover behaviors already observed in other soft materials such as protein gels (4). When a constant force is applied, the strain rate first decreases with a power law then increases sharply before the final rupture.

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The Role of Viscoelasticity and Dissipation in Fracture of Elastomeric Membranes

Ciambella Jacopo (1), Lancioni Giovanni Stortini Nico

1 - Department of Structural and Geotechnical Engineering - SAPIENZA University of Rome (Via Eudossiana 18, 00184 Rome, Italy Italy)

Speaker: Ciambella Jacopo. **Wednesday**. Start time: **18:05**. Room: Rhône 2 LVL1. Link to abstract.

Understanding crack propagation mechanisms in thin elastomeric membranes is crucial for various engineering applications, yet accurately modeling their complex behavior poses significant challenges due to the inherent material nonlinearity. In this contribution, we present a novel viscoelastic constitutive model specifically tailored to capture the time-dependent response of elastomers subjected to mechanical loading and damage, with particular emphasis on finite strain effects. Developed by following the classical approach to phase field fracture, the model incorporates both short and long-term nonlinear elastic energy densities {Ciambella2024}, as well as dissipation mechanisms {Fischer2014}, that are attenuated by damage through distinct degradation functions.

Our primary objective is to accurately predict crack propagation velocities in thin viscoelastic membranes, accounting for the geometric and material nonlinearities that characterize their behavior, a problem tested in several recent papers in the literature. Energy dissipation around a propagating crack is the primary mechanism for the enhanced fracture toughness in elastomers. Such mechanism is spatially non-uniform and is highly coupled to the crack propagation process due to both the history-dependent nature of viscoelasticity and the large deformations involved. It is mainly driven by two processes: one intimately associated with viscoelasticity, which is controlled by the breaking and healing kinetics of ionic bonds as well as the degree of chemical crosslinking in the bulk material, and another occurring in the fracture process zone where the polymer chains experience extreme stretches, leading to significant strain-stiffening before their ultimate rupture.

By coupling finite strain elasticity, viscoelasticity, and damage, our model allows us to better highlight the combined role of material nonlinearity and dissipative mechanisms in crack propagation speeds. To validate the model, we conduct numerical simulations of a range of mechanical tests, including 1D and 2D simulations, that showcase the model's ability to capture the interplay between geometric nonlinearity, viscoelasticity, and crack propagation.

Characterization of local poroelastic swelling near the tip of a propagating crack in a hydrogel

Li Chenzhuo (1), Kolinski John (2)

1 - School of Engineering, EPFL (Switzerland), 2 - School of Engineering, EPFL (Switzerland)

Speaker: Li Chenzhuo. **Wednesday**. Start time: **18:25**. Room: Rhône 2 LVL1. Link to abstract.

Polyacrylamide hydrogels are widely used as model materials in experimental fracture mechanics due to their transparency and low Rayleigh-wave velocity. While traditionally regarded as "brittle" and analyzed using linear elastic fracture mechanics (LEFM), hydrogels can exhibit poroelastic swelling at the crack tip when the experimental timescale is comparable to the poroelastic timescale. This swelling, despite lacking direct measurements, can significantly influence fracture behavior, leading to rate-dependent effects and delayed fracture (1). Here, we employ a particle tracking technique augmented by digital image correlation to capture high-resolution 3D particle trajectories and measure the 3D kinematic fields near the tip of a slowly propagating crack. For the first time, we experimentally quantify the local swelling field by evaluating the determinant of the deformation gradient tensor. The kinematic measurements confirm the complex multi-axial stretching and the substantial geometric nonlinearity near the crack tip, as well as an increasing disagreement with LEFM predictions. Significant poroelastic swelling is resolved spatially near the crack tip, with its magnitude strongly correlated to local stretch values. Our quantification of the near-tip swelling is expected to provide insights for the development of constitutive models in swelling-coupled fracture problems. The experimental method we used can be readily adapted to study complex 3D deformation fields.

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MS3.5 - Nonlinear Elasticity

Organisers: Yibin Fu (Keele Univerisity) and Bilen Abali (Uppsala University, Sweden)

On particle cracking in Li-ion Si-based battery electrodes

Per Isaksson (1), Damsgaard-falck Hanna (1)

1 - Uppsala University (Sweden)

Speaker: Per Isaksson. Keynote. **Monday**. Start time: **10:10**. Room: Saint Clair 1 LVL2. Link to abstract.

Silicon is recognized as a promising material for next-generation lithium-ion batteries, offering a storage capacity approximately 10 times higher than that of conventional carbon-based electrodes. Despite extensive research and industrial development, the practical use of silicon-based electrodes remains constrained by a significant loss of capacity. This issue is primarily attributed to microscopic cracks caused by substantial swelling of Si particles during cycling, which places an extremely high burden on the mechanical stability and structural integrity of the electrode (1). Mechanical stresses, induced by chemical reactions as lithium ions diffuse into silicon particles during cycling, nucleate and drive cracks that hinder further ion transport, ultimately leading to capacity loss. The lithiation of silicon is a complex electro-chemo-mechanical process that is not yet fully understood.
Our high-fidelity computational multiphysics in-house models incorporate key structural features across various length and time scales while capturing some of the dominant physical phenomena that dictate battery efficiency. The simulation results are compared with findings reported in the literature, including observations of deforming silicon particles in real Si-based battery cells under cycling (e.g. in-situ synchrotron X-ray CT experiments (2)). While the striking agreement between simulations and experiments is promising, it also highlights the need for a deeper understanding of the lithium-ion diffusion process in silicon, particularly the multiple material phase changes that occur between lithium and silicon, Li_xSi_y.

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Deformation in batteries during charging and discharging

Abali Bilen Emek (1)

1 - Uppsala Universitet [Uppsala] (Sweden)

Speaker: Abali Bilen Emek. Invited. **Monday**. Start time: **10:50**. Room: Saint Clair 1 LVL2. Link to abstract.

Despite the emergence as the archetype for energy storage, lithium ion batteries did not reach their possible full potential, partly owing to difficulties in understanding multiphysics mechanisms occurring collectively and differently in charging and discharging. Specifically deformation is often left aside although in a conventional lithium ion, 5% strain is usually detected during ions entering and intercalating the electrode. With such geometric nonlinearities, we discuss a unified theory for thermomechanics and electromagnetism due to diffusion of charged particles leading to a set of coupled and nonlinear equations. Since the formulations are in different frameworks, numerical implementation is an open problem. In this talk, we observe a possible approach by using the finite element method and open-source packages.

Chemo-mechanical coupling problems in mechanics of solids

Freidin Alexander (1)

1 - Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences (Russia)

Speaker: Freidin Alexander. Invited. **Monday**. Start time: **11:10**. Room: Saint Clair 1 LVL2. Link to abstract.

Highlights

- Due to the competition of chemistry and mechanics, there are chemical reactions that are affected by stresses and chemical reactions that are caused by stresses.
- There is principal difference between chemical reaction with elastic and viscoelastic reaction products. In the case of viscoelastic reaction product, unlike an elastic case, stress relaxation can protect the reaction from blocking. Two regimes of the front propagation in the case of viscoelastic product are possible: kinetic regime and quasi-equilibrium propagation regime.
- Various diffusion patterns are described depending on diffusion coefficients for the diffusion through the initial and transformed solid constituents. A phase field model has been developed aimed at a unified description of localized and volumetric reactions and related to the chemical affinity tensor. Chemical affinity tensor is a proper tool for describing chemical reactions in solids.

Introduction

Chemo-mechanical coupling remains one of the mainstreams of modern multiphysics. Lithiation of silicon in Lithium-ion batteries (charge–discharge cycles of the batteries), oxidation of silicon in integrated circuits and semiconductor technologies, formation of intermetallic phases in lead-free solders, oxidation and fracture of polycrystalline silicon microscale parts of MEMS are among important examples of reactions between solid and diffusing reactants accompanied by the transformation strain (volumetric expansion, for example up to 300% in the case of silicon lithiation), which generates stresses which, in turn, affect the reaction rate, see e.g., (1,2,3,4) or reviews (5,6). So, the appearance of stresses due to the transformation strain and the effect of stresses on the rate of a chemical reaction up to its blocking are well-documented facts.

Initial-boundary value problem of chemo-mechanics

In the present paper, we start by considering the reactions localized at the reaction front (a sharp interface). The system of equations includes:

- diffusion equation with a boundary condition and the condition at the reaction front (mass balance) with a sink defined by the reaction rate which depends on the concentration of the diffusing constituent and mechanical stresses;
- mechanical equilibrium equation with boundary conditions and conditions across the interface.
- to close the system, one needs constitutive equations for the diffusion flux, for mechanical behaviour of solid constituents and an equation defining the dependence of the reaction rate on the concentration and mechanical stresses.

Thus, like a phase transition problem, we have a coupled problem with propagating unknown interface the velocity of which depends on stresses and concentration, while the stresses and concentration depend on the interface position.

Kinetics of the propagation of the chemical reaction front in elastic and viscoelastic frameworks

The kinetics of the front propagation is described in the framework of an approach in which stresses affect the reaction rate through a chemical affinity tensor A scalar chemical affinity is one of the basic notions

of physical chemistry (7). Tensorial nature of the chemical affinity in the case of deformable solids follows form the consideration of the reaction not just in points but at oriented area elements. (There is an analogy with the stress tensor defining tractions at oriented area elements.) The concept of the chemical affinity tensor was developed earlier (8) (see also (9)). The expression of the chemical affinity tensor was derived from fundamental balances and entropy inequality, and a number of boundary value problems were solved, which demonstrated how mechanical stresses can retard and block the reaction (see, e.g., (10,11) and reference therein), including stability analysis (12).

In the present considerations, after the general formulation of the initial boundary value problem "diffusion -chemistry-mechanics", we focus on the following aspects of the problem:

(i) There are stress-affected and stress-induced chemical reactions, reflecting the competition between pure chemistry and mechanics (there is an analogy with stress-induced phase transitions in nonlinear elastic materials with non-convex energy) (12).

(ii) The influence of the relationships of elastic moduli of solid constituent on strains and stresses which block and unblock the chemical reaction (13).

(iii) The effects of changing the rheology of the material due to the reaction. Our first results on chemical reactions in an elastic–viscoelastic mechanical framework were presented in (13) where the propagation of a plane reaction front was considered at zero stress in the direction perpendicular to the interface. Now, considering a chemical reaction front propagation under uniaxial deformation, we focus on studying the kinetics of the reaction front in dependence on external strains, including cyclic deformation, and emphasize the differences with the elastic case. Unlike in the case of solid elastic components, in the viscoelastic case, the stresses relax, which protects the reaction from blocking and leads to the coupling of the kinetics of the reaction front and the stress relaxation process.

A special attention is paid to unlocking the previously blocked reaction due to the stress relaxation. Possibility of two regimes of the front propagation in the case of viscoelastic constituent is discussed: "kinetic regime" of the front propagation controlled by the chemical affinity tensor defining the corresponding configurational force, and quasi-equilibrium propagation of the front when chemical equilibrium is maintained at the front during propagation.

(iv) Various diffusion patterns and conditions at the reaction front for the diffusion problem (see also (11)). Two different problem formulations are examined for which:

- Diffusion through the untransformed material does not occur, as it is, for example, in the case of lithiation of crystalline silicon (14).
- Diffusion is possible through both transformed and untransformed materials, and the diffusing constituent located ahead of the reaction front in the untransformed material affects the velocity of the front as well as from the side of the transformed material.

Comparison of quasi-steady-state and non-steady-state diffusion approaches is also made. Within the framework of the developed approach, the propagation of the reaction front, controlled by the reaction rate or the diffusion rate, is discussed.

Volumetric reactions

Finally, we present a modification of the model in the spirit of the phase field approach aimed at a unified description of localized and volumetric reactions. A special attention is paid to the definition of a reaction extent in the case of finite strains, since it acts as a phase field parameter. It is shown how the configurational force driving the volumetric reaction is related to the chemical affinity tensor (15). The time evolution of space distributions of reaction extent and the concentration of the diffusing constituent is studied in dependence of the diffusion and reaction rate parameters. It is demonstrated how the pattern changes depending on whether mechanical stresses are taken into account or not.

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Stability Analysis of an Inflated, Axially Extended, Residually Stressed Circular Cylindrical Tube

Melnikov Andrey (1), Merodio Jose

1 - Nazarbayev University (Kazakhstan)

Speaker: Melnikov Andrey. Invited. **Monday**. Start time: **11:30**. Room: Saint Clair 1 LVL2. Link to abstract.

Residual stress may have an important influence on the mechanical response of residually stressed materials. This paper is concerned with the effects of residual stress on the stability of inflated, axially extended, residually stressed circular cylindrical tube. To this end, the theory of small incremental deformations superimposed on a large underlying finite deformation is used. Asymmetric and axisymmetric types of bifurcation are considered. It is found that for residual stress parameter gamma of the same sign the effect of the residual stress is different depending on the type of bifurcation. For example, for asymmetric bifurcations with mode number m = 1 and with positive gamma inclusion of residual stress makes the tube more stable, on the other hand, for axisymmetric bifurcations inclusion of residual stress, corresponding to positive residual stress parameter gamma, leads to increase of instabilities. In all cases, residual stress with positive and negative residual stress parameter gamma leads to a symmetric character of bifurcation curves.

Keywords: Nonlinear elasticity; Residual stresses; Incremental elastic deformations; Tube bifurcation.

THE REPULSION PROPERTY IN NONLINEAR ELASTICITY

Sivaloganathan Jeyabal (1)

1 - University of Bath [Bath] (United Kingdom)

Speaker: Sivaloganathan Jeyabal. Keynote. **Monday**. Start time: **13:40**. Room: Saint Clair 1 LVL2. Link to abstract.

The Lavrentiev phenomenon in one-dimensional variational problems occurs when the infimum of an integral functional on the class of absolutely continuous functions is strictly lower than the infimum on the class of smooth functions. This phenomenon is significant in the Calculus of Variations as it signals a possible loss of regularity in minimisers and, in some cases, it implies a repulsion property: approximating a global minimizer with smooth functions results in approximate energies that diverge. Consequently, standard numerical methods like the finite element method may fail for these problems.

In this talk, we will demonstrate that a generalised repulsion property applies to three-dimensional elasticity problems exhibiting cavitation and propose a novel scheme that circumvents this issue. Our approach utilizes a modification of the Modica - Mortola functional in which the phase function is coupled with the determinant of the deformation gradient in the elastic stored energy functional. We prove that approximations using this method satisfy the lower bound Γ-convergence property in multi-dimensional, non-radial cases. Moreover, we establish convergence to the actual cavitating minimizer for a spherical body under radial deformations.

Analytical and numerical quasiconvex relaxation of planar Biot-type energies

Martin Robert (1), Ghiba Ionel-dumitrel (2) (3), Köhler Maximilian (4), Balzani Daniel (5), Sander Oliver (6), Neff Patrizio (7)

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Speaker: Martin Robert. Invited. **Monday**. Start time: **14:20**. Room: Saint Clair 1 LVL2. Link to abstract.

We derive the quasiconvex relaxation of the Biot-type energy density |U-1|^2, where U denotes the right Biot stretch tensor, 1 is the identity tensor and |.| is the Frobenius norm, for planar mappings in two different scenarios. First, we consider the case where the gradient of the mapping is constrained to the positive general linear group, in which case the energy can be expressed as the squared Euclidean distance to the special orthogonal group SO(2). We then allow for planar mappings with arbitrary deformation gradient; in the context of solid mechanics, this lack of determinant constraints on the deformation gradient would not exclude local self-interpenetration of matter. We demonstrate that the two resulting relaxations do not coincide and compare the analytical findings to numerical results for different relaxation approaches, including a rank-one sequential lamination algorithm, trust-region FEM calculations of representative microstructures and physics informed neuronal networks.

Symmetries of the Stiffness Tensor Induced by the Jaumann Rate of the Stress

Federico Salvatore (1), Neff Patrizio (2)

1 - The University of Calgary (Canada), 2 - Universitat Duisberg-Essen (Germany)

Speaker: Federico Salvatore. Invited. **Monday**. Start time: **14:40**. Room: Saint Clair 1 LVL2. Link to abstract.

In Continuum Mechanics in general and in Nonlinear Elasticity in particular, it is important to define *objective* rates of the Cauchy stress or the Kirchhoff stress, the latter being particularly important in Computational Mechanics. Objectivity means invariance under any arbitrary diffeomorphism (Marsden and Hughes, 1983), a differentiable map with a differentiable inverse.
The Jaumann rate (also known as Zaremba-Jaumann rate; Zaremba, 1903; Jaumann, 1905) is extensively used to define stress rates because it is not only objective, but also *corotational* with respect to the spin tensor (the skew-symmetric part of the velocity gradient). A time-dependent basis is called co-rotational if the time derivative of each of the basis vectors is obtained locally via Poisson's theorem, i.e., as the spin tensor applied as a linear map on the basis vector. In a spin-tensor-corotational basis, the components of the Jaumann rate of the stress tensor are the same as the components of the regular substantial (material) derivative of the stress tensor (Neff et al., 2024ab; Palizi et al., 2020). This makes the Jaumann rate particularly convenient from the computational point of view.

This work (Federico et al., 2024) has three main objectives.

First, we review the properties of the Jaumann rate in a completely covariant setting, and show its relation with the Lie derivative (Marsden and Hughes, 1983; Federico, 2022).

Second, we review the symmetries of the stiffness tensors induced by the Jaumann rate. These tensors generally possess both minor symmetries (i.e., invariance under exchange of the indices in the first pair and the indices in the second pair, separately) but, while major symmetry (invariance under exchange of the first pair of indices with the second) is achieved for the stiffness tensor related to the Kirchhoff stress, it is not for the stiffness tensor relative to the Cauchy stress. Some of these symmetries were missed in some past work (Palizi et al., 2020).

Third, we provide an absolute expression of both stiffness tensors, in terms of an expression not involving contractions with arbitrary second-order tensors. These absolute expressions, both in component-free form and component form, are particularly useful for numerical applications.

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Constitutive modeling of hyperelastic materials based on the upper triangular decomposition

Li Yongqiang (1), Gao Xin-lin (2)

1 - Nanjing University of Aeronautics and Astronautics [Nanjing] (China), 2 - Southern Methodist University [Dallas, TX, USA] (United States)

Speaker: Li Yongqiang or Gao Xin-Lin. Invited. **Monday**. Start time: **16:00**. Room: Saint Clair 1 LVL2. Link to abstract.

The upper triangular decomposition provides an alternative method to multiplicatively decompose the deformation gradient tensor into a product of a rotation tensor and an upper triangular distortion tensor (1,2). The six components of the distortion tensor can be directly related to pure stretch and simple shear deformations, which are physically measurable. In this study, constitutive equations for hyperelastic materials are derived using strain energy density functions in terms of the distortion tensor. An untangled crosslinked network model and a tube-like constraint model are employed along with inverse Langevin function approximations to construct four strain energy density functions. The Cauchy stress components, derived directly as partial derivatives of the strain energy density function with respect to the distortion tensor components, have simpler expressions than those based on the invariants of the right Cauchy-Green deformation tensor. To validate the newly proposed constitutive equations, four fundamental deformation modes - uniaxial tension, pure shear, equi-biaxial tension, and simple shear - are considered. Experimental data from rubber and brain tissues are utilized to calibrate the model parameters. The fitting results reveal that each of the four proposed constitutive models can effectively capture the mechanical behaviors of hyperelastic materials using a single set of parameters. Hence, these models furnish a practical alternative approach to describing hyperelatic materials based on the upper triangular decomposition of the deformation gradient tensor, offering measurable and physically interpretable constitutive relations.

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On the Constitutive Boundary Conditions in Non-local Elasticity

Pramanik Dipendu (1), Nobili Andrea (2)

1 - Università degli Studi di Modena e Reggio Emilia = University of Modena and Reggio Emilia (Italy), 2 - Università degli Studi di Modena e Reggio Emilia (Italy)

Speaker: Pramanik Dipendu. Invited. **Monday**. Start time: **16:20**. Room: Saint Clair 1 LVL2. Link to abstract.

Non-local elasticity theory is a powerful framework for capturing small-scale effects in micro- and nano-structured engineering materials, with Eringen's theory of non-local elasticity widely employed to support such modelling. However, the differential formulation of Eringen's non-local elasticity theory exhibits inconsistencies when applied to finite bodies. These inconsistencies arise due to the violation of constitutive boundary conditions (CBCs), resulting in a lack of equivalence between the differential and integral formulations. In this study, we propose a novel approach to address this issue by modifying the kernel function while preserving the original differential operator. Indeed, a general procedure to modify the kernel has been shown for any set of generalised self-adjoint boundary conditions. To illustrate the proposed framework, we analyse static Euler-Bernoulli cantilever beams under various self-adjoint boundary conditions and demonstrate how inconsistencies in CBCs are resolved. The resulting non-local problems are formulated as non-homogeneous Fredholm integral equations of the first kind, which are solved using an eigenvalue-eigenfunction approach. Our findings highlight that the modified kernel extends the applicability of non-local elasticity by overcoming the limitations of restrictive boundary conditions. This work establishes a robust and versatile methodology for achieving consistency in non-local elasticity, enabling broader applications in advanced material modelling.

The role of physical constants in nonlinear micropolar elasticity at finite strains

Schek Lucca (1), Müller Wolfgang H. (1)

1 - Technical University of Berlin / Technische Universität Berlin (Germany)

Speaker: Schek Lucca. **Monday**. Start time: **16:40**. Room: Saint Clair 1 LVL2. Link to abstract.

A geometrically nonlinear formulation of the physically linear micropolar elasticity theory is investigated numerically using mixed finite elements in the open-source software FEniCSx, formulated in the Lagrangian reference frame. The micropolar continuum theory introduces additional rotational degrees of freedom, along with six elastic parameters in an isotropic formulation. While a good physical intuition has been established for these parameters within a geometrically linear framework of small deformations, no such understanding exists for a framework incorporating large deformations. Since micropolar theories have proven effective for materials such as foams, which can undergo large deformations without damage, further investigation is warranted. The physically linear material law for large deformations, generalized from the law for small deformations, retains the same form as the St. Venant-Kirchhoff law in classical elasticity. However, it does not directly correspond to the classical formulation, as the strain measures differ in nature. A comparison of the two formulations is presented. The numerical implementation is validated against available three-dimensional analytical solutions. The problems of cylindrical bending and torsion of a beam as well as the torsion of a cylinder are revisited, with a special focus on the physical meaning of the elastic constants.

Finite Strain Formulation of Electro-Visco-Hyperelastic Nematic Elastomers

Karlicic Danilo (1), Cajic Milan (2), Paunovic Stepa (2)

1 - Department of Mechanics, Mathematical Institute of the Serbian Academy of Sciences (Serbia), 2 - Mathematical Institute of the Serbian Academy of Sciences (Serbia)

Speaker: Karlicic Danilo. **Monday**. Start time: **17:00**. Room: Saint Clair 1 LVL2. Link to abstract.

Nematic liquid crystal elastomers (NLCE) form a important class of highly responsive multifunctional materials combining the anisotropy and self-organisation of liquid crystal mesogens with the flexibility of cross-linked polymeric networks. They also display significant programmable and rapid shape changes in reaction to different stimuli, light, heat, or electric fields, where effects of soft-elasticity and rate dependence play an important role. This work is dedicated to computational implementation of finite strain model of electro-visco-elastic interactions that occur in dielectric NLCE, with including key phenomena such as Maxwell's stress, director rotation, nonlinear deformations, electric Fréedericksz transition and energy dissipation. By integrating the framework of continuum mechanics, Maxwell's equations, and the principle of virtual power, the governing equations for dielectric NLCEs are systematically derived. This approach ensures the formulation of thermodynamically consistent constitutive relations, capturing the coupled electro-mechanical behavior and time-dependent viscoelastic response while adhering to the physical plausibility. The presented model involves two dissipation mechanisms: viscous dissipation of the director rotation and viscoelastic dissipation within the polymer matrix introduced as internal variables, both of which play critical roles in governing the material's electro-mechanical response. Special attention will be given to the finite element implementation in the FEniCSx software, focusing on two electro-viscoelastic instabilities: pull-in and wrinkling. The study will explore various deformation modes that may emerge during these phenomena. Finally, the implemented numerical simulations will include the hysteresis response and a validation study comparing the obtained numerical results with analytical solutions from the literature.

Modeling the Constitutive Behavior of Complex Elastomers

Shah Nurul Hassan (1), Faruque Ali Shaikh (1)

1 - Indian Institute of Technology Madras (India)

Speaker: Shah Nurul Hassan or Faruque Ali Shaikh. **Monday**. Start time: **17:20**. Room: Saint Clair 1 LVL2. Link to abstract.

Soft elastomers are cross-linked networks of polymer chains capable of undergoing significant deformations under external loading. Constitutive modeling of these materials primarily follows two approaches: the phenomenological approach and the micromechanical approach. The phenomenological approach combines mathematical formulations with empirical observations, whereas the micromechanical approach is grounded in statistical physics. Micromechanical models require fewer parameters with clear physical significance, while phenomenological models often rely on more parameters that lack direct microstructural connections.
For specific applications, specialized elastomers such as tough elastomers (1) are indispensable. These materials are crafted through precise copolymerization, with additional mechanisms like hydrogen bonding introduced to enhance toughness via specific interactions. Similarly, the glassy behavior of elastomers (2), driven by temperature variations, exhibits a complex stress-strain response characterized by high initial stiffness and early chain locking during deformation. Modeling these behaviors presents significant challenges, necessitating advanced micromechanical frameworks. While phenomenological models can approximate stress-strain responses, they often fail to capture underlying microstructural phenomena. By contrast, even simple micromechanical models provide deeper insights into the micro-level behavior, making them invaluable for understanding and predicting material performance.

This study offers a comparative analysis of micromechanical and phenomenological models to better understand and predict the complex mechanical behavior of tough and glassy elastomers. The micromechanical framework provides a detailed representation by decomposing the total stress response into three distinct components, P = Pc + Pe + Pb. Here, Pc represents the stress from the stretching of the cross-linked network, capturing the elastic response of the chemically bonded structure. Pe corresponds to the stress arising from the deformation of the entangled polymer network, reflecting chain mobility and physical interactions. Lastly, Pb accounts for the stress associated with the stretching of intermolecular bonds, representing weaker, non-covalent interactions. These components are meticulously formulated to reflect the microstructural contributions, enabling a robust understanding of the material's overall mechanical response. In contrast, the phenomenological model employs a more simplified approach, relying on macroscopic observations to describe the material's behavior. However, this model is still under development and includes six key parameters that require further characterization and calibration. While the micromechanical model offers profound insights by linking material behavior directly to its microstructure, the phenomenological model provides a practical but less detailed perspective. Together, these models serve as complementary tools to accurately capture and predict the mechanical performance of tough and glassy elastomers under varying conditions.

The proposed framework for both micromechanical and phenomenological models was validated using experimental data from tough and glassy elastomers. Fitting analysis demonstrates that the models effectively capture critical features of the stress-strain response, including the high modulus observed during initial deformation and the subsequent stiffening behavior. These findings highlight the framework's ability to bridge the gap between phenomenological fitting and micromechanical interpretation, offering a comprehensive tool for understanding and predicting the behavior of these specialized elastomers.

This study contributes to the field by presenting a robust and insightful modeling strategy, paving the way for the design and optimization of advanced elastomeric materials tailored for specialized applications.

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Large deformations of planar periodic trusses with rheological non-linearity

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1 - École Nationale des Travaux Publics de l'État (France), 2 - Università degli studi di Catania = University of Catania (Italy)

Speaker: Boutin Claude. Keynote. **Tuesday**. Start time: **10:00**. Room: Saint Clair 1 LVL2. Link to abstract.

Both geometrical and rheological non-linearities can be involved in highly deformable trusses. The aim of this paper is to derive explicit descriptions of the plane behavior of periodic trusses subjected to both non-linear effects.
The trusses under consideration are composed of bars that only support axial forces and that are connected by perfect hinges. Assuming a large scale evolution of the deformation, the homogenization method allows the macroscopic behaviour to be determined. In fact, although the deformed configuration differs significantly from the initial one, the homogenization can is still be carried out on parametric Lagrangian variables, taking advantage of the periodicity of the initial configuration. The procedure uses a variational approach similar to that introduced in (Caillerie et al. 2006), (Raoult et al. 2008) and (Gazzo et al. 2020). This approach, applies to trusses of any topology, and in particular to trusses whose cells contain a single node. In that case the equilibrium conditions (expressed in the deformed configuration) of the node and the cell coincide. This allows to formulate analytically the constitutive laws at large deformations can be established, and this equally well to bars with linear ornon-linear behavior.
For linear elastic bars, the non-linear effect is due to geometric non-linearities alone. For stiffening or softening elastic behavior, the two non-linear effects interact. It should also be noted that these media are by nature highly anisotropic. All these characteristics lead to very rich behaviors, as illustrated by some examples. Having an explicit model that takes into account the morphology of the cell, the constitutive law of its constituents and its evolution at large deformations allows to have a deep understanding of the physical interaction of these mechanisms.
This study can be extended in various ways, e.g., by considering cells composed of bars of different types (visco-elastic trusses), by introducing buckling instability, by considering 3D truss networks, or by imposing rigid connections between the elements and replacing the bars by bending beams.

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Bifurcation of the free surface of a rectangular block with second-gradient nonlinear elasticity

Pandurangi Shrinidhi Shrikant (1)

1 - Department of Mechanical Engineering, Indian Institute of Technology Bombay (India)

Speaker: Pandurangi Shrinidhi Shrikant. Invited. **Tuesday**. Start time: **10:40**. Room: Saint Clair 1 LVL2. Link to abstract.

We are motivated by the formation of spatially localized deformations, known as creases, on the surface of soft elastic solids subjected to compressive loading. From the celebrated work of Biot (1963), it is well known that the flat surface of a hyperelastic half-space necessarily forms wrinkles at the critical buckling load. However, the wavelength of the wrinkles at this critical load is arbitrary. This corresponds to the failure of complimenting condition for a boundary value problem involving a traction-free surface (Negrón-Marrero and E.L. Montes-Pizarro (2011)). To overcome this degeneracy, bifurcations problems for a non-homogeneous solids, such as a functionally graded materials or a thin stiff film bonded to the surface of the soft solids are studied in the literature (Pandurangi et al. (2022)).
In this work, we will consider the bifurcations of rectangular block of non-simple material whose strain energy density depends on the first and second gradient of deformation. The second gradient term is assumed to have a quadratic form multiplying a small scalar parameter. The block is subjected to an axially compressive load with sliding boundary conditions at the two ends. We are interested in the bifurcations of the free surface from its initial flat state. After introducing the boundary value problem, we discuss the linearization of the equations about the trivial line of solutions corresponding to the homogeneous solution. The local bifurcation analysis will be presented.

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Analysis of strain-dependent elasto-capillary necking and bulging in hyperelastic cylinders based on a one-dimensional model

Zhu Pingping (1), Dun Li Xiang Yu Zheng Zhong

1 - Harbin Insititute of Technology, Shenzhen (China)

Speaker: Zhu Pingping. **Tuesday**. Start time: **11:00**. Room: Saint Clair 1 LVL2. Link to abstract.

Surface effect attracts more and more attention as the rapid development of soft materials, structural miniaturization and micro/nono-technology. Various works model the surface effect in solids as a constant surface tension. However, the assumption of constant surface stress is not applicable for solids due to the low mobility of atoms/molecules. Experimental evidence for strain-dependent surface effect has been reported. Investigating the elasto-capillary behaviors in solids with strain-dependent surface effect is imperative. The post-bifurcation response of elasto-capillary instability in solid structures with strain-dependent surface effect remains unexplored either analytically or even numerically. To address this, we derive a one-dimensional (1d) gradient model from three-dimensional (3d) finite-strain formulation for characterizing the necking/bulging instabilities in a hyperelastic cylinder with strain-dependent surface effect. With the aid of the 1d reduced model, the fully nonlinear evolutions of the necking/bulging behaviors can be obtained very easily. A finite-element scheme of the 3d formulation is also proposed to validate the efficiency of the reduced 1d model. Three typical loading scenarios are considered to reveal the effects of surface tension, surface elasticity, surface compressibility, axial force and geometrical size on the surface-bulk interactions. This work lays a theoretical foundation for the further investigation of strain-dependent surface-stress problems and provides substantial suggestions for tuning the surface effect in soft solids by structure and composition designs.

Mechanics of Magnetic Gel Balloons

Shaikh Nadeem (1), Tamadapu Ganesh (1)

1 - Indian Institute of Technology Madras (India)

Speaker: Shaikh Nadeem. **Tuesday**. Start time: **11:20**. Room: Saint Clair 1 LVL2. Link to abstract.

The inflation of polymeric balloons presents a fascinating challenge due to the involvement of large deformations in nonlinear materials. This complex interplay of geometric and material nonlinearities renders the governing differential equations susceptible to various types of bifurcations. These bifurcations, in turn, manifest as distinct physical instabilities, each with unique characteristics and implications.
One prominent phenomenon is limit point instability, where the balloon undergoes a sudden and uncontrollable expansion (burst) when the internal pressure reaches a critical threshold. This is characterised by a non-monotonic relationship between internal pressure and material stretch, signalling a loss of stability. Another instability, symmetry-breaking, occurs when the inflated balloon deviates from its initial mirror-symmetric shape, adopting an asymmetric configuration as the structure loses balance across a plane of symmetry.

Shape bifurcation is yet another form of instability, where the balloon transitions between distinct geometric configurations, such as shifting from a spherical to a pear-shaped (1) structure under certain conditions. Additionally, wrinkling arises due to localised compressive stresses exceeding the material's ability to resist deformation (2). This results in crumpling or folding of the membrane, a consequence of its minimal bending stiffness.

These instability-related phenomena not only illustrate the complex mechanics of polymeric balloons but also highlight their sensitivity to material properties and loading conditions, making them a compelling and interesting subject.

Interestingly, balloons made from active materials such as gels, piezoelectric polymers, or magneto-elastic composites introduce additional control parameters. The application of external fields to these materials offers an exciting avenue to investigate how these fields influence the onset and evolution of instabilities, providing deeper insights into their behaviour and potential applications.

In this work, we investigate the inflation mechanics of an initially spherical balloon made of magnetic gel, focusing on the influence of a magnetic field on various instability-related phenomena. A nonuniform magnetic field is generated by a DC current-carrying circular coil placed around the equator of the balloon, combined with the application of internal hydrostatic pressure. The analysis employs an energy formulation incorporating magneto-mechanical coupling, which accounts for the magnetisation energy and the material strain energy described by the Neo-Hookean and six-parameter Ogden material models. The inflation process is classified into two regimes based on the pressurisation duration, tp: slow inflation and fast inflation. During slow inflation, sufficient time allows solvent molecules to migrate into or out of the gel membrane, leading to compressible inflation behaviour. In contrast, during fast inflation, the movement of solvent molecules is restricted, resulting in incompressible inflation. The impact of the applied magnetic field on the balloon's behaviour is systematically analysed within both slow and fast inflation regimes, providing insights into the complex interplay between magnetic fields and the balloon's mechanical response.

The deformation of the balloon is assumed to be axisymmetric, allowing the construction of the left Cauchy-Green deformation tensor, C. The governing differential equations for axisymmetric deformation are derived using a variational formulation, which yields a system of coupled nonlinear ordinary differential equations (ODEs). These equations, together with the specified geometric boundary conditions, define the problem as a two-point boundary value problem.

To solve this problem, the shooting method is employed in conjunction with the Nelder-Mead optimisation technique. Computational results indicate that the intensity of the magnetic field has a significant effect on the limit point instability pressure for both slow and fast inflation regimes. To further analyse the stability of the deformed axisymmetric configuration, linear perturbations are introduced using Legendre polynomials. A pronounced influence of the magnetic field on the symmetry-breaking bifurcation point

and the post-bifurcation equilibrium branch is observed. Additionally, the effect of material parameters on the symmetry-breaking bifurcation point and the post-bifurcation equilibrium branch is thoroughly investigated, shedding light on their role in the system's stability and deformation behaviour.

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Post-buckling of fiber-reinforced materials

Liu Yang (1) (2)

1 - Mathematical Institute, University of Oxford (United Kingdom), 2 - Department of Mechanics, School of Mechanical Engineering, Tianjin University (China)

Speaker: Liu Yang. Invited. **Tuesday**. Start time: **14:15**. Room: Saint Clair 1 LVL2. Link to abstract.

Many biological tissues are fiber-reinforced, enhancing their physical properties and exhibiting inherent anisotropy. The interplay of fiber stiffness, fiber orientation, and the elastic properties of the matrix on pattern formation and evolution in layered tissues still requires a comprehensive understanding. We consider a paradigmatic model with a film coated to a half-space where either the film or the substrate is anisotropic. In particular, the Holzapfel-Gasser-Ogden model is used to capture fiber-reinforcements. To investigate post-buckling evolution, a weakly nonlinear analysis is performed to derive an amplitude equation applicable to both scenarios. A detailed parametric study unravels the effects of fiber orientation, fiber stiffness, and modulus ratio on the post-buckling solution. When the film is fiber-reinforced, it turns out that the bifurcation will always be supercritical if $r < 0.571$ where r is the ratio of the shear modulus of the substrate to that of the film. We further identify an additional condition under which subcritical bifurcations can emerge. If the substrate is fiber-reinforced, the integrated impact of material anisotropy becomes more complicated. Finally, we explore from our post-buckling solution where the fibers first experience compression and also plot the bifurcation diagram from which the evolution of the wrinkled amplitude is depicted. These analytical post-buckling solutions offer valuable insights into the morphological development of biological tissues.

Creasing on finite domains and its connection to Biot's surface instability

Groh Rainer (1)

1 - University of Bristol [Bristol] (United Kingdom)

Speaker: Groh Rainer. Invited. **Tuesday**. Start time: **14:35**. Room: Saint Clair 1 LVL2. Link to abstract.

Over the past decades the applications of soft polymeric materials have exploded. A yet unresolved phenomenon is how and when a soft solid loses stability under compression to form a sharp inwards localisation (a crease with self-contact) at a free surface. Despite many years of research on surface instabilities in soft solids, there is still no consensus on how creases form, at what compressive strain this occurs, the nature of the instability (local or global bifurcation) and, crucially, its connection to the classical and periodic Biot instability.
This talk presents results from a finite element (FE) analysis conducted in an in-house code that combines higher-order elements with numercial continuation and branch-switching algorithms to study, in detail, the nature of the creasing instability on finite domains. Assuming a quasi-incompressible Neo-Hookean material model, the findings are as follows. The fundamental path of uniform compression loses stability, i.e. the tangent operator of the force balance loses determinacy, at the classical Biot instability of 0.455 compressive strain. The larger the dimension of the finite-sized FE analysis in the loading direction (the model length), the greater the degeneracy of the bifurcation point, i.e. the longer the model, the greater the number of critical eigenmodes at the bifurcation point. The critical eigenvectors at this compound bifurcation point always take integer multiples of cosine half-waves along the model length starting at one single half wave, irrespective of the overall model length. Hence, as the model length tends to infinity, as is the case in Biot's original halfspace problem, the wavelengths of the critical eigenmodes appropriately tends to zero. Branch switching at the degenerate bifurcation point using only pure modes (one eigenmode at a time) leads to highly unstable post-critical paths (sub-critical bifurcation) where the periodic eigenmodes very quickly localise into various creases located at the minima of the periodic eigenmodes. Thus, after only a short distance along any post-critical path the eigenmode with one half-wave localises into half of a crease at either loaded end of the model; the eigenmode with two half-waves localises into a central crease or two half-creases at either end of the model; and so on.

Interestingly, all post-critical paths are sharply subcritical and lead to material self-contact at approximately 0.36 compressive strain-the experimental value often reported for the creasing instability. However, the post-critical equilibrium paths that fall from the Biot instability (0.455 strain) and lead to a self-contacting crease (0.36 strain) do not converge with increasing mesh refinement and neither does the depth of the crease localisation. Indeed, with increasing mesh refinement the crease depth tends to zero, even though the compressive strain at which self-contact occurs remains the same at 0.36. Related observations on mesh refinement by others in the literature has led to the conclusion that the self-contacting crease must therefore be a new type of instability that branches from the fundamental path of pure compression at a strain of 0.36, but which is not picked up by the degeneracy of the tangent operator. An alternative hypothesis considered here, which maintains a more classical flavour, is that the vanishing depth of the localisation with mesh refinement is indicative of a singularity that needs to be renormalised by additional physics. By adding surface energy (surface tension) into the model the post-critical paths do converge with mesh refinement and the greater the ratio of surface energy to shear modulus, the less sharp the sub-critical paths that emanate from the Biot instability. Finally, stochastic analysis are conducted by seeding surface imperfections into the model in the form of Gaussian random fields, which illustrate that imperfections alone can account for the difference between Biot's instability of 0.455 compressive strain derived from a perfect model, and the creasing strain of 0.36 observed in inherently imperfect experiments.
In conclusion, creasing in various forms is shown to occur as localisations along unstable post-critical paths that branch from the compound bifurcation of the Biot instability and that the post-critical regime needs to be renormalised by surface energy to give physically meaningful results. Then, the lower creasing strain observed in experiments compared to Biot's prediction takes on a classical flavour since it is governed by the subcriticality and imperfection sensitive response of the problem.

A nonlinear toroidal shell model for surface morphologies and morphogenesis

Wang Ting (1), Potier-ferry Michel (2), Xu Fan (3)

1 - Tongji University (China), 2 - Université de Lorraine (France), 3 - Fudan university (China)

Speaker: Wang Ting. Invited. **Tuesday**. Start time: **14:55**. Room: Saint Clair 1 LVL2. Link to abstract.

Geometric forms are intrinsically linked to fundamental biological functions, with curvature serving as a key descriptor of local geometry that has been shown to be critical for the performance of biological systems. In addition to the classical uniform curved surfaces, when tubular structures are bent or branched, they introduce curvature in the second principal direction, leading to regions with positive or negative Gaussian curvatures, as seen in the toroidal model. However, theoretical understanding and prediction of their nonlinear instability are quite challenging. In this study, we systematically develop a nonlinear toroidal shell model based on general differential geometry and derive analytical solutions that can effectively predict critical buckling behavior. Our results analytically demonstrate that, in toroidal geometries with nonuniform curvatures, the critical instability stress is proportional to both the curvature and the stiffness, in agreement with numerical predictions. We also present a universal phase diagram of critical topographies, determined by two dimensionless parameters across a wide range of parameter space, which is further validated through experimental demonstrations.

A model for curvature-induced morphing of hyper-elastic shells

Taffetani Matteo (1), Pezzulla Matteo (2)

1 - University of Edinburgh (United Kingdom), 2 - Aarhus University [Aarhus] (Denmark)

Speaker: Taffetani Matteo. Invited. **Tuesday**. Start time: **15:15**. Room: Saint Clair 1 LVL2. Link to abstract.

The deformation of slender structures is largely described by the most famous theorem in differential geometry, the Gauss' theorema egregium, which states that infinitesimally thin objects deform into shapes that preserve lengths. Therefore, as a consequence of their slenderness, thin structures largely deform by bending with small amounts of stretching, often via elastic instabilities. Active and biological membranes exploit this type of mechanism in their morphing strategies, usually undergoing large strains and large rotations.
To investigate the effect of material non-linearities in the morphing of thin, and naturally curved, slender objects, in this work we derive an effective two dimensional energy functional via a formal dimensional reduction of a three dimensional Neo-Hookean morphoelastic material. We include the role of a non-mechanical stimulus via the multiplicative decomposition of the deformation gradient tensor which considers the presence of an incompatible configuration that, in our case, is associated to a prescribed incompatible curvature stimulus (1). We also include the role of a through-the-thickness adaptation during the morphing, following the work of (2).

The energy functional that we derive is suitable to be implemented in finite element codes. We thus use our model to investigate how non-linearities affect the curvature-induced snapping of spherical caps.

(1) Matteo Pezzulla, Norbert Stoop, Mark P. Steranka, Abdikhalaq J. Bade, and Douglas P. Holmes. Curvature-induced instabilities of shells. Phys. Rev. Lett., 120:048002, 2018. (2) Olivier Ozenda and Epifanio Virga. On the kirchhoff-love hypothesis (revised and vindicated). J. Elast., 143:359–384, 2021.

Wrinkling patterns of stiff shallow film mounted on curved substrate under biaxial strain

Kordolemis Alexis (1), Giannakopoulos Antonios (2)

1 - University of Greenwich (United Kingdom), 2 - National Technical University of Athens [Athens] (Greece)

Speaker: Kordolemis Alexis. **Tuesday**. Start time: **15:35**. Room: Saint Clair 1 LVL2. Link to abstract.

A thin film mounted on a compliant substrate under biaxial compressive strains wrinkles in different patterns such as cylindrical, checkerboard, herringbone and hexagonal.
In this study, we provide a thorough analysis of the above wrinkling modes which have been well documented experimentally and numerically. Particular attention is paid to the role of the curvature-induced anisotropy in the geometrical characteristic of these particular surface wrinkling modes, i.e. the wavelengths in the two principal directions as well as the corresponding amplitudes.

The film is assumed to be much stiffer than the substrate and the bilayer system is cylindrically curved and is acted upon biaxial compressive strains. The film is modelled as a shallow shell with finite rotations while the substrate is assumed as a linear three-dimensional elastic solid. Utilising the minimization of the total energy of the system semi-analytical expressions for the critical values of the wavelengths and the corresponding amplitudes associated with the onset of the various wrinkling modes are provided.
The obtained results has been found to be in a very good agreement compared to experimental and numerical findings of other studies. It is shown that the presence of the initial curvature in the bilayer delays the critical strain and the wrinkling
amplitudes significantly for all wrinkling modes, compare to the flat system, and moreover explains the inward buckling of the hexagonal mode which has been observed experimentally.

A constrained minimization theory to prevent material overlapping in nonlinear elasticity

Aguiar Adair (1), Rocha Lucas (1)

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Speaker: Aguiar Adair. Invited. **Tuesday**. Start time: **16:35**. Room: Saint Clair 1 LVL2. Link to abstract.

The theory of classical linear elasticity predicts self-intersection in a neighborhood of interior points of anisotropic solids, crack tips, and corners. This physically unrealistic behavior is characterized by the violation of the local injectivity condition, according to which, the determinant of the deformation gradient, $J \triangleq \det\{F\}$, must be positive. One way to impose this condition in elasticity consists of minimizing the total potential energy subjected to the condition $J \geq \varepsilon > 0$, where ε is a small positive parameter. We present a minimization theory constrained by $J \geq \varepsilon > 0$ for hyperelastic solids undergoing finite deformations and derive necessary conditions for a deformation field to be a minimizer, which include both continuity of traction and a dissipation-free condition across a surface of discontinuity. We then apply this theory in the analysis of equilibrium of an annular disk made of an orthotropic St Venant-Kirchhoff material. The disk is fixed on its inner surface and compressed by a constant pressure on its outer surface.

In this work, the disk problem is formulated as a boundary value problem (disk BVP), which yields non-smooth solutions for large enough pressure. We use a phase-plane technique to construct a trajectory of solution for the disk BVP. Elsewhere, we have also formulated the disk problem as a minimization problem (disk MP), which is solved by using the finite element method together with nonlinear programming tools. Results obtained from the solutions of both the disk BVP and the disk MP are in very good agreement and satisfy all the necessary conditions for an admissible minimizer, including the injectivity condition.

In particular, analytical and numerical results show that, for the annular disk, the Lagrange multiplier field associated with the imposition of the local injectivity constraint remains bounded as ε tends to zero. This behavior is different from the one reported in the literature for the disk problem formulated in the context of a constrained linear theory. In this case, the Lagrange multiplier becomes unbounded as ε tends to zero.
For comparison purposes, we have also formulated the disk BVP using a compressible and orthotropic Mooney-Rivlin material without imposing the local injectivity constraint. The solution of this unconstrained problem tends to the solution of the constrained disk BVP for small ε as a certain elasticity constant tends to zero.

A self-contact preventing energy for nonlinear elastic filaments

Chiara Lonati (1)

1 - University of São Paulo, São Carlos, SP (Brazil)

Speaker: Chiara Lonati. Invited. **Tuesday**. Start time: **16:55**. Room: Saint Clair 1 LVL2. Link to abstract.

Nonlinear elastic filaments with small non-vanishing thickness can represent various physical phenomena, such as DNA folding and protein modeling, or, more generally, charged flexible structures. A fundamental notion to obtain physical descriptions is the constraint of non-interpenetration of matter and preservation of the isotopy class of the midline, i.e. its knot type.
Several expressions for local and global injectivity of the configuration map of an inextensible and unshearable closed rod were stated in the last decades (Ciarlet-Nečas, Gonzalez, Schuricht). We prove equivalences between them and a natural constraint on virtual displacements and we stress the similarity between notions of self-intersection and self-distance of knots and the corresponding treatment for thick filaments.
We then present a new repulsive energy functional defined on the surface of tubular neighbourhoods of inextensible curves: it is a generalization to thick filaments of the electrostatic inspired Mobius energy for knots by O'Hara. The functional preserves isotopy classes and degenerates to infinity if and only if self-contact or interpenetration occurs, so it acts as a natural constraint that guarantees physically acceptable configurations, without the necessity of reducing the space of admissible rods with complicated conditions. The main properties that we prove for this energy, supported by numerical simulations, are analogous to the ones proved for knots by O'Hara.

Asymptotic and experimental modelling of three-point bending of sheet metal

Zaat Eva (1), Krawec Phillip (2), Hudson Thomas (1), Hazra Sumit (2), Brambley Ed (1) (2)

1 - Catholic University of Sacred Heart (Italy)

Speaker: Zaat Eva. **Tuesday**. Start time: **17:15**. Room: Saint Clair 1 LVL2. Link to abstract.

The three-point bending test evaluates a metal sheet's response to bending. The ability to accurately predict the behaviour of material in this experiment is sought-after by mechanical engineers, as it would provide a link between experimental results and the material's properties. We endeavour to gain a comprehensive understanding of the underlying principles governing the deformation and failure of materials during this test by constructing a mathematical model of three-point bending.

We will discuss the experimental setup, the challenges encountered in obtaining consistent results and the analysis of the data collected. The key factors that were identified as influencing the outcomes at various length-scales include the direction of the grains in the material, the hardening of the material and the friction between the sheet and the punch of the testing equipment. We therefore explore hardening and friction laws to formulate an accurate mathematical description of the experiment. Additionally, we would like to address some of the challenges posed by non-linearities in the underlaying governing equations, using asymptotic analysis and numerical simulations to provide insights into the influence of these factors. In the long term, this model would be validated against further experimental data and could be adapted to other experimental scenarios.

Tanh outperforms power-law for modeling experimental hardening of UHS steels

Singh Ravi (1) (2), Krawec Phillip (2), Brambley Ed (1) (2), Hazra Sumit (2)

1 - Warwick Mathematics Institute, University of Warwick (United Kingdom), 2 - Warwick Manufacturing Group [Coventry] (United Kingdom)

Speaker: Singh Ravi. **Tuesday**. Start time: **17:35**. Room: Saint Clair 1 LVL2. Link to abstract.

The accurate modeling of tensile behavior in ultra-high-strength steels (UHSS) presents a significat challenge due to the inherent limitations of conventional power-law-based models in capturing the transition and strain-hardening behavior across diverse deformation regimes. Traditional models, such as the power-law and its derivatives, assume a constant strain-hardening exponent and linear logarithmic relationships between true stress and true strain. These assumptions fail to account for the nonlinearities observed in experimental stress-strain curves in logrithmic space, particularly in the transition and strain-hardening regions. Consequently, conventional models often yield significant discrepancies when applied to materials with limited ductility, such as UHSS grade S960MC.This study proposes a novel hyperbolic tangent (tanh)-based hardening model to overcome these limitations. The model is mathematically expressed as: $\sigma = \boldsymbol{a}\tanh(\alpha\epsilon) + \boldsymbol{b}\tanh(\beta\epsilon)$, where σ represents the true stress, ϵ is the true strain, a corresponds to the stress contribution in the elastic region, equal to the yield strength (Y), b corresponds to the stress increment due to hardening, defined as UTS–Y, α and β are scaling parameters controlling the strain's influence on stress response in the elastic and plastic regions, respectively.The first term in the model captures the elastic behavior of the material, transitioning smoothly to the yield strength, while the second term governs the nonlinear hardening response in the plastic deformation region. A key advantage of this formulation is its ability to provide a smooth and continuous transition between elastic and plastic behavior, avoiding the unphysical stress predictions often encountered in power-law models. Additionally, the derivative of the stress-strain curve at zero strain corresponds to the Young's modulus (E), satisfying the boundary conditions required for accurate material modeling.The model parameters were fitted to experimental tensile data of S960MC UHSS using a non-linear least squares approach implemented via the Levenberg-Marquardt (LM) algorithm. This iterative optimization minimized residual errors, resulting in an accurate representation of the stress-strain behavior across elastic, transition, and strain-hardening regimes.The proposed tanh-based model demonstrated significant advantages over traditional power-law models. Maximum errors in the transition and hardening regions were significantly reduced. By incorporating key material properties such as E, Y and UTS directly into its formulation, the tanh model offers both physical relevance and predictive accuracy.

Nonlinear dynamics of a geometrically exact beam subjected to a moving mass

Kumar Kush (1), Gupta Shakti S. (1)

1 - Warwick Mathematics Institute, University of Warwick (United Kingdom), 2 - Warwick Manufacturing Group [Coventry] (United Kingdom)

Speaker: Kumar Kush. **Tuesday**. Start time: **17:55**. Room: Saint Clair 1 LVL2. Link to abstract.

This work derives the governing equations of motion for the Reissner-Simo geometrically exact (GE) beam (1-2) subjected to a moving mass. The motion of the moving mass is externally controlled and specified relative to the beam. These governing equations are applicable to any general motion of the mass. A nonlinear finite element (NLFE) method is developed to obtain the finite element equations of motion for the system, with Newmark's time integration scheme employed to solve these equations. The response of the GE beam and moving mass system is analyzed for scenarios involving uniform motion, acceleration, and controlled actuation of the mass. The formulation is validated using classical example problems from the literature. Finally, the developed method is applied to investigate the nonlinear dynamics of a hanging cable under a moving mass, considering both ascending and descending mass scenarios to solve various initial-boundary value problems (IBVPs).

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MS3.6 - Recent Advances in Plasticity and Damage Mechanics

Organisers: Gergely Molnár (LAMCOS), Claudia Comi (Polimi) and Corrado Maurini (Institut Jean le Rond D'Alembert)

ON MODELING COUPLED THERMOELASTICITY WITH GRADIENT DAMAGE UNDER DYNAMICS CONDITIONS

Kamagate Banouho (1) (2), Abdelmoula Radhi (3), Danho Emile (2), Cheng Long (4), Kondo Djimedo (1)

1 - Institut Jean Le Rond d'Alembert (France), 2 - Université Félix Houphouët BOIGNY (Côte d'Ivoire), 3 - LSPM (France), 4 - Georessources (France)

Speaker: Kondo Djimedo. Keynote. **Monday**. Start time: **10:10**. Room: Saint Clair 2 LVL2. Link to abstract.

Local damage models generally exhibit pathological sensibility to mesh size or orientation. A common way to improve such damage models consists in incorporating gradient-damage terms which involve a length scale. The variational setting of such models allows to link them to fracture modeling (3). Variational gradient damage models have been also extended in various directions among which those allowing to account for thermoelastic effects (generally in an uncoupled form) or for dynamics conditions (2) (4). In the footstep of these works, the present study aims at developing a variational framework for gradient damage combined with a fully coupled thermoelasticity under dynamics conditions. To this end, we rely on Biot's Lagrangian formalism of dynamics equations in presence of dissipative phenomena Biot (1) (see also (6)),. This is similar to the introduction of a Rayleigh-like dissipation function in the classical Lagrange equations. Combined with global normality rule, the procedure yields a variational inequality for the dynamics gradient damage model with thermal effects.
Adopting a time discretization allows to establish an incremental variational setting involving a three fields (displacement, temperature, damage) functional (except for the dynamics contribution, this has some similarities with (7),(8)). The numerical resolution of the model is performed in a staggered manner by first determining the temperature field through the solution of the heat equation, then the displacement and velocity field by means of a Newmark integration scheme and finally the damage field by a minimization of functional at the current time step with an account for the damage irreversibility condition. This is done until convergence.

For illustration purpose, we had performed various simulations of dynamic fracture propagation in a thermoelastic-damageable materials. For instance, a plate submitted to a a thermal shock together with a mechanical loading (see for instance (5), also for materials properties) has been considered.The numerical results demonstrate the capabilities of the model to predict crack branching in such context. A full discussion of the temperature field, stress and displacement field, as well as the evolution of the different energies is performed.

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A variational model coupling cavitation and damage for fracture in nearly incompressible materials

Zolesi Camilla (1), Marigo Jean-jacques (1), Maurini Corrado (2)

1 - Laboratoire de mécanique des solides (France), 2 - Institut Jean Le Rond d'Alembert (France)

Speaker: Zolesi Camilla. Invited. **Monday**. Start time: **10:50**. Room: Saint Clair 2 LVL2. Link to abstract.

Variational phase-field models for brittle fracture are widely used due to their ability to reproduce complex crack patterns without the need for ad hoc criteria (1) and to effectively handle crack nucleation under tensile loading (2). However, the treatment of crack nucleation under multi-axial stress states in phase-field models remains a topic of active discussion, with several unresolved challenges. Among these challenges are the inability to flexibly define the crack nucleation criterion under multi-axial stress states and the difficulty of modeling crack nucleation in materials approaching the incompressibility limit. In this contribution, we focus on the issue of crack nucleation in nearly incompressible materials, with particular attention to the well-known poker-chip test introduced by Gent and Lindley (3). We propose a novel phase-field model coupled with a nonlinear model describing cavitation at the macroscopic level. The nonlinear cavitation model describes two phases: the first phase captures the material's behavior when it is nearly incompressible and undergoes minimal deformation until the cavitation threshold is reached, while the second phase reflects a nonlinear response caused by the presence of bubbles in the material. These bubbles lead to the loss of the material's nearly incompressible nature, enabling expansion. We combine this macroscopic cavitation model with a variational phase-field model in which the scalar damage variable influences the cavitation threshold. The variation of the cavitation threshold with the damage thus becomes the new variational driving force. In this way, we capture the key features of cavitation and fracture processes in nearly incompressible materials, relying solely on energy minimization and remaining within the variational framework without using ad hoc criteria and non-variational driving forces.

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A Traction-Compression Asymmetric Damage Phase Field Model based on a Fourth-order Degradation Tensor

Marco Bittencourt (1), Esteves Carlos (1), Rodrigues Eduardo (2), Boldrini José (1)

1 - Universidade Estadual de Campinas = University of Campinas (Brazil), 2 - Universidade Estadual Paulista Júlio de Mesquita Filho = São Paulo State University (Brazil)

Speaker: Marco Bittencourt. Invited. **Monday**. Start time: **11:10**. Room: Saint Clair 2 LVL2. Link to abstract.

In this work, we extend a previous phase-field model with a fourth-order degradation tensor to simulate failure mechanisms for components with traction and compression asymmetric behavior. We apply the obtained model for reinforced concrete (RC) beams, particularly in beams with high steel reinforcement ratios. The model is designed to capture complex fracture behaviors under tensile and compressive loadings by employing distinct phase-field parameters. Numerical analyses focus on RC beams under four-point bending, comparing results with experimental data from the literature to validate its accuracy. Quantitative results show that the model effectively replicates load-displacement curves, accurately reflecting the influence of geometric and material properties on the mechanical behavior of RC beams. Qualitatively, the model reproduces crack initiation, propagation, and coalescence patterns that closely correspond to experimental observations, capturing complex failure modes such as diagonal tension (DT), shear-compression (SC) and concrete crushing (CC).

Thermodynamic framework for variance-based non-local constitutive models: Application to polycrystalline plasticity

Mareau Charles (1)

1 - LAMPA, Arts et Métiers Institute of Technology (France)

Speaker: Mareau Charles. **Monday**. Start time: **11:30**. Room: Saint Clair 2 LVL2. Link to abstract.

Many constitutive models used for thermo-mechanical applications rely on the internal variable concept to represent the effect of microstructural transformations (e.g., hardening, damage, phase transitions) on the behavior of solid materials. For the majority of constitutive models, the evolution equations associated with the different internal variables are purely local. Specifically, the evolution of the internal state of a material point solely depends on the current state of that material point. However, there are some situations for which it is needed to include some information regarding the spatial distribution of state variables. As discussed by Bazant and Jiràsek (2002), there are different motivations for such constitutive models, which are often referred to as non-local. Indeed, non-local models allow (i) considering deviations from locality due to material heterogeneity at small scales, (ii) limiting strain localization resulting from softening, which is largely used in the context of damage mechanics, and (iii) capturing size effects associated with metal plasticity or fracture of ceramic materials.
Non-local constitutive models can be classified as either gradient-type or integral-type model. Gradient-type models treat the spatial gradients of internal variables as additional state variables. The consequence is that the evolution of internal variables is governed by a set of equilibrium equations and some boundary conditions. Such equations and boundary conditions are generally derived from an extended principle of virtual power. Gradient-type models have been largely used in the context of conventional plasticity, either to capture size effects or to limit strain localization associated with softening. Also, the role of Geometrically Necessary Dislocations (GND) on strain hardening can be incorporated in the framework of crystal plasticity by considering the spatial gradients of plastic shear strains as state variables. The phase-field method, which is widely used for solving interfacial problems, also relies on the spatial gradients of some order parameters to evaluate surface energy. Many applications of the phase-field method to either brittle or ductile fracture have been proposed. When applied to fracture, the phase-field method allows circumventing the difficulties associated with excessive damage localization and considering the increase of surface energy resulting from crack nucleation and crack growth.

In contrast with gradient-type models, integral-type models use some non-local variables obtained after spatial integration of their local counterparts. Generally speaking, such non-local variables can be interpreted as the spatial averages of the corresponding local variables over the neighborhood of the material point of interest. Integral-type models have been largely used in the context of brittle or ductile fracture, mostly to limit damage localization. Integral-type models for plasticity-induced softening have also been developed. A common approach consists of introducing the spatial average, i.e., the zeroth moment, of either the plastic strain tensor or the hardening variable in constitutive relations.

The present work aims at enriching integral-type constitutive models by incorporating not only the spatial average, but also the spatial variance of internal variables in constitutive relations. The objective is to include additional information regarding the spatial distribution of internal variables when constructing integral-type constitutive models. The proposed framework is developed in the context of continuum thermodynamics and can be applied to different types of problems, including plasticity and damage. In the first part of this presentation, the definitions of the average and the variance of an internal variable will be introduced. The general form of constitutive equations, which relies on continuum thermodynamics, will be detailed in the second part. Particular attention will be given to the treatment of near-boundary regions for which different options will be proposed.
For the purpose of illustration, a crystal plasticity-based model developed within the proposed framework will be exposed in the final part of this presentation. Such a model treats the average and the variance of the plastic deformation gradient tensor as additional variables. For the treatment of near-boundary regions, two different options, referred to as the " hard " or " soft " surrounding assumptions, are evaluated. For a given material point, the former option assumes that each crystallite is surrounded by a

fictitious elastic medium while the latter option considers that the fictitious surrounding experiences the same plastic deformation as the material point of interest. The numerical examples indicate that, when the soft surrounding assumption is adopted, the effect of non-locality is limited to the diffusion of plastic strains, no size dependency of the macroscopic behavior being observed. At the opposite, when the hard surrounding assumption is used, the macroscopic hardening rate is found to depend on the mean grain size. Such a size-effect is related to the role of non-locality on the development of internal stresses, which provide an additional contribution to kinematic hardening.

Variational methods applied to discrete models in brittle damage

Bonhomme Elise (1)

1 - Département de mathématiques Université Libre de Bruxelles (Belgium)

Speaker: Bonhomme Elise. Keynote. **Monday**. Start time: **13:40**. Room: Saint Clair 2 LVL2. Link to abstract.

In this talk, I will study a discrete model of brittle damage in different regimes where the damaged zone concentrates on vanishingly small sets. We will identify the nature of the effective limit models obtained by means of an asymptotic analysis based on the Gamma-convergence of the total energies. I will recall the mechanical model of brittle damage introduced by Francfort and Marigo (1993), specified to the discrete setting where the total energies are restricted to piecewise affine continuous displacements, and I will, in particular, show how the size of the mesh influences the effective models.

On sharp-interface cohesive models with a relaxed bulk energy

Rodella Andrea (1), Maurini Corrado (2), Marigo Jean-jacques (2), Vidoli Stefano (1)

1 - Università degli Studi di Roma "La Sapienza" (Italy), 2 - Institut Jean Le Rond dÁlembert (France)

Speaker: Rodella Andrea. Invited. **Monday**. Start time: **14:20**. Room: Saint Clair 2 LVL2. Link to abstract.

This study investigates the challenge of unrealistic stress predictions that arise when associating cohesive interface energy with standard linear elasticity, building upon findings in (1). We focus on anti-plane elasticity under mode III loading, leveraging the Linear Elastic Fracture Mechanics (LEFM) solution (2). The traditional approach can lead to situations where predicted stress components exceed the fracture strength of the material.
To address this, we incorporate a relaxed bulk energy approach from (3). This approach utilizes a quadratic law for small strains, transitioning to linear growth upon reaching a critical strain threshold specific to the material. This modification ensures a well-posed problem, paving the way for a viable solution.
We validate our approach through numerical simulations showcasing crack nucleation and propagation along a predefined path. The results show adherence to the stress yield condition, supporting the effectiveness of our methodology in overcoming the limitations of the traditional approach.

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Strength-based phase-field approach to cohesive fracture

Maurini Corrado (1), Bourdin Blaise (2), Marigo Jean-jacques (1)

1 - Institut Jean Le Rond d'Alembert (France), 2 - McMaster University [Hamilton, Ontario] (Canada)

Speaker: Maurini Corrado. Invited. **Monday**. Start time: **14:40**. Room: Saint Clair 2 LVL2. Link to abstract.

The fundamental phenomenological properties in fracture mechanics are the critical stress required to nucleate a crack in a pristine material (the strength) and the energy required to propagate it (the toughness).
Cohesive-fracture models and gradient damage models have been shown to capture these main features of fracture mechanics, but with different limitations. On one side, sharp interface cohesive-fracture models pose mathematical and numerical difficulties when the crack path is left to evolve freely. On the other side, formulating damage models with arbitrary strength surfaces under multi-axial loading while preserving Griffith's criterion for crack propagation is challenging.
We introduce here a novel variational approach for building phase-field fracture models with a strength-based formulation.
The fundamental idea is to consider undamaged energies with linear growth at infinity and let the damage (or phase-field) variable affect its slope. This allows us to introduce an explicit strength criterion in the model and to recover Griffith's criterion for crack propagation.
We will present in detail the case of antiplane shear, introducing an original numerical solution scheme based on the use of convex-optimization tools. Finally, the extension to the 3D case will be outlined.

Investigating Damage and Plasticity in RC Nuclear Facilities Under Seismic Loading

D'orio Giulia (1) (2), Bleyer Jérémy (3), Combescure Christelle (4) (5), Voldoire François (1), Cherubini Stefano (1), Raude Simon (1), Fléjou Jean-luc (1)

1 - EDF (France), 2 - Laboratoire Navier (France), 3 - Laboratoire Navier (France), 4 - Institut de Recherche Dupuy de Lôme (France), 5 - Académie militaire de Saint-Cyr Coëtquidan (France)

Speaker: D'orio Giulia. Invited. **Monday**. Start time: **15:00**. Room: Saint Clair 2 LVL2. Link to abstract.

Reinforced concrete (RC) structures in the nuclear field are subject to stringent regulations, particularly for seismic demands. Understanding RC behavior under mechanical loads especially during earthquakes, and modeling this behavior numerically is crucial for assessing the robustness and safety of the structures and the hosted equipment, both at the design and reassessment stages.
Our research focuses on developing a multi-layer, multi-material plate model (Love-Kirchhoff kinematics) within the finite element (FE) framework, designed for large-scale simulations of RC structures in nuclear facilities and capable of representing engineering key quantities such as the floor spectra and the energy dissipation. The model aims to reflect the effects of microscopic non-linearities at a macroscopic level: the top and bottom layers in the thickness of the RC plate will be modeled as an equivalent homogenized material representative of the steel grids, the surrounding concrete, and the interface between the two materials; while the core will be modeled using a non-linear damage model for concrete. The model will strive to strike a crucial balance between accurately representing the complex material behavior and ensuring computational efficiency, practical usability, and parameter calibration.

RC's composite nature and the steel-concrete interaction at the interface are critical for the understanding of the stress redistribution, the tension stiffening, and the energy balance in RC elements under seismic loading. Therefore, a detailed investigation into the non-linear behavior of the steel-concrete interface and its interaction with the surrounding damaged concrete is at the core of this study.

We have conducted an extensive bibliographic review and we have performed several numerical tests to identify the most critical features influencing the macroscopic response. These tests help us understand interface behavior aspects (interlocking effect of steel ribs causing concrete compression and plastic deformation, frictional degradation in the post-peak phase, cumulative damage effect during cyclic loading) and their interaction with the surrounding damageable concrete and how they impact the overall structural performance.

A simple rheological model representative of a 1D reinforced concrete tie has been analyzed under various load conditions (static, dynamic, monotonic, and cyclic) to assess the role of different modeling assumptions on global (response spectra, energy balance) and local (stress redistribution) responses. The results, validated using experimental references, have confirmed the necessity of including the non-linear interface in numerical models for RC and have emphasized the need for a comprehensive understanding of non-linear phenomena and their interactions.

These initial results have been extended to the study of a Representative Elementary Volume (REV) representative of the top and bottom layers of an RC plate, including the steel bars, the surrounding concrete, and the interface. The REV has been tested under various loading conditions to investigate the concrete damage field and the coupled effects of concrete damage and steel-concrete relative sliding. The primary objectives of this analysis are to propose a macroscopic damage description and understand concrete damage and interface sliding interaction.

All the collected results will be integrated in the homogenization process for the plate's membrane behavior under the hypothesis of periodic media and using the averaging method (1) (2) (3). The homogenization will be conducted in the linear elastic framework, at fixed values of the internal variables and integrating the effect of the steel-concrete interface (4)(5). Particular attention will be given to the definition of the thermodynamic framework of the model for the homogenized RC layer to ensure its validity for ideally any kind of cyclic loading; and to the identification of the parameters defining the

macroscopic constitutive relation, employing optimization algorithms in order to ensure the convexity of the free energy potential.

Presentation key points: bibliographic review, the homogenization methodology: the linear framework and the taking into account of damage and plasticity, results of the numerical simulations on the REV

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Variational phase-field modeling of cohesive fracture with flexibly tunable strength surface

Vicentini Francesco (1), Heinzmann Jonas (1), Carrara Pietro (1), Lorenzis Laura De (1)

1 - ETH Zurich

Speaker: Vicentini Francesco. **Monday**. Start time: **15:20**. Room: Saint Clair 2 LVL2. Link to abstract.

Variational phase-field models for brittle fracture (1) are powerful computational tools for studying Griffith-type crack **propagation** under complex three-dimensional and multiaxial loading scenarios. However, they struggle to accurately capture fracture **nucleation**, i.e., the onset of cracks in quasi-brittle materials. While effective for tensile-driven fractures (mode I) (2), they fail under multiaxial loading due to the lack of flexibility in prescribing a **material-specific strength surface** (3).
Traditional energy decomposition approaches often lead to questionable residual stresses (4), prompting non-variational modifications (5) that sacrifice the physical, mathematical, and numerical advantages of an energy minimization framework. This limitation stems from the fact that classical phase-field models merely regularize the sharp Griffith fracture model (6), which lacks a nucleation concept, unlike sharp cohesive fracture models.

To overcome this, we propose a **variational** phase-field model that approximates **cohesive fracture** allowing the inclusion of an **arbitrary strength surface** as a material property (7). Additionally, similar to what was observed in (8), we demonstrate that this formulation enables **sharp cohesive fractures**, providing an approximation that avoids smearing of the displacement field. The model naturally incorporates a sharp **non-interpenetration** condition, thus eliminating the need for additional energy decompositions.

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Time-dependent mechanical behaviour and failure of PVDF composites

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1 - Eindhoven University of Technology - Department of Mechanical Engineering (Netherlands)

Speaker: Geers Marc. Keynote. **Monday**. Start time: **16:00**. Room: Saint Clair 2 LVL2. Link to abstract.

Many demanding applications, operating in harsh conditions, require sustainable materials with superior efficiency and performance. High-performance fiber reinforced composites are increasingly attractive due to their high strength-to-weight ratio, design flexibility, and corrosion resistance. This class of materials are excellent candidates for storing and transporting green hydrogen, by means of carbon-overwrapped pressure vessels and thermoplastic composite pipes. Carbon fiber-reinforced polyvinylidene fluoride (PVDF) is a light weight material that shows great promise for these applications. The strong carbon fibers offer the required strength to the composite. The semi-crystalline thermoplastic PVDF matrix serves over a wide temperature range, and its corrosion and chemical resistance allows its usage in extreme conditions. Combining experimental results and multi-scale simulations, this presentation focuses on the analysis of the rate- and temperature dependent behaviour of unidirectional (UD) carbon fiber-reinforced PVDF at different loading conditions.
To characterize the matrix, a 3-dimensional (3D) elasto-viscoplastic constitutive model is used to describe the rate- and temperature dependent behaviour of pure PVDF, with a deformation-dependent activation volume and Eyring viscosity. The material parameters were experimentally identified at three specific temperatures, 23, 55 and 75∘C, by means of uniaxial compression and tensile tests. The model is validated with independent experiments, revealing an accurate description of the temperature dependent behaviour.

In order to establish a multi-scale framework, the fibre distribution in the composites was analyzed with optical and electron microscopy. Using this data, a 3D micromechanical FE model was developed by generating a representative volume element (RVE) and the earlier developed constitutive models. Appropriate boundary conditions are used, allowing for off-axis uniaxial loading. In parallel to the simulations, dedicated compression test were carried out on the composite at different strain rates and temperatures, revealing poor adhesion between the fibers and the matrix. Accordingly, interfacial decohesion has been incorporated in the RVEs. To enhance the stability of such complex failure simulations, a novel energy dissipation-based arc-length solver was developed applicable to time-dependent models. The average engineering stress-strain response from the RVE simulations with nominal fiber volume fraction is compared to experimental data and a reference model with perfect fiber-matrix adhesion. Transverse tensile simulations are in line with the experiments. Investigation of the local response reveals that damage initiated at many fiber-matrix interfaces, but localizes at a few only. The equivalent plastic strains in the matrix remain limited. Transverse tensile simulations on a model with lower fiber volume fraction reveal lower local stresses in the matrix and lower tractions at the interface, whereas the model with higher fiber volume fraction results in more damaged interfaces, accompanied by higher overall stresses in the matrix. For most fiber orientations, the model reveals that damage localization is more present for off-axis loading, whereas it is more evenly distributed for transverse tension.
The developed model helps in unravelling the fiber-matrix failure initiation and evolution at the microscale, but would benefit from an extension allowing for matrix damage. In this form, this multi-scale model will be instrumental for the development of PVDF-based fiber reinforced materials.

Towards plastic wrinkles

Bonfils Anthony (1), O' Kiely Doireann (1)

1 - MACSI (Mathematics Applications Consortium for Science and Industry), Department of Mathematics and Statistics, University of Limerick (Ireland)

Speaker: O' Kiely Doireann. **Monday**. Start time: **16:40**. Room: Saint Clair 2 LVL2. Link to abstract.

Wrinkles in thin sheets have been the object of numerous investigations in recent decades. Wrinkles are generated by compressing a sheet while it is attached to a compliant substrate, or while it is subjected to a tension or curvature in a transverse direction. One of the drivers for these investigations has been in metamaterials, namely the promise that wrinkles can be used to add structure to an object or its surface in order to modify its behaviour – for example, a suitably wrinkled surface will selectively filter light.
A core focus of research on wrinkles to date has been on prediction of the critical stress for their appearance and the wrinkling pattern when they do appear. Despite success in predicting and controlling these features, an important question remains: which wrinkles are reconfigurable, and which are permanent? If the deformation is purely elastic, then wrinkles indeed disappear if the stresses responsible for their generation vanish. In this talk, we will discuss conditions under which wrinkles in a thin sheet may lead to permanent plastic yielding, both theoretically and in real-world scenarios.
Our approach is based on a combination of direct and indirect damage measurement methods, utilising mathematical models to predict the threshold for yielding of wrinkled sheets in conjunction with an experimental search for signs of damage within a wrinkled sheet. Our long-term goals include both delimiting the parameters for which wrinkles are reversible and reconfigurable, and designing and controlling permanent wrinkles. Relevant applications range from traditional materials such as metals undergoing metal forming to innovative materials used in soft electronics and optical applications.

A transversely isotropic bimodular elasto-visco-plastic model for polymeric yarns and cords

Moscatelli Marco (1), Comi Claudia (2), Novati Giorgio (3), Pires Da Costa Lucas (3), Caracino Paola (4)

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Speaker: Moscatelli Marco. Invited. **Monday**. Start time: **17:00**. Room: Saint Clair 2 LVL2. Link to abstract.

Polymeric yarns are made up of hundreds of textile filaments (or fibers) twisted together. Typically, yarns (of the same or different fibrous materials) are then twisted together to form cords, also known as multi-ply yarns. These 1D structural elements possess high flexural flexibility while having high stiffness and strength in the longitudinal tensile direction, making them an optimal solution as reinforcements in composite materials.
This work aims to present a mesoscopic 3D mechanical model to predict the mechanical behavior of this class of fibrous structural elements. Specifically, yarns and cords are here treated as transversely isotropic elasto-visco-plastic continua, with a bimodular elastic stiffness to account for the different behavior under tensile and compressive conditions.

The model is built under the framework of generalized standard materials, using the theory of structural tensors (1) under the assumption of small perturbations, and is implemented in a finite element code. Its capabilities are assessed by comparing the results of numerical simulations and experimental tests carried out in Pirelli's laboratories. As shown in (2) and (3), starting from the material behavior at the level of the fibers, and including geometric effects, we can effectively predict the behavior of the aforementioned class of fibers-based structural elements in different stress conditions.

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Role of the electron irradiation on the plasticity of a-Al2O3: atomistic simulations meet experiments

Materzanini Giuliana (1), Orehkov Andrey (2), Baral Paul (3), Frankberg Erkka J. (4), Rignanese Gian-marco (1) (5), Pardoen Thomas (1), Idrissi Hosni (1)

1 - Université Catholique de Louvain (Belgium), 2 - University of Antwerp (Belgium), 3 - Ecole Nationale Supérieure des Mines de Saint-Étienne (France), 4 - Tampere University (Finland), 5 - Northwestern Polytechnical University (China)

Speaker: Materzanini Giuliana. **Monday**. Start time: **17:20**. Room: Saint Clair 2 LVL2. Link to abstract.

Investigating the response of amorphous oxides to stress is crucial for applications such as wear-resistant coatings, catalysis, and microelectronic devices. The current experimental setup includes a push-to-pull deformation device for tensile testing and a transmission electron microscope (TEM) for imaging the evolving microstructure. However, during TEM experiments, the electron beam (e-beam) can alter the specimen, affecting its elastic and plastic properties and leading to structural rejuvenation of the amorphous material. In this study, we combine in situ quantitative tensile testing of amorphous alumina (a-Al2O3) in the TEM with large-scale molecular dynamics simulations (∼900,000 atoms) using classical force fields to simulate tensile strain. The e-beam effect is modeled as one-time kinetic energy excitations applied to a small fraction of selected atoms at regular intervals. Both experimental and computational stress-strain curves reveal that the presence of the e-beam reduces stress, enhances plasticity, and increases strain-rate sensitivity in a-Al2O3. Furthermore, analysis of the coordination number and local nonaffine displacement evolution under strain shows that the e-beam promotes bond switching, which relaxes local stresses and favors plasticity. These findings provide new insights into the local structural modifications and rejuvenation of amorphous oxides under electron irradiation.

Role of welding interfaces on the anisotropic mechanical response of a recycled material obtained through an extrusion process of aluminium chips.

Perrin Jason (1), Corre Thomas (1), Gebhard Johannes (2), Schulz Oliver (2), Duchateau Théo (3) (4), Lilensten Lola (4), Laurent-brocq Mathilde (3), Tekkaya A. Erman (2), Huneau Bertrand (1)

1 - Institut de Recherche en Génie Civil et Mécanique (France), 2 - Institute of Forming Technology and Lightweight Components (IUL) (Germany), 3 - Institut de Chimie et des Matériaux Paris-Est (France), 4 - Institut de Recherche de Chimie Paris (France)

Speaker: Perrin Jason. **Monday**. Start time: **17:40**. Room: Saint Clair 2 LVL2. Link to abstract.

Primary production of aluminium from ore is very energy intensive, and accounts for about 2 % of global CO2 emissions (IEA, 2022). Recycling by melting requires about 20 times less energy (Das & al., 2010). Aluminium can also be recycled through solid processes, minimizing the environmental impacts and material losses even further, with respect to remelting routes (Duflou & al., 2015). Aluminium AA-6060 machining chips can be recycled by such means, for example see Schulze & al. 2022. The extrudate keeps, however, a specific thermo-mechanical history. The chips display, at their interfaces, strongly anisotropic welding seams which may affect the mechanical response.
Some mechanical properties in the quasi-static regime have already been investigated for such a material (Corre & al. 2024). This study showed that the tensile and shear responses of a chip-based material are similar to that of a material which is not made out of chips. An anisotropic response was however observed, the welded chips being strongly elongated in the extrusion direction.

CT (Compact Tensile) specimens will be machined from extrudates of rectangular section to investigate more thoroughly the anisotropic response of the material. Such specimen will be used to evaluate the anisotropic tensile toughness of the material. They will also be used to study fatigue cracks' propagation in various directions. Particular attention will be given to the crack path with regard to the specific microstructure induced by the extrusion of aluminium chips.

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Application of the in-plane torsion test to a set of engineering metallic materials

Grolleau Vincent (1) (2), Colon Xavier (2), Xueyang Li (3), Galpin Bertrand (4), Roth Christian (3), Mohr Dirk (3)

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Speaker: Grolleau Vincent. **Tuesday**. Start time: **10:00**. Room: Saint Clair 2 LVL2. Link to abstract.

One of the major advantages of the in-plane torsion test is that it provides shear loading of a sheet specimen up to fracture while using a specimen exempted from free edges.
During the test, the dish-shaped specimen is clamped on its outer diameter while a hydraulic rotary motor applies torque to the inner side of the specimen for quasi-static tests. During high-strain rate testing, a preloaded Hopkinson-type torsion bar is used to apply the loading to the inner clamping. A circular groove is machined on one face of the specimen. This local thickness reduction ensures a strain localization away from the clamped central area of the specimen. The setup grants full optical access to the sheared gauge section, allowing 2D-DIC measurements on the flat side of the specimen. The sheet anisotropy leads to a periodic evolution of the strain along the circular gage section. This effect is illustrated on a set of engineering metals tested under quasi-static conditions. The capabilities of the high-strain rate in-plane torsion test are illustrated on a deep drawing and a dual-phase steels.

Instability based ductile fracture prediction in AA 7075-T651 using acoustic emission data

Chakraborty Subham (1), Banerjee Anuradha (2), Keralavarma Shyam (1)

1 - IIT Madras (India), 2 - IIT Madras (India)

Speaker: Chakraborty Subham. **Tuesday**. Start time: **10:20**. Room: Saint Clair 2 LVL2. Link to abstract.

Cracks initiate in ductile materials through the process of void nucleation, growth, and coalescence. Micromechanical models, such as the Gurson-Tvergaard-Needleman (GTN) model, are widely used to predict ductile fracture. The failure criterion in the GTN model is based on the attainment of a critical volume fraction of voids, which often fails to capture the loading path dependence of ductile fracture. A more recent approach by Keralavarma et al. (2020) uses a stress-state dependent crack initiation criterion based on Rice's plastic instability theory, combined with a void coalescence criterion. The failure criterion depends on the material's plastic constitutive law and void nucleation parameters. The criterion can be incorporated into both uncoupled and coupled damage plasticity approaches, offering robust prediction of fracture initiation. Accurate calibration of model parameters is critical for reliable predictions. This study integrates the stress-state dependent fracture criterion into an uncoupled damage-plasticity framework using rate-independent J2 plasticity theory. The approach requires the parameters related to strain hardening and void nucleation to be calibrated from experimental data. The parameters in the hardening law are calibrated in the usual way using uniaxial tensile tests. Here, we proposed a novel methodology to calibrate void nucleation parameters in the strain controlled void nucleation law of Chu and Needleman (1980) using acoustic emission (AE) data. These parameters were first calibrated using the AE amplitude data from a dogbone specimen, and validated against the AE data obtained from notched tensile specimens with varying notch radii. The mean and standard deviation of the nucleation strain are calibrated using AE data, and the maximum volume fraction of nucleating voids (fN) is determined through a parametric study. Predictions using the calibrated model are validated against experimental data for a range of specimen geometries, including notched bars, compact tension (CT) specimens, and four-point bend specimens. The model accurately predicts ductility of notched bars and CT specimens with an a/W ratio of 0.46. The study demonstrates the model's accuracy and potential as a reliable alternative to phenomenological ductile fracture models.

A Monolithic Finite Element Framework for Fully-Coupled Chemo-Mechanics and the Non-Local Gurson-Tvergaard-Needleman Model

Patil Siddhi Avinash (1), Prüger Stefan (1), Roth Stephan (1), Kiefer Bjoern (1)

1 - Technische Universität Bergakademie Freiberg (Germany)

Speaker: Patil Siddhi Avinash. **Tuesday**. Start time: **10:40**. Room: Saint Clair 2 LVL2. Link to abstract.

The transition from fossil fuels to sustainable energy sources across various sectors elevates the risk of hydrogen embrittlement in ductile materials, such as steel, used for hydrogen storage and transportation. Due to its small size, hydrogen easily diffuses into the metal lattice when exposed to various environments, inducing a ductile-to-brittle transition (1, 2). Ductile damage in steel is characterized by the nucleation, growth, and coalescence of microvoids-a process that is further accelerated in the presence of hydrogen. Theories explaining the hydrogen-induced reduction of strength in steels include hydrogen-enhanced decohesion (HEDE), hydrogen-enhanced localized plasticity (HELP), and hydrogen-enhanced strain-induced vacancies (HESIV) (3). The HEDE mechanism results in a principal stress-controlled brittle failure mode, while the HELP and HESIV mechanisms are driven by plastic deformation, accelerating void growth and coalescence. To address the latter aspect of this complex stress-diffusion process, we propose a mesh-independent finite element framework by combining coupled chemo-mechanics and the well-known non-local Gurson-Tvergaard-Needleman (GTN) damage model (4, 5). This fully-coupled framework is motivated by Fick's law for standard diffusion and the mixed rate-type potential approach introduced in (6), which accounts for the influence of hydrogen concentration on the material's mechanical response. Furthermore, the effects of hydrogen on damage are incorporated by extending the original non-local GTN model to account for hydrogen-enhanced void nucleation and growth, as suggested in (1, 3, 7). The stress-diffusion coupled system of equations is solved using a monolithic approach. The mutual interactions are explored in various representative boundary value problems to assess the impact of hydrogen on material degradation and the stress state on diffusion.

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Modeling Intergranular Damage Assisted by Oxidation in Nickel-Based Superalloys

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Speaker: El-Habyb Ayoub. Invited. **Tuesday**. Start time: **11:00**. Room: Saint Clair 2 LVL2. Link to abstract.

Nickel-based superalloys, such as the DS200+Hf, are extensively used in high-temperature components of aerospace turbines, particularly for low-pressure turbine blades in CFM-56 and LEAP engines (1). These alloys generally feature a columnar grain structure with the main grain axis closely aligned with the principal loading direction (e.g., centrifugal forces in rotating components). Furthermore, the directional solidification process ensures that the main grain axis is typically near a (001) crystallographic orientation.
This study focuses on modeling the mechanisms of intergranular damage in the directionally solidified DS200 + Hf superalloy, considering local phenomena such as cracks, microcavities, and oxidation, which critically influence the initiation and propagation of intergranular cracks. The damage evolution was examined using finite element simulations and experimental data (2), with the microstructural characteristics, including grain size and texture, determined through electron backscatter diffraction (EBSD) analyses.

To capture these complex phenomena, a novel phase-field method for fracture modeling in polycrystalline materials was developed. Numerous studies have addressed this issue by incorporating cohesive models at grain boundaries (3, 4). However, these models often face convergence challenges, particularly in complex surface geometries. Musienko et al. (5) proposed an alternative approach, defining grain boundaries through a viscoplastic model with damage, implemented using a specifically designed mesh to represent grain boundaries with a finite thickness. While this model demonstrates good convergence, it introduces a sharp transition in behavior between the grains and the grain boundaries. To address these limitations, the phase-field model offers a versatile framework with an internal length scale tailored for systems with sharp interfaces. Nguyen et al. (6, 7) proposed a phase-field approach for polycrystalline materials, where interface failure is governed by a cohesive law embedded within a regularized variational framework. The interfaces in their model are captured using a level-set method.

The present study focuses on developing a model that excludes the influence of oxidation. This model is built on the finite strain framework and integrated into the Méric-Cailletaud model, employing a two-potential approach for low strain rates and high strain rates to capture crystalline viscoplasticity at the grain level. The model is enhanced with a static phase-field method, enabling the distinction between grain boundaries and grains through a diffuse interface representation. Additionally, a Lemaitre-type damage law is incorporated to describe the evolution of damage, including deformation mechanisms induced by damage. This model is implemented in the finite element code Z-set, with both explicit and implicit resolution.

The model was validated through simulations of creep and tensile tests, with results compared to experimental data obtained under vacuum conditions. The findings highlight the model's ability to replicate the nucleation and propagation of intergranular cracks, offering valuable insights into the damage mechanisms of directionally solidified superalloys.

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Fracture Mechanisms in Irradiated Fe–Ni–Cr Alloys: Atomic-Scale Insights and Energy-Based Modeling of the Ductile-to-Brittle Transition

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Speaker: Ustrzycka Aneta. **Tuesday**. Start time: **11:20**. Room: Saint Clair 2 LVL2. Link to abstract.

Neutron irradiation induces profound microstructural changes in structural materials, critically influencing their fracture behavior and posing significant challenges for nuclear reactor safety. This study employs molecular dynamics (MD) simulations to elucidate the mechanisms driving the radiation-induced ductile-to-brittle transition (DBT) in Fe–Ni–Cr alloys, a phenomenon distinct from classical temperature-driven DBT. While previous studies (1, 2) have focused on thermal effects, this work introduces a comprehensive analysis of how irradiation-induced defects, specifically voids and dislocation loops, govern fracture dynamics by altering dislocation mobility and energy dissipation pathways.
Crack propagation in irradiated Fe–Ni–Cr alloys was systematically investigated using MD simulations across a broad range of displacements per atom (dpa parameter) (3, 4). Radiation-induced voids reduce cohesive energy, accelerating crack growth through coalescence, while dislocation loops act as immobile barriers, redirecting cracks and promoting secondary crack formation. At higher dpa, dense defect networks suppress plasticity.

Crack propagation is driven by three competing mechanisms: (1) void coalescence weakens the lattice, lowering resistance and promoting crack growth along weakened zones, often leading to branching, (2) dislocation loops form stable structures, obstruct the motion of dislocations near the crack tip, which temporarily halts crack progression, (3) high defect densities, particularly dislocation loop clusters, induce crack branching and secondary crack formation due to stress concentration effects, increasing fracture complexity.

A key aspect of this study is the energy-based framework for quantifying irradiation-induced embrittlement. The critical energy release rate, Gc, is decomposed into two fundamental contributions: surface energy, which represents the energy required to create new fracture surfaces, and plastic work, associated with dislocation motion and other inelastic deformations. To isolate these components, we leverage a low-temperature reference state where plasticity is significantly suppressed, allowing Gc at this condition to approximate the surface energy. By comparing fracture energy at a higher temperature, where plasticity is active, to the near-brittle reference state, the plastic work contribution can be extracted. This approach enables a generalizable assessment of embrittlement, independent of specific temperature values, as long as the selected low-temperature condition captures near-brittle behavior and the high-temperature condition allows sufficient plasticity. Simulation results reveal that irradiation progressively reduces plastic work, directly linking irradiation hardening to suppressed dislocation activity.

This study advances the understanding of irradiation embrittlement through three key contributions. First, it establishes a direct link between defect density, crack morphology, and energy dissipation, demonstrating that voids weaken the material by reducing cohesive strength, while dislocation loops obstruct crack propagation by pinning dislocations, collectively driving the transition from ductile tearing to brittle cleavage. Second, it develops a microstructural-mechanical framework that bridges atomic-scale defect interactions with macroscopic fracture resistance, correlating defect-driven crack morphology with energy dissipation changes. Third, it refines the decomposition of Gc to quantify irradiation-induced plasticity suppression, distinguishing irradiation-driven embrittlement from thermal effects and providing a predictive framework for fracture behavior based on defect density.

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Assessment of different non-linear kinematic hardening laws at variable temperature

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Speaker: Perez Maël. **Tuesday**. Start time: **11:40**. Room: Saint Clair 2 LVL2. Link to abstract.

The progressive increase in temperatures and mechanical loads applied to aeroengine components leads to an enhanced need for the fatigue design to introduce non-linear phenomena linked to the inelastic behavior of materials. In order to model cyclic plasticity at variable temperature, a solution is to consider a non-linear kinematic hardening law, such as the Armstrong-Frederick one (1). The material parameters have then to be identified on a temperature range, most often from isothermal tests. Because of the parameters temperature dependency, some spurious model responses may arise (2). One of the "dangerous" effects is the cumbersome occurrence of plastic flow when varying temperatures after an isothermal preloading. Cailletaud and coworkers attribute such an issue to the saturation of the (dimensionless) kinematic hardening internal variable. A sound modeling considers instead a multi-kinematic hardening formulation with constant (or almost constant) backstress parameter.
The present work aims at understanding the subtleties concerning the history at variable temperature of the different thermodynamics variables: the stress and both kinematic hardening variables (the dimensionless internal variable as well as the associated thermodynamics force, homogeneous to stress). We propose an additional numerical uniaxial test under anisothermal conditions, which underlines the cumbersome plastic flow. Our numerical test shows that a temperature change translates the yield surface in the stress space, since the Prager hardening modulus changes with temperature. This plastic flow can change the value of the (dimensionless) kinematic hardening internal variable. Both the cumbersome plastic flow and the translation of the yield surface have an undesired effect on the cyclic plasticity model response.

An alternative to the multi-kinematic hardening is to consider a non-saturating, power-law type, kinematic hardening law (3), for which we provide two non-isothermal generalizations. These non-saturating kinematic hardening laws are then assessed on numerical tests. We use a set of material parameters cross-identified on the initial Armstrong-Frederick modeling. This type of non-saturating kinematic hardening law partially solves the cumbersome plastic flow problem, but it has a little effect on the undesired yield surface translation. We investigate the behavior of such non-saturating kinematic hardening laws at variable temperature.

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An alternative Elastoplastic Model for Ductile Fracture with graded plasticity

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Speaker: Pham Clémence. **Tuesday**. Start time: **14:15**. Room: Saint Clair 2 LVL2. Link to abstract.

The prediction of failure modes in metallic structures is a crucial step in the safety analysis of industrial components subjected to significant mechanical loads (e.g., nuclear power plant components, pipelines, etc.). To perform such analyses, it is essential to accurately simulate the propagation of a defect in the ductile regime, characterized by large plastic deformations before and during propagation.

Predictive numerical simulation of ductile fracture remains an open scientific and technical challenge, despite significant progress in recent years. The so-called local approach to fracture is widely used to model ductile fracture; however, like all softening models, it exhibits dependency on spatial discretization.

The objective of this work is to propose a robust approach for modeling and simulating ductile fracture at the structural scale. It introduces an elastoplastic model with a bounded gradient of accumulated plastic strain and an associated set of internal constraints. This method aims to eliminate mesh dependency, without increasing the number of degrees of freedom of the numerical problem as it can be the case for most of non-local models. So, the proposed model strives for fast and efficient numerical computations at the structural scale.
The feasibility of this approach is demonstrated through the resolution of problems on simple geometries, such as cylinders or spheres made of composite elastoplastic materials. Tests on 316L steel specimens are also conducted to further validate the robustness of this method.

Eulerian rates of elastic incompatibilities in finite crystal elastoplasticity

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Speaker: Bardella Lorenzo. **Tuesday**. Start time: **14:35**. Room: Saint Clair 2 LVL2. Link to abstract.

The measures of rates of elastic incompatibilities developed in (Rubin and Bardella, 2024, "Eulerian rates of elastic incompatibilities applied to size-dependent hardening in finite torsion", J. Mech. Phys. Solids 193, 105905) are adopted to study the incompatibility in crystals undergoing finite deformations within an Eulerian framework for anisotropic elastoplastic materials. Such framework relies on the evolution of microstructural vectors. It is emphasized that the rates of incompatibilities depend on the constitutive equation for the rate of plasticity. For small strains and rotations, such rates are equal to the negative of the components of the rate of Nye-Kroner's dislocation density tensor. The application to the finite-deformation bending of a single crystal allows isolating and discussing the contributions to incompatibility of pure densities of geometrically necessary dislocations and of the deformation of the crystal lattice. These contributions can be used to enhance the hardening with a size-dependent term that can increase or decrease during loading history, modeling the generation and annihilation of defects.

Modelling of damage in 3D printed concrete: the role of interfaces and plasticity phenomena

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Speaker: Monaldo Elisabetta. Invited. **Tuesday**. Start time: **14:55**. Room: Saint Clair 2 LVL2. Link to abstract.

3D printing of concrete is a promising construction technology, that offers the potential to build geometrically complex structures without the use of costly formwork. The layer-wise deposit of filaments during the 3D printing process results in an intrinsically orthotropic mechanical behavior in the hardened state. The overlapped layers of material can influence not only the overall mechanical properties, but also the failure modes. The presence of interfaces between subsequent layers represents a critical issue, as these areas are weaker than the homogeneous material, making them susceptible to initiation of damage mechanisms. In addition, the material behavior of each deposited filament- as commonly accepted for cementitious materials - is governed by a nonlinear behavior, characterized by irreversible deformations, strain hardening, strain softening and a degradation of the material stiffness.
The aim of this work is to propose a numerical model to simulate the mechanical behaviour of 3D printed concrete (3DPC). A plasticity and non-local damage approach is developed to describe the mechanical behaviour of the solid filament. The evolution of the plastic strain is governed by the introduction of a suitable yield function. The stiffness degradation is described by introducing two scalar damage variables: a tensile and compressive damage. In particular, the growth of the compressive damage is governed by the nonlocal value of the accumulated plastic strain, while the evolution of the tensile damage depends on the nonlocal measure of the equivalent elastic strain. To overcome the analytical and computational issues induced by the softening constitutive law, an integral-type regularization technique is adopted. For the interfaces between the 3D printed layers, a cohesive interface law is considered, taking into account unilateral contact, damage initiation, and friction effects. The proposed numerical procedure is implemented in a finite element code.

Moreover, an experimental program has been conducted to investigate the mechanical behavior of 3DPC. Various tests, including compression and shear tests, were performed to characterize the mechanical properties and identify the different damage mechanisms. Furthermore, additional tests were carried out to compare the experimental data with the proposed numerical approach.
Overall, the proposed model provides a computationally efficient modeling approach that could be exploited for large-scale finite element simulations of 3DPC structures.

1D hybrid beam-shell tube model for progressive cracks in pipelines

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Speaker: Coron Amalio. **Tuesday**. Start time: **15:15**. Room: Saint Clair 2 LVL2. Link to abstract.

The energy sector, from nuclear to oil and gas, manages large scale pipelines networks in both standard operation and accidental events. It is critical for them to know the reaction of the piping structure during nominal conditions, but also when unattended phenomenons occur. Those events can be rapid dynamic loading that cause damage and cracks in the pipe. The mechanical response of both intact and notched pipes under dynamic loading has been a subject of interest of recent published studies.

This type of unexpected event must be considered in the nuclear power plant (NPP) safety studies conducted at EDF R&D, including violent pipe deformation and fracture. The hypothetical events of pipe rupture in a NPP are the Loss Of Coolant Accident (LOCA) and High Energy Line Break (HELB), two scenario specific to the nuclear sector. The Loss Of Coolant Accident considers a crack in the primary loop causing a de-pressurization wave to propagate that may adversely affect the components of the primary loop and the vessel internals. The High Energy Line Break situation involves pipe that carry a high temperature and pressure fluid. In case of a break, such pipe will face violent deformation and whipping effects. Such phenomena are hard to model in 3D, as the structure are large and complex, and important local plastic deformation can occur. Therefore, this works aims to develop a high-fidelity 1D cracked pipe model to model the piping rupture scenario.

A unixial enriched beam model has been developed in previous studies to simulate straight pipe without any crack (intact). The model associates an Euler-Bernoulli beam kinematics that represents the pipe's global behavior, and a Kirchhoff–Love shell motion for the pipe's cross section deformation. The shell displacement fields of the model are expanded as a Fourier series on the pipe section angular variable θ, and the Fourier coefficients become the degrees of freedom of the shell kinematics for the 1D model. The stress is also integrated analytically across the section of the pipe and the thickness of the shell to compute generalized forces of the model. Formalized in a time-explicit framework, the model was implemented in the fast transient research and industrial code Europlexus. The details and analysis of the intact straight pipe model was presented in (1) and (2), where both static and dynamic behavior of the model were validated against a 3D finite element shell model.

The proposed work is focused on the extension of the enriched beam model to represent the evolution of a progressive crack in a pipeline. As a first step, the kinematics of the model is completed to depict a pipe with a straight lengthwise notch of a fixed length. To achieve this, a plausible kinematics is computed from an "open ring" analytical solution. Its addition to the Fourier expansion of the shell kinematics allows the representation of the opening of the pipe under various loads with three new degrees of freedom corresponding to the displacement jumps between the crack lips. This addition keeps the model uniaxial, as the displacement jumps only varies along the length of the cracked pipe. An a priori validation of the kinematics is conducted by comparison with full-scale numerical simulations. The full scale solution across a section is projected on the proposed kinematics function of θ, and the resulting function is compared to the full scale solution. The model is found to be in good adequacy with the full scale reference, especially for the loading of pipe under pressure. In addition, a sensibility analysis on the number of Fourier modes in the expansions is conducted.

After this verification, the new model of notched pipe is developed analytically in the same framework as the intact model. The contribution of the crack's degrees of freedom in the pipe motion and in the generalized forced is analyzed analytically. The new model is implemented in the same explicit dynamic code Europlexus, and comparison both static and dynamic are conducted with 3D numerical solutions for various type of boundary condition, such as internal pressure and bending. Even if the dynamic of the pipe is analyzed, the crack remains of a fixed length at this step of the development.

After this first step of extension of the model to notched pipe with a lengthwise crack on its surface, the problematic of pipe crack propagation is questioned. Indeed, a global linear fracture framework is chosen to study the crack propagation on the pipe. An analytical energy release rate of the crack can be computed from the degree of freedoms and a propagation criterion can be defined. Results are compared to references simulation and experiments of the litterature.

The resulting model is only meshed in 1D, and aims to model a complex behavior in an industrial tool for simulation of piping networks across a facility. Therefore, computation costs are greatly reduced. Toward future work, the 1D model also helps to add a fluid-structure interaction, as the fluid contribution can be computed analytically, and added as an exterior contribution in the equations of motions. Currently, the material is linear elastic, as the study focuses on the interest of the 1D model more than the material specificity. However, the model could be extended to more complex elasto-plastic behavior for better precision, and the computation of pipe whip phenomenon in case of a plastic hinge.

A Variational Gradient Plasticity Model Allowing for Shear Band Localization

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1 - Department of Structural and Geotechnical Engineering, Sapienza University of Rome (Italy)

Speaker: Comella Maria Chiara. Invited. **Tuesday**. Start time: **16:35**. Room: Saint Clair 2 LVL2. Link to abstract.

This contribution explores a novel approach to gradient plasticity within the variational framework, focusing on a modification of the classical energy functional. Traditional elasto-plastic models combine a quadratic energy term associated with the elastic strain and a dissipation term dependent on the norm of the plastic strain rate. Gradient plasticity models enhance these formulations by introducing regularization terms that smooth plastic strain gradients and prevent localization effects.
In contrast, we propose replacing this regularizing term with a non-quadratic contribution, allowing for threshold effects, that fundamentally alters the model's behavior, by means of the curl of the plastic strain. This terms measures the degree of incompatibility in the plastic strain field, indicating the presence of internal defects or dislocations that prevent smooth, continuous deformation. It is closely related to the dislocation density tensor, providing a measure of the number and distribution of dislocations in the material.
This formulation impacts the plastic threshold and emphasizes dislocation interactions at the tips and curved regions of shear bands, facilitating the formation of highly localized plastic zones. Unlike classical gradient plasticity, this approach does not regularize the solution but instead enables sharper representations of shear bands.
Our analysis examines the implications of this novel term on the energy landscape, threshold conditions, and localization evolution. Results highlight its capacity to model phenomena such as dislocation nucleation and the evolution of curved plastic regions with improved fidelity, providing new insights into material behavior under extreme conditions.

A finite deformation dislocation thermomechanics model without multiplicative decomposition

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Speaker: Upadhyay Manas V.. **Tuesday**. Start time: **16:55**. Room: Saint Clair 2 LVL2. Link to abstract.

A finite deformation model for field dislocation thermomechanics based entirely on measurable state variables is proposed. Instead of starting from a physically undetermined ordering-dependent multiplicative decomposition of the total deformation gradient tensor, the widely accepted additive decomposition of the velocity gradient into elastic, plastic and thermal distortion rates is obtained as a natural consequence of the conservation of Burgers vector, extending the results of Acharya and Zhang (2015) in the mechanical setting to the thermomechanical case. Based on this equation, the model consistently captures the contribution of transient heterogeneous temperature field on dislocation density evolution (postulated by Kröner in 1959 and demonstrated in Upadhyay JMPS 145 (2020) 104150 in a small deformation framework). Furthermore, in combination with the First Law, the model allows studying temperature evolution during plastic work and computing the Taylor-Quinney factor without requiring any phenomenological expression for accumulated plastic strain or any other conventional plasticity-based variables. Finally, in the small deformation limit, it reduces to the model proposed in Upadhyay JMPS 145 (2020) 104150.

A standard thermodynamic-based extension of the Modified Cam-Clay model for elastoviscoplastic geomaterials

Raude Simon (1), Bacquaert Goustan (1)

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Speaker: Raude Simon. Invited. **Tuesday**. Start time: **17:15**. Room: Saint Clair 2 LVL2. Link to abstract.

In geotechnical engineering, the development of constitutive models for geomaterials is crucial, especially when designing **underground repositories for radioactive waste**. This study investigates the **mechanical behavior of Callovo-Oxfordian (COx) claystone**, a key material used in such repository in France. We propose an advanced **elastoviscoplastic critical state constitutive model** that combines plastic and viscoplastic behaviors within the **Generalized Standard Materials** framework. In contrast to the **Modified Cam-Clay model,** our approach replaces the elliptical yield criterion with a parabolic one, offering a more accurate description of the shear strength surface for rocks. The proposed model effectively captures both the **instantaneous** and **long-term behavior** of COx claystone, while incorporating the **critical state concept**. Additionnally, to account for the **inherent transverse isotropy** of COx claystone, we propose a straightforward representation of plastic anisotropy. This is achieved using the **tensor representation** framework for oriented solids, initially developed in the 1970s and recently revived for modeling geomaterials.

The model is calibrated using triaxial compression and creep test data on COx claystone, demonstrating its accuracy. The relatively small number of parameters required, compared to other models of similar complexity, allows for a simple and efficient calibration process. Finally, finite element simulations conducted with **Code Aster** validate the model's robustness and applicability for **industrial-scale applications**.

Implicit Non-Smooth Material Point Method for Non-Associated Elasto-plastic Soils

Guillet Louis (1), Acary Vincent (1), Bourrier Franck (2), Goury Olivier (1)

1 - Modélisation, simulation et commande des systèmes dynamiques non lisses (France), 2 - Modélisation, simulation et commande des systèmes dynamiques non lisses (France)

Speaker: Guillet Louis. **Tuesday**. Start time: **17:35**. Room: Saint Clair 2 LVL2. Link to abstract.

From footing simulations to slope stability analyses, geomaterials are frequently described by non-associated elasto-plastic constitutive models. To ensure dissipativity and exact resolution of the constitutive model at each time step, an implicit formulation of the numerical method is often preferred. It is typically combined with the classical return mapping algorithm (Simo et al., 1989). This work, in continuity with Acary et al., (2023), proposes an alternative approach through the development of a monolithic solver capable of simultaneously solving the plastic constitutive equation, the potential hardening and the Coulomb friction with unilateral contact. This approach avoids in particular the challenging computation of the consistent tangent operator and enables the use of efficient and robust solvers that come from numerical optimization.
In order to account for case studies where, as it is the case with slope failures, the material is subjected to a loading phase followed by a flow phase exhibiting large deformations, we use the Material Point Method (MPM). The method, developed by Sulsky et al. (1994), employs both Eulerian and Lagrangian discretisation, and thus making it well suited for this class of problems. To allow for a rigourous comparison with the robust and frequently used Finite Element Method (FEM), the solver is first developed in an FEM framework then adapted to MPM. The constitutive equations are written as a differential inclusion, inspired by the Implicit Standard Material (ISM) framework (Berga and De Saxcé, 1994). A semi-smooth Newton method (Alart and Curnier, 1991; Christensen, 2002; Hager and Wohlmuth, 2009) and a non-smooth Gauss-Siedel method (Jourdan et al., 1998) are used to solve the constitutive law within an implicit time scheme.

Among its favorable mathematical properties, we highlight the good energy balance of the solver and the existence of solution in non-associated case. The convergence can be proven analytically in associated cases while in practice the solver shows in any cases quadratic convergence, even for large time steps, or load-increments. The monolithic structure of the solver permits the implementation of non-conforming boundary conditions inspired by contact dynamics. The relevance of the method is demonstrated with a footing problem and slope stability simulations where the existence of an analytical solution in limit analysis is established (Chen, 2013). The simulation demonstrates a high degree of correlation between the MPM and the analytical solution with regard to ultimate bearing capacity, as well as a good adequation between the MPM and the FEM stress and strain distributions. Further simulations are performed to account for the transition from load to flow in the case of slope instability.

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Incremental variational approach to gradient damage and poroelastic coupling of saturated media

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1 - University of Lorraine (France), 2 - Sorbonne University (France)

Speaker: Cheng Long. **Tuesday**. Start time: **17:55**. Room: Saint Clair 2 LVL2. Link to abstract.

We aim at investigating the full coupling between gradient damage, poroelasticity and fluid flow phenomena in saturated porous media. To this end, we first extend the thermodynamics-based Biot-Coussy theory of porolelasticity in order to incorporate gradient damage processes. Inspired by Stainier 2013 (Adv. Appl. Meca., Vol 46, pp. 69-126) in thermomechanics, we introduce the concept of kinetic porosity that allows to well clarify the interaction between skeleton deformation and fluid filtration in the connected pore space. This extension is then implemented to establish an incremental variational formulation expressed as a four-field minimization problem of an incremental total energy functional, which incorporates poroelastic energy, as well as the dissipation associated with damage evolution and fluid flow over a time increment. Moreover, by taking advantage of a suitable approximation of the kinetic porosity in the current time increment, the above mentioned minimization problem is reduced to a three-fields dependent one, involving the skeleton's displacement and damage fields, along with the fluid pressure field, which is shown to result in the equilibrium state of the saturated porous media. An incremental variational principle is thus established. Subsequently, a variational model for the fully coupled problem is consistently proposed and is numerically implemented by means of a semi-staggered optimization algorithm and the platform FEniCs. This procedure is applied in a benchmark modeling for which relevant solutions and numerical results related to hydraulic fracturing are available. The model is also employed for the evaluation of an Excavation Damage Zone (EDZ) around a waste storage underground gallery. The model is shown to be able to deliver sufficiently reliable predictions, which extends to cases involving coupled poroelastic effects or pure elastic-damage couplings.

Aperiodic lattice metamaterials with improved resilience to impact

Cherkaev Andrej (1), Bhattacharya Debdeep (2), Evans Tyler

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Speaker: Cherkaev Andrej. **Wednesday**. Start time: **10:00**. Room: Saint Clair 2 LVL2. Link to abstract.

Protective structures are designed to shield and safeguard vital assets must absorb and dissipate the energy imparted by an impact without losing structural integrity. The absorbed energy is dissipated due to the formation of local structural damage. Theoretically, the material could absorb the energy until it melts, but structures fail long before that due to stress concentration, an inherent feature of unstructured solid materials. The impact causes localized stress to increase, exacerbating the damage and promoting crack formation. Once a crack propagates, the structure fails, but the pieces of a failed structure can absorb additional energy if appropriately integrated into a resilient design. The design of resilient metamaterials aims to counteract the natural tendency of stress concentration and subsequent crack propagation. These metamaterials are designed to allow the initiation and sequential arrest of faults in different places without compromising the overall structural integrity, which enables the structure to absorb more energy without catastrophic failure.
This paper explores the failure mechanisms of lattice structures and the designs that enhance the resilience of them. We perform numerical experiments on the dynamic of lattices with breakable links and study various structural means that increase resilience. Namely, we find that resilience increases due to the following means:
(a) Adding additional "sacrificial" links to the structure that absorb energy but prevent the damage of the essential structural links.
(b) Use an aperiodic structure to eliminate the directions of easy damage propagation. A study of Penrose's aperiodic lattice reveals that the damage is scattered away, forming a damaged spot rather than cracks.
(c) Random perturbation of lattice node positions and the use of sacrificial links break the symmetry and induce delocalization: more links that are not fully destroyed but only partially damaged.
(d) Random perturbation of link strength also reduced the crack growth.

We measure the quality of equally impacted structures by comparing the dissipated energy (number of broken links) and radii of significantly and lightly damaged zones. Our findings suggest that using asymmetric geometry and sacrificial links in protective lattice structures significantly improves structural integrity.

A continuum material model for concrete

Dhakal Sulata (1), Kouhia Reijo (1), Hartikainen Juha (1), Saksala Timo (1), Vilppo Jani (1), Calonius Kim (2), Fedoroff Alexis (2), Kolari Kari (2)

1 - Tampere University (Finland), 2 - VTT Technical Research Centre of Finland (Finland)

Speaker: Dhakal Sulata. **Wednesday**. Start time: **10:20**. Room: Saint Clair 2 LVL2. Link to abstract.

A thermodynamically consistent constitutive model for concrete is presented. The model is based on proper expressions for the specific Gibbs free energy and the complementary form of the dissipation potential. Damaging of the material is described by a symmetric positive definite second order damage tensor. Invariant theory is used in construction of the potential functions which guarantees that the proper symmetry behaviour is satisfied and no artificial symmetrisation operations need not to be done. Especially, the failure surface is formulated in such a way that it will mimic the behaviour of the well known Ottosen*j*s four parameter failure surface. While testing the model against the experimental results found in literature, the results were in good agreement in uniaxial tensile and compressive loadings as well as in biaxial compression. Besides the correct failure stress states, the model predicts the correct failure modes of concrete: axial splitting along the direction of uniaxial compression and tensile damaging normal to the direction of tension, which is extremely important in analysing complex loading paths. The predictions of the proposed model are compared to the Concrete Damaged Plasticity (CDP) model available in the commercial finite element software Abaqus in uniaxial and equibiaxial cases. Addition of the plasticity component is also discussed as well as issues related to the regularization of the model for reliable computation in the strain-softening range.

Mathematical modelling of wire flat-rolling

Erfanian Mozhdeh (1), Brambley Ed (1) (2), Slater Carl (2)

1 - Warwick Mathematics Institute (United Kingdom), 2 - Warwick manufacturing group (United Kingdom)

Speaker: Erfanian Mozhdeh. **Wednesday**. Start time: **10:40**. Room: Saint Clair 2 LVL2. Link to abstract.

This study introduces a mathematical model for wire flat-rolling, building on the framework established in the sheet rolling model reported in the Arxiv preprint (https://doi.org/10.48550/arXiv.2408.01347). By assuming a small rate of change in both thickness and width relative to the length, the continuum mechanics and plasticity equations, along with boundary conditions, are simplified to represent plane-stress deformation. Notably, this model is the first to predict lateral spread without requiring any fitting parameters. The predictions demonstrated good agreement with experimental data across various rolling conditions and wire diameters, achieving an average absolute error of 0.2 mm for 27 data points. While the model accurately captured the order of magnitude for roll pressure distribution along the rolling direction, finite element (FE) results fell between the predictions for plane-stress and plane-strain deformation.

Modeling the anisotropic elasto-plastic material behavior of paper and paperboard at finite deformations

Kopic-osmanovic Nadir (1), Prume Erik (2), Felder Sebastian (3), Kloppenburg Greta (4), Simon Jaan-willem (1)

1 - University of Wuppertal (Germany), 2 - RWTH Aachen University (Germany), 3 - RWTH Aachen University (Germany), 4 - University of Wuppertal (Germany)

Speaker: Simon Jaan-Willem. **Wednesday**. Start time: **11:00**. Room: Saint Clair 2 LVL2. Link to abstract.

Paper and paperboard are widely used as writing, printing, and packaging materials, today. The exceptional mechanical properties and excellent recyclability of paper make it a promising substitute for traditional engineering materials such as metals or plastics. However, its wider application in engineering is currently limited by its intricate material behavior. This is due to the microstructural fiber network present in paper, which has a significant impact on macrostructural properties, including anisotropic elasto-plasticity.

In a continuum mechanical framework, paper can be considered as a homogeneous anisotropic material. The anisotropy results from the manufacturing process and is characterized by three principal directions, which are defined by the orientation of the fibers. While the in-plane deformations in paper can be considered as relatively small, significant deformations occur in the out-of-plane direction. Further, the Poisson's ratio in the out-of-plane direction is negligible, thereby enabling the decoupling of in-plane and out-of-plane behavior. Still, in order to address the complex deformations, for example, those occurring during forming processes, a unified model is required.

In this work, the material formulation was based on the multiplicative split of the deformation gradient. The inherent anisotropy of the material was introduced into the thermodynamic potentials via the concept of structural tensors. In order to include the densification effect, the strain energy function was formulated such that its elastic component depended on the plastic deformation. Furthermore, a well-known yield criterion was adjusted to the framework of finite elasto-plasticity. Additional changes were made in order to account for several inconsistencies regarding initial yield stresses and plastic strain ratios. Lastly, anisotropic plastic hardening was considered by defining a set of coupled internal variables. The model's validity is confirmed through several simulation results.

Modelling of Visco-Plasticity Using Neural Networks

Kroon Martin (1)

1 - Linnaeus University (Växjö Sweden)

Speaker: Kroon Martin. **Wednesday**. Start time: **11:20**. Room: Saint Clair 2 LVL2. Link to abstract.

Neural networks can be used to replace complicated functional expressions. In the present work, neural networks are employed to model material hardening and rate-dependence of materials. The material model consists of an Eulerian framework (i.e. all state variables are defined in the current state of the material), and neural networks are added to this framework. The theoretical framework guarantees that such requirements as frame-indifference and thermodynamical consistency are fulfilled by definition. The framework as such has been developed in previous works, and in the present work, neural networks are used to model the rate-dependence and hardening of the material. Both isotropic and directional hardening is considered. No functional expression for these behaviours need to be defined in advance.
The neural network model is implemented in Python and the library Pytorch is used for modelling the neural networks. Simple feed-forward neural networks are used in the present study, and in most cases a single hidden layer is used. The number of neurons in this layer is varied. Poisson's ratio is assumed to be 0.3 or 0.4, depending on which material is considered (steel or polymer). During the training procedure, the shear modulus is estimated along with the network parameters associated with the inelasticity. The error function is defined as the average mean square difference between the reference stress response and the trained stress response.

The neural network-based model is applied to both theoretical reference data as well as actual experimental data in the form of stress–strain data. Different optimisation methods are explored for optimising and training the neural networks. The model was able to reproduce both the theoretical reference solutions as well as the experimental data very well.
An implicit FE formulation is also provided in the form of a subroutine (UMAT) in Abaqus. The implementation was applied to two 3D examples, and the implementation seems to be robust and shows nice convergence properties. Overall, the present neural network-enhanced framework seems to be promising and there is potential for further development.

MS3.7 - Modeling fatigue of materials and structures

Organisers: Jean-Yves Buffière (MATEIS) and David Nowell (Imperial College London)

From short to long crack in thermo-mechanical fatigue, a focus on crack closure

Maurel Vincent (1)

1 - Centre des matériaux (France)

Speaker: Maurel Vincent. Keynote. **Wednesday**. Start time: **14:30**. Room: Saint Clair 2 LVL2. Link to abstract.

The role of crack closure has been established as a key factor in the long crack regime since the early work of Elber. Based on both advanced experimental characterization techniques and 3D finite element analysis (FEA), this topic can now be extended to the analysis of both short and long crack regimes. This paper focuses on the role of crack closure considering anisothermal fatigue loading, the so-called thermo-mechanical fatigue (TMF), focusing on the low cycle fatigue (LCF) regime inducing large scale yielding condition.
First, using machine learning techniques combined with in situ surface imaging, it has been shown that for out-of-phase TMF loading (OP-TMF) in the short crack regime, crack closure is partial along the cycle. This promotes high temperature damage where the crack experiences compression. Eventually, in this context, the fatigue crack growth rate (FCGR) reaches the FCGR for isothermal condition made at the maximum temperature of the cycle (1-2).

Second, for long crack analysis, it has been shown that damage mechanisms in OP-TMF and isothermal condition at the maximum temperature of the cycle could be very different (3): isothermal loading associated with large scale yielding induces creep damage (intergranular cracking) and a dense network of microcracks, whereas TMF promotes a single crack. Again, crack closure is a key factor in the subsequent FCGR, which is intermediate between the maximum and minimum temperature of the considered thermal cycle.

FEA has been systematically applied for both cases, based on conformal remeshing techniques, to highlight the driving forces controlling FCGR in the context of general scale yielding (4-5). Finally, the fatigue life assessment is discussed based on the combination of in situ measurements and such FEA method.

KEYWORDS: TMF, micro-crack, machine learning, conformal remeshing, large scale yielding

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Fatigue Crack Propagation under Non-Proportional Loading: Experiments and Modelling

Sheen Bemin (1), David Nowell (1)

1 - Imperial College London (United Kingdom)

Speaker: David Nowell. **Wednesday**. Start time: **15:10**. Room: Saint Clair 2 LVL2. Link to abstract.

A number of engineering components suffer two or more independent sources of loading and this can lead to a stress-state which is non-proportional. A particular instance occurs in bladed disks or 'blisks' in gas turbines, where loading arises from rotation as well as from blade vibration. Tthere are a number of well-established theories to predict crack growth direction under multiaxial load, for example maximum tangential stress (MTS) or maximum strain energy (MSE), these do not necessarily cope well with non-proportional loading. The paper describes a number of experiments which subject a cruciform specimen to biaxial and bending loading. Crack growth trajectories are measured under a different range of load. These are compared to simulations using MTS or MSE. It is demonstrated that certain combinations of load lead to crack growth which is poorly predicted. Hence a modified criterion is suggested which better represents crack growth direction under the full range of loads.

A new incremental fatigue crack propagation model accounting for history effects under complex thermomechanical loading

De Moura Pinho Raùl (1), Lopes Leal Junior Marcos (1)

1 - Safran Aircraft Engines (France)

Speaker: De Moura Pinho Raùl. **Wednesday**. Start time: **15:30**. Room: Saint Clair 2 LVL2. Link to abstract.

The proposed fatigue crack propagation model incorporates the effects of history induced by complex thermomechanical loading. While inspired by the work supervised by Sylvie Pommier (1-2), it differs in its formalism and the set of phenomena it seeks to predict.

The model is formulated incrementally over time, eliminating the concept of cycles, although it is possible to draw a parallel with certain cyclic propagation models (3). Key history effects discussed include overload and underload effects, as well as their interactions. Additionally, some history effects arise from temporal variations in temperature. The study aims to introduce the developed formalism and explore correlations between experimental results and the model's predictions.

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High Cycle Life Fatigue Analysis of Spot Welds with High-Fidelity Modeling

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Speaker: Ekra Yao. **Wednesday**. Start time: **15:50**. Room: Saint Clair 2 LVL2. Link to abstract.

Keywords**:** Spotweld; Fatigue; High cycle life; Cycle jump method; 3D modelling

Industrial context:
Resistance spot welding is a widely used joining process for assembling two or three sheets, particularly valued in the automobile industry. It allows for cost-efficient high-quality assemblies and to automate a big part of the assembly chain. Despite its use in the automobile industry for over 100 years, the modeling of spot welds remains a challenge, especially for durability simulations, as fatigue is the primary failure mode of spot welds. In fact, the models currently used are not precise enough and the need to have a full 3D spot weld accuracy is rising (3,4). However, given the large number of spotwelds on a car's body, reduced models of those "high-fidelity" models are commonly used for the simulation of structures with several spotwelds (4).

Content:
In this work, we focus on the high cycle fatigue modeling of a spotweld using a "high-fidelity" model. In this model, a spot weld is represented by a 3D fine mesh in the high cycle simulation performed in **Abaqus/Standard** using the **cycle jump** method (2). Two approaches are investigated to model the fatigue failure of spotwelds.
The first one is based on element deletion coupled with the continuum damage mechanics (2). A damage variable is assigned to each element and elements are deactivated when their damage value exceeds a threshold of 1.
The second method is based on eXtended Finite Element Method (XFEM) combined with linear elastic fracture mechanics (LEFM). Crack growth is estimated using LEFM.
We evaluate these two methods by modeling U-shaped fatigue samples with a single spot weld submitted to shear and tension loading. The results are then compared in term of crack profiles, stiffness evolution and mesh objectivity.

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Multiscale modeling strategy for predicting fatigue life of steels

Kazuki Shibanuma (1)

1 - The University of Tokyo

Speaker: Kazuki Shibanuma. **Wednesday**. Start time: **16:45**. Room: Saint Clair 2 LVL2. Link to abstract.

This study presents a multiscale modelling strategy for accurately predicting the high-cycle fatigue strengths of steels. In the proposed strategy, total fatigue life is estimated from crack growth life alone based on the experimental facts.
The entire model comprises three sub-models, for: (i) a macroscopic finite element analysis, (ii) microstructure, and (iii) crack growth. The required input data are only microstructural information, tensile properties, and loading conditions, without any adjustable material constants. The aim of the model for (i) a macroscopic finite element analysis is to define an active zone where sufficiently contains the whole of possible crack initiation area and to obtain the strain amplitude field in the active zone. In the model for (ii) microstructure, we employed a modeling strategy with two steps of 2D problems, which is modeling for surface and inside of material considering the features of actual fatigue crack initiation and growth behaviors. The Monte Carlo method is applied to simulate distribution of the microstructure, which is a nature of the scatter of fatigue life. In the model for (iii) crack growth, we employed the interaction theory between crack and grain-boundaries. The driving force of the crack growth is quantified using crack tip sliding displacement (CTSD) formulated based on the continuously distributed dislocation theory considering slip transmission between adjacent grains. The material resistance of each phase is determined as the friction strength to move dislocations. All the grains assigned in the surface of the active zone are assumed as possible crack initiation sites and the number of cycles to failure is determined based on the weakest link assumption.

The model was strictly validated against the results of experiments performed on three different steels under various loading conditions using four types of specimens. Although the experimental fatigue life results exhibited wide variation, the predicted and experimental data were accurately matched over the entire range. The notch sensitivity of the fatigue limits depending on the material strength were successfully reproduced by the proposed model. The transition of the crack growth rate was also accurately predicted compared with the experimental results.
The results demonstrate that the fatigue life of steels under high-cycle fatigue can be accurately predicted from crack growth life alone. Furthermore, the proposed strategy is capable of effectively explaining the dependence of fatigue strength on microstructure and loading conditions based on the advanced fracture mechanics.

Transition from steel wire to cable in fatigue life prediction under complex loads

Gaudillat Maëlle (1) (2), Gandiolle Camille (1), Larippe Laure (2), Mary Nicolas (3), Téraube Olivier (2), Cousinet Gaëtan (2), Poncelin De Raucourt Edouard (2), Aubin Veronique (1)

1 - Laboratoire de Mécanique Paris-Saclay (France), 2 - Manufacture Française des Pneumatiques Michelin (France), 3 - Laboratoire MATEIS (France)

Speaker: Gaudillat Maëlle. **Wednesday**. Start time: **17:05**. Room: Saint Clair 2 LVL2. Link to abstract.

A truck tire is a complex assembly of several composite plies composed of an elastomer matrix reinforced by steel cords. These cords consist of several thin, high-strength brass-coated steel wires assembled in a helix. Their primary function is to support the mechanical cyclic loading induced by the vehicle rolling, which leads to fatigue damage. However, during tire life, oxygen and water from the ambient environment can diffuse through the polymer matrix because its aging causes a change in its chemical properties, adding a combined corrosion effect to mechanical fatigue.
To reduce the global weight of a truck tire, the total mass of steel cords, which represents 25 % of the tire's mass, should be reduced, leading to higher stresses on the material. Still, this reduction can only be done by ensuring similar or better performances. Therefore, it is of primary importance to predict the fatigue behavior of steel cords under mechanical and chemical loadings. This study aims to develop a reliable model predicting the fatigue life of steel cords, which implies understanding fatigue and fatigue-corrosion mechanisms. Considering a multiscale approach, a pre-existing lifetime prediction model at the scale of a single wire (1) has been enriched to consider the fatigue-corrosion mechanism of brass-coated steel wires, which is caused by a double galvanic coupling: dealloying of the brass and, due to a not fully covering coating, preferential corrosion of iron (2). This damage of fatigue corrosion was studied using an experimental setup that enabled electrochemical measurements to be carried out during a bending rotation test.

A lifetime prediction model at the scale of the steel cords was developed based on this single wire model. Stress states in each wire were obtained using finite element simulations of a cable surrounded with a rubber matrix and subjected to bending and tension-bending loadings. The damage of these wires was first considered independent from one another, and their fatigue lives were computed using the single wire model, enabling the computation of a probability of rupture. The lifetime results were compared to experimental fatigue lives of cables subjected to bending-tension cyclic loadings.

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Creep-induced subsequent fatigue crack retardation and acceleration in wrought nickel-based superalloy GH4169: Competing mechanism of creep damage and creep deformation using DIC technique

Yang Rong (1), Wang Qiuyi (1), Lu Songsong (1), Bao Rui (1)

1 - Beihang University (China)

Speaker: Yang Rong. **Wednesday**. Start time: **17:25**. Room: Saint Clair 2 LVL2. Link to abstract.

Wrought nickel-based superalloy GH4169 (i.e., IN 718) is widely used in aero engine turbine disks. During operation, these disks experience alternating and sustained loads, leading to significant creep-fatigue interactions. Precise life prediction for these critical components requires quantitatively understanding the creep-fatigue interaction mechanisms during the crack propagation of GH4169.

Previous studies on creep-fatigue interaction have mainly used trapezoidal waveforms with dwell at maximum load to investigate the effect of creep on fatigue crack propagation rate. These investigations have attributed increased crack propagation rates to creep cavitation resulting from creep damage, while decreased rates have been linked to stress relaxation or crack tip blunting due to creep deformation. However, the quantitative mechanisms governing strain and damage development around the crack tip remain unclear.

In this study, the influence of prior creep on subsequent fatigue crack propagation behavior in nickel-based superalloy GH4169 was investigated, with a focus on the relationship between strain evolution and damage accumulation around the fatigue crack tip and fatigue crack propagation rate after applying the dwell loads based on digital image correlation (DIC). Crack propagation tests were conducted using compact tension (C(T)) specimens by introducing a single tension dwell at 650 ∘C into fatigue loading at ambient temperature. Various single dwell loads with different dwell times (600 s, 6000 s and 50000 s) were introduced into triangular cyclic loads at a similar initial stress intensity factor (25 MPa·m1/2) to introduce different creep effect on fatigue crack propagation, thereby revealing creep-induced retardation and acceleration effects. The results showed that the fatigue crack propagation rate, after applying dwell loads, demonstrated three distinct scenarios compared to the pure fatigue crack growth rate: 1) an instantaneous retardation for 600 s, 2) an instantaneous acceleration followed by retardation for 6000 s, or 3) an instantaneous rapid acceleration followed by slow acceleration for 50000 s. Ultimately, all scenarios converge to the pure fatigue propagation rate. Additionally, the cyclic strain distribution characteristics ahead of the crack tip and the crack opening and closure responses behind the crack tip using the DIC technique were analyzed. These analyses aimed to understand how creep deformation and damage influence the fatigue crack propagation rate and to obtain fracture parameters that quantitatively characterize the intrinsic mechanisms of creep-induced retardation and acceleration. The findings demonstrated that: 1) More evident strain and an increasing plastic strain region around the crack tip cause correspond to creep-induced acceleration. 2) A higher increasing rate in CTOD (crack tip opening displacement) and a larger severe strain (strain $>$ 3.6%) zone correspond to reduced fatigue crack growth (FCG) resistance due to creep damage, leading to a more pronounced acceleration effect. 3) The crack surface may be destroyed in certain regions after creep due to oxidation, suggesting that creep-induced retardation may be related to the oxidation-induced crack closure effect and the decrease in stress concentration due to oxidation-induced ΔCTOD acceleration. Furthermore, the uniform manifold approximation and projection (UMAP) algorithm was used to analyze the difference between different strain fields associated with different creep damage and creep strain from a unique perspective.

Continuum based fatigue modelling

Kouhia Reijo (1), Mohammad Jalaei (1), Kuupakko Juho (1), Saksala Timo (1), Orelma Heikki (1), Ristinmaa Matti (2), Ottosen Niels Saabye (2), Meneghetti Giovanni (3), Campagnolo Alberto (4), Pelizzoni Sofia (4), Andersson Tom (5), Freimanis Andris (5), Laukkanen Anssi (5), Lindroos Matti (5), Rubio Ruiz Arturo (6), Vaara Joona (6), Frondelius Tero (6)

1 - Tampere University (Finland), 2 - Lund University (Sweden), 3 - University of Padova (Via Venezia, 1 35131 - Padova Italy), 4 - University of Padova (Italy), 5 - VTT Research Centre Of Finland (Finland), 6 - Wärtsilä Marine Solutions, R&D and Engineering (Finland)

Speaker: Kouhia Reijo. **Wednesday**. Start time: **17:45**. Room: Saint Clair 2 LVL2. Link to abstract.

Ottosen, Stenström and Ristinmaa proposed in 2008 a continuum based high-cycle fatigue (HCF) model which is inherently multiaxial and offers several advantages in comparison to classical multiaxial fatigue models. The key ingredients of such model are construction of a moving endurance function and the evolution equations describing the movement and damage evolution. This format is quite general, inherently multiaxial and is not based on heuristic cycle-counting approaches. In this talk we discuss extensions of the basic isotropic HCF model to anisotropy and low-cycle fatigue. Different forms to construct the endurance function are given, e.g. how to better capture the mean stress behaviour (Haigh-diagram). This is archieved by using the solution of diffusion-reaction equation. Based on the famous Murakami equation, which describes how fatigue strength depends on defect size, we also discuss how the influence of defect size on the endurance function can be taken into account. Coarsening from micromechanical crystal plasticity models is also discussed.

A FFT-based method for analyzing dissipation and fatigue behavior under low-amplitude cyclic loading in polycrystalline aggregates

Calazans Menescal De Souza André (1), Moyne Sylvain (2), Doudard Cédric (1), Saint-sulpice Luc Calloch Sylvain

1 - École Nationale Supérieure de Techniques Avancées Bretagne (France), 2 - Institut de Recherche Dupuy de Lôme (France)

Speaker: Calazans Menescal De Souza André. **Wednesday**. Start time: **18:05**. Room: Saint Clair 2 LVL2. Link to abstract.

The analysis of dissipation under cyclic loading, commonly referred to as self-heating measurements, is increasingly popular as a method for estimating the fatigue properties of materials in high-cycle conditions. To fully leverage this experimental technique, it is essential to develop models that link self-heating data to material fatigue behavior. This study proposes a method using the fast Fourier transform (FFT) applied to a representative volume element (RVE) of a polycrystalline aggregate to examine the evolution of dissipation during low-amplitude cyclic loading and to construct predictive models.
The approach emphasizes obtaining both qualitative and quantitative self-heating curves by analyzing how steady-state cyclic dissipation evolves under varying loading amplitudes. Both uniaxial and multiaxial cyclic loading conditions are investigated. The research particularly focuses on the heterogeneous distribution of micro-plasticity within the polycrystalline aggregate, where dissipation is driven by localized plasticity in a small number of grains. This study also establishes connections with models using Poisson point processes to describe the gradual and localized emergence of these dissipation phenomena. Additionally, the investigation examines how several factors-such as grain orientation distribution, grain number, boundary conditions, stochastic critical resolved shear stresses, and loading multi-axiality-affect the onset of dissipative phenomena within the polycrystal. Finally, a fatigue criterion based on intrinsic dissipation is proposed to predict fatigue crack initiation. The initial results are in good agreement with experimental data reported in prior studies.

Low cycle fatigue life estimation by crystal plasticity and machine learning

Mostafavi Mahmoud (1), Dorward Hugh Peel Matthew Knowles David

1 - Department of Mechanical and Aerospace Engineering, Monash University, Clayton, Victoria 3800 (Australia)

Speaker: Mostafavi Mahmoud. Keynote. **Thursday**. Start time: **10:00**. Room: Saint Clair 2 LVL2. Link to abstract.

An essential part of estimating low cycle fatigue life of an engineering component undergoing complex cyclic loading is establishing an accurate response of the material to cyclic loads with constant strain. Often, the resulting hysteresis loop is defined via semi-theoretical equations such as those proposed by Armstrong-Frederick (Frederick and Armstrong 2007) or Lemaitre-Chaboche (Lemaitre and Chaboche 1990). However, such models are either too simplistic and cannot accurately predict the cyclic response of the material or so complex that require large experimental programmes to calibrate them to the point, the experimental results are sufficient for prediction of material response.
An alternative approach is devising a numerical model that represents the right micromechanical physics of cyclic behaviour so it can accurately predict the response of the material and use it to predict the micromechanical hysteresis at different strain ranges. The first step in this approach is to identify the micromechanical physical parameters that influence the macromechanical response. While there are many parameters that play a role in cyclic behaviour, the key variables for macromechanical hysteresis loop are the evolution of kinematic and isotropic hardenings which implicitly capture the evolution of the Bauschinger effect. Crystal plasticity finite element simulations are well suited to capture these two parameters as the constitutive law includes formulation for hardening thus accounting for the isotropic behaviour. The hardening can be defined in a phenomenological fashion(Ashraf et al. 2024) or a more physics-based approach such as strain gradient plasticity (Dorward et al. 2024) can be used. These models represent the hardening of the material and often are suitable for monotonic deformations even to high levels of plasticity such as forming.

However, the kinematic hardening as observed in the case of cyclic loading is less studied and harder to represent. It could be argued that the key mechanism for hardening is intergranular (back-stress) and intragranular stresses also referred to as type III and type II residual stressed (Withers 2007). Crystal plasticity finite element frameworks inherently capture the intragranular residual stresses as the difference in the compliance of grains due to their orientation with respect to loading direction is accounted for thus, upon unloading the misfit between grains automatically simulates type II residual stresses. Type III residual stresses on the other hand must be explicitly formulated. While micromechanical rules such as the gradient of the distribution of geometrically necessary dislocations have been proposed (Bayley, Brekelmans, and Geers 2006) for modelling type III residual stresses, their measurement is not straightforward due to large uncertainty in distribution of geometrically necessary dislocation whose derivative becomes unreliable.

Since the final aim of our model is to extract macromechanical properties, we have used a set of phenomenological constitutive laws with less influential micromechanical parameters captured via physics-based calibrating parameters. For example, the kinematic hardening has been modelled via one parameter that captures back stress in the material and can be calibrated via synchrotron X-ray diffraction. Inevitably by reducing the microstructural reliance of the model, its predictivity becomes limited. However, it reduces the complexity and therefore reduces the computational cost.

Despite the computational savings made in the model by moving towards a phenomenological constitutive law with combined calibrating parameters, it is still too complex and time-consuming to produce and solve model of a size which is comparable to that of an industrially relevant component. It therefore has a similar problem to a fully experimental approach, to run the model enough times to cover the full solution envelop, it will be computationally unfeasible although at much lower cost compared to experimental programmes.

The next step therefore is to reduce the computational cost of such complex models. We have em-

ployed a machine learning algorithm, that is Gaussian Process, to do this. Gaussian process regression predicts a conditional probability at each testing datapoint therefore giving an estimate for the output value and a variance at each point. The relationship between points in the input variable space can be described by a kernel function which for our case, we used a second order polynomial. Since the response of the material to cyclic loading is complex, first we used Functional principal component analysis (fPCA) to deconstructs the materials response (i.e. each half hysteresis loop) into a set of basic functions parameterised by scalar constants thus reducing the model that predicts the response. We could estimate the cyclic behaviour at each cycle by a combination of only 4 basic functions thus the Gaussian Process needed to predict 4 scalers for each half cycle for each strain condition.

After producing the surrogate model of the crystal plasticity framework, the model was tested against a set of experimental programme carried out previously on stainless steel 316H at 550oC. The experiments were uniaxial low cycle fatigue experiments with either constant strain ranges (between -0.6% to +0.6%) or variable strange ranges. The model performed well in predicating this behaviour. To make the model accessible by engineers, UHARD within ABAQUS. While the Abaqus simulations with UHARD could implement the model for industrial applications, it is currently limited to uniaxial conditions only not able to predict the evolution of yield surface in the case of multi-axial loading correctly. We therefore plan to expand the surrogate model to multi-axial condition, requiring defining a full 3D scale UMAT for all possible combinations of cyclic loadings in three dimensions.

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Competition of different fatigue crack initiation mechanisms under torsional load of cast AlSi7Mg03 alloy: An investigation using synchrotron 3D observations

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Speaker: Le Viet-Duc or Buffière Jean-Yves. **Thursday**. Start time: **10:40**. Room: Saint Clair 2 LVL2. Link to abstract.

This paper focuses on the effect of the microstructure, including porosities, eutectic zones and alpha grains, on the mechanisms of fatigue crack initiation and crack propagation under torsional loads for the cast AlSi7Mg03 aluminium alloy. The objective of this work is to understand the effect of grain crystallographic orientation, the grain size and the presence of porosity on the crack initiation and propagation mechanisms in torsion, not only on the surface but also in the volume. In order to achieve this objective, in-situ fatigue tests have been conducted in a synchrotron beamline at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. These experiments made it possible, on one hand, to obtain high resolution and high contrast 3D tomography images of the microstructure (with the voxel size of 1.3 μm) in which we can observe clearly micro-cracks (with an opening distance smaller than the voxel size). On the other hand, thanks to the Diffraction Contrast Tomography (DCT) technique, the 3D images have been rendered which include information about the grains size, the grain morphology and the grain orientation. The superposition of the 3D tomography and DCT images make it possible to know all of the necessary information related to the microstructure. These data were captured throughout the fatigue life of the specimen in the in-situ torsional tests.
Unlike tension loading mode, which only reveals tension cracks from pores, torsion enables the simultaneous observation of crack initiation mechanisms from both Persistence Slip Bands (PSBs) and pores. This point is very important because it make possible to analyse the different mechanisms (and the effect of surrounding microstructure) of cracks in the same specimen, i.e., under exactly identical loading conditions. It was observed that for the cracks initiated from PSBs, crack initiation occurs in a shear mode and is greatly influenced by the grain orientation. All observed cracks occur on the slip system plans presenting the highest resolved shear stress. The presence of a pore increases the shear stress amplitude at the local point, making it easier to activate crack initiation from PSBs. The crack propagation from one grain to adjacent grains is governed by two factors: the resolved shear stress of the latter and the twist and tilt angles between these grains. The grain boundaries are the main microstructural barrier arresting crack growth.

For the crack initiations from pores, these cracks occur in the opening mode on the plans presenting the highest macroscopic normal stress. No link to the grain orientation was found. The pore size is the key factor governing this crack initiation mechanism. Regarding the propagation mechanism, no clear microstructural barrier slowing crack growth down was observed. The growth rate of cracks in this mode is relatively steady but generally much lower than the cracks formed from PSBs.
Finally, a statistical analysis of the competition of the two mechanisms to form the final crack (that leads to the failure of specimens) showed that, depending on the density of initiated cracks and the crack growth kinetic, the cracks initiated from PSBs govern at high applied stress levels (tau_amp$>$ 90MPa) while at lower stress levels (tau_amp$<$ 80MPa) the cracks initiated from pores win.

Influence of Plastic Localization on Fatigue Crack Nucleation and Life Dispersion in Inconel 718 at the Microstructural Scale

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Speaker: Musy-Haspel Mathieu. **Thursday**. Start time: **11:00**. Room: Saint Clair 2 LVL2. Link to abstract.

Nickel-based superalloys are extensively used in the aerospace industry due to their exceptional high-temperature performance and corrosion resistance. A key characteristic of these materials is their tendency to deform heterogeneously, leading to the formation of slip bands on the material's surface, which are particularly pronounced in the case of Inconel 718. During cyclic loading, intense slip bands play a critical role in the nucleation of fatigue cracks. These bands are strongly dependent on the microstructure, a relationship that may hold the key to understanding the variability in fatigue life. Despite the importance of this phenomenon, existing microstructure-sensitive fatigue models often neglect it in numerical simulations due to computational limitations, as fine meshes are required to accurately represent slip bands.
This study investigates the influence of incorporating slip localization into polycrystalline simulations for predicting fatigue crack nucleation. The objective is to evaluate whether considering plastic localization enhances the accuracy of predictions and, if so, to what extent.

The methodology is as follows: Experimental characterizations are first used to create representative microstructures that replicate key features of Inconel 718 specimens, such as a high number of twin grain boundaries and non-metallic inclusions (NMI)-two known crack nucleation sites. During cyclic loading, slip bands and cracks primarily develop at the surface of samples, so introducing a free surface in the simulation is crucial for accurately capturing this phenomenon. Crystal plasticity simulations are then performed on these microstructures using the spectral solver AMITEX. The resulting fields are analyzed to calculate Fatigue Indicator Parameters (FIP) (1), which quantify the driving force for crack initiation. These FIPs act as a bridge between plasticity and fatigue through a life-prediction model, as in (2). The FIPs in this study incorporate local plastic strain or stress measures to account for cracking mechanisms associated with slip bands and NMI.

To account for plasticity localization in crystal plasticity simulations, two methods are compared to classical crystal plasticity models. The first uses a softening behavior law (3), while the second employs a geometrical approach based on weakest link theory (4).

Finally, all models are calibrated using cyclic tests on Inconel 718. Numerical results are compared to experimental micromechanical test data to assess their accuracy. The ultimate goals of this work are twofold: first, to investigate crack nucleation sites and validate the predictions against experimental results; second, to explore the variability in fatigue life predictions and evaluate the ability of the different approaches to capture microstructure-induced fatigue life dispersion.

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Numerical study of a printed circuit board with embedded components under thermal cycling: influence of the manufacturing process

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Speaker: Perin Paul. **Thursday**. Start time: **11:20**. Room: Saint Clair 2 LVL2. Link to abstract.

Over the time, the structure of printed circuit boards (PCBs) has gotten more and more complex, evolving from single-layer PCBs to multi-layer assemblies. The materials constituting these layers present very different coefficients of thermal expansion (CTEs). This mismatch induces stress inside a PCB when it undergoes thermal loading.
Furthermore, to improve thermal and electrical properties as well as to increase interconnexion density, a new generation of PCBs is under development (1). This technology consists in embedding components inside the PCB during its manufacturing process. However, by doing so, the material heterogeneity of the assembly is increased. Therefore, the reliability of this technology needs to be assessed.

A PCB has to successfully pass several qualification tests, among which the thermal cycling test. More precisely, (-55∘C/125∘C) thermal cycles have been applied on a 3D finite element model, whose geometry is based on an actual four-layer PCB with embedded components. This study focuses on the vicinity of one of these components. Since the latter is connected to the copper tracks via solder bars, a particular attention has been given to the geometry of the solder connections and the copper layers. Furthermore, a precise description of the thermo-mechanical constitutive behavior of the materials is proposed. Hence, the dielectric materials (the woven composite and its resin) were fully characterized by a combination of experimental and numerical methods (2). Based on a literature survey, the thermo-elasto-viscoplastic behavior of the solder material (SAC305) has also been implemented in ABAQUSTM via an UMAT subroutine (3).

A first model, considering that the assembly stress free before thermal cycling has shown that the solder pads represent the most critical region due to an important plastic strain accumulation, leading to a possible low-cycle fatigue (4). This is mainly due to the combined tension-bending loading of the component. It also appears, via a parametric study, that the resin-filled cavity, which encapsulates the chip, plays a primary role in this response.

For this reason, a second model, representative of the manufacturing process has been developed. This model is based on an experimental evaluation of the dielectric chemical shrinkage during curing (5). With the latter model, the stress fields inside the PCB after processing have been evaluated. A significant change in the response of the PCB to thermal cycling has been observed when these residual stresses are introduced. Therefore, it appears that when numerically studying the reliability of a PCB with an embedded component, it is of paramount importance to also model the manufacturing process.

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Keywords: Printed Circuit Boards; Embedded component; Finite element modelling; Solder bars; Manufacturing process

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Thermo-mechanical fatigue crack growth of a coated superalloy

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Speaker: Marioton Louise. **Thursday**. Start time: **14:15**. Room: Saint Clair 2 LVL2. Link to abstract.

This study focuses on combustion chambers made of superalloys, coated with thermal barriers to offer protection against extreme heat. These chambers experience severe thermal gradients and out-of-phase (OP) cyclic loading, characterized by tensile stress at low temperatures and compressive stress at high temperatures. This induces significant mechanical stresses, leading to damage in the form of fatigue cracks. The aim of this work is to investigate the propagation of pre-existing cracks, with a particular focus on their path and speed, to evaluate the durability of combustion chambers, especially when Thermal Barrier Coatings (TBCs) are applied.
The component is subjected to complex thermo-mechanical loads, consisting of variable-amplitude cycles with significant temperature gradients, which can lead to large scale yielding deformation. Furthermore, the presence of a TBC, composed of a NiCrAlY bond coat layer and an yttria-stabilized zirconia ceramic layer applied by Air Plasma Spraying (APS), adds further complexity. The mechanisms of crack propagation under these conditions are not well understood. Previous work has characterized crack initiation (1) and propagation (2) on the substrate. The challenge of this study is, therefore, to develop experimental and numerical techniques that accurately represent the loads experienced by the component and replicate the crack propagation observed in coated combustion chambers.

Consequently, an experimental test series has been designed to understand the role of both coating layers in crack propagation, using image correlation techniques and infrared thermography. The purpose of these tests is to first analyze the impact of temperature conditions on crack propagation across different layers. To achieve this, thermomechanical fatigue (TMF) experiments are conducted on pre-notched specimens. One set of specimens is coated solely with a NiCrAlY layer and subjected to biaxial loading conditions, while another set is coated with an additional thermal barrier coating (TBC) and tested under uniaxial loading conditions. The tests are performed at a constant temperature of 900∘C and at varying temperatures ranging from 300∘C to 900∘C, incorporating different heating and cooling rates under OP conditions.
In parallel, finite element simulation methods, informed by experimentally measured fields, are being employed to analyze the forces driving crack propagation. In particular, a non-local remeshing method (3) adapts the mesh around the crack, simulating crack propagation and enabling precise computation of the energetic data associated with each increment of crack growth. This approach makes direct comparison with experimental data feasible. A complementary phase-field approach is also being developed to simulate the damage field induced by thermomechanical loading and to model its interaction with plasticity. The phase-field method is particularly valuable for capturing the coupled effects of damage and plasticity, especially near closed crack tip regions, where these interactions significantly influence the material response (4).

Influence of overload on the propagation of 3D short fatigue cracks

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Speaker: Limodin Nathalie. **Thursday**. Start time: **14:35**. Room: Saint Clair 2 LVL2. Link to abstract.

Short abstract
The influence of tensile overload on fatigue crack growth of a short 3D crack has been monitored in 3D using X-ray tomography, and displacement fields computation with digital volume correlation.

Introduction
Structural components, *e.g.* aircraft, railways, or automotive applications, are inevitably submitted to Variable Amplitude fatigue (Schijve, 2001). Even when components are designed for constant amplitude loading, occurrence of overloads or underloads in service is frequent and affect the fatigue crack growth rate. In most metallic alloys a few cycles of crack acceleration followed by FCG retardation are usually observed after a tensile overload. Since the early seventies, the study and modelling of overload has been focused on long through cracks. However fatigue cracks are inherently 3D objects that remain part-through short cracks during a large fraction of the fatigue life (Schijve, 2001). Due to a lack of experimental data, the fundamental mechanisms of the propagation of 3D cracks under non-constant amplitude loading have not received enough attention yet. The goal of this study is thus to understand overload effects on physically small 3D fatigue cracks in order to build predictive models.

Methodology
The material of the study, an AlSi7Mg0.6 cast aluminium alloy, was specifically designed by the CETIM to provide a fine speckle pattern of eutectic Silicon particles for Digital Volume Correlation (DVC). Besides it has a grain size (@150μm) small enough to ensure a smooth crack plane. The experimental procedure consisted in subjecting corner-notched dog-bone type samples to cyclic tensile loading (frequency=20Hz, R=0.27) in-situ at PSICHÉ X-ray tomography beamline of SOLEIL synchrotron. When the crack has propagated away from the previous overload, another overload was applied until the unbroken ligament became too small. Up to 4 overloads, at decreasing load ratio (FOL/Fmax from 1.8 to 1.3), could be applied on one specimen. During the loading sequence, 3D tomography scans of the sample were regularly acquired before, during and after a single overload. On some key cycles, several acquisitions were obtained at intermediate load steps between the extremums to study crack opening and closure.

Results
Analysis of the raw tomographic volumes allows the crack fronts, hence crack growth rates, to be obtained while analysis of the displacement fields from DVC allows extracting Stress Intensity Factors (SIF) and crack opening displacement along the crack front. DVC was performed with UFreckles software (Réthoré, 2018) using a size of element of 8 pixels (20.8μm) and SIF were computed by projecting the 3D displacement field onto Williams series solutions (Lachambre et al., 2015). Characteristic periods of crack retardation after overloads are observed, with crack growth recovery occurring first in the bulk of the sample, then later close to the free surfaces.
Interestingly, no correlation between the measured Stress Intensity Factors (SIF) and crack growth rates after the overload is evidenced. The SIF range of post-overload cycles are unaffected by the overload. Although the crack is effectively blocked after the overload, the value of ΔKI remains the same. Finite

Element calculation using DVC as boundary conditions corroborates the SIF values obtained with DVC and allows to characterize the evolution of the plastic zone along the crack front to confirm the larger plastic zone close to the free surfaces in relation with a larger closure effect.
If the SIF parameter is no more an appropriate driving force after the overload, the analysis of the crack opening displacement from measured displacement fields allows to understand what happens at the crack tip during the overload cycle with plastic deformation, crack tip blunting and residual effect of the overload. Finally, the evolution of crack tip opening after the overload seems a more promising parameter to correlate with fatigue crack growth delay and crack recovery than the SIF.

Conclusion
This study allows to characterize the effect of tensile overloads on a 3D short fatigue crack evidencing strong differences between the free surfaces and the bulk that could not have been observed and quantified without x-ray tomography and digital volume correlation.

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Direct current potential drop method for the identification of onset fatigue damage in triply periodic minimal surfaces lattice structures for heat exchange applications

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Speaker: Brambati Giovanni. **Thursday**. Start time: **14:55**. Room: Saint Clair 2 LVL2. Link to abstract.

The research activity presents a methodology for monitoring the onset of fatigue damage in Triply Periodic Minimal Surface (TPMS) lattice structures using the Direct Current Potential Drop (DCPD) technique. The aim of the study is to validate an experimental setup capable of interrupting a fatigue test at the early propagation phase, prior to crack propagation through the entire wall thickness, which represents the operational failure condition for TPMS-based heat exchangers. The DCPD technique is described in detail, including the modifications made to conventional testing setup, in order to consider the specific case of lattice structures. Additionally, the challenges encountered for these modifications and the strategies employed to overcome them are discussed. The validation of the proposed methodology is supported by a detailed analysis of the fracture surfaces of samples for which the test was interrupted using the DCPD technique. The results of the potential drop method are analysed and compared with common methods of fatigue test monitoring — i.e. axial stiffness drop.

Identification and characterization of acoustic fatigue signatures through continuous acoustic data mining

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Speaker: De La Selle Théotime. **Thursday**. Start time: **15:15**. Room: Saint Clair 2 LVL2. Link to abstract.

Acoustic emission (AE) is a key method in the field of fatigue, both as a high-performance non-destructive testing (NDT) tool for structural monitoring and as a refined approach to physical investigation. To tackle the challenge of exploring new signals and recognizing sources based on both statistical and physical analyses in fatigue experiments, a relevant tool for representing time series, known as a Deep Scattering Network (DSN), has been developed. A DSN shares a similar architecture to that of deep convolutional neural networks: it implements a cascade of convolutions using wavelet filters, a modulus function, and pooling operations. Combined with dimensionality reduction techniques and clustering methods, unsupervised classification of time series reaches particularly high performance, as signal representations called Deep Scattering Spectra are locally invariant to translation while preserving transient phenomena such as attack and amplitude modulation. Depending on the dimensionality reduction method and network parameters, Deep Scattering Spectra of the continuous recordings are used either to detect recurrent transient signals of short duration or to cluster the entire input signal by focusing on the background wavefield. Thus by applying this method to continuous AE recordings at high sampling rate, obtained during fatigue tests on steel and aluminum alloys, we demonstrate that the background signal contains relevant information. This information can be extracted -even at very low signal-to-noise ratios-, grouped into distinct source mechanisms (separated from mechanical and electronic noise), and investigated to provide in-depth insights into fatigue crack activity (e.g., closure, crack-tip plasticity, etc.). Fatigue acoustic signatures are identified and distinguished within each fatigue cycle and correlated with loading and strain measurements throughout the duration of the experiments to track the long-term evolution of the sources. The acoustic content of these fatigue signatures is characterized using deep scattering spectra and frequency- or time-based descriptors, enabling a typology of acoustic fatigue signatures to be proposed.

A Fatigue Damage Diagnosis and Prognosis Method Based on Strain Monitoring for 2024 Aluminum Plates with Central Holes

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Speaker: Han Liang. **Thursday**. Start time: **15:35**. Room: Saint Clair 2 LVL2. Link to abstract.

A fatigue diagnosis and prognosis method based on strain monitoring has been developed for 2024 aluminum plates with central holes. Fatigue experiments were conducted to obtain strain and crack information from the specimens. Crack occurrence was detected through a thresholding method applied to the strain measurements. A data-driven Gaussian Process Regression (GPR) algorithm was employed to establish the relationship between crack length and strain characteristic parameters. For real-time crack propagation prediction, a Dynamic Bayesian Network (DBN) was constructed by integrating the GPR algorithm with the Paris formula. An experiment was carried out to illustrate the accuracy of the method. The results indicate that the threshold method can effectively detect fatigue cracks. The GPR algorithm accurately identifies fatigue crack lengths and has higher recognition accuracy than other algorithms. Additionally, the DBN provides more accurate crack propagation predictions with reduced computational time compared to traditional mechanics-based crack growth analyses.
Note: This work was previously published in the International Journal of Fatigue in 2023.

Formulating an advanced severe gust load spectrum for transport aircraft, grounded in analyzed measured load data

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Speaker: Wei Kunyu. **Thursday**. Start time: **15:55**. Room: Saint Clair 2 LVL2. Link to abstract.

Developing a severe load spectrum for transport aircraft structures is essential to enhance the correlation between full-scale fatigue testing results and operational service conditions. This study addresses the lack of standardized methods for severe spectrum development by proposing an innovative approach to constructing a severe gust load spectrum based on the acceleration cumulative exceedance surface.

Measured load data were analyzed using a novel model that employs the cumulative exceedance surface to characterize exceedance number variations. An improved multivariate Markov Chain Monte Carlo sampling method was utilized to estimate fleet fatigue damage distribution, enabling the precise determination of severe spectrum severity and its corresponding cumulative exceedance surface. A severe gust load spectrum was then constructed based on this surface.

The proposed methodology minimizes the randomness of peak-trough pairs by incorporating the correlation between spectrum peaks and troughs, thus reducing variation in fleet fatigue damage. This reduction decreases the required severity of fatigue damage in severe spectra, improving the efficiency of fatigue analysis. Extending the conventional one-dimensional curve representation to a two-dimensional surface, this approach provides a more accurate depiction of acceleration cumulative exceedance number variations, offering a significant advancement in fatigue damage calculations. The findings serve as a valuable reference for developing severe load spectra for transport aircraft, promoting improved reliability and structural performance.

Note: This work was previously published in the International Journal of Structural Integrity in 2024.

Exploration of rolling contact fatigue using an ultrasonic testing device.

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1 - Institut National des Sciences Appliquées de Lyon (France)

Speaker: Didier Adrien. **Friday**. Start time: **10:00**. Room: Saint Clair 2 LVL2. Link to abstract.

In fields in which human safety is at stake, such as in aeronautics, or in sensitive installations like nuclear power plants or dams, extremely low failure rates ($< 10^{-7}$), or even zero for certain critical components, are required. It is therefore necessary to design parts that are capable of surviving tens of billions of cycles, corresponding to decades of operation. However, the damage mechanisms associated with such a long lifespan are still poorly understood. This is particularly due to a critical lack of experimental data, which is especially laborious and time-consuming to obtain in such contexts using conventional analyses. This lack of experimental data, combined with the extremely high number of cycles to simulate, makes the numerical simulation of such damage difficult or even impossible.
In order to render the study of very high cycle fatigue more accessible, we have designed an ultrasonic fatigue device capable of approaching the rolling contact fatigue (RCF) stress state experienced during rolling on an indented surface, in order to understand the primary cause of failures in aeronautics. It relies on testing specimens made of M50 steel while inducing compressive preload. This leads to a localized multi-axial and non-proportional stress field, induced by an artificial surface defect created via electro-discharge machining (EDM). The experimental device, therefore, enables to simulate the equivalent of several decades of use, or several billion cycles, in just a few dozen hours. This study has thus established numerous links between rolling contact fatigue and ultrasonic fatigue.
Observations reveal that the surface crack initiation occurs along the EDM beyond 108 cycles, with no shift observed from surface defects to sub-surface defects, as commonly seen in VHCF regime. Our analysis suggests that the stress intensity factor range, ΔK, may govern surface initiation in the VHCF regime, particularly when the formation of FGA is not feasible. Consequently, under fixed stress conditions, there exists a critical surface defect size below which short crack initiation becomes improbable. These results mirror the behaviour usually observed for indentations and thereby connect ultrasonic loading with RCF. Besides, initiations of fatigue buttery and FGA appear to be associated with VHCF tests, compression, high levels of multi-axial stresses, and the refinement of microstructure at low temperatures. These findings shed light on a potential link between fatigue buttery and FGAs, attributed to the same underlying cause: cross-slip.

Cyclic behaviour of pure alpha titanium alloy with and without hydrogen

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Speaker: Feaugas Xavier. **Friday**. Start time: **10:20**. Room: Saint Clair 2 LVL2. Link to abstract.

The impact of hydrogen on the low cycle fatigue behavior of T40 is investigated at room temperature. The mechanical behavior could be divided into three stages and related in terms of hydrogen concentrations, types of hydrides and their influence on mechanical properties. Different morphologies of hydrides, γ, and δ-hydrides, the formation and evolution of defects and dislocations distribution, have been studied using transmission electron microscopy (TEM) to explain the evolution of internal stresses. It revealed that the physical effect of hardening or softening on the effective stresses and back stress depends on the hydrogen content and its location (hydride or in interstitial solid solution). The relationship between microstructural observations and mechanical results is then discussed to understand the origin of softening and hardening as well as the mechanisms of crack initiation and propagation.

Observation and analysis of internal fatigue cracks propagating in a Ti64 alloy with or without air presence.

Hébrard Louis (1), Ranc Nicolas (2), Palin-luc Thierry (3) (4), Buffière Jean-yves (1)

1 - MATEIS (France), 2 - PIMM (France), 3 - I2M (France), 4 - I2M (France)

Speaker: Palin-Luc Thierry. **Friday**. Start time: **10:40**. Room: Saint Clair 2 LVL2. Link to abstract.

It is now well established in the scientific community that in metallic engineering materials (steel titanium, aluminium or nickel alloys) the most frequent location of fatigue crack initiation in the Very High Cycle Fatigue (VHCF) regime (i.e. very low stress amplitudes and N_failure _~ 108 cycles and more) is the bulk of the material or its sub-surface. In steels the famous " fish-eye " is the typical feature of a fracture surface in VHCF where a central non-metallic inclusion is the reason invoked by many authors of such non-surface crack initiation. However, internal fatigue crack have also been observed without inclusion in steels (1) and in titanium alloys (2). In such cases several heterogeneities of the microstructure can explain this phenomenon (heterogeneous cyclic plastic deformation in the grains, macro zones, segregation of some chemical elements...). But the reasons why crack initiation tends to occur from the material surface instead of those internal defects when the stress amplitude is increased (i.e. for a lower number of loading cycles) are still not well understood.
Some authors claim that the environment plays a key role in this phenomenon: surface cracks initiate and propagate in air whereas the internal ones initiate and propagate in vacuum. In this later type of environment, the crack growth rates are much slower than in air but the surface is exposed during a very long time to the ambiant air in VHCF and consequently should be critical. Moreover, direct measurements of $da/dN = f(\Delta K)$ curves remain scarce in the literature because the direct observation of internal crack growth is a difficult task. That is why some authors have used fatigue tests results obtained on surface cracks propagating in high or ultra-high vacuum to discuss and simulate the environment undergone by internal fatigue cracks. But these results are debated because the local stress strain states are different between a surface small crack (plane stress) and an internal one (plane strain).

To progress in this question, an in-situ synchroton ultrasonic fatigue testing machine was used to study the propagation of internal fatigue cracks growing from an artificial sharp internal defect in a Ti-6Al4V alloy cycled at 20 kHz (3, 4). A laser vibrometer and a real-time FFT analysis were used to detect crack initiation and simultaneously an infra-red camera recorded the temperature field evolution at the specimen surface all along the fatigue tests. Synchrotron X-ray micro-tomography allowed us to image the internal crack propagation under load. Two sets of specimens were produced by an home made methology to introduce internal and calibrated sharp defect (5). The first one contains a central canal along the specimen axis which brings air from the laboratory to the internal notch and then to the internal crack emanating from this notch. In the second set the notches are not connected to the surface.

Systematic failures were observed with crack emanating from the internal artificial defect for the two types of specimens. The fatigue lives of the specimens with air present at the internal crack tips are significantly lower than those of the specimens with internal cracks isolated from air. For specimens containing a defect isolated from air, internal cracks propagate at a much slower rate than when the defect is connected with ambient air. The SEM observations of the fracture surfaces are in good agreement with literature for natural internal cracks in Ti-Al alloys. For the defects connected to air a supplementary region surrounding the defects appears on the fracture surface with a pronounced faceted / crystallographic aspect containing striations whereas no striation was observed on the facets of the cracks isolated from air. A detailed analysis with FIB-SEM and EBSD - TKD of the striated facets revealed that the striation marks are due to twinning.

Furthermore based on both the evolution versus time of the temperature fields at the specimen surface and the 3D internal crack growth obtained by tomography after different number of cycles, a thermo-mechanical finite element model was developed to identify the evolution of the heat sources located the crack tip in the reversed cyclic plastic zone. Even if the accuracy of these data is at the limit of this techniques there is a clear tendency showing that the part of the plasticity strain energy dissipated in

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Physically-based notch strain methods for fatigue life prediction of welded tubular connections in offshore wind turbine support structures

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Speaker: Haider Muhammad Jaon. **Friday**. Start time: **11:00**. Room: Saint Clair 2 LVL2. Link to abstract.

Given the increasing demand for energy and the need to address climate change, offshore wind energy is a valuable renewable energy source. To make wind energy an economical energy resource, upscaling of offshore wind turbine support structures is necessary. Welded joints in support structures are critical locations for fatigue failure, particularly with uncertain aero- and hydro-dynamic loading conditions. The present work focuses on the development of a physically based (PB) notch strain methodology for fatigue life assessment of welded tubular joints in offshore wind turbine (OWT) support structures.
To incorporate the welding microstructure effect in structural steels like S355 ferritic-pearlitic steel, PB cyclic plasticity model is presented for the effects of welding zones on the cyclic elastic-plastic response of welded tubular joints. A modified Neuber method is combined with the PB cyclic plasticity model and global-local modelling of welded joints in the NREL OC4 reference jacket structure under dynamic loading, to demonstrate the PB notch strain methodology. The significance of this study is that we can capture welding-induced microstructure effects on localised notch strain for fatigue life prediction in a computationally efficient method.

High Cycle Fatigue of 2507 Super Duplex Stainless Steel: comparison between Laser Powder-Directed Energy Deposition and forge processes

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Speaker: Szmytka Fabien. **Friday**. Start time: **11:20**. Room: Saint Clair 2 LVL2. Link to abstract.

Super-duplex 2507 stainless steel is a two-phase austeno-ferritic steel known for its good mechanical properties, particularly in fatigue, as a result of its mixed ferritic and austenitic microstructure (1). The study involves a comparison of two manufacturing processes: forging and additive manufacturing using the Laser Powder-Directed Energy Deposition (LP-DED) process, and the impact of heat treatment on the latter. The microstructures developed for each process are however very different. The forged material shows a fairly balanced microstructure (59% ferrite) with grains that are all similar (columnar along the forging axis, globular along the perpendicular one) compared with the LP-DED raw material, which is around 75% ferrite and has a very heterogeneous distribution of austenite depending on thermal history and the deposition strategy. Applying a heat treatment at 1200∘C for 3 hours to the LP-DED product brings the microstructure closer to that of forging, with a balance between the phases and a homogeneous distribution of grains in the material.

The fatigue behaviour of the various material/process combinations is then analysed in this study. Two methods for determining the fatigue limit were investigated: the processing of Staircase campaigns with reloading of unruptured specimens (3), used as a basis for fatigue limit estimation at 2 million cycles, and the empirical evaluation of self-heating tests (4). The Staircase campaigns highlighted the benefits of using the LP-DED process compared with forging, with an increased fatigue limit of more than 100 MPa. The use of heat treatment following LP-DED process, on the other hand, brings the fatigue properties closer to the forged material, while remaining very slightly higher (about 10MPa). Empirical analysis of self-heating tests is not completely satisfactory for all the tested configurations. For the forged and the LP-DED and heat-treated materials, the results are very encouraging, with differences of less than 10%. Unfortunately, the LP-DED raw material showed a larger difference. This might be expected, given the method assumptions and the impact of the material heterogeneity. The fatigue behaviour of forged alloy and heat-treated LP-DED is also investigated for loading levels above the fatigue limit, with a comparison of resistance and variability.

For the raw LP-DED material, a first modelling of the self-heating tests is also proposed to enable a more detailed analysis of the results and to take into account the two-phase microstructure. A first proposition taking into account the differences in behaviour between ferrite and austenite is thus made, in order to be able to predict the self-heating of a duplex stainless steel as a function of its ferrite/austenite ratio.

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How Varying Fatigue Loads Affect the Damage Evaluation in Front of the Crack in Hydrogels

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1 - LTS2 - EPFL (Switzerland)

Speaker: Umut Altuntas. **Friday**. Start time: **11:40**. Room: Saint Clair 2 LVL2. Link to abstract.

Industrial materials are exposed to different types of loads over many years. Therefore, understanding crack initiation and propagation under cyclic loads is one of the keys to making a successful design. However, the complexity of damage evaluation under fatigue loading and the lack of clear observations makes it very difficult to reveal and understand the mechanisms behind fatigue fracture. Polyacrylamide hydrogels, with their unique combination of brittleness and elasticity, serve as ideal material models for studying fatigue fracture in brittle systems. This study investigates strain field evolution and plastic deformation near the crack tip in hydrogels subjected to cyclic loading. Our experimental findings reveal that even when the applied energy release rate is below the fatigue crack propagation threshold, microdamage occurs in the process zone. Strain field analysis shows early strain concentration near the crack tip, leading to localized microdamage. When the applied energy is insufficient to sustain fatigue crack propagation, strain relaxation mechanisms are observed. These mechanisms act as a form of toughening, reducing strain concentration. In contrast, when the applied energy exceeds the threshold, strain relaxation is not observed. The maximum strain near the crack tip and the size of the damaged zone converge at values dependent on the applied energy. For energy just above the threshold, crack propagation rates are linear with no plastic deformation in the unloaded state. However, at significantly higher energy levels, consistent with Region II of the Paris law, crack propagation rates initially decrease and eventually stabilize, reflecting an energy-dependent equilibrium.

TOPIC: Experimental Mechanics

MS4.1 - Experimental Micromechanics and Nanomechanics

Organisers: G. Dehm (MPIE-Dusseldorf), J. Molina (IMDEA-Madrid) and G. Kermouche (LGF-EMSE)

Accurate mechanical phase mapping in heterogeneous materials combining high-speed nanoindentation with a novel Machine learning-driven pile-up error correction

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Speaker: Rossi Edoardo. Invited. **Monday**. Start time: **10:10**. Room: Salon pasteur LVL1. Link to abstract.

Accurate mapping of mechanical properties across extensive areas in heterogeneous materials is essential for understanding phase-specific contributions to strength and hardness. High-Speed Nanoindentation Mapping (HSNM) enables their x-y spatial mapping through a fast and dense grid of indents. However, truthful measurements are complicated by *pile-up*, the plastic displacement of material laterally and vertically around an indent, often causing hardness and modulus overestimation, especially in materials with varying phase compliance. Traditional correction methods rely on time-consuming, localized Atomic Force Microscopy (AFM) measurements, which are impractical for large-area mapping.
This study presents a fast, generalized, and semi-automated method for evaluating and correcting pile-up effects in high-speed nanoindentation mapping (HSNM) leveraging the induced measurable changes in surface roughness (Sa), which are quantifiable through fast optical profilometry. By correlating these changes in roughness with the pile-up height measured via atomic force microscopy (AFM), universal calibration functions were derived and validated for a wide range of bulk materials and thin films, with additional verification provided through Finite Element Modeling (FEM). The method was demonstrated on 1-micrometer thick gold (Au), copper (Cu), and titanium (Ti) coatings on silicon substrates, as well as mechanically polished bulk titanium, aluminum, copper alloys, and bulk metallic glass samples. High-speed nanoindentation arrays were produced at different indentation depths (300, 500, 600, and 1000 nanometers), using a 10-times spacing rule to generate varying levels of pile-up. In bulk materials, a unique linear correlation was observed between changes in surface roughness and pile-up height, while coatings exhibited distinct slopes with a clear linear correlation maintained. This method offers a robust basis for quickly estimating pile-up height and correcting hardness and elastic modulus values, overcoming limitations posed by conventional AFM acquisition and expanding the applicability through the integration of machine learning for selective pile-up correction over large areas.
Applied to a benchmark Co-Cr-W hard metal alloy, the method uses unsupervised clustering to identify piling-up phases in the cobalt matrix while excluding the hard carbides. This approach reduced the hardness and modulus errors by up to 7%, uniquely enabling accurate phase-specific property mapping in high-speed nanoindentation advancing the mechanical microscopy frontier.

Deep Learning Mechanical Properties Classification of Metal-Ceramic Composites Using Nanoindentation Curves

Ortiz-membrado Laia (1) (2), Rossi Edoardo (3), Sebastiani Marco (3), Llanes Luis (4) (2), Jiménez-piqué Emilio (4) (2)

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Speaker: Ortiz-Membrado Laia. **Monday**. Start time: **10:30**. Room: Salon pasteur LVL1. Link to abstract.

Metal-ceramic composites display a distinctive microstructure wherein the metallic matrix and ceramic particles are interpenetrated and partially interconnected. This microstructure enables the combination of the hardness and wear resistance of the ceramic phase with the toughness and ductility of the metallic matrix. As a consequence, these materials are highly effective in certain applications that require resilience under extreme mechanical and thermal conditions. These composites present a significant challenge, as their mechanical behaviour is dominated by intricate interactions between the phases, particularly in proximity to interfaces or regions containing subsurface features. High-speed nanoindentation represents an effective tool for probing interactions at the nanoscale and for creating detailed hardness and elastic modulus maps. However, the mechanical phase identification remains challenging due to averaging in interphase regions and the influence of subsurface features on property measurements, which complicate interpretation and correlation.
To address these challenges, in this work, the morphology of the nanoindentation curves of each constituent phase of the composite material is incorporated to train a deep learning model to obtain a good micromechanical classification of the material. Before training the model, the nanoindentation curves were carefully analyzed to understand their shape and behavior depending on the location of the indentation on the material's surface. This included examining areas influenced by subsurface features, which were revealed through cross-sectional cuts made using Focused Ion Beam (FIB) techniques.

Properly labeled curves are transformed into images using the Gramian Angular Field (GAF), which is a representation for encoding time series as images. A ResNet neural network, was trained to analyze these images and facilitate phase classification. The resulting comprehensive classification distinguishes each distinct phase without interference from others, phases influenced by neighboring regions, ideal interphase where both phases contribute equally, and data representing failures or defects.

This classification, which considers all relevant dimensions-surface location and subsurface features-facilitates a more profound comprehension of the composite's mechanical behavior. Moreover, the classifications are represented in a spatial context in X and Y coordinates, in conjunction with the classification of the indentation curves, thereby creating a comprehensive mechanical map that reveals the spatial distribution and interactions of the material's phases and interfaces. By addressing these complexities, this approach provides a powerful tool for studying complex composite systems, facilitating precise material design, and optimizing performance.

Local assessment of residual stresses in a metal using FIB-DIC-FE: application to two-phase austeno-ferritic alloys

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1 - Groupe de physique des matériaux (France), 2 - Groupe de physique des matériaux (France), 3 - Université de Technologie Tarbes Occitanie Pyrénées (France), 4 - Groupe de physique des matériaux (France)

Speaker: Barbe Fabrice. **Monday**. Start time: **10:50**. Room: Salon pasteur LVL1. Link to abstract.

The presence of high residual stresses in additively manufactured metals is a well-known phenomenon. It is an unavoidable consequence of the interactions between high energy inputs and metallurgy involved in the processing, causing the development of irreversible strain mechanisms to accommodate the thermally induced internal stresses. As for other processing techniques involving high temperatures and metallurgy, these residual stresses must be considered with great concern as they can significantly affect the mechanical behavior (fracture, fatigue) of the produced part. Their magnitude can be measured on a millimeter scale with conventional techniques (e.g. X-Ray Diffraction), but this only provides an indication of the average state of stress in a highly heterogeneous context -both from the point of view of the microstructure and from that of the stress field.

The FIB-DIC method (1) is based on the removal of matter by micrometric Focused Ion Beam machining and Digital Image Correlation measurements from Scanning Electron Microscopy pictures to evaluate the 2D strain state resulting from the local relaxation of residual stresses. SEM enables to select the position and the shape of the machining operation and to collect the images provided to the DIC algorithm. The Finite Element method, by reproducing the operation of FIB machining in the microstructural context of the experiment, provides the mean to relate the measured relaxation strains to the local internal stress field being relaxed during machining. The generalization and automation of this FIB-DIC-FE method could lead to the possibility of mapping and quantifying multiaxial residual stresses at the intragranular scale of a metal alloy, considering the grains and their orientation in the vicinity of the machined grain.

In this work, a robust experimental protocol was developed to optimize the experimental parameters (machining, speckles, imaging, image processing, etc.) and applied to austeno-ferritic alloys. This specific alloy has a microstructure consisting of a few hundreds of micron-size grains. It is suspected that one phase induces stresses in the other, which affects the alloy ageing rate (2). The FIB-DIC method was applied in order to measure the residual stresses in both phases, as well as the potential gradients within the grains. The experiment is also coupled with Finite Elements modelling to consider the local properties anisotropy influenced by the crystalline orientation of the grains. Finally, the results are compared to the values obtained by X-ray diffraction, enabling the capabilities of the FIB-DIC method to be assessed.

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Nanomechanical investigation of plasticity mechanisms in Al/Al2O3 nanolaminates with ultrathin oxide layers

Edwards Thomas (1)

1 - Research Center for Structural Materials, National Institute for Materials Science (Japan)

Speaker: Edwards Thomas. **Monday**. Start time: **11:10**. Room: Salon pasteur LVL1. Link to abstract.

The last few decades have seen a rapid development of techniques to measure material properties at small length-scales, such as thermal analysis at the nano-scale (1), micro/nano-mechanical testing (2), even functional properties of specific microstructural features (3). However, deformation processing of materials has received much less attention at small length-scales: mainly only work-free processes – e.g. thermal – have been carried out in situ in electron microscopes. Indeed, few bulk deformation processing methods are adaptable at the micron or nano-scale, due to the need for complex tooling – e.g. rollers or extrusion dies. However, forging at the micron scale may be considered, even multi-axially, across a range of temperatures (-150 – 700 ∘C currently) and deformation schedules (monotonic or fatigue). Such multi-axial micro-forging is demonstrated here on a micron-scale cube of lamellar γ-TiAl alloy as a method to engineer, in a targeted manner, a hierarchically nanotwinned microstructure. Compared to regular lamellar γ-TiAl, this approach aims to reduce the strength anisotropy measured in subsequent micromechanical tests, which is normally thought to be the cause of poor inter-grain compatibility, and hence a low ductility of such alloys.

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Indentation of brittle materials – what micro-photoelasticity tells us about the stress field

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Speaker: Barthel Etienne. **Monday**. Start time: **11:30**. Room: Salon pasteur LVL1. Link to abstract.

Since the end of the 60s, our knowledge of the advanced mechanical properties such as plasticity, damage and cracking in brittle or quasi-brittle materials has made great progress thanks to the development of indentation (1,2). The choice of the applied load and the indenter geometry can selectively activate one or the other of these mechanisms, at least in part. As a result, indentation offers unparalleled insight into the non-linear and rupture properties of many brittle materials such as single crystal oxides and nitrides, semi-conductors, ceramics and glasses, and the effect of composition and processing.
Indentation studies in brittle materials are successful because the usually unstable fracture development is contained by the surrounding half space. However, this asset becomes a drawback when it comes to quantitative analysis because the deformation is very inhomogeneous and the indentation stress field is complicated. For more insight, several analytical or semi analytical models have been developed to take into account the presence of a plastically deformed zone below the indenter and its impact on the elastic field in the confining half space. Among these models, Yoffe's (3) has been used extensively because of its simple form (4). However, several questions are still open. For example, there has been some controversy over the suitability of indentation to measure fracture toughness (5), or the analysis of the experimentally observed cracking threshold in silicate glasses (6). In addition, it was recently found that Yoffe's model deviates considerably from the FEM predictions based on recently developed constitutive relations, to a point which raises doubts about the analysis of observed crack patterns (7). To clarify these and other questions, it would be expedient to accurately measure the stress field under indentation in brittle materials. However, this requires a mapping of stress or strain at a scale of the order of microns, to resolve the limited size achievable in a brittle material before fully developed fractures appear, and this is not an easy task.

To tackle this problem, we have used a highly-sensitive imaging system to record the low birefringence signal around shallow indents in silicate glasses, with optical path differences in the range of tens of nanometers. We analyze the data through the forward calculation of the birefringence pattern from FEA stress fields using accurately calibrated constitutive relations for the plasticity of silicate glasses. Comparison of predictions and experiments strongly support the validity of the method while suggesting refinements for the constitutive relations. In contrast, the photoelastic response predicted from Yoffe's analytical stress field is shown to differ significantly from the data, except in the far field. The perspectives opened by the method will also be discussed.

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A Novel Method for Rapid Assessment of Residual Stress: The Ball Impact Test

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1 - Department of Mechanical Engineering, Faculty of Engineering, Tokyo University of Science (Japan)

Speaker: Meng Yuxian. **Monday**. Start time: **11:50**. Room: Salon pasteur LVL1. Link to abstract.

Conventional methods for evaluating residual stress in mechanical components, such as X-ray diffraction and the hole-drilling method, are time-consuming. To improve efficiency, a non-destructive technique-the ball impact method-was proposed to rapidly assess the surface residual stress of components. This study investigated the response of a WC (tungsten carbide) ball impacting an Al2024 substrate under uniaxial residual stress using the finite element method. The effects of residual stress amplitude, impact velocity, and ball size on the coefficient of restitution (COR) were analyzed. The current results indicated that the COR decreases with an increase in tensile residual stress but increases with compressive residual stress. Furthermore, the impact velocity of 1 m/s is more suitable than those at 0.5, 3, and 5 m/s, as it results in a more apparent variation in the COR when the residual stress changes. However, ball size did not show significant influence on the COR. Additionally, a theoretical equation based on the Winkler model was developed, demonstrating high accuracy in predicting the tensile residual stress when the impact velocity higher than 1 m/s. Future studies will explore other influencing parameters, such as the biaxial residual stress field and substrate thickness. Experimental work will also be conducted to validate the reliability of this method.

Ultra-tough, strong and ductile Al2O3/Al hybrid nanolaminates

Pardoen Thomas (1) (2), Baral Paul Idrissi Hosni Raskin Jean-pierre Van Loock Frederik (3), Rusinowicz Morgan (4), Jaddi Sahar Coulombier Michael (5), Favache Audrey Lucas Stéphane (6), Bagherpour Alireza Gauquelin Nicolas (7), Verbeeck Jo Orekhov Andrey (8)

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Speaker: Pardoen Thomas. Keynote. **Monday**. Start time: **13:40**. Room: Salon pasteur LVL1. Link to abstract.

Amorphous alumina is hard but brittle like all ceramic type materials which affects durability under impact or scratch. In order to produce alumina-based ductile and tough coatings, alumina layers below 100 nm thickness were stacked with aluminium interlayers of thickness of 10-20 nm. The idea is that below 100nm alumina is ductile while the aluminium interlaminar can play a role of toughening agent. The Al2O3/Al nanolaminate exhibits exceptional performances including toughness equal to 300 J m-2 determined by on chip nanomechanics. This is almost two orders of magnitude higher than bulk alumina and higher than any other thin hard coatings. A hardness above 8 GPa combines with a fracture strain above 5 %. The origin of this excellent set of properties is unravelled via in–situ TEM and mechanical models. The combination of constrained alumina layers with ductile behaviour, strong "accommodating" interfaces, giant shear deformability of Al layers, and plasticity-controlled crack shielding cooperate to stabilize deformation, dissipate energy and arrest cracks. These performances unlock several options of applications of Al2O3 in which brittleness under contacts prevents benefiting from remarkable functional properties and chemical stability.

Measuring plastic anisotropy and toughness at small scale

Aubin Veronique (1), Lefranc Vivien (1), Boujnah Abir (1) (2), Ceron Arana Enzo (1) (2), Cornet Louis (1), Héripré Eva (3), Gandiolle Camille (1), Neggers Jan (1), Solas Denis (4)

1 - Laboratoire de Mécanique Paris-Saclay (France), 2 - Manufacture Française des Pneumatiques Michelin (France), 3 - Laboratoire Procédés et Ingénierie en Mécanique et Matériaux (France), 4 - Université Paris-Saclay, CNRS (France)

Speaker: Aubin Veronique. Invited. **Monday**. Start time: **14:20**. Room: Salon pasteur LVL1. Link to abstract.

Some materials are available in very small volumes, yet their mechanical properties have a strong influence on those of the structure. This is the case, for example, with steel drawn wires. These wires are obtained by wire drawing after severe plastic deformation and typically have a diameter of 200 microns. This is also the case for the tribologically transformed layer, known as TTS, which is formed under cyclic fretting loading and measures around 100 microns in thickness. Accessing the mechanical properties of these materials by conventional means is difficult. It is therefore necessary to set up micromechanical tests to gain access to their local properties.

During wire drawing, anisotropy in microstructure and mechanical behaviour develops in the steel wire. There is a lack of experimental data supporting this assumption since the classical methods used to characterize anisotropic yield behaviour is challenging on specimens with such small dimensions. Plastic anisotropy was characterized in these small-diameter wires in two complementary ways. Firstly, Knoop microhardness tests were carried out in both longitudinal and transverse directions assuming transverse anisotropy. Secondly, compression tests on FIB-machined micropillars were carried out using an in situ nanoindenter in the SEM. Both types of tests showed good agreement in terms of yield stress anisotropy. The yield anisotropy was then translated into Hill's yield criterion formulation. Results show a clear evolution of the shape of the yield surface and increasing plastic anisotropy as a function of wire-drawing strain.
In the fretting fatigue contact zone, a very hard, transformed layer appeared. Questions arise as to its role in contact, requiring characterization of its properties, both hardness and toughness. To this end, a bending test on a FIB-machined chevron-notched microbeam was carried out in situ in the SEM-FIB using a home-made testing machine. Crack size was determined by comparing DIC and FEM calculations, and toughness was measured during crack propagation. The results show that TTS is particularly brittle.

ENRICHING NANOINDENTATION WITH IN SITU ELECTRICAL MEASUREMENTS AND SEM OBSERVATIONS

Volpi Fabien (1), Rusinowicz Morgan Boujrouf Chaymaa Parry Guillaume Braccini Muriel Verdier Marc

1 - Science et Ingénierie des Matériaux et Procédés (1130 rue de la Piscine, BP 75 38402 Saint Martin DḤères France)

Speaker: Volpi Fabien. **Monday**. Start time: **14:40**. Room: Salon pasteur LVL1. Link to abstract.

A nanoindentation set-up coupled to electrical measurements and integrated into an SEM will be presented. Its application to the understanding of the interplay between mechanical and electrical behaviors of materials will then be discussed.

First, it will be shown how electrical measurements can be used to monitor the contact area between the indenter tip and the sample during indentation. The case of ideal materials (oxide-free surface (1)) or real materials (with a passivating surface layer (2)) will be considered. The in-situ SEM configuration is used for the precise positioning of indents on a complex system (precision _~100nm, Figure 1). The local mechanical properties will then be extracted accurately at a micrometer-scale (Figure 2).

Then, the interplay of mechanical and electrical behaviors of dielectric thin films will be addressed. First, we will show how a mechanical stress can modify the electrical conduction mechanism in a dielectric film (3). Counterintuitive observations will be fully explained numerically (by FEM analysis) by correcting the Poole-Frenkel conduction law with a strain-dependent factor. A threshold strain is identified as the keystone linking this strain-dependent conduction to the current line distribution within the dielectric. Finally, we will briefly show how an electrical stress can degrade the mechanical properties of dielectrics.

This presentation aims at demonstrating the strength of coupling electrical measurements to nanoindentation, either to process mechanical raw data or to understand the strong mechanical-electrical interplay in materials.

Statistical analysis of micro-deformation mechanisms of HCP zinc coatings by in-situ SEM-DIC aligned to EBSD

Hoefnagels Johan (1), König Dennis Slokker Gert-jan Mornout Casper Francesco Maresca Vermeij Tijmen

1 - Eindhoven University of Technology (Netherlands)

Speaker: Hoefnagels Johan. **Monday**. Start time: **15:00**. Room: Salon pasteur LVL1. Link to abstract.

HCP plasticity is complex due to the high anisotropy, apparent brittleness, and the alternative plasticity mechanisms that often activate, such as twinning, grain boundary sliding, and/or grain boundary migration, alongside plasticity of multiple active HCP crystallographic slip families. Detailed understanding of HCP plasticity is important for many applications, such as zinc corrosion coatings for steel. In this study, a range of novel methodologies for high-resolution and robust measurement and identification of micromechanical deformation mechanisms are applied to identify all the different plastic mechanisms. The methodologies are based on *in-situ* EBSD-SEM-DIC testing, capable of obtaining strain fields with a _~40nm spatial resolution aligned to EBSD microstructure maps (1,2), with recently developed advanced EBSD-SEM-DIC analysis routines to quantify all HCP slip system activity maps as well as the activity maps of twinning, grain boundary sliding, and grain boundary migration (3,4). A detailed statistical analysis has been conducted of these different plasticity mechanisms and their mutual interactions in zinc coatings, including $>$ 300 grains, corresponding to a total grain boundary length of $\sim$2.9 mm. This huge statistical analysis resulted in a detailed hypothesis that tries to explain the activation of the 4 active zinc slip families, the occurrence of twinning, and the statistical analysis between the various identified GB properties of each GB segment, including the identified in-plane sliding and/or apparent opening kinematics, its angle with the loading direction, the crystallographic misorientation angle. Additionally, the interaction between these plasticity mechanisms has been studied, as will be presented at ESMC in Lyon.

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Combining nano-DIC and ACOM TEM to study the grain boundary mediated plasticity of aluminium films

Baral Paul (1), Kashiwar Ankush (2) (3), Coulombier Michael (3), Delannay Laurent (3), Hoummada Khalid (4), Jean-pierre Raskin (5), Idrissi Hosni (2) (3), Pardoen Thomas (3) (6)

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Speaker: Baral Paul. **Monday**. Start time: **15:20**. Room: Salon pasteur LVL1. Link to abstract.

The viscoplastic response of metallic nano-crystalline films has been widely studied in the literature by means of nanomechanical testing, such as with in situ TEM experiments (1), (2) or dedicated on chip test methods (3). The enhancement of ductility (as compared to large grain samples) has been attributed to different mechanisms, including grain boundary sliding, grain growth or kinematic hardening due to dislocation pile up (2), (4). However, observations of the polycrystal deformation are challenging due to highly refined grain sizes.
The correlative methodology developed in this work allows probing the relationships between the microstructural changes and the total strain field, at a scale never resolved before – i.e. sample size of 2.5 x 25 μm and strain field resolution of 50 nm. The aluminium films deposited by sputtering (210 nm thickness) are mechanically loaded with an on chip method (3) and then observed after deformation in the transmission electron microscope (TEM). Nanoscale digital image correlation (nano-DIC) reveals multiple necking regions appearing at low plastic strains and further spreading along the sample gauge without leading to critical failure. Automated crystal orientation mapping (ACOM TEM) indicates that strain localization bands correspond to grain boundaries (GB) and that the global texture remains unchanged. The local shear amplitude achieved by such GB sliding correlates, to some extent, with the GB character. The complementary results obtained by both techniques shed some new light on the link between GB mediated plasticity and enhanced macroscopic ductility (5).

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Role of grain boundaries and temperature on the fracture toughness of CrN and AlN hard coatings

Lee Subin (1), Zhang Yinxia (1), Bartosik Matthias (2), Kirchlechner Christoph (1)

1 - Karlsruhe Institute of Technology (Germany), 2 - University of Leoben (Austria)

Speaker: Lee Subin. Invited. **Monday**. Start time: **16:00**. Room: Salon pasteur LVL1. Link to abstract.

The application of hard coatings, such as carbides and nitrides, has become essential in industries like aerospace, automotive engineering, and cutting tools, primarily due to their high hardness and ability to withstand harsh environments. However, fracture toughness is equally crucial, as coatings with insufficient toughness are prone to cracking and failure under cyclic thermal or sudden impact stress (e.g. in interrupted cutting processes). Grain boundaries (GBs) play a significant role in influencing both hardness and fracture toughness, yet the mechanisms governing fracture toughness, particularly at elevated temperatures, remain unclear. At room temperature, we conducted in situ scanning electron microscope microcantilever bending tests to examine the effects of GB orientation and density on the fracture toughness of CrN, AlN, and CrN/AlN multilayered structures. Specifically, we varied the loading direction relative to the columnar grain structure, observing a 10% increase in fracture toughness when the loading direction was perpendicular to the growth direction. Additionally, we compared submicron-sized columnar microstructures with epitaxial structures, noting a 30% higher fracture toughness in the epitaxial coating, which was free of GBs. Furthermore, at elevated temperatures, fracture toughness significantly decreased due to void formation and oxidation, particularly at the deposition temperature.

Multi-scale approach applied to the macro/micro-mechanical characterization of chromium-coated Zr-based nuclear fuel claddings

Taïbi Yanis (1) (2), Sao-joao Sergio (2), Kalacska Szilvia (2), Kermouche Guillaume (2), Saby Paul (2), Charbal Ali (1), Brachet Jean-christophe (1)

1 - CEA - DES ISAS DRMP SRMA (France), 2 - Mines Saint-Etienne (France)

Speaker: TaÏbi Yanis. **Monday**. Start time: **16:20**. Room: Salon pasteur LVL1. Link to abstract.

Micromechanical testing such as micro-pillar compression or micro-cantilever bending, have been significantly developed in the field of material science. These methods can provide good evaluation of mechanical properties at microstructural scales, offering insights into material behavior that traditional macroscale testing cannot provide. Small samples subjected to controlled loading conditions, allow studying deformation mechanisms, fracture behavior, and properties such as elasticity, yield strength, and plasticity at the microscale. These methods are well suited for the investigation of deposited chromium coatings recently applied to Enhanced Accident Tolerent Fuel (EATF) Zirconium based claddings. The generated coating microstructure (columnar near the outer surface and equiaxed near the substrate) and residual stresses induced by the fabrication process (HiPIMS-PVD) may provide specific mechanical properties of the thin chromium coating compared to pure (bulk) chromium materials. It is in this context that micromechanical testing are used to help understanding microstructure-mechanical properties relationships of chromium coated cladding tubes. To that end, micromechanical tests have been recently adapted and used on 15μm thick chromium coatings deposited on a Zr-based nuclear fuel cladding. In this poster, different micromechanical behavior characterization methods are illustrated and applied to the chromium coatings of interest. Firstly, bending test on pre-notched microcantilever coupled with EBSD is illustrated to assess the coating's toughness by tracking the crack propagation modes. Secondly, the elastoplastic behavior of the coating is assessed using micro-compression test. This micromechanical approach provides a good evaluation of the yield strength for instance. Finally, two methods to determine the residual stresses states are assessed: (1) traditional X-ray diffraction using the "$\sin^2(\Psi)$ method" and (2) by combination of Focused Ion Beam (FIB) machining and Digital Image Correlation (DIC), (so called FIB-DIC method).

Study of the effect of chromium doping on the grain boundary character and toughness of WC-Co

Giuliani Finn (1)

1 - Department of Materials [Imperial College London] (United Kingdom)

Speaker: Giuliani Finn. Invited. **Monday**. Start time: **16:40**. Room: Salon pasteur LVL1. Link to abstract.

Cemented carbides tools are used in applications demanding high hardness and toughness. However, fracture during operation of WC-Co tools is deleterious for tool performance and lifetimes. Interfaces in WC-Co, especially the WC grain boundary network are crucial, as crack path is mostly intergranular. Therefore, it is beneficial to gain knowledge about the WC boundaries. This will in turn allow for grain boundary engineering (GBE) of WC-Co tools with superior performance and lifetimes.
To achieve this, first WC grain boundaries have been examined using wedge loaded double cantilever beam (DCB) fracture tests. Since the literature review of WC-Co revealed that Σ2 twist boundaries are the most abundant boundary type, these have been studied with DCB tests,. Ideal Σ2 twist boundaries (perpendicular to the surface) for fracture testing have been identified from electron backscatter diffraction (EBSD) data via a custom MATLAB script working in MTEX. The fracture energy of Σ2 twist boundaries on a WC-10wt%Co sample have been compared to cleaving the lowest energy plane (type II) in a WC single crystal. Fracture energies of 3.59 ± 0.30 Jm-2 and 7.04 ± 0.36 Jm-2 were measured for cleaving Σ2 twist boundaries and type II planes respectively.

As a complementary study, grain boundary character distribution (GBCD) analysis for the most abundant boundaries (Σ2 boundaries and Σ13 boundaries) in WC-Co was performed. This analysis is based on Rohrer et al.'s five parameter grain boundary character distribution (GBCD) analysis where relative areas of different grain boundary types are specified as a function of lattice misorientation and boundary habit plane normal (2). Boundary populations are inversely correlated with boundary energy. Hence, GBCD analysis will provide an indication of grain boundary energy. Furthermore, the effect of chromium doping on WC boundary populations of a chromium doped sample (WC-10wt%Co-1wt%Cr) was examined and compared with an undoped WC-Co (WC-10wt%Co) sample. boundaries compared to all WC boundaries.

Manganese-silicate inclusions in iron: microstructural and mechanical insights to guide steel design

Hernández Escobar David (1), Lipcsei Sándor (1), Mortensen Andreas (1)

1 - École Polytechnique Fédérale de Lausanne (EPFL) - Laboratory of Mechanical Metallurgy (Switzerland)

Speaker: Hernández Escobar David or Lipcsei Sándor. **Monday**. Start time: **17:00**. Room: Salon pasteur LVL1. Link to abstract.

Despite significant advancements in steelmaking through history, complete removal of inclusions still remains an elusive goal for the metallurgical industry. In response, inclusion engineering emerged as a scientific endeavour aiming to harness the potential benefits of inclusions, by focusing on tailoring their nucleation, growth, and evolution with specific compositions, shapes, and distributions. Among the wide range of inclusion types, manganese-silicates stand out due to their deformability during hot working and low elastic mismatch with the iron matrix (1, 2), thereby minimizing local stress concentrations during elastic deformation and improving high-cycle fatigue and fracture toughness.
In this study, rhodonite ($MnSiO_3$) and tephroite (Mn_2SiO_4) inclusions are synthesized within a pure iron matrix via sequential deoxidation during arc-melting under an inert atmosphere. Microstructural characterization and compositional analyses are conducted using scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS), electron backscatter diffraction (EBSD), Raman spectroscopy and transmission electron microscopy (TEM). Local mechanical properties of the inclusions, namely, hardness and elastic modulus, are measured via nanoindentation, taking into account elastic contributions from the matrix (3, 4). Findings reveal a strong influence of the inclusion microstructure, stoichiometry and crystallinity on their mechanical properties, hence offering a range of hardness and stiffness combinations within the MnO-SiO_2 pseudo-binary phase system.
Microcantilever bending beams, produced by FIB milling on free specimen surfaces are designed to probe both the bending strength of individual inclusions and their inclusion-matrix interfacial strength through a series of displacement-controlled in-situ SEM micromechanical testing (5). These experiments yield two findings: (i) manganese-silicate inclusions can exhibit significant plastic deformation at room temperature, and (ii) the inclusion-matrix interfacial strength is comparable to the local strength of the oxides. Additional evaluation of the fracture toughness is performed in microcantilever bending beams micromachined within individual inclusions, estimating crack propagation through beam measurements of deflection in combination with FEM-derived crack length vs compliance curves.

In situ monitoring crack growth in nanostructured materials

Kiener Daniel (1), Jelinek Alexander (1), Moravcik Igor (1), Alfreider Markus (1)

1 - Montanuniversität Leoben, Department Materials Science (Austria)

Speaker: Kiener Daniel. **Monday**. Start time: **17:20**. Room: Salon pasteur LVL1. Link to abstract.

While nanostructured materials excel in strength, they commonly exhibit deficiencies in terms of ductility and fracture toughness. In order to better understand the processes governing local fracture processes and consecutively enhance the material performance, it is essential to identify the local energy dissipation mechanisms. Here we propose the use of miniaturized *in situ* fracture experiments conducted inside electron microscopes. This approach enables us to combine mechanical data, such as far field loading and local stress intensities, in analogy to macroscopic experiments. Furthermore, the actual crack length can be determined from continuous stiffness measurements, while local crack tip descriptors, such as the crack tip strain field or crack tip opening displacement, are assessable by employing digital image correlation of the recorded high resolution electron microscopy images. In harnessing these possibilities, we are able to establish correlations between common macroscopic static and cyclic failure characteristics and the herein assessed local crack tip processes. These insights contribute to enhancing our understanding of failure processes in nanostructured materials, and subsequently increase the respective contributions to further toughen these attractive class of materials.

Correlating mechanical damage with electrical resistance of foldable thin films

Cordill Megan (1)

1 - Erich Schmid Institute of Materials Science (Jahnstrasse 12, 8700 Leoben Austria)

Speaker: Cordill Megan. Keynote. **Tuesday**. Start time: **10:00**. Room: Salon pasteur LVL1. Link to abstract.

In order to assess the longevity of foldable electronics, folding or bending tests on model systems need to be performed to determine how the electrical resistance changes with the evolution of mechanical damage. However, not all bending tests are created equal in that different configurations lead to different amounts of mechanical damage, thus different electrical response. Two 90○ bending instruments were compared using two model metallic thin film systems on polyimide to establish if the two seemingly similar bending tests yield the same results in mechanical damage and electrical resistance. For statistics, 10-12 samples were tested of each film systems on each folding device using the same applied bending strain and number of cycles. Samples were intermittently characterized with confocal laser scanning microscopy and electrical resistance to correlate the amount of mechanical damage (crack density) and the electrical normalized resistance ratio of the damaged area. Results will show that even with the same bending radius, similar but not the same amount of mechanical damage forms for both bending devices. Additionally, the resistance as a function of cycles also differs after 10,000 cycles. A closer examination of the damage, especially in the Al/Mo film system indicates that the speed of the bending and if the samples experience spring back, can alter the received mechanical damage. The in-situ resistance data was further examined to correlate the evolution of cracks with resistance. The new knowledge gained about how the electrical data delivers mechanical damage information will aid in providing specific failure criteria for flexible electronics. Without specific failure criteria the electro-mechanical reliability of flexible and foldable material systems cannot be properly evaluated.

Deciphering Acoustic Emission of Microsamples with Machine Learning

Berta Dénes (1), Katzer Balduin (2), Ugi David (1), Groma István Schulz Katrin (3), Ispánovity Péter Dusán (4)

1 - Eötvös Loránd University (Hungary), 2 - Karlsruhe Institute of Technology (Germany), 3 - Karlsruhe Institute of Technology (Germany), 4 - Eötvös Loránd University (Hungary)

Speaker: Ispánovity Péter Dusán. Invited. **Tuesday**. Start time: **10:40**. Room: Salon pasteur LVL1. Link to abstract.

Plastic deformation in crystalline materials often exhibits significant inhomogeneity on the micron scale, presenting itself as a series of random local slip events of varying sizes. So far two robust techniques have been used independently to monitor this stochastic behaviour: microcompression for small-scale samples and acoustic emission (AE) for bulk specimens. While AE, with its high sampling rate (_~2.5 MHz), yields a rich dataset, its interpretation remains challenging due to the complexity of the measurement process.

In this talk, results from coupling these two experimental techniques will be presented in order to gain a more comprehensive understanding of the meaning of the AE signals. The first part of the talk will focus on microcompression of Zn single crystal micropillars oriented for basal slip. These samples are mounted on an AE sensor and compressed in situ within an SEM using a specially designed device for this purpose. Our findings reveal a precise correlation between the acoustic events detected during compression and the stress drops measured by the micromechanical device, facilitating the interpretation of AE signals.

The second part will delve into uncovering additional insights that can be gleaned from the AE data. To achieve this, we will leverage machine learning to investigate the extent to which stress-strain curves and their finer details can be reconstructed from the AE signal.

Finally, experiments will be presented where the orientation of the Zn micropillars are varied in order to tune the dominant deformation mechanism between dislocation glide, twinning and fracture. This allows the more precise interpretation of the AE through different deformation mechanisms. The presentation will conclude with a glimpse into potential future applications of combining micromechanics and AE.

Phase transformation in zirconia ceramics doped with ceria: A study by in-situ EBSD coupled with microcompression

Demetrio De Magalhaes Marcelo (1), Kalacska Szilvia (2), Comby-dassonneville Solène (3), Douillard Thierry (1), Reveron Helen (1), Meille Sylvain (1), Cornelius Thomas W. (3), Rodney David (4), Kermouche Guillaume (2), Thomas Olivier (3), Chevalier Jérôme (1)

1 - MateÍS (France), 2 - Laboratoire Georges Friedel (LGF) (France), 3 - im2np (France), 4 - Institut Lumière Matière (ILM) (France)

Speaker: Demetrio De Magalhaes Marcelo. **Tuesday**. Start time: **11:00**. Room: Salon pasteur LVL1. Link to abstract.

It has recently been proposed that ceria-stabilised tetragonal zirconia (CSTZ) could be utilised to overcome the typical trade-off between strength and ductility observed in difficult-to-deform materials. This can be achieved thanks to the ability of these ceramics to undergo a stress-induced martensitic transformation (tetragonal-to-monoclinic, *t-m*) at quite moderate stresses. CSTZ exhibits transformation-induced plasticity (TRIP), analogous to shape-memory alloys, which is directly linked to the phase transformation. The phase transformation is found to be significantly influenced by both crystal orientation and grain distribution. By understanding the impact of these factors, it is possible to focus on the processing of ceramics with high transformability, optimising the use of their TRIP effect.
In this study, the tetragonal-to-monoclinic (t-m) phase transformation is investigated, with particular emphasis on the role of microstructure in driving and influencing this transformation. The investigation focuses on both the crystallographic and mechanical factors that govern the initiation and subsequent propagation of the phase transformation. To explore these aspects, single- and oligocrystalline zirconia micropillars containing 12 mol% ceria (CeO2) were fabricated by focused ion beam (FIB) micromachining out of bulk material. Incorporating this amount of ceria ensures the stability of the tetragonal phase, whilst still allowing for phase transformation to occur when a critical stress is reached. Subsequently, *in-situ* electron backscatter diffraction (EBSD) coupled with microcompression testing was performed, to provide information concerning the crystallographic orientation and phase change. Finite-element method (FEM) analysis was performed to better understand the impact of the boundary conditions on the localization of the transformation.
The results demonstrate that in single-crystalline micropillars, stress concentrations arising from boundary conditions play a key role in determining the onset of phase transformation. In oligocrystalline micropillars, the crystalline orientation and arrangement of grains as well as the presence of defects significantly influence both the initiation and progression of the transformation. This approach facilitates a deeper analysis of the interplay between microstructural features and the evolution of the t-m phase transformation under mechanical loading.

In-situ transmission kikuchi diffraction during tensile testing for assessing deformation mechanism at the nanoscale in SEM

Maeder Xavier (1), Vermeij Tijmen Kroeker Philipp Sharma Amit Lou Jun Michler Johann

1 - EMPA Mechanics of Materials and Nanostructures (Switzerland)

Speaker: Maeder Xavier. Invited. **Tuesday**. Start time: **11:20**. Room: Salon pasteur LVL1. Link to abstract.

We have developed the capability to perform in-situ Transmission Kikuchi Diffraction (TKD) during tensile testing in SEM, enabling nanoscale characterization of the evolution of complex plasticity mechanisms. This was achieved by integrating a modified in-situ nanoindenter with a microscale push-to-pull (PTP) device, a conventional EBSD detector and a STEM detector in the SEM. A dedicated Focused Ion Beam (FIB) procedure was developed for site-specific specimen fabrication, including lift-out, thinning, and shaping into a dog-bone geometry. We will show the application of this methodology for several case studies: (i) To understand the initiation and evolution of nanoscale twinning and stress-induced martensitic transformation on a β-Ti single crystal, (ii) investigate strain localization and defect evolution in metal/ceramic nanolaminates, and (iii) investigate twin initiation and propagation in Re single crystals loaded along the c-axis direction. Overall, the in-situ TKD approach provides a robust alternative to in-situ EBSD and TEM testing, facilitating detailed analysis of deformation mechanisms at the nanoscale.

Coupling micro-compression testing and Laue micro-diffraction

Comby-dassonneville Solène (1), Demetrio De Magalhaes Marcelo (1) (2), Rhodes Bailey (3), W. Cornelius Thomas (1), Douillard Thierry (2), Reveron Helen (2), Huynh Gaël (4), Texier Michaël (1), Amodeo Jonathan (1), Meille Sylvain (2), Rodney David (4), Gianola Daniel (3), Chevalier Jérôme (2), Thomas Olivier (1)

1 - Aix Marseille Univ, Univ Toulon, CNRS, IM2NP UMR 7334, 13397 Marseille, France (France), 2 - Matériaux, ingénierie et science [Villeurbanne] (France), 3 - Materials Department, University of California, Santa Barbara, CA, 93106, USA (Santa Barbara, CA, 93106, USA United States), 4 - Institut Lumière Matière (France)

Speaker: Comby-Dassonneville Solène. Invited. **Tuesday**. Start time: **11:40**. Room: Salon pasteur LVL1. Link to abstract.

White-beam Laue micro-diffraction is a robust technique for probing the crystalline structure and orientation of materials, which, in particular, can highlight local crystalline deformations. Through detailed shape analysis of individual Laue spots, this method can also evidence the activation of specific slip systems (1). By tracking Laue diffraction spots over time, Laue micro-diffraction can also capture in situ structural changes such as phase transitions, making it highly suitable for *in situ* mechanical testing. In this communication, we will present two original studies based on the coupling between micro-compression testing, using a FT-NMT04 nanoindenter equipped with a diamond flat punch, and Laue micro-diffraction performed at BM32 ESRF synchrotron beamline.
The first investigation explores the TRansformation Induced Plasticity (TRIP) effect in ceria-doped zirconia single-crystalline micropillars with varied crystalline orientations (2). The TRIP effect in zirconia ceramics, which arises from the transformation from the tetragonal phase to the monoclinic phase under applied stress, is responsible for substantial plastic deformation, reaching up to 7%. Understanding this phase transformation is essential for advancing the development of 'ductile' ceramics. In this study, micro-pillar compression was conducted in situ during Laue micro-diffraction to investigate the effect of pillar orientation on the ease of phase transformation. The deformation pathways through various possible variants in the crystalline transformation between the tetragonal and monoclinic phases were compared with the crystallographic theory of martensitic transformation.

The second investigation focuses on plastic deformation in ferromagnetic intermetallic Heusler alloys (3). In these alloys, magnetic ordering is strongly influenced by local atomic environments and, consequently, by the introduction of plastic defects. Therefore, understanding how plasticity impacts the magnetic properties of these alloys requires a detailed analysis of plastic deformation mechanisms. In this study, the initial stages of plastic deformation in a $MnCu_2Al$ Heusler alloy were examined. Laue diffraction patterns were recorded at multiple stages of deformation, providing insight into crystal orientation and defect formation. In particular, the distribution of crystallographic orientations following micro-compression was analyzed. The elongation of orientation distributions on the inverse pole figure in the deformed state, as well as elongated features in the Laue spots, indicated lattice rotations, from which specific slip systems were identified.

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Revealing Transformation Toughening Size Effects in Ceria-Stabilized Zirconia via micro-Pillar Splitting combined with Raman spectroscopy

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Speaker: Sebastiani Marco. Keynote. **Tuesday**. Start time: **14:15**. Room: Salon pasteur LVL1. Link to abstract.

Fundamental applications of Yttria-stabilized zirconia (YSZ) include biomedical implants such as dental crowns and hip replacements. YSZ's enhanced toughness results from yttria stabilizing the metastable tetragonal phase of zirconia, which induces a martensitic transformation to the monoclinic phase under stress, increasing volume and closing cracks due to compressive stress. However, low-temperature degradation (LTD) reduces the material's ability to undergo this transformation, causing structural failures due to volume increase. Recent studies focus on ceria-stabilized zirconia (CeSZ) ceramics, which are being investigated to address the LTD issue. This study examines CeSZ with 10 mol %, 11 mol %, and 12 mol % ceria content to understand the toughening behavior, including R-curve behavior and the impact of ceria content and microstructural conditions. In this work, micro-pillar-splitting method is adopted for spatially resolved measurement of fracture toughness in CeSZ ceramics. Pillars ranging from 7 μm to 49 μm in diameter were fabricated via focused ion beam (FIB), in progressive increments of 7 μm, and tested using various nanoindentation tips. The method reveals a significant dependence of toughness on pillar diameter in CeSZ, with an increase from 2.5 to 4.0 MPa$\sqrt{m}$ for the 12 mol % ceria content linked to the activation energy for phase transformation and crack deflection. Raman spectroscopy is used to understand the development of phase transformation within the volume of the pillars before and after splitting. This research provides a novel framework for faster determination of contributions to toughening mechanisms in composite ceramic materials, paving the way for developing materials with superior strength and toughness.

Impact of Intrinsic Stress on Multiple Resonance Modes in Silicon Nanowires

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Speaker: Muzammil Muhammad. **Tuesday**. Start time: **14:55**. Room: Salon pasteur LVL1. Link to abstract.

Nanowires (NWs) are fundamental building blocks for next-generation sensors and micro-/nanoelectromechanical systems (MEMS/NEMS) due to their unique electrical, mechanical, and optical properties. However, these properties are significantly influenced by intrinsic stresses that can develop during fabrication or post-fabrication treatments. For instance, the buckling behavior of suspended silicon (Si) NWs due to intrinsic stresses can result in variations in mechanical properties and the dopant diffusion mechanism within the NWs. With the increasing technological focus on utilizing Si NWs as resonators, it is crucial to investigate the impact of intrinsic stresses on their resonant frequencies to ensure the reliable design of next-generation devices. This study systematically induces and characterizes stresses in Si NWs and evaluates their effect on multimodal resonant frequencies. A top-down fabrication approach was used to create double-clamped Si NWs with lengths of 40 μm and sub-micron widths and thicknesses, all fabricated on a stress-free substrate. The Si NWs are obtained in a suspended configuration with an etch depth of up to 2 μm, making them suitable for vibrational analysis. Once the samples were prepared, Raman spectroscopy was used to measure the intrinsic stresses in the as-fabricated Si NWs. The resonant frequencies up to the first three vibrational modes were then measured using a Laser Doppler Vibrometer (LDV). Following the initial measurements, standard thermal processing was applied to induce additional stresses in the Si NWs. Raman characterization was conducted again to confirm the presence and quantification of the stress induced by thermal processing. Subsequently, resonant frequencies were measured to assess the effect of intrinsic stresses across three vibrational modes. The results demonstrated a significant variation in the resonant frequencies of the Si NWs after the introduction of stresses. These findings emphasize the critical role played by intrinsic stresses in determining the vibrational behavior of Si NWs and provide a practical pathway for optimizing the functionality of Si NW-based resonators.

Fracture Toughness and Durability of HiPIMS-Deposited Hard Coatings

Molina-aldareguia Jon (1) (2), García Carrero Arley (2) (3), Santiago Jose Antonio (3), Diaz-rodriguez Pablo (3), Monclús Miguel (2), Fernandez Ivan (3), Guzmán-bautista Álvaro (1), Kirchlechner Christoph (4), Lee Subin (4)

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Speaker: Molina-Aldareguia Jon. **Tuesday**. Start time: **15:15**. Room: Salon pasteur LVL1. Link to abstract.

The High-Power Impulse Magnetron Sputtering (HiPIMS) technique enables the deposition of coatings with high hardness, low defect densities, and uniform, conformal coverage over complex 3D geometries, meeting the strict tolerances required in micromachining applications. High-speed machining (HSM) applications demand not only high hardness but also sufficient fracture toughness, which is critical for maintaining the structural integrity of both bulk and coated engineering components. However, these mechanical properties are often antagonistic, particularly in materials capable of plastic deformation, where high hardness typically correlates with lower fracture toughness. This study aims to systematically evaluate the fracture toughness and machining performance of AlTiN- and TiN-based coatings doped with Si, deposited by HiPIMS using different process parameters. Micro-fracture toughness was assessed on freestanding films using single cantilever bending tests, effectively minimizing residual stress and substrate interactions to obtain precise KIC values. Crack formation at the cutting edge of a 0.4 mm diameter microdrill was observed using FIB, while the composition of the coatings was determined by GDOES. Additionally, XRD was employed to analyze grain growth texture and peak shifts, enabling the evaluation of biaxial stresses. The AlTiSiN coatings exhibited a hardness of 35 GPa, while TiSiN coatings reached 40 GPa. Fracture toughness ranged from 1.78 MPa$\cdot\sqrt{m}$ to 2.2 MPa$\cdot\sqrt{m}$, depending on the HiPIMS parameters used. In micromachining tests on the TiAl6V4 alloy, the coatings allowed continuous micro-milling to be extended from 40 minutes to over one hour. These findings link toughness values, stress reduction, and crack formation at the cutting edges with tool durability in machining applications.

Electrically induced viscous flow in oxide glasses at Room: temperature: electrical-nanoindentation tests vs e-beam effect

Rusinowicz Morgan (1), Volpi Fabien (2), Braccini Muriel (2), Parry Guillaume (2), Verdier Marc (2), Pardoen Thomas (3), Jean-pierre Raskin (4), Delannay Laurent (3), Sao-joao Sergio (5), Guillaume Kermouche (6)

1 - Laboratoire Georges Friedel (France), 2 - Science et Ingénierie des Matériaux et Procédés (France), 3 - Institute of Mechanics, Materials and Civil Engineering [Louvain] (Belgium), 4 - Institute of Information and Communication Technologies, Electronics and Applied Mathematics (Belgium), 5 - Mines Saint-Etienne (France), 6 - Laboratoire Georges Friedel (France)

Speaker: Rusinowicz Morgan. **Tuesday**. Start time: **15:35**. Room: Salon pasteur LVL1. Link to abstract.

Over the past decade, several studies have demonstrated the possibility of inducing strong creep/relaxation phenomena in amorphous silica at room temperature during mechanical testing under TEM/SEM electron beam irradiation. Depending on the e-beam parameters, the viscous flow can be so pronounced that silica exhibits ductile behavior, described as superplastic by the authors, allowing it to be shaped at room temperature. These intriguing observations raise several questions. What electrical magnitude drives the mechanical processes? Does the phenomenon also occur in other oxide glasses? Is this solely an effect of electron irradiation, or can it be replicated with a DC current? The present work aims to address these questions by performing electrical-nanoindentation tests on amorphous thin films, deposited on silicon substrates, of a dense Al2O3 model material and a nanoporous SiOCH material used in microelectronic applications. The tests involve biasing the substrate and measuring the current flowing through the tip during mechanical loading. Significant viscous flow was observed in both materials, indicating that this is indeed a purely electrically-assisted phenomenon and appears to be generic to oxide glasses. Furthermore, electrical-nanoindentation tests have also shed light on the relevant electrical magnitude, which was previously challenging to determine in e-beam irradiation experiments that involve multiple less well controlled parameters: acceleration voltage, probe current, magnification, irradiation time, irradiated volume, etc. Finally, micropillar relaxation tests of amorphous silica under e-beam irradiation were conducted to quantify the mechanical response of the oxide glass in relation to the electrical quantity of interest.

Indentation size effect in metallic materials in sub-micrometer scale

Čech Jaroslav (1)

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Speaker: Čech Jaroslav. Invited. **Tuesday**. Start time: **16:35**. Room: Salon pasteur LVL1. Link to abstract.

Indentation size effect (ISE) is frequently observed in the nanoindentation of metals and alloys, and it is manifested by an increase of hardness with a decreasing penetration depth. This makes it very difficult to compare the values of hardness obtained at different (in particular, small) depths. The classical explanations of this phenomenon are based on the concepts of strain gradient plasticity. In the dimensions where the density of statistically stored dislocations (SSDs) is too low to accommodate the shape of the indenter (i.e., in low penetration depths), geometrically necessary dislocations (GNDs) must be considered. Indentation size effect at shallow indentation depths still remains a challenge as it cannot be correctly described by the Nix–Gao model based on the concept of strain gradient plasticity and geometrically necessary dislocations, which is valid for higher penetration depths. The reasons for this discrepancy may be various, and multiple microstructural factors may play a role at the nanoscale. The effects of several material (e.g., grain size, crystal orientation, pre-deformation) and experimental (e.g., indenter tip radius) parameters on the indentation size effect in sub-micrometer scale were studied. The results on several metallic materials show interesting insight into the deformation mechanisms and the evolution of the plastic zone during the low-depth indentation.

Experimental study of the mechanical properties of oxygen enriched Ti alloys

Bornowsky Lucille (1) (2), Marano Aldo (3), Oudriss Abdelali (2), Feaugas Xavier (2)

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Speaker: Bornowsky Lucille. **Tuesday**. Start time: **16:55**. Room: Salon pasteur LVL1. Link to abstract.

A major limitation to the use of titanium alloys at higher operating temperatures in aircraft engines is the degradation of mechanical properties due to long-term exposure to oxygen. The high solubility and diffusion coefficient of oxygen in titanium result in the formation of a brittle layer due to the oxygen diffusion gradient under the surface. Despite the small size (< 200 μm) of this oxygen-rich layer (ORL) relative to the dimensions of structural components, the mechanical gradient induced by oxygen diffusion can cause premature damage and subsequent failure. Most fatigue life prediction models for titanium alloys are based on simplifying assumptions and do not consider the chemical, microstructural and mechanical heterogeneities in the oxygen-affected zone.
The aim of this work is to quantify the effect of oxygen on local elastic and plastic properties through micro-scale observations. A further aim is to correlate the mechanical property gradient with changes in the mechanical behavior and fatigue life of macroscopic samples.
Micro-tensile specimens were prepared from Ti6242s, a commercial quasi-alpha alloy. Specimen were pre-oxidized at 600∘C for 3000h, resulting in an ORL extension of 100 μm. First, we measured the effect of oxygen on local properties using high-speed nanoindentation to quantify the evolution of reduced elastic modulus and hardness as a function of oxygen concentration. Second, we investigated the effect of pre-oxidation on slip localization through micro-mechanical tensile testing combined with Digital Image Correlation (DIC) and Scanning Electron Microscopy (SEM). For both investigations, the effect of grain type and crystalline orientation is discussed by correlation with EBSD (electron backscatter diffraction).

Advanced Thin Film High Entropy Alloys with Tailorable Microstructure and Mechanical Properties

Vacirca Davide (1), Bignoli Francesco (1) (2), Li Bassi Andrea (2), Best James Paul (3), Dehm Gerhard (3), Djemia Philippe (1), Ghidelli Matteo (1)

1 - Laboratoire des Sciences des Procédés et des Matériaux (France), 2 - Dipartimento di Energia [Milano] (Italy), 3 - Max-Planck-Institute for sustainable materials (Germany)

Speaker: Vacirca Davide. **Tuesday**. Start time: **17:15**. Room: Salon pasteur LVL1. Link to abstract.

High entropy alloy thin films (HEAs-TF) have recently gained attention due to their possibility to combine mutually exclusive properties, such as high yield strength, ductility and thermal stability, while offering a wide range of chemical compositions. For this reason, HEAs-TF have potential applications for microscale electrical devices or high-performance coatings (1). However, microstructural control for advanced HEAs-TF (nanocrystalline films, nanolaminates) is often limited by traditional thin film deposition techniques such as magnetron sputtering, hindering the formation of HEAs-TF with large mechanical properties (yield strength, ductility). In this regard, pulsed laser deposition (PLD) was used to prepare advanced HEAs-TF allowing to easily control the nanoarchitecture of nanocrystalline films and ultrafine nanolaminates.
In this context, firstly I will focus on the synthesis of nanocrystalline CoCrCuFeNi HEA-TFs by PLD with a wide range of microstructures (grain size and morphology) obtained simply by controlling the background gas pressure, while comparing with sputter-deposited counterparts. A transition from compact to nanogranular morphology was observed for deposition pressures > 1 Pa, leading to a decrease in mass density and grain size (6.81 g/cm3 and 11 nm, respectively) compared to the compact counterpart (7.72 g/cm3 and 40 nm, respectively). These films by PLD show increased hardness ($\approx$11 GPa) compared to sputter-deposited films ($\approx$8.3 GPa) due to their ultrafine grain structure leading to Hall-Petch strengthening. Similarly, micropillar compression tests show high yield strength of 1.9 GPa with high plastic deformability (30% strain). Post-thermal annealing treatments reveal grain coarsening and segregation of a secondary BCC phase starting at 400∘C for both compact and nanogranular films. However, nanogranular films maintain a lower grain size during annealing ($<$ 20nm), thus retaining higher hardness of 8.5 GPa (Hall-Petch strengthening).

Secondly, I will focus on Al/HEA nanolaminates (NLs) by PLD and magnetron sputtering, aiming to block the propagation of dislocations by controlling the interface density to improve hardness and yield strength (2). Nanolaminates with different atomic compositions have been fabricated by magnetron sputtering, involving semi-coherent (FCC/FCC Al/CoCrCuFeNi) and incoherent (FCC/BCC Al/Al25(CoCrCuFeNi)75) interfaces to further hinder cross-layer dislocation propagation and boost mechanical properties. Among the main results, *in situ* micropillar compression test shows that incoherent interfaces have greater capability to improve yield strength (up to 2.2 GPa), while still showing great plastic deformability with no appearance of cracks even at 30% deformation. Using PLD, a wide range of bilayer periods (Λ) was explored, allowing to prepare ultrafine NLs with a bilayer period as low as 2.5 nm up until 400 nm. These NLs show high hardness, with a maximum of 9.8 GPa for $\Lambda = 25$ nm due to the high interface density, despite having a 50% volume fraction of Al.

Our results show how PLD and sputtering can be used to control the nano-engineering of TF-HEAs, resulting in improved and tunable mechanical properties with key implications for industry applications.

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(2) A. Sàenz-Trevizo *et al.*, Nanomaterials by design: a review of nanoscale metallic multilayers Nanotechnology, 31, 2020

Tailoring composition and microstructure to control mechanical properties and thermal stability of thin film metallic glasses

Poltronieri Cristiano (1), Brognara Andrea (2), Djemia Philippe (1), Faurie Damien (1), Dehm Gerhard (2), Best James Paul (2), Ghidelli Matteo (1)

1 - Laboratoire des Sciences des Procédés et des Matériaux (France), 2 - Max-Planck-Institute for sustainable materials (Germany)

Speaker: Ghidelli Matteo. **Tuesday**. Start time: **17:35**. Room: Salon pasteur LVL1. Link to abstract.

Thin film metallic glasses (TFMGs), with thicknesses below _~500 nm, are materials characterized by a unique mechanical properties involving large yield strength (close to the theoretical limit) and ductility (> 10%) due to the activation of mechanical size effects (1). However, several scientific questions dealing with their mechanical properties and deformation behavior together with thermal stability are still open, especially focusing on the role of the composition, addressing key questions involving the effect of local order, bond strength and free volume. This is crucial in order to synthetize TFMGs with engineered microstructure (i.e. fully amorphous nanolaminates) with even controlled/boosted mechanical properties and high thermal stability which can be maintained and extended to large thicknesses (> 3 um).
Within this context, I will first focus on the effect of composition on mechanical and thermal properties of ZrxCu100-x TFMGs with a large composition range from 24 up to 61 Zr at.% (2). Different crystallization temperatures have been found with the maximum value of _~380∘C for Zr52Cu48, reporting the highest number of mixed Zr-Cu bonds and mixing enthalpy. Moreover, the hardness increases with Cu content, from 5.5 up to 7.7 GPa for Cu-rich specimens showing a closer atomic distances and stronger bonds. Additionally, the loading rate dependency analysis revealed that larger pop-in's appeared at low Cu (at.%) content due to a more disordered atomic structure with less strong atomic bonds enabling the formation of annular shear bands around the indent (2).

In a second part of the talk, I will expand the TFMGs compositional space to ternary alloys in which Al is added to ZrCu (from 0 to 12 at.%), while focusing on the mechanical properties and thermal stability (3). Synchrotron X-Ray diffraction reveals that the addition of Al reduces the average interatomic distances by _~10 pm with the formation of shorter bonds (Al-Zr and Al-Cu), influencing the mechanical response (shear/elastic moduli and hardness) which increases by _~15% for 12 at.% Al. The glass transition (Tg) and crystallization (Tx) temperatures increase by Al addition reaching 450 and 500 ∘C, respectively, for ZrCuAl12 due to the reduction in atomic mobility inhibiting atomic reconfiguration (3).

Finally, I will show how we can exploit the previous knowledge with the fabrication of fully amorphous Zr24Cu76/Zr61Cu39 and ZrCu/ZrCuAl9 nanolaminates with different nanoscale bilayer period (from 200 down to 50 nm) and total thickness of 3 um (4). The combined effect of local chemistry variation and nanointerface density influences the thermal stability as well as the deformation behavior and the mechanical properties with severe shear displacements and strong compositional intermixing along the shear band-deformed zone. Among the main results, I will show an enhanced thermal stability above the single layer constituents as well as modular mechanical properties with large plastic deformation (> 10%) in compression together with yield strength values > 1.5 GPa achieved for the smallest bilayer periods.

In conclusion, I will provide guidelines to the design of compositional and microstructural-tailored TFMGs with tuned mechanical properties and thermal stability with potential impact for applications.

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Investigation of the effect of SMAT on IN718 mechanical behavior using in situ SEM micromechanical testing

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1 - ONERA (France), 2 - Université de Technologie de Troyes (France)

Speaker: Garambois Anna. **Tuesday**. Start time: **17:55**. Room: Salon pasteur LVL1. Link to abstract.

Mechanical surface treatments are widely used in the aeronautical industry with the dual objective of enhancing the surface properties of crucial components and delaying fatigue crack initiation. Indeed, fatigue damage was identified as the primary mechanism of failure for turbine disks, with crack initiation predominantly occurring on the surface.
Surface Mechanical Attrition Treatment (SMAT) is a process that creates a nanocrystalline layer on the surface of treated mechanical parts in addition to superficial compressive residual stress and strain hardening. Previous studies have shown that SMAT can increase the yield strength, stress at failure, and improve the fatigue life of metal parts by inducing severe plastic deformations at the surface of the material without altering its chemical composition or core microstructure. Given the thermal and mechanical loads experienced by aeronautical components during service, it is important to investigate the relaxation of residual stresses introduced by SMAT and the associated changes in material properties. Such an understanding is vital for accurately assessing the real impact of SMAT on the longevity and reliability of these components.

This study aims to investigate the effect of SMAT on the mechanical properties of a nickel-based superalloy, Inconel 718. This material, especially in its Direct Aged (DA) condition, is commonly used in aeronautical applications due to its good mechanical properties and corrosion resistance. Existing literature and measurements indicate that the microstructural changes induced by SMAT are localized within the first few hundred of micrometers of the sample surface and may impact the mechanical properties of the material under thermomechanical loading. In order to capture these evolutions at the appropriate scale, innovative characterization techniques, such as *in situ* SEM testing, seemed an appropriate choice. *In situ* SEM four-point bending tests were performed at 20∘C and 450∘C on both untreated and SMAT-treated samples, with two different sets of SMAT parameters. Combined with Digital Image Correlation (DIC), this technique allows access to the local strain fields of the specimen by calculating the displacements of each pixel between the reference image and the images of the deformed material taken during the test. Local changes in microstructure and mechanical parameters can be monitored using this experimental protocol, especially as these tests are coupled with EBSD analysis.

Initially, a broad zone was examined to determine the strain across the full depth of the specimen, using the inherent microstructure of the material as a speckle pattern for pixel identification. First results show a delayed onset of plasticity at 20∘C and 450∘C for the SMAT-treated material, compared with the untreated material, in both the compression and tension solicited zones. The observation of similar results in the compression and tension zones is noteworthy, particularly in light of the significant compressive residual stresses that were measured. This suggests that SMAT may induce a work hardening effect, which compensates the influence of compressive residual stresses.

This broader approach offers an overview of macroscopic specimen behavior; however, it lacks the resolution to capture strain localization and slip bands. Therefore, the sample was also studied at more refined scale, with a speckle pattern created through electron-beam lithography, to observe strain localization and plasticity mechanisms. EBSD maps were also acquired during the tests, to visualize the evolution of strain hardening in the sample via Kernel Average Misorientation (KAM) measurements.
In parallel, simulations of the bending tests were conducted, incorporating the surface residual stress gradient obtained from XRD profiles and considering the work hardening. Comparison of these simulations with experimental results enables the dissociation of the contributions from residual stresses, work hardening and grain refinement, thereby providing a deeper understanding of the experimental observations. This work also supports the development of a model that captures the cyclic non-linear behavior of the

material, providing a basis for more accurate fatigue life estimations for the SMAT-treated material.

Superelastic behaviour at the nanoscale in shape memory alloys

San Juan Jose M. (1), Gómez-cortés José F. (1), Nó Maria L. (1)

1 - University of the Basque Country (Spain)

Speaker: San Juan Jose M.. Invited. **Tuesday**. Start time: **18:15**. Room: Salon pasteur LVL1. Link to abstract.

Shape memory alloys (SMA) are functional materials exhibiting the shape memory and superelastic effects. These phenomena were also observed at mico/nano scale, particularly in Cu-Al-based SMA (1-3), where ultrahigh mechanical damping was discovered during nano-compression tests in micro and nano pillars. The reproducibility of the superelastic behaviour along thousands of nano-compression cycles was also tested in micro and nano pillars, which undergo a long-term stable behaviour during years (4,5).
In the present work we approach a study of the stress-induced martensitic transformation in a series of micro and nano features, for potential damping applications in MEMS technology. Different kind of micro/nano pillars, specific dog-bone nano-samples and micro-bridges were milled by focused ion beam in a FEI Helios Nanolab 650, on (001) oriented single crystal slides of Cu-Al-Ni SMA. Then, the samples were tested in compression and bending at the Hysitron 950 nanoindenter, as well as in tension during in-situ experiments with the Hysitron Picoindenter PI-85 mounted inside the JEOL 7000F field emission scanning electron microscope, and using a flat diamond indenter of 20 micrometres in diameter. An experimental difficulty was to evaluate the required load to induce the stress-induced transformation avoiding an overload that could scratch the sample in the first test. This is a particularly critical aspect because of the size effect on the critical stress for superelasticity observed in these SMA (6,7), but the predicted model in such works allowed a successful estimation of the stress required for each sample.

In this work a complete study of the superelastic behaviour at the nanoscale in compression and tension, which was approached in several Cu-Al-based shape memory alloys, will be presented. Exceptional superelastic strain above 8%, with a complete recovery when withdrawing the stress, will be reported. These results exhibit a relevant potential interest for its application in Micro-Electro-Mechanical Systems (MEMS). In addition, during superelastic tests, the Cu-Al-based SMA exhibit an exceptionally high mechanical damping (2, 5, 8, 9) that can be used to damp noisy vibrations in MEMS technology. Then, we also report a comparative study of the superelastic damping at the nanoscale in several Cu-Al-based SMAs and in different sollicitation modes, compression, tension and bending.

These results pave the way for designing micro/nano actuators and micro-dampers of Cu-Al-based SMA, which can work in different mechanical modes of compression, bending, and torsion, opening the way for many applications on micro/nano mechanics at the nanoscale.

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Abnormal temperature dependence of strength in Fe-2.4wt.%Si by microscale cryogenic testing

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Speaker: Tian Chunhua. Invited. **Wednesday**. Start time: **10:00**. Room: Salon pasteur LVL1. Link to abstract.

Well-known is that the strength of body-centered-cubic (bcc) metals exhibits a strong temperature dependence, namely, increasing with decreasing temperature, which is correlated with the thermal assistance of kink pair nucleation. However, by microscale cryogenic testing (-80 ∘C to 25 ∘C) on Fe-2.4 wt.% Si, we have observed a strength anomaly with temperature. The anomaly is most significant for 1 μm (diameter) small pillar size and gradually weakened by increasing pillar size (Fig.1c). Besides the strength anomaly, the compressed morphology of slip patterns differs noticeably. Particularly at -30 ∘C where the lowest strength occurs, the slip traces are so diffusive which are instead localized at 25 ∘C. The diffusive complex patterns might originate from the intensive cross slips, as we see wavy dislocation lines in TEM images implying changing slip planes. Molecular dynamics simulation is performed to further understand the strength anomaly.

Update of the HTSI method: application to mechanical characterization of CaF2 up to 800°C

Tiphéne Gabrielle (1), Adogou Benedicte (2), Guillonneau Gaylord (3), Kermouche Guillaume (4), Bergheau Jean-michel (5), Oliver Warren (6), Loubet Jean-luc (3)

1 - Institute of Mechanics, Materials and Civil Engineering [Louvain] (Belgium), 2 - Laboratoire Georges Friedel (France), 3 - Laboratoire de Tribologie et Dynamique des Systèmes (36 Avenue Guy de Collongue, 69134 Ecully Cedex France), 4 - Laboratoire Georges Friedel (France), 5 - Laboratoire de Tribologie et Dynamique des Systèmes (France), 6 - KLA Nanomechanics (United States)

Speaker: Loubet Jean-Luc. **Wednesday**. Start time: **10:20**. Room: Salon pasteur LVL1. Link to abstract.

The recent development of the High-Temperature Scanning Indentation (HTSI) method (1) allows for the characterization of material mechanical properties quasi-continuously over a large temperature range in 1-day experiments. However, such a technique employs a nanoindentation cycle with a constant maximum load applied regardless of the temperature. Thus, for materials exhibiting an Indentation Size Effect (ISE), the variations in hardness with temperature can stem from both temperature and ISE. It becomes more challenging to differentiate between these two effects and analyze their impact on the mechanical properties.
To address this issue, a new 1-second indentation cycle has been implemented. A 0.5-second half-sine function is utilized during loading, followed by a 0.1 to 1-second creep segment and the 3-step unloading function used previously. To control the maximum achieved depth across temperatures, the maximum applied load is adjusted experimentally between each indentation, using previous indentation tests and results. This approach allows for the determination of hardness, Young's modulus, and creep properties of a material at a given maximum depth over a wide temperature range.

This methodology has been applied to CaF2 single-crystal from room temperature (RT) to 800∘C. The implemented cycle enables the characterization of this material at 1000nm depth over the entire temperature range. Comparison with tests performed using the previous indentation cycle highlighted the impact of the ISE in temperature. The obtained results were compared to conventional indentation results.

(1) G. Tiphéne *et al.*, " High-Temperature Scanning Indentation: A new method to investigate in situ metallurgical evolution along temperature ramps ", *J. Mater. Res.*, vol. 36, no 12, p. 2383-2396, juin 2021, doi: 10.1557/s43578-021-00107-7.

Analysis of Thermally Activated Processes via High Temperature Scanning Indentation

Sos Marcel (1), Bruns Sebastian (1), Bruder Enrico (1), Durst Karsten (1)

1 - Physical Metallurgy, TU Darmstadt (Germany)

Speaker: Sos Marcel. **Wednesday**. Start time: **10:40**. Room: Salon pasteur LVL1. Link to abstract.

Nanoindentation serves as a tool to map mechanical properties of materials not only at room temperature, but also at temperatures at or close to the operating temperature of materials used for high temperature applications. Thermally activated processes can then be characterized via the calculation of strain rate sensitivity and activation volume at different temperatures.
Testing at elevated temperatures, however, presents its own issues in the form of thermal drift due to temperature mismatch and pronounced tip-sample-interactions.

The temperature matching procedure in particular can be time-consuming, which limits the applicability of conventional high temperature nanoindentation to materials with sufficiently stable microstructures at the testing temperature. To overcome some of these limitations, the High Temperature Scanning Indentation (HTSI) technique was introduced by Tiphene et al. (1). It utilizes a large amount of high speed tests (on the order of 1s each) to generate a high density of data points and measure mechanical properties during thermal ramping of a sample. This allows for not only the investigation of dynamic processes like recrystallization, but also for the characterization of brittle-to-ductile or phase transitions with unprecedented data density.

In this contribution, the HTSI technique is applied to investigate the thermal stability of ultrafine-grained copper alloys processed via high pressure torsion (2,3), following different thermal profiles to evaluate hardness and strain rate sensitivity of a function of temperature and time. Fused silica is used as a reference material to show the reliability of the obtained data and the comparability to other testing methods. Additionally, the applicability to brittle-to-ductile transitions is demonstrated on Chromium.

(1) G. Tiphene J. Mater. Res. 2021, 36(12), 2383-2396
(2) E. Bruder Scripta Mater. 2018, 144, 5-8
(3) T. Keil IOP Conf. Ser.: Mater. Sci. Eng. 2022, 1249(1), 12003

HIGH TEMPERATURE SCANNING INDENTATION: LAST RESULTS ON AMORPHOUS SELENIUM

Moul-el-ksour Fatima-zahra (1), Tiphéne Gabrielle (2), Guillonneau Gaylord (1), Kermouche Guillaume (3), Loubet Jean-luc (1)

1 - LTDS, UMR CNRS 5513 (France), 2 - IMAP, iMMC, UCLouvain, Belgium (Belgium), 3 - LGF, UMR CNRS 5307 (France)

Speaker: Moul-El-Ksour Fatima-Zahra. **Wednesday**. Start time: **11:00**. Room: Salon pasteur LVL1. Link to abstract.

The High-Temperature Scanning Indentation (HTSI) technique is a quasi-continuous measurement method renowned for its ability to monitor material properties and their variations across a wide temperature range. It has demonstrated the capability to detect critical phenomena such as static recovery, recrystallization, glass transition, and brittle-to-ductile transitions in various materials, including pure cold-rolled copper, aluminum, and thin-film metallic glasses. Over time, HTSI has proven to be a robust and effective tool for correlating measurable properties with the microstructural evolution of materials.
Amorphous selenium (a-Se), a member of the chalcogenide family, is mainly known for its interesting semiconducting and optoelectronic properties. One of its important characteristics is its temperature and humidity-dependent sensitivity.
In this conference, we present our latest findings using HTSI on amorphous selenium. The technique was employed to measure Young's modulus, hardness, and creep properties in situ during cyclic heat treatment. We will highlight how these properties evolve with temperature, showcasing the fundamental behaviors and transformations observed in the studied material.

Small scale deformation of cemented carbides at high temperature

Francesc Barbera (1), Ortiz-membrado Laia (1) (2), Cabezas I Peñalva Laura (1), Cruañes Diego (1), Ruiz Diego (1), Llanes Luis Miguel (1) (2), Jiménez-piqué Emilio (1) (2)

1 - Center for Research in Structural Integrity, Reliability and Micromechanics of Materials (CIEFMA), Universitat Politècnica de Catalunya [Barcelona] (Spain), 2 - Barcelona Research Center in Multiscale Science and Engineering, Universitat Politècnica de Catalunya-Barcelona TECH, Barcelona (Spain)

Speaker: Francesc Barbera. **Wednesday**. Start time: **11:20**. Room: Salon pasteur LVL1. Link to abstract.

Cemented carbides are one of the most successful examples of effective implementation of multiphase composites for structural applications due to the strongly different properties of their two constituents: hard ceramic particles embedded in a metallic binder. Hard metals exhibit an excellent combination of toughness, strength, and toughness together with a unique resistance to wear and abrasion. As a result, they are prime candidates for tools used in the manufacturing industry, as well as for structural and wear-resistant components in a variety of other industrial sectors. Therefore, the use of cemented carbides at high temperature is a common and critical scenario.
In order to improve the performance of these materials in high-temperature environments, understanding the deformation mechanisms that occur at the nanometric scale is essential. In this study, nanoindentation and advanced microscopy techniques have been combined to perform *in-situ* measurements of mechanical properties under temperatures up to 600ºC. The main objective is, therefore, to identify the deformation mechanisms and micromechanical response of cemented carbides at room temperature and compare them to those observed at high temperature, with the ultimate goal of optimizing the materials design and application in extreme conditions.

To achieve this, micropillar compression tests were conducted. This technique is particularly suitable for studying deformation mechanisms in cemented carbides, as it allows the activation and observation of different mechanisms under controlled conditions. The uniaxial loading mode and limited interaction volume in micropillar compression tests reduce constraining effects and enable a more accurate analysis of plastic deformation fields, providing a controlled environment for studying the micromechanics of these materials.

Additionally, this approach minimizes artifacts, such as those induced by sample size or boundary conditions, which can complicate results in bulk testing.
Focused Ion Beam (FIB) milling was used not only to manufacture the micropillars, but to perform a post-deformation characterization by the obtaining of topographies. The combination of FIB milling and post-deformation characterization enables the detailed observation of localized deformation, crack initiation, and phase interactions, offering critical insights into the mechanical and thermal behavior of these multiphase composites.

Creep Dominated High Cycle Fatigue of Freestanding Gold Thin Films at Room: and Elevated Temperatures

Merle Benoit (1), Krapf Anna (2), Gammer Christoph (3), Gebhart David (3), Cordill Megan (3)

1 - University of Kassel, Institute of Materials Engineering, 34125 Kassel, Hessen, Germany (Germany), 2 - Friedrich-Alexander-Universität Erlangen-Nürnberg (Germany), 3 - Erich-Schmid-Institute of Materials Science Leoben (Austria)

Speaker: Merle Benoit. **Wednesday**. Start time: **11:40**. Room: Salon pasteur LVL1. Link to abstract.

Freestanding metallic thin films experience cyclic loading conditions when they are used in flexible electronic devices, e.g. as interconnects. While supported thin films have been extensively studied, comparatively little is known about the fatigue behavior of freestanding films, largely due to experimental challenges. In addition to sharing with supported films a unique PVD-resulting microstructure, freestanding films stand out due to the ubiquitous presence of a free surface, which likely further alters the classical fatigue mechanisms known from their bulk counterparts. Using bulge testing, we conducted a comprehensive investigation of the high cycle fatigue behavior of gold thin films over a temperature range of 20 to 100∘C, closely reflecting operational conditions in microelectronic devices. Interrupted testing, coupled with transmission electron microscopy, was used to monitor the microstructural evolution. Through analysis of activation parameters and comparisons to reference creep bulge tests, we demonstrated that the cyclic behavior is dominated by creep mechanisms. A transition from dislocation to diffusion controlled deformation was observed as temperature and microstructures were varied. The distinct behaviors of columnar ultrafine-grained and nanocrystalline samples will be discussed in detail during the presentation.

Micromechanics under extreme conditions: high strain rate testing

Kalacska Szilvia (1)

1 - Laboratoire Georges Friedel, CNRS (France)

Speaker: Kalacska Szilvia. Keynote. **Wednesday**. Start time: **14:30**. Room: Salon pasteur LVL1. Link to abstract.

Materials often exhibit different mechanical properties (e.g., strength, ductility, and toughness) at high strain rates (HSR) compared to quasi-static conditions. HSR testing reveals strain rate sensitivity, critical for designing materials for dynamic environments. Some materials undergo phase transformations or changes in their microstructure depending on the deformation speed, that can significantly affect their performance. Exploring strain rate sensitive properties can reveal anomalous behaviour, providing crucial input for simulations developed for dynamic event modeling. The presentation will highlight the state-of-the-art capabilities of HSR micromechanical testing performed on various materials, such as single/dual phase metals (1) and additively manufactured samples (2).

References:
(1) S. Kalácska, A. Sharma, R. Ramachandramoorthy, Á. Vida, F. Tropper, R. Pero, D. Frey, X. Maeder, J. Michler, P. D. Ispánovity, G. Kermouche, Micromechanics reveal strain rate dependent transition between dislocation mechanisms in a dual phase high entropy alloy. (2024) DOI: 10.48550/arXiv.2409.20368
(2) S. Kalácska, L. Pethö, G. Kermouche, J. Michler, P. D. Ispánovity, Anomalous strain rate sensitivity of a Cu/Al2O3 multi-layered thin film. (2024) DOI: 10.48550/arXiv.2407.21392

Extraction of reliable deformation activation parameters from nanoindentation tests covering strain rates from 0.00001 to 10,000 /s and associated changes in deformation mechanisms in metals

Bhusare Suprit (1), Cherukuri Rahul (1), Lambai Aloshious (1), Mathews Nidhin George (1), Schwiedrzik Jakob (2), Johann Michler (3), Ramachandramoorthy Rajaprakash (4), Mohanty Gaurav (1)

1 - Materials Science and Environmental Engineering, Faculty of Engineering and Natural Sciences, Tampere University, 33014 Tampere, Finland (Finland), 2 - Laboratory for High Performance Ceramics, Empa - Swiss Federal Laboratories for Materials Science and Technology, Ueberlandstrasse 129, 8600 Dübendorf, Switzerland (Switzerland), 3 - EMPA Mechanics of Materials and Nanostructures (Switzerland), 4 - Max Planck Institute for Sustainable Materials (Germany)

Speaker: Mohanty Gaurav. Invited. **Wednesday**. Start time: **15:10**. Room: Salon pasteur LVL1. Link to abstract.

Deformation activation parameters like activation volumes, energies and rate exponents are considered as signatures of the material deformation behavior. With advances in micromechanical test techniques (e.g. nanoindentation and micropillar compression), there is a rapidly growing body of literature reporting these parameters extracted at small length scales. However, the reliability of the extracted deformation parameters from indentation tests is still largely unproven for indentation relaxation, creep and high strain rates. In cases where the activation parameters deviate significantly from standard/expected values, does it suggest that the rate controlling deformation mechanism(s) have changed at smaller length scales? Or are the results misleading, most likely due to artefacts of measurements and/or incorrect testing methodology and data analysis? This presentation will address this critical issue through case studies on both polycrystalline and single crystalline metals using both transient and high strain rate micromechanical tests. The focus will be on studying the deformation mechanisms in indentation across 10 orders of strain rates.

This presentation will address the issue of reliability of extracted deformation parameters through systematic micropillar compression and nanoindentation tests carried out on nanocrystalline metals that enable a direct comparison between different test techniques and the extracted parameters. The rationale for choosing nanocrystalline metals was that micro-compression of a large sized pillar (_~ 2-5μm diameter) and nanoindentation to large depths (> 1μm) interrogates more than thousands of grains such that the test results can be considered to represent "bulk" behavior to enable a systematic comparison. Small grain size also avoids size effects in mechanical properties, typically observed in micromechanical testing on single crystals. Results from recently developed indentation stress relaxation tests will be presented and compared with other transient tests like strain rate jump and creep tests. The extracted strain rate exponents and activation parameters (activation volume and activation energies) from transient tests provide valuable insights into the rate controlling deformation mechanism(s) in metals with respect to dislocation plasticity and grain boundary mediated processes. It will also report the changes in deformation mechanisms in indentation at high strain rates. High strain rate testing is attractive not only for testing materials under impact conditions, but also to bridge the timescales between atomistic simulations and experiments. Micropillar compression (up to 1000 /s) and nanoindentation (up to 10,000 /s) tests, performed on both polycrystalline and single crystal metals, will be presented to discuss changes in deformation mechanisms as a function of indentation depth, strain rate and grain size. We will report controlled constant strain rate nanoindentation up to 10,000 /s whereby the strain rate remains constant with indentation depth. This is in stark contrast to previous impact and rebound based indentation tests where the strain rate rapidly decreases with increasing depth. It is hoped that this study will pave the way for routine transient and high strain rate indentation tests for experimentally exploring deformation mechanisms as a function of structure, strain rates and temperatures in various other materials systems.

High-Strain-Rate Nanoindentation: Revisiting the Hardness Upturn in Metals

Bhaskar Lalith Kumar (1), Sonawane Dipali (1), Holz Hendrik (1), Paeng Jeongin (1), Rao Jing (1), Bellón Bárbara (1), Frey Damian (2), Pethö László (3), Michler Johann (3), Schwiedrzik Jakob (4), Mohanty Gaurav (5), Dehm Gerhard (1), Ramachandramoorthy Rajaprakash (1)

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Speaker: Bhaskar Lalith Kumar. Invited. **Wednesday**. Start time: **15:30**. Room: Salon pasteur LVL1. Link to abstract.

The Fourth Industrial Revolution has ushered in rapid advancements in high-speed transportation, machining, and miniaturized electronics, exposing materials to extreme conditions, including high strain rates. While macroscale techniques like split-Hopkinson pressure bars, Kolsky bars, and gas gun experiments can reach strain rates of up to 10^4 s^{-1}, maintaining a constant strain rate during testing remains challenging. These methods require extreme actuation speeds, often in the range of several hundred meters per second, which can introduce shock propagation and complicate post-deformation analysis. Instrumented nanoindentation offers a promising alternative, in which one could achieve very high strain rates of up to 10^5 s^{-1} with actuation speeds as low as _~100 mm/s over indentation depths upto _~1 μm. Additionally, nanoindentation using exponential displacement profiles allows for a constant strain rate, which is advantageous for post-deformation analysis and generating reliable load-displacement curves. Despite these benefits, current limitations in hardware and protocols restrict the highest reported constant strain rate nanoindentation to only 10^2 s^{-1}. This presentation will provide an overview of a highly specialized, high-speed piezoelectric-based micromechanical setup designed to achieve constant strain rate nanoindentation up to an unprecedented strain rate of 10^5 s^{-1}. Key aspects of the custom-modified electronic hardware and essential experimental protocols for capturing precise load-displacement data during high-strain-rate indentations and accurately extracting hardness values will be discussed. The presentation will also examine the material behavior of two different materials: single-crystalline BCC molybdenum and nanocrystalline FCC nickel. Notably, a significant hardness upturn was observed in these materials beyond strain rates of 10^3 s^{-1} and 10^4 s^{-1} for nanocrystalline nickel and molybdenum, respectively. This upturn, linked to strain-rate-dependent microstructural changes, resulted in a threefold increase in strain rate sensitivity for both materials. The observed hardness variations and underlying deformation mechanisms will be supported by transmission electron microscopy (TEM) analysis and thermal activation studies.

Hardness measurements across eleven decades of strain rate using a high throughput indentation method

Borasi Luciano (1), Schuh Christopher A. (1)

1 - Northwestern University (United States)

Speaker: Borasi Luciano. **Wednesday**. Start time: **15:50**. Room: Salon pasteur LVL1. Link to abstract.

This study presents a novel microindentation method that enables the measurement of hardness across eleven orders of magnitude in strain rate, from quasi-static to phonon drag-dominated rates, on a single material surface under uniform testing conditions. The approach combines standard and impact indentation with laser-induced particle impact testing (LIPIT) to evaluate hardness over a wide strain rate range. This method has been successfully applied to multiple materials, providing clearer insights into high-rate deformation mechanisms. Our results demonstrate a gradual increase in hardness with strain rate from quasi-static up to ultra-high rates, where a sharp upturn is observed.

Recent developments to measure surface mechanical properties at high temperature and high strain rate

Guillonneau Gaylord (1), Tiphéne Gabrielle (2), Adogou Benedicte Moul-el-ksour Fatima-zahra (3), Abouhadid Fadlallah Oliver Warren (4), Kermouche Guillaume (5), Loubet Jean-luc (3)

1 - LTDS, UMR CNRS 5513 (France), 2 - IMAP, iMMC, UCLouvain, Belgium (Belgium), 3 - LTDS, UMR CNRS 5513 (France), 4 - KLA (United States), 5 - PMM-ENSMSE- Département Physique et Mécanique des Matériaux (France)

Speaker: Guillonneau Gaylord. Invited. **Wednesday**. Start time: **16:10**. Room: Salon pasteur LVL1. Link to abstract.

Accurate measurement of surface mechanical properties is crucial for understanding the deformation mechanisms occurring at the micrometer or nanometer scale, on material surfaces and thin films. Current micromechanical tools, such as nanoindentation, micropillar compression, and microtension, effectively address this need and are now commonly used, especially at room temperature and deformation rates ranging from 10-^{3} s^{-1} to 1 s^{-1}. Over the past years, significant advancements have been made to enable reliable micromechanical measurements at high temperature and high strain rates. These developments aim to assess surface mechanical properties under conditions that closely mimic those encountered in real-world industrial applications, and particularly under tribological loadings, in our case.
In this talk, the latest developments made to reliably measure the mechanical properties of surfaces and thin films at very high temperature and high strain rates will be presented. The first development concerns the "High Temperature Scanning Indentation" (HTSI) method (1). This technique enables continuous measurement of near-surface mechanical properties of materials through nanoindentation during a complete thermal cycle. By correlating hardness evolution with microstructural changes, it provides valuable insights into microstructural transformations occurring during thermal cycling- information that is often challenging to obtain with conventional characterization techniques (2–4).The second development focuses on the micro-shear technique. This technique consists in compressing micropillars with two notches machined at a 45◦ angle relative to the loading direction to induce shear (5). Initially designed to mimic tribological loading conditions, this technique also proves highly effective at high strain rates due to its geometry. Notably, this geometry enables an increase of one order of magnitude in strain rate in comparison to conventional micropillar compression. Thus, our micromechanical system reliably extracts mechanical properties via micro-shear testing at deformation rates up to 10^4 s-^{1}.

This talk will detail these two techniques and highlight recent applications on various materials. Finally, future development prospects will be discussed.

(1) G. Tiphéne, P. Baral, S. Comby-Dassonneville, G. Guillonneau, G. Kermouche, J.-M. Bergheau, W. Oliver, J.-L. Loubet, High-Temperature Scanning Indentation: A new method to investigate in situ metallurgical evolution along temperature ramps, J. Mater. Res. (2021). https://doi.org/10.1557/s43578-021-00107-7.
(2) G. Tiphéne, G. Kermouche, P. Baral, C. Maurice, G. Guillonneau, J.-M. Bergheau, W.C. Oliver, J.-L. Loubet, Quantification of softening kinetics in cold-rolled pure aluminum and copper using High-Temperature Scanning Indentation, Mater. Des. 233 (2023) 112171. https://doi.org/10.1016/j.matdes.2023.112171.
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(5) G. Guillonneau, S. Sao Joao, B. Adogou, S. Breumier, G. Kermouche, Plastic Flow Under Shear-Compression at the Micron Scale-Application on Amorphous Silica at High Strain Rate, JOM (2022). https://doi.org/10.1007/s11837-021-05142-7.

Operando small scale flow behavior – promising applications for spherical nanoindentation

Maier-kiener Verena (1), Schaffar Gerald Zeiler Stefan

1 - Montanuniversität Leoben (Rosseggerstrasse 12 8700 Leoben Austria)

Speaker: Maier-Kiener Verena. Invited. **Wednesday**. Start time: **16:45**. Room: Salon pasteur LVL1. Link to abstract.

An enticing proposition for materials scientists is to characterize the flow behavior of materials with minimal experimental effort while ensuring highly reliable results. Nanoindentation emerges as a promising technique to achieve this goal. Although it is established as a standard method for extracting hardness and Young's modulus, the technique has not been fully exploited for determining localized flow curves. This gap exists due to the inherent challenges in understanding the correlations between mechanical properties obtained from spherical indentation experiments and uniaxial data.
To address this issue and accurately account for tip imperfections, a calibration procedure based on fundamental geometrical considerations is applied. This procedure lays the groundwork for strain-rate-controlled experiments, enabling the experimental evaluation of the constraint factor while considering mechanical properties and induced strain. Consequently, this approach facilitates the extraction of reliable flow curves.
These protocols are applicable under both ambient and non-ambient conditions, including high temperatures as well as electrochemical scenarios, by employing a novel in-situ electrochemical charging approach known as the side-charging cell. It is evident that electrochemical charging not only increases hardness and flow stress but also results in a reduced constraint factor. This reduction provides further insights, indicating a significant influence on the deformation behavior under electrochemical charging.

In situ Extreme Micromechanics – Recent Innovations and Prospects

Randall Nicholas (1), Paul Viola (1), Pero Renato (1), Breguet Jean-marc (1)

1 - Alemnis AG, Thun (Switzerland)

Speaker: Randall Nicholas. **Wednesday**. Start time: **17:05**. Room: Salon pasteur LVL1. Link to abstract.

In situ SEM micro- and nanomechanical testing is an indispensable technique for materials design as well as for fundamental mechanics research. Many new protocols and testing geometries beyond traditional nanoindentation now enable the study of microstructure–property relationships, material intrinsic behaviour including orientation-dependence and plasticity, fracture dynamics, or the performance of novel micro-3D-printed metamaterials, to name but a few.
Thanks to its versatility, *in situ* SEM-based micromechanics is contributing to numerous scientific domains, including thin films and coatings, metallurgy, glasses and ceramics, semiconductors, biomechanics, or architectured materials. Performing micromechanical tests in situ in a SEM offers two important advantages: (1) unmatched control, stability, and positioning accuracy, and (2) the possibility to perform unique correlative experiments based on, for example, the combination of mechanical data with direct imaging or EBSD measurements.

An increasingly important branch of micromechanical testing can be found in the simulation of real-world, extreme operation conditions, such as high temperatures in engines, cryogenic temperatures in hydrogen storage, dynamic loading under shock or impact, high frequency cyclic fatigue, or a combination thereof. Progress in the understanding of material behaviour at such conditions is clearly linked to the availability of laboratory equipment that can perform reliable tests under such conditions.
We present the most recent developments in instrumentation for in situ extreme mechanics testing at the micro and nanoscales. In the focus is a testing platform capable of strain rate dependent testing over the range from 0.0001 s-1 up to 10'000 s-1 (8 orders of magnitude) with simultaneous high-speed actuation and sensing capabilities with nanometer and micronewton resolution, respectively. Furthermore, the challenges and solutions to performing extreme micromechanics over the temperature range from -150 ∘C to 1000 ∘C, and the inherent advantages of using small volumes of sample material will be discussed. Finally, we present examples of such extreme micromechanical in situ tests and discuss future research directions in the field of extreme micromechanics.

3D Laue microdiffraction: characterization of dislocation structures at grain boundaries during fatigue cycling

Fréville Robin (1), Molin Jean-baptiste (1), Micha Jean-sébastien (2), Ulrich Olivier (2), Robach Odile (2), Gruber Patric (1), Kirchlechner Christoph (1)

1 - Karlsruhe Institute of Technology = Karlsruher Institut für Technologie (Germany), 2 - Université Grenoble Alpes (France)

Speaker: Fréville Robin. **Wednesday**. Start time: **17:25**. Room: Salon pasteur LVL1. Link to abstract.

Fatigue damage is of outmost importance for our daily lives, as it limits the lifetime of almost all engineering components. Most of the knowledge on fatigue damage prior to crack initiation was obtained by transmission electron microscopy (TEM), which effectively images microstructural features such as dislocation cells and cell walls. However, TEM is limited to thin samples and, therefore, cannot investigate damage processes occurring in buried grains and grain boundaries. Laue microdiffraction (μLaue) experiments can then be used to study fatigue damage (1). However, due to the high density of stored dislocations next to a grain boundary during cyclic loading, this 2D method was not suitable for bi-crystals. To deconvolute volume integrated signals in Laue microdiffraction, an additional aperture was added to an existing μLaue beamline, which extends the μLaue technique to "Differential Aperture X-Ray Microscopy" (DAXM) (2,3), allowing for 3D subvolumetric reconstruction. Using this approach, the local crystallographic phase, orientation, and the full elastic strain tensor are determined with a three-dimensional resolution below $1\mu m^3$ voxel.
The experiments were conducted at the BM32 beamline of the European Synchrotron (ESRF) during fatigue cycling of copper bi-crystal microcantilevers ($5x5x25\mu m^3$) prepared by focused ion beam (FIB) machining. Grain boundaries were selected based on known properties, such as penetrability, particularly regarding slip transfer systems. Through the analysis of the local deviatoric strain tensor and local orientation (KAM), we observed and quantified the unexpected cyclic storage and annihilation of dislocations at an impenetrable grain boundary during low-cycle fatigue loading (up to 10 cycles). For comparison, a penetrable grain boundary was also studied in the same way. This grain boundary is expected to show continuous slip irreversibility and requires a long time (more than 10 cycles) before a steady state of the dislocation structure is reached. The combined DAXM - in situ deformation setup (3) offers unique possibilities to study the influence of specific grain boundaries on cyclic slip of dislocations and the eventual subsequent formation of dislocation structures during fatigue.

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Hydrogen effect on the strain rate sensitivity of nanocrystalline Pd thin films

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Speaker: Colla Marie-Stéphane. Invited. **Wednesday**. Start time: **17:45**. Room: Salon pasteur LVL1. Link to abstract.

Nanocrystalline (nc) materials are used in a large variety of micro- and nanoscale devices and sensors. The reliability of these devices requires maintaining adequate mechanical integrity of structural elements over time. This represents a real challenge due to their far from equilibrium microstructure. The stability of nanocrystalline materials is usually addressed in the literature in terms of thermal stability of a microstructure under heating or under severe plastic deformation. In this study, the mechanical stability will be evaluated under environmental perturbation using the rate sensitivity as a marker of stability. In the context of hydrogen technologies requiring sensors and catalyst applications, palladium in hydrogen environment is a good model system for investigating reliability issues. The objective of this work is thus to relate the hydrogen-induced microstructural changes in nc Pd thin film to its rate sensitivity, the latter being a signature of the viscoplastic mechanisms taking place. Pd thin films are characterized experimentally under different hydriding environment. The evolution of residual stress by defect recovery and creep is analyzed. On-chip microtensile testing technique and nanoindentation, coupled with advanced TEM microscopy, are used to quantify and understand the level of rate sensitivity of the specimens as well as the microstructural effects of hydrogen absorption. Finally, the mechanical perturbation applied via the indenter or using internal on-chip actuation of the material is evaluated and compared with respect to the different hydriding conditions.

Impact of mobile hydrogen on the plasticity of bcc FeCr alloys via in situ micropillar compression

Rao Jing (1), Kostka Aleksander (2), Peter Nicolas (3), Vogel Alexandra (4), Rohwerder Michael (4), Dehm Gerhard (1), Duarte Correa María Jazmin (1)

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Speaker: Rao Jing. Invited. **Wednesday**. Start time: **18:05**. Room: Salon pasteur LVL1. Link to abstract.

A key challenge in understanding hydrogen-induced mechanical degradation of materials is the role of mobile hydrogen. Currently, most studies rely on post-mortem analysis of ex-situ hydrogen charged probes. These approaches often overlook the behavior of mobile hydrogen, including its desorption, migration and release during mechanical testing. To advance our understanding of the hydrogen interactions with metals, it is essential to investigate its effects at the microstructural scale, where embrittlement initiates, while maintaining a continuous hydrogen supply.
We developed an in-house, *in situ* backside hydrogen charging setup, assembled inside a standard nanoindentation device where the testing sample remains isolated from direct electrolyte contact (1). Using specific hydrogen charging protocols, we investigated the effects of mobile hydrogen on ferritic Fe-20 wt.% Cr alloys with varying dislocation densities. This setup enables time-resolved measurement of nanoindentation-related mechanical properties, shedding light on the hydrogen diffusion behavior through the studied materials (2). For the case of micropillar compression, the presence and spatial distribution of mobile hydrogen on the micropillar surface is verified using scanning Kelvin Probe force microscopy. The hydrogen content in the FeCr alloys is quantitatively assessed through thermal desorption spectroscopy, providing valuable insights into hydrogen uptake and retention characteristics as a function of Cr content, dislocation density and grain size. In addition, microstructure analyses are performed before and after mechanical testing (3).

Our results show that mobile hydrogen induces strain hardening, correlating with an increased dislocation density observed via scanning transmission electron microscopy. In addition, hydrogen promotes the formation of a cellular structure compared to uncharged reference samples, which was observed in micropillars with a (110) grain orientation. The consequences of these findings will be discussed to provide new insights into hydrogen embrittlement mechanisms.

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When brittle crystals turn ductile – understanding the crystal plasticity of intermetallics from their fundamental building blocks

Korte-kerzel Sandra (1), Freund Martina (1), Gasper Christina (1), Stollenwerk Tobias (1), Ulumuddin Nisa (1), Sun Pei-ling (1), Xie Zhuocheng (1)

1 - Institute of Physical Metallurgy and Materials Physics [RWTH Aachen University] (Germany)

Speaker: Korte-Kerzel Sandra. Keynote. **Thursday**. Start time: **10:00**. Room: Salon pasteur LVL1. Link to abstract.

In materials design, understanding and manipulating the behaviour of dislocations - key drivers of plastic deformation - is a cornerstone. Yet while dislocations are well-explored in simple crystalline materials, their structure and mechanisms of motion remain largely enigmatic for complex crystals, such as topologically closed-packed phases. This vast class of materials contains many intermetallics ranging from high-temperature structural materials to functional crystals that can act as superconductors, magnets, or hydrogen storage materials. In all of these applications, structural integrity and therefore controlled plasticity is paramount. We aim to bridge our current knowledge gap in plasticity of complex crystals by delving into the most prevalent among them, the Laves phase, and other related phases that contain elements of the Laves phase as building blocks, such as the μ-phase. Small-scale mechanical testing is key to this research as the reduction in size suppresses cracking in favour of plastic deformation. By transmission electron microscopy, we then unveil previously unreported defect structures in the cubic Laves and the μ-phase. Complementing these observations, atomistic simulations elucidate the underpinning mechanisms, revealing novel deformation behaviours. We spotlight the role of full dislocations traversing multiple {1 1 n} slip planes, a departure from the conventional confinement to {1 1 1} planes in the cubic Laves phase, and reveal changes in dislocation mechanism and critical stress induced by slight changes in composition that in turn give rise to sublattice order. Based on this better understanding on how the most fundamental building blocks of intermetallic crystals behave and change upon combination into larger unit cells, we propose a tangible pathway to understand the plasticity of brittle intermetallics. Ultimately, our goal is to provide characterisation and design strategies that will enable phase selection and materials engineering for intermetallics in advanced alloys, where much too often they are still considered as detrimental or at the very least unchangeably brittle, although first examples exist where this is not the case.

Experimental evidence and first-principles verification of deformation of basal twist grain boundaries in Ti

Llorca Javier (1) (2), Yang Biaobiao Yang (1) (2), Hémery Samuel (3), Shao Wei (1) (2), Tucker Victoria (2) (4), Titus Michael (2) (4), Monclús Miguel (2)

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Speaker: Llorca Javier. **Thursday**. Start time: **10:40**. Room: Salon pasteur LVL1. Link to abstract.

Titanium (Ti) alloys are high performance materials used in many applications requiring lightweight, strength, and corrosion resistance. Increasing severity of in-service conditions and extended lifetimes are important objectives from the viewpoint of structural applications. Fatigue failure, as a result of repeated mechanical loadings, is a critical design concern for metallic alloys, and Ti alloys in particular. As a result of the improvement of industrial practices, forged components are generally free of defects such as pores or non-metallic inclusions. Instead, microstructural characteristics, including microtexture, and multimodal size distribution of α precipitates, determine the resistance to crack nucleation and the fatigue performance in the high-cycle fatigue regime. Recent experimental results provided evidence of fatigue crack nucleation along basal planes in equiaxed α particles , while cracks lying along prismatic planes were more rarely reported. The associated mechanism was recently revisited to suggest a critical role of Basal Twist Grain Boundaries (BTGBs) located in clusters of equiaxed α grains. These microstructure configurations are composed of two hexagonal close-packed α crystals rotated about the (0001) axis and separated by a grain boundary parallel to (0001) planes. BTGBs are planar α/α grain boundaries where no β phase, or detectable elemental segregation is present. While the competition with other crack nucleation mechanisms is still a subject of discussion, broad relevance was demonstrated considering a variety of alloys and loading conditions. In particular, recent investigations suggested that the high variability in fatigue lifetimes in Ti alloys reported in prior studies could be related to the low density of BTGBs found in engineering microstructures. To clarify the origin of this critical behavior, the mechanical response of bicrystal micropillars containing BTGBs was characterized by means of micropillar compression tests. This approach ruled out any contribution of the microstructural environment, which is difficult to assess in polycrystalline samples. Also, the reference behavior associated with the onset of conventional intragranular slip activity was extracted using single-crystal micropillars for comparison. Afterwards, the deformation mechanisms around the BTGB were analyzed by means of high-resolution scanning and transmission electron microscopy. I. It was found that shear deformation occurred by the glide of one basal grain over the other basal grain at very low values of the critical resolved shear stress (45 - 205 MPa), much lower than that of basal slip (400 - 600 MPa). To understand this mechanism, the Grain Boundary Energies (GBEs) of coincident site lattice BTGBs with different twist angles were determined by means of first-principles calculations of supercells. It was found that the GBE variations with respect to twist angle and in-plane translation were negligible for all coincident site lattice BTGBs investigated, leading to a very low shear resistance.

Elementary deformation mechanisms in single-crystal MAX phase Cr2AlC: analysis of twin-dislocations interactions by micromechanical testing and Transmission Electron Microscopy

Akou Mohamed (1), Joulain Anne (2), Tromas Christophe (2)

1 - Institut Pprime (France), 2 - Institut Pprime (France)

Speaker: Akou Mohamed. **Thursday**. Start time: **11:00**. Room: Salon pasteur LVL1. Link to abstract.

MAX phases are a family of materials characterized by their nano-lamellar structure, which grants them an advantageous combination of metallic and ceramic properties, making them attractive for various industrial applications. However, understanding their plastic deformation mechanisms remains a challenging and evolving field of study.
MAX phases exhibit a hexagonal crystallographic structure, and their plastic behaviour is predominantly governed by basal slip. However, this mechanism alone is insufficient to accommodate any given deformation. In other words, other mechanisms must intervene and indeed contribute to the plasticity of these materials. Recently, deformation twinning has been reported and characterized in Ti2AlN and Cr2AlC MAX phases. This was new since twinning had been ruled out in the early papers about MAX phases. This implies the necessity of a thorough re-examination and revaluation of the mechanical properties and elementary deformation processes in MAX phases.

In this study, we aim to enhance our understanding of the elementary plastic deformation mechanisms in MAX phases, particularly about twinning. The objective is to examine the deformation structure of single-crystal Cr2AlC MAX phase, induced by nanoindentation and micropillar compression tests on samples oriented in configurations where basal slip is the least favourable. To achieve this, the use of different experimental techniques is necessary, combining surface and volume characterization techniques such as atomic force microscopy (AFM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM), with automated crystal orientation mapping such as (EBSD and ASTAR). TEM thin foils and micropillars are prepared using focused ion beam (FIB), ensuring the area of interest is precisely targeted. This will lead to a more comprehensive view of the structure under analysis and a better understanding of the overall deformation behaviour and mechanisms.

By combining the different techniques mentioned in the previous paragraph and exploring new TEM foil configurations, we were able to obtain original observations of deformation structures that clearly show dislocation-twin boundary interactions as well as dislocation cross-slip. These observations indicate the variety and complexity of the plastic response of these materials, which led us to conduct a more detailed analysis of these defects and deformation structures.
Ultimately, this detailed analysis will contribute to a better understanding of the diverse plasticity in MAX phases and highlights the significance of revisiting and expanding our knowledge of these materials under mechanical stress.

Characterization of Slip System Activity and Deformation Behaviour in P91 Steel by Micropillar Compression Testing and Crystal Plasticity Simulation

Isavand Samaneh (1), Sreenivasa Rao Pavan (1), Bondarev Andrey (1), Wang Siyang (2), Giuliani Finn (2), Leen Sean (3), O'dowd Noel (1)

1 - University of Limerick (Ireland), 2 - Imperial College London (United Kingdom), 3 - University of Galway (Ireland)

Speaker: Isavand Samaneh. **Thursday**. Start time: **11:20**. Room: Salon pasteur LVL1. Link to abstract.

This study investigates the slip system activity and deformation mechanisms of P91 martensitic steel at room temperature using micropillar compression tests and crystal plasticity finite element (CPFE) modelling. Circular cross-section micropillars were fabricated from martensitic blocks within polycrystalline P91 steel using focused ion beam (FIB) and scanning electron microscopy (SEM) techniques. These micropillars, with various crystallographic orientations, were designed to activate different slip plane families in the body-centered cubic (BCC) structure. Compression tests were performed under both displacement-controlled and load-controlled conditions. Following compression, post-deformation electron backscatter diffraction (EBSD) analysis was conducted on the micropillar cross-sections to determine the grain distribution along their lengths. Slip system activation during compression was observed by analysing slip traces in the SEM images.

The micropillar compression tests were simulated using finite element (FE) modelling, incorporating phenomenological crystal plasticity. The geometry and crystallographic orientation of each micropillar, derived from SEM and EBSD data, were integrated into the simulations. The CPFE model was calibrated for each slip family based on the stress-strain curves from the micropillar tests, and the simulated slip traces were compared with experimental observations.

The analysis reveals that most micropillars follow Schmid's law, with non-Schmid effects having minimal influence on slip activation. Additionally, the yield stress and strain hardening behaviour of the micropillars are significantly influenced by the testing method. Across all series examined, the load-controlled tests generally exhibited lower strain hardening compared to the displacement-controlled tests. Finally, the critical resolved shear stress (CRSS) for each slip family was evaluated, and the accuracy of slip trace predictions-particularly regarding the angle of slip traces and the shape of the deformed micropillars for the {110}, {112}, and {123} slip plane families-was verified.

SMALL SCALE MECHANICAL BEHAVIOUR OF WC-Co CEMENTED CARBIDES: NANOINDENTATION, FIB TOMOGRAPHY AND NUMERICAL MODELLING

Jiménez-piqué Emilio (1), Sousa Machado Pedro (1), Caner Ferhun (1), Llanes Luis

1 - Universitat Politecnica de Catalunya (Spain)

Speaker: Jiménez-Piqué Emilio. Invited. **Thursday**. Start time: **11:40**. Room: Salon pasteur LVL1. Link to abstract.

Cemented carbides, also known as hard metals, are materials widely used in forming, metal and wood cutting as well as mining operations. They are generally composed of two interpenetrating phases: a hard WC ceramic phase and a metallic binder, usually a Co alloy. Understanding and modelling the micromechanical behavior is key to enhance performance in engineering applications. However, numerical models based on continuum assumptions, or in idealized simplistic microstructures fail to capture the complex behavior of these materials and to stablish robust methodologies for behavior prediction and implementation of alternative compositions.

In this work, we attempt to link experimental micromechanical testing with numerical model using realistic microstructures. First, we produce a tomography by focused ion beam of the material, segmenting both phases. This tomography is them meshed to produce realistic reconstructions of the microstructure. Micromechanical data is acquired by nanoindentation, high-speed nanoindentation, microcantilevers, micropilars and microtesile tests and used as imputs for modelling.

Using these experimental imputs, two deterministic models are used: Microplane J2 Plasticity for the ductile Co phase and Model M7WC for the hard WC phase. Once these deterministic models are in place, we delve into the stochastic behavior of these composites at the small specimen level. At this scale, the material faces significant uncertainty due to random assembly of its constituent phases, variations in crystal orientation of WC grains, intrinsic residual stresses, and variable confinement by the metallic binder. To address this uncertainty, we introduce a Stochastic Model that complements the deterministic ones. This model incorporates an autocorrelated grafted Gaussian-Weibullian distribution to capture expected variations in local strength. Numerical predictions are then contrasted with complementary experimental micromechanical tests (micropillar compression) as well as macroscopical strength data, achieving an excellent agreement.

In situ compression of oxide nanocubes in Transmission Electron Microscopy

Zhang Rongrong (1), Masenelli-varlot Karine (1), Laurens Gaétan (2), Albaret Tristan (2), Dunstan David (3), Chaput Frederic (4), Joly-pottuz Lucile (1)

1 - Materiaux: Ingénierie et Science (France), 2 - Institut Lumière Matière [Villeurbanne] (France), 3 - School of Physical and Chemical Sciences, Queen Mary University of London, (United Kingdom), 4 - Laboratoire de Chimie (France)

Speaker: Joly-Pottuz Lucile. Invited. **Thursday**. Start time: **14:15**. Room: Salon pasteur LVL1. Link to abstract.

The behaviour of materials at the nanometre scale may strongly differ from their bulk counterparts because of the small size of the stressed volume, and because of the large surface-to-volume ratio. In addition, oxide materials contain ionic bonds, which may strongly affect the deformation mechanisms. However, the literature still lacks information regarding plasticity mechanisms in many oxides.
In situ mechanical testing in Transmission Electron Microscopy (TEM) is a convenient technique to study plasticity in nano-objects as it provides force measurements associated with live video recording up to atomic resolution. The experimental set-up and the procedure used for data processing will first be described. We will show results obtained on cerium oxide (CeOx) nanocubes, with sizes in the range 20-130 nm. Importantly, CeOx can be reduced during analysis due to the electron beam. This process leads to the transformation from CeO2 (fluorite) to CeO1.5 (bixbyite) (1). This transformation is reversible, the fluorite phase being recovered after beam blanking thanks to the presence of residual oxygen gas. It is therefore crucial to control the experimental conditions to understand the acquired data.
Experiments under different conditions (dose rate, environment gas pressure) will be shown. On fluorite, the values measured for the Young modulus on single nanocubes under different conditions will be compared with theoretical values and discussed (2). The plasticity mechanism will also be determined and compared with simulation results. On bixbyite, the active slip systems will be determined. The appearance of stacking faults in bixbyite but not in fluorite will be shown experimentally, and discussed. Finally, we will investigate the effect of the nanocube size on the yield stress, and discussed the value of the exponent in light of the literature.

Acknowledgements
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Grain-scale nanoindentation on mixed uranium-plutonium oxides: a coupled experimental and simulation approach

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1 - CEA, DES, IRESNE, DEC, Cadarache, Saint-Paul-lez-Durance, 13108, France (France), 2 - CEA, DES, ISEC, DMRC, Marcoule, Bagnols-sur-Cèze, 30207, France (France)

Speaker: Bertin Julie. **Thursday**. Start time: **14:35**. Room: Salon pasteur LVL1. Link to abstract.

Uranium-plutonium mixed oxides ((U,Pu)O_2) are currently the reference fuels for future French Gen-IV Sodium-cooled Fast Nuclear Reactors due to their thermomechanical performance and extensive operating experience. These fuels are manufactured as dense ceramic pellets (_~95% of theoretical density), with a plutonium molar fraction ranging from 15% to 35% and an oxygen-to-metal ratio (O/M) from 1.96 to 1.99. Under irradiation, (U,Pu)O_2 undergoes significant microstructural and compositional changes due to the high thermal gradient (_~1500 K over a 3 mm radius) and the accumulation of fission products.

The resulting heterogeneity leads to local variations in mechanical properties such as Young's modulus and Poisson's ratio. These properties are essential inputs for multi-scale fuel performance codes such as GERMINAL (CEA) or TRANSURANUS (JRC), which simulate the fuel behaviour during irradiation (1, 2). Despite their importance, experimental data available on (U,Pu)O_2 remain scarce in the literature, limiting the validation of molecular dynamics results (3). Furthermore, the elastic properties of single crystals are of paramount interest as they are fundamental for establishing reliable correlations between composition, microstructure, and mechanical behaviour. This work aims to address this lack through a combined experimental and simulation approach.

The experimental strategy relies on nanoindentation measurements to investigate the grain-scale mechanical properties on fully characterised (U,Pu)O_2 samples. Due to the radiotoxicity of plutonium, all experiments, including sample preparation and handling, were conducted in glove boxes within the ATALANTE nuclear facility of CEA Marcoule centre. Our nuclearised nanoindentation setup enables local measurements ($<$ μ-scale), providing indentation modulus and hardness data. For each parameter studied (Pu content, oxygen stoichiometry, alpha self irradiation, grain orientation, density), multiple indentations were performed to ensure sufficient quality data for statistical analysis, while invalid measurements near porosities or grain boundaries were discarded. Complementary techniques, including Electron BackScattered Diffraction for grain orientation, Raman spectroscopy and Electron Probe MicroAnalysis for local Pu content and oxygen stoichiometry determination, and optical microscopy for porosity analysis, further helped analysing local composition and microstructural influences.

To extract elastic properties from raw force-displacement data, the approach developed by Oliver and Pharr (4), although widely used, does not account for anisotropy or heterogeneities. To interpret these measurements and understand their variability due to crystal anisotropy and surrounding microstructural effects, a finite element digital twin was developed. The latter includes the tip blunting and local microstructural parameters, such as surrounding grains or porosities. The mechanical behaviour of oxide ceramics at the grain scale was modelled using recently developed constitutive laws in a crystal plasticity framework (5).

Measurements on samples with varying plutonium content (0-100%) provide novel data, including PuO_2 elastic constants for grains of known crystallographic orientation. These results fill gaps in the literature, especially at high Pu contents and give some insight into the effect of elastic anisotropy in nanoindentation measurements. Additionally, sensitivity and parametric studies conducted using the numerical model provide valuable guidance for estimating measurement uncertainties, allowing for more accurate interpretation of experimental results and increased confidence in the derived elastic constants values.

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Investigation of sapphire strength across the scales

Henry Ronan (1), Doitrand Aurélien (2), Meille Sylvain (3)

1 - GPM Rouen (France), 2 - MATEIS (France), 3 - MATEIS (France)

Speaker: Henry Ronan. **Thursday**. Start time: **14:55**. Room: Salon pasteur LVL1. Link to abstract.

In the absence of a pre-existing crack or notch, the fracture stress parameter is commonly used to describe the failure process in brittle materials. However, this parameter is subject to a significant size effect: the larger the specimen, the lower the apparent stress at fracture.
First, we highlight the effect of size on the strength of monocrystalline alumina (sapphire) through multi-scale bending tests ranging from characteristic dimensions of just a few microns to several millimeters. We then investigate the fracture of the sapphire on the μcantilever bending tests. Different types of specimen are prepared by FIB and then tested in flexion. We vary the dimensions of the specimens, the way in which they are prepared and the crystalline orientation, but we also deliberately introduce defects, all with the aim of studying the variation that this induces in the levels of measured fracture strength.

The aim of this work is to generate data on this effect of size on brittle fracture, and also to study the applicability of a model to describe it. These phenomena are often described by a probabilistic law of the Weibull type (1), *i.e.* the larger the volume probed, the greater the probability of finding a defect leading to failure. We are evaluating the effectiveness of such a model, and are also investigating the possibility of using a deterministic law to describe this fracture size effect (2).

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Additive manufacturing of microscale metal-ceramic architectures with tunable mechanical properties

Schwiedrzik Jakob (1) (2), Alexander Groetsch (3) (4), Killang Pratama (2), Watroba Maria (2), Schweizer Peter (4), Gunderson Christopher (4), Diaz Ana (5), Leclezio Helen (6), Utke Ivo (4), Kochmann Dennis (7), Johann Michler (4)

1 - EMPA High Performance Ceramics (Switzerland), 2 - EMPA Mechanics of Materials and Nanostructures (Switzerland), 3 - KTH Royal Institute of Technology, Stockholm (Sweden), 4 - EMPA Mechanics of Materials and Nanostructures (Switzerland), 5 - Paul Scherrer Institute (Switzerland), 6 - Mechanics & Materials Laboratory, ETH Zürich (Switzerland), 7 - Eidgenössische Technische Hochschule - Swiss Federal Institute of Technology [Zürich] (Switzerland)

Speaker: Schwiedrzik Jakob. Invited. **Thursday**. Start time: **15:15**. Room: Salon pasteur LVL1. Link to abstract.

Over the past years, significant progress has been made towards improving our understanding and manufacturing capability of 3D architectured materials at the nano- and microscale. This holds the potential for preparing novel materials that combine usually mutually exclusive properties such as high strength, toughness, and low density through intelligent design making use of size effects and material architecture.
In the last years, we have developed a process combining template assisted electrodeposition and atomic layer deposition (ALD) that allows synthesizing complex shaped metal-ceramic architectures at the microscale. Polymeric molds are created by two photon lithography and filled with metals including Cu, Co, Au, Zn, Ni, and NiP using electrodeposition from aqueous electrolytes. After removing the polymer using oxygen plasma etching, the metal architectures are coated by ALD to create metal-ceramic core-shell structures with improved properties. Micromechanical testing inside a scanning electron microscope at various boundary conditions combined with transmission electron microscopic analysis allows investigating the microstructure and dominating deformation mechanisms.

As a case study, the preparation and in-depth analysis of complex Al2O3-coated Ni structures will be presented combining synchrotron nanoCT imaging, electron microscopy, micromechanical testing, and finite element modeling. The combination of methods allowed us to investigate the distribution of defects and geometric imperfections and their role in the apparent deformation behaviour of the complex architectures as well the deformation mechanisms of the metal lattice at the atomic scale including stress-induced densification of dislocation networks, creation of nano-twins, and localized grain refinement. Finite element analysis was employed to study stress distribution in the complex structures and the effects of stress sharing between the different phases. Thus, our multiscale analysis spanning from the atomic to the component level allowed us to identify the deformation mechanisms and their respective contributions to the apparent structural behavior.
This work opens up pathways towards the future design and synthesis of metal-ceramic nanocomposites and metamaterials for various applications from impact mitigation for MEMS devices to functional biomaterials.

Using the nanoindentation to question the impact of hydrogen on the elasticity and plasticity behaviors of pure nickel

Oudriss Abdelali (1), Ben Jedidia Yasmine Murugan Siva Iskounen Nadjib Feaugas Xavier

1 - LaSIE UMR - 7356 CNRS - Université de La Rochelle (France)

Speaker: Oudriss Abdelali. **Thursday**. Start time: **15:35**. Room: Salon pasteur LVL1. Link to abstract.

The influence of electrochemical hydrogen charging and subsequent room temperature hydrogen desorption on elastic modulus, incipient plasticity (or pop-in) and indentation hardness were investigated in nickel single crystals using a series of nanoindentation tests. The evolution of hydrogen and vacancies contents during the desorption was analysed using thermal desorption spectroscopy and differential scanning calorimetry. Antagonist softening and hardening effects of hydrogen are related and commented on the base of TEM, HR-EBSD observations and Molecular static simulations using embedded-atom method potential. The irreversible reduction of reduced modulus, i.e., softening in the elastic regime, is a result of hydrogen induced vacancy clusters in the surface and subsurface zones due to the hydrogen charging. The analysis of incipient plasticity disclosed the hydrogen-vacancy clusters enhanced lattice friction against the formation of dislocation, which resulted in an increase in the critical load and critical resolved shear stress for the first pop-in. Moreover, the activation volume for the pop-in and dislocation nucleation decreased by the hydrogen intake. From this, it is rational to conclude that the mechanism governing the pop-in in hydrogen charged conditions is the hydrogen-vacancy clusters induced heterogeneous dislocation nucleation on a subsurface.

MS4.2 - In situ Mechanics

Organisers: D. Juul Jensen (DTU), J.P.M. Hoefnagels (TU-Eindhoven) and D. Seyedi (CEA-Saclay)

A New Laboratory-Based X-ray Diffraction Technique for Pointwise Stress-Strain Measurements.

Amir Ben (1), Gandhi Vatsa (1), Shaikeea Angkur (1), Dennis Anthony (1), Sudhir Deshpande Vikram (1)

1 - University of Cambridge [UK] (United Kingdom)

Speaker: Amir Ben. Keynote. **Monday**. Start time: **10:10**. Room: Saint Clair 3B LVL2. Link to abstract.

The explosion of data-driven modeling often uses so-called supervised learning models that require data in the form of stress-strain pairs. Measurement of these pairs typically involves a large number of separate experiments as standard methods such as digital imaging correlation (DIC) only provide spatial strain distributions and no information on local stresses. This makes generating such data experimentally prohibitively expensive. The solution lies in measuring the spatial distributions of stress and strain in a single geometrically complex specimen that samples a wide range of the stress space. This presentation introduces a groundbreaking experimental technique that enables pointwise stress-strain measurements in such geometrically complex specimens within a laboratory setting. We harness a high-flux metal jet X-ray source to conduct energy dispersive diffraction measurements along with DIC to get spatial information of elastic and total strain distributions in metallic specimens. Therefore, we have brought synchrotron technologies into a laboratory setting and opened the possibility of generating data for application in data-driven material models. The presentation will showcase the application of this innovative method to various specimen geometries, focusing on designing specimens and loading conditions that sample a wide range of the stress space. Through meticulous full-field measurements and advanced machine learning algorithms, we aim to develop data-driven material models that accurately capture complex elasto-plastic responses of metals.

Validation of a test for measuring fretting contact damage using X-ray tomography

Gandiolle Camille (1), Maazaz Zakariae (1) (2), Younes Youssef (1), Smaniotto Benjamin (1), Teissedre Jean-christophe (2), Arnaud Pierre (2)

1 - Laboratoire de Mécanique Paris-Saclay (France), 2 - Centre des Matériaux (France)

Speaker: Gandiolle Camille. **Monday**. Start time: **10:50**. Room: Saint Clair 3B LVL2. Link to abstract.

Mechanical assemblies are often subjected to vibrations that generate micro-friction at the contacts: fretting. These slight displacements can lead to cracking and/or wear, reducing the service life of the assembly. Numerous models and tests exist to predict contact life, but there is still considerable room for improvement, based on a poor understanding of what happens in the contact. Indeed, most models use a continuous, homogeneous interface, whereas the actual contact area, pressure distribution and friction coefficient depend on the local state of the contact. Access to the evolution of the interface over time, as well as to its damage through wear and cracking, is therefore necessary to further the understanding and simulation of mechanical assemblies. In-situ tomography testing would provide access to this information. The aim of this work is to present the development and validation of an in-situ fretting test for X-ray tomography. It has been designed to quantify local information (friction, stiffness, slip) during loading, thanks to sensors. The main challenge is ensuring quantifiable contact forces, while placing as little material as possible at the source to ensure sufficient transmission, while at the same time being representative of industrial contacts. The set-up has been validated against the fretting vibration test under controlled load, with many cycles. It also makes it possible to reproduce the damage generated on conventional macroscopic test benches. The final design combines technical and material choices that enable good reconstruction. The first deformation fields, obtained from an in-situ fretting test, are proposed and compared to FE simulation. The local coefficient of friction is fitted using contact shear displacement.

X-ray CT scanning and in-situ densification test of sulfide electrolytes: LPS vs LPSCl

Martini Margherita (1), Adrien Jérôme (2), Villevieille Claire (3), Demortière Arnaud (4), Maire Eric (1)

1 - MateIS (France), 2 - MateIS (France), 3 - lepmi (France), 4 - LRCS (France)

Speaker: Martini Margherita. **Monday**. Start time: **11:10**. Room: Saint Clair 3B LVL2. Link to abstract.

All-solid-state batteries, where a solid electrolyte replaces the liquid flammable electrolyte, are expected to be the next-generation energy storage devices because of their enhanced safety. The material choice is crucial influencing the final cell electrochemistry, and a good battery performance highly depends on the electrolyte; however, its nature modification can change the dynamics within the entire cell, making its characterization pivotal to research progress. Although the investigated electrolyte materials are numerous, sulfides are noteworthy because they have good densification properties and high ionic conductivities at room temperature; moreover, they can be cost-effectively synthesized. Specifically, Li6PS5Cl (LPSCl, crystalline) and Li3PS4 (LPS, amorphous) are remarkable. Nevertheless, their study is not trivial being particularly sensitive to humidity and generating toxic H2S gas. Thus, an *in-situ* and non-destructive characterization is required, and x-ray micro-CT scanning turns out to be particularly suitable. This technique allows to perform compression test inside the final battery assembly and to visualize the electrolyte densification at different pressures. Powder of LPS and LPSCl is sited inside of Swagelok cells and is scanned at 2 microns resolution; pressure is steadily increased until complete densification. Similarities and differences of these two sulfide electrolytes are highlighted by this *in situ* compression test, and LPS shows a better densification at room temperature because of its amorphous structure.

Experimental characterization of elastomer deformation using x-ray tomography: application to the study of contact with a road surface

Adrien Jérôme (1), Lachambre Joel (1), Sibellas Aurelien (1), Papillon Justine (1), Bruant Rémi (2), Maurel Gaëtan (2), Maire Eric (1)

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Speaker: Adrien Jérôme. **Monday**. Start time: **11:30**. Room: Saint Clair 3B LVL2. Link to abstract.

The grip and rolling resistance of car wheel tires on a road surface is strongly influenced by the mechanical properties of the rubber and especially by the deformation of this rubber during indentation by the road asperities. Rubber deformation due to the macro texture of the roadway is cited as an important rolling resistance phenomenon. Numerous experimental and simulation studies have been carried out (1-3). However, recently Sun et al. (4) showed that better specifying the texture parameters associated in the indentation of rubber remains an important and timely subject.The phenomena involved are difficult to observe using conventional techniques such as optical microscopy, due to the opaque nature of the elements concerned. The spatial scale of the order of a millimeter is the relevant one to study for rolling resistance (5).
The aim of this work was to develop a new methodology to measure the deformations, in the bulk, of a rubber exposed to indentation-type stresses. To this purpose, advanced techniques such as X-ray computed tomography (XRCT) combined with Digital Volume Correlation (DVC) were used. Numerous studies have shown that XRCT, based on X-ray absorption, can be used to obtain quantitative data (6) on non-transparent bodies. The ability of XRCT to provide directly and non destructively three dimensional (3D) images of various materials makes it a valuable tool to study quantitatively the deformation mechanisms during in situ deformation (6). The main difficulties are linked to the attenuation of the materials used (i.e. high attenuation for the soil and much lower for the rubber), the large deformations to be achieved, and the complexity of a road surface. In addition, DVC requires the presence of a speckle in the material's microstructure. In order to validate our approach, an in-situ indentation test using a low X-ray absorbent plastic ball was first conducted to evaluate the performance of DVC algorithm. Analytical rubber samples, specifically produced for this study, made of a SBR type rubber (Styrene Butadiene Ruber) and representative of a tread of a commercial passenger vehicle tire were used. Silica large particles were added to serve as markers and reinforcement of the rubber. The experimental results were compared with numerical simulations in Abaqus.

The results of these analyses will be presented first. Next, research carried out in order to better reproduce the real conditions of contact between the rubber of a passenger car tire and the road will also be discussed.

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(2) J. A. Cabrera J. Castillo, A. Pérez De La Blanca and A. Simón. An optical tire contact pressure test bench. Vehicle System Dynamics, 44(3):207–221, 2006.
(3) Filip Feldesi, Theunis R. Botha, and P. Schalk Els. Full-field strain measurements of the inside of an agricultural tyre using digital image correlation. Journal of Terramechanics, 91:309–318, 2020.
(4) Zhaojie Sun, W. A.A.S. Premarathna, Kumar Anupam, Cor Kasbergen, and Sandra M.J.G. Erkens. A state-of-the-art review on rolling resistance of asphalt pavements and its environmental impact. Construction and Building Materials, 411, 2023.
(5) William Levesque, André Bégin-Drolet, and Julien Lépine. Effects of pavement characteristics on rolling resistance of heavy vehicles: A literature review. Transportation Research Record, 2677(6):296–309, 2023.
(6) E. Maire and P. J. Withers. Quantitative x-ray tomography. International Materials Reviews, 59(1):1–43, 2014.

The Road Nano Scale DVC metrology with In Situ Computed Tomography

Arzoumanidis Alex (1), Bay Brian (2), Phillion André (3)

1 - Psylotech, Inc. (United States), 2 - Oregon State University; School of Mechanical, Industrial, and Manufacturing Engineering (United States), 3 - McMaster University [Hamilton, Ontario] (Canada)

Speaker: Arzoumanidis Alex. Invited. **Monday**. Start time: **11:50**. Room: Saint Clair 3B LVL2. Link to abstract.

An in situ universal mechanical testing system is presented with a rotating load train. Rotating the specimen offers a number of advantages for computed tomography. In conical beam microCT, the source can be placed close to the sample, maximizing appraisal resolution compared to systems with polymer to be support structures. Also compared to tubular alternatives, samples are simpler to mount and no X-rays are attenuated. For nanoCT, placing the source and detector closer to the sample reduces scan time.
Despite the advantages, rotating the load train within the frame introduces substantial challenges. For example, two rotation axes increase alignment complications. A four degree of freedom alignment fixture is shown to be critical for micron scale tomography. Additionally, a second rotating axis exacerbates bearing runout errors in the reconstruction. The ultimate goal is micron scale resolution, which is finer than the specifications of high precision bearings.

A software solution is proposed for the mechanical runout problem. Consider that digital image correlation has been shown to achieve sub pixel displacement field resolution as small as 1/100th of a pixel. Such careful DIC requires imaging system calibrations. Analogous procedures can be applied to DVC. Spherical fiducial markers are first bonded to the top and bottom of the sample's gauge section with a low modulus adhesive. The markers are tracked in all of the radiographs of the tomography scan. The software solution then leverages DIC methods to measure runout from the marker positions, comparing them to ideal. Finite element algorithms distort and stretch the radiographs before reconstruction, correcting for errors. The result is a plausible path to achieve sub-micron metrology in 3D space.

In-situ mechanical experiments analyzed via 2P-DVC

Vargas Rafael (1), Heermant Johannes (1), Lachambre Joël (1), Adrien Jérôme (1), Hild François (2), Jailin Clément (2), Roux Stéphane (2), Maire Eric (1)

1 - MatéIS (France), 2 - LMPS (France)

Speaker: Vargas Rafael. Keynote. **Monday**. Start time: **13:40**. Room: Saint Clair 3B LVL2. Link to abstract.

X-ray tomography is a consolidated tool to investigate material microstructures and their correlation with processing parameters. It can be applied to a wide range of materials and is commonly used for composites, ceramics, metals, and natural materials, among others. Another benefit is the vast range of resolution, which is constantly evolving with the developments of new x-ray sources and detectors – in laboratory tomographs and synchrotron facilities – with one voxel of the volume being able to represent sub-micron dimensions up to the millimeter scale. In mechanical analyses, in-situ experiments can be performed by imaging the same sample sequentially after some loading. This may give a direct visualization of damaging mechanisms such as cavitation after plastic deformation or crack initiation and propagation. The common practice is maintaining the load at a few different steps for complete tomographic acquisitions to avoid (or diminish) motion blur in the reconstructed volumes. In this approach, Digital Volume Correlation (DVC) can be applied to the acquired volumes, giving access to spatially rich 4D measurements.

It is possible to increase by approximately 1000 times the temporal resolution by directly exploiting radiographs taken during the experiment – without the need to stop the loading – instead of entire volumes, allowing further exploration of experiments where significant changes may happen during loading dwells. For this, the so-called projection-based DVC (P-DVC) can increase temporal resolution at the expense of reduced spatial kinematics. In P-DVC, an initial reference volume is reconstructed, and a residual is defined as the difference between the radiographs acquired during the experiment and the volume reprojection. The residual is iteratively minimized by correcting the volume with a motion described by its components on a chosen kinematic basis. When dealing with a radiograph, one drawback is the low sensitivity to displacements perpendicular to the detector plane. Although this may be tackled by rotating the sample during the experiment (with added complexity in the analysis), this remains a physical constraint that may limit the test duration.

This work aims to perform ultrafast experiments by fully exploiting the dual-beam microfocus high-energy tomograph located at INSA-Lyon (France), with P^2-DVC exploring the radiographs taken simultaneously from two crossed tomograph lines. By having the second line orthogonal to the first one, the sensitivity in the out-of-plane direction of each line is enriched, further increasing the spatial resolution of the obtained kinematics compared to a single tomograph case. For this, a single initial volume is reconstructed with the Astra toolbox using radiographs from both lines after a precise calibration of the system geometry. Then, radiographs are acquired on the fly from both lines during the mechanical test. In a post-processing step, the difference between these radiographs and the volume reprojection in both directions is minimized simultaneously with respect to kinematic parameters. The latest advances in this methodology will be presented with examples of experiments with fast phenomena, such as viscoelasticity or crack propagation, showing the current state of the implementation and usage at the MatéIS laboratory.

DVC Analyses and LEFM parameter calibration for additively manufactured Inconel 718 mini-CT specimens

Valmalle Malo (1), Smaniotto Benjamin (1) (2), Marae-djouda Joseph (1) (3), Hild François (1)

1 - Laboratoire de Mécanique Paris-Saclay (France), 2 - DER Génie Mécanique ENS Paris Saclay (France), 3 - EPF-Ecole d'Ingénieurs Cachan (France)

Speaker: Valmalle Malo. **Monday**. Start time: **14:20**. Room: Saint Clair 3B LVL2. Link to abstract.

In the present work, the mechanical response of additively manufactured mini CT specimens made of Inconel 718 alloy were studied when subjected to tensile loading. The specimens were printed with two build orientations, flat and upright and with +/- 45∘C and 0∘/90∘ raster orientations. The effect of the printing parameters on the fracture parameters was evaluated. The tests were monitored using X-ray tomography. Kinematic fields were measured via Finite Element based (global) Digital Volume Correlation (DVC). A special mesh accounting for the crack (i.e., allowing for displacement discontinuity along the crack plane) was used. These kinematics fields were used to extract Linear Elastic Fracture Mechanics parameters by using William's series. The mesh adaption greatly improved the correlation residuals and the LEFM parameters were successfully extracted from the measured displacement fields using the aforementionned procedure. It is shown that the fracture toughness and Young's Modulus of the sample printed in the vertical direction decreased compared to the other two printed horizontally. Conversely, there were no significant differences between the two 'flat' samples with different raster angles.

In-situ characterization of Plastic Strain Localization and Strain Partitioning in Polycrystalline Materials via 3D X-ray Diffraction Imaging Techniques

Romain Charles (1) (2), Texier Damien (3), Proudhon Henry (4), Héraud Lorène (5), Berveiller Sophie (6), Ludwig Wolfgang (2) (7), Malard Benoît (8)

1 - Ecole Nationale Supérieure de Chimie de Montpellier (France), 2 - European Synchrotron Radiation Facility [Grenoble] (France), 3 - IMT École nationale supérieure des Mines d'Albi-Carmaux (France), 4 - Mines Paris, PSL University (France), 5 - École Nationale Supérieure d'Arts et Métiers [Bordeaux-Talence] (France), 6 - École Nationale Supérieure d'Arts et Métiers (France), 7 - Matériaux, ingénierie et science [Villeurbanne] (France), 8 - Centre interuniversitaire de recherche et d'ingénierie des matériaux (France)

Speaker: Romain Charles. **Monday**. Start time: **14:40**. Room: Saint Clair 3B LVL2. Link to abstract.

Plastic deformation in metals often manifests as localized slip bands, which are characterized by complex dislocation structures leading to lattice distortions and rotations. Advanced 3D X-ray diffraction imaging techniques enable the non-destructive visualization and quantification of these phenomena, as demonstrated by Ludwig et al. (2019). This study highlights recent advancements in the characterizing lattice rotation fields during the early stages of plastic deformation in alloys such as Inconel 718, pure Ti, 304L, and 316L. The focus is on the roles of twin-related domains, phase transformations, and microstructural evolution under applied external stresses.
To complement synchrotron-based diffraction techniques, high-resolution digital image correlation (HR-DIC) from laser scanning confocal microscopy (LSCM) and scanning electron microscopy (SEM), provide additional insights into local slip activity (Stinville et al., 2023). The integration of near and far field methods (e.g., Diffraction Contrast Tomography, Topotomography, 3DXRD and s3DXRD) with high-resolution tomography enables multimodal characterization during in-situ tensile tests at room and elevated temperature, particularly at the ID11 synchrotron beamline. This combination yields comprehensive data on grain topography, mosaicity, and local strain fields across the sample volume (Arnaud et al., 2025).

The results underscore the potential of these advanced imaging techniques to unravel mechanism of strain localization and partitioning in polycrystalline materials. Through a synthesis of experimental data and simulations, the study demonstrates the critical influence of crystallographic orientation and twin-related domains on strain distribution and slip activity. Furthermore, high-temperature in-situ experiments reveal the evolution of deformation mechanisms under realistic loading conditions. These findings shed light on grain interactions, twin nucleation processes, and the microstructural responses to applied stresses, paving the way for improved understanding of plastic deformation in polycrystalline systems. Ultimately, this knowledge informs the design and optimization of next-generation high-performance alloys.

Arnaud, A., Sun, J., Bachmann, F., Esin, V., Proudhon, H., 2025. 3D mosaicity of a single-crystal nickel-based superalloy by lab-based diffraction contrast tomography. Scr. Mater. 257, 116463. https://doi.org/10.1016/j.scripta
Ludwig, W., Vigano, N., Proudhon, H., 2019. Observation of slip bands in the bulk of polycrystals using a combination of DCT and Topotomography, in: 40th Risoe International Symposium : Metal Microstructures in 2D, 3D and 4D. Risoe, Denmark.
Stinville, J.C., Charpagne, M.A., Maaß, R., Proudhon, H., Ludwig, W., Callahan, P.G., Wang, F., Beyerlein, I.J., Echlin, M.P., Pollock, T.M., 2023. Insights into Plastic Localization by Crystallographic Slip from Emerging Experimental and Numerical Approaches. Annu. Rev. Mater. Res. 53, 275–317. https://doi.org/10.1146/annurev-matsci-080921-102621

In-situ synchrotron X-ray investigation of 3D microscale strain fields during tensile loading of LPBF AlSi10Mg

Defer Marion (1), Rocco Alessandro (2), Andriollo Tito (3), Tarantino Gabriella (2), Hild François (2), Kantor Innokenty (4), Zhang Yubin

1 - DTU Construct, Department of Civil and Mechanical Engineering (Denmark), 2 - Université Paris-Saclay, CentraleSupélec, ENS Paris-Saclay, CNRS, LMPS - Laboratory of Mechanics Paris-Saclay (France), 3 - Aarhus university, Department of Mechanical and Production Engineering - Mechanics and Materials (Denmark), 4 - MAXIV, DanMAX (Sweden)

Speaker: Defer Marion. **Monday**. Start time: **15:00**. Room: Saint Clair 3B LVL2. Link to abstract.

AlSi10Mg is a widely-used alloy for Laser Powder Bed Fusion (LPBF) due to its good processability. Its as-printed refined microstructure, featuring an AlSi eutectic network at the aluminium cell wall boundaries and grain boundaries, results in yield stress and ultimate tensile strength frequently exceeding those of its cast counterparts. Furthermore, its lightweight, low cost, and excellent corrosion resistance, combined with the advantages of LPBF, make the AlSi10Mg alloy particularly interesting for aerospace and transportation applications. However, LPBF often generates high residual stresses along with the presence of matrix porosity in as-printed AlSi10Mg, which significantly lower the ductility. Annealing heat treatment allows the residual stresses to be relieved but also leads to the degradation of the AlSi eutectic network resulting in the formation of Si particles. These particles coarsen further upon longer annealing times, potentially impacting the alloy's mechanical performance. Additionally, the heat treatment may alter the distribution of pores within the material. An in-depth understanding of the influence of the Si particles and pores on the microscale deformation mechanisms is crucial for optimizing heat treatments and achieving enhanced mechanical properties.
To investigate these effects, miniaturized dog-bone samples made of LPBF AlSi10Mg annealed at 520∘C were studied by synchrotron X-ray tomography during uniaxial tensile testing. The fast image acquisition rate combined with superior contrast and spatial resolution (ca. 275 nm) provided by the DanMax beamline at the MAXIV synchrotron enabled the visualization of the pores as well as micro-sized Si-rich particles dispersed within the aluminum matrix.
Using full-field measurements obtained via digital volume correlation, 3D strain fields were extracted during tensile deformation, and the microscale mechanisms of strain localization which eventually led to fracture, were revealed. The results indicate that the development of strain bands was affected by the alloy microstructure, including structural features of the Si particles, pore distribution and 3D melt pool morphology. The findings are presented, and it is discussed how they may be used to guide the refinement of heat treatments to improve the mechanical properties of LPBF AlSi10Mg.

Investigating strain heterogeneity leading to fracture in an aluminium alloy under plane strain tension using 3D (nano)tomography and crystal plasticity simulations

Gille Maryse (1), Proudhon Henry (1), Oddershede Jette (2), Quey Romain (3), Morgeneyer Thilo (1)

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Speaker: Gille Maryse. Invited. **Monday**. Start time: **15:20**. Room: Saint Clair 3B LVL2. Link to abstract.

Aluminium alloys are increasingly utilized in the automotive industry as substitutes for steel to address the demand for lightweight materials and contribute to reducing CO_2 emissions. New challenges thus arise to optimize their formability to obtain the complex geometries required for automotive body panels. Given that most stamping defects occur under conditions close to plane strain tension, this study focuses on analyzing the strain heterogeneity that leads to ultimate fracture in plane strain tension specimens made of 6016 T4 aluminium alloy. The polycrystalline effects on the internal strain heterogeneity are investigated using correlative 3D tomography techniques within the material bulk, and finite element simulations based on the real grain structure of the tested specimen, including grain shape and orientation.
A miniaturized plane strain tensile specimen, based on the design proposed by Park et al. (1), validated via surface DIC to confirm the plane strain state, is used. The specimen is tested *in situ* testing within a laboratory tomograph. Initially, a non-destructive 3D grain map of the central region is obtained using lab-based Diffraction Contrast Tomography (DCT) (2). This is followed by an *in situ* tensile test performed in 12 loading steps until fracture, imaged by Absorption Contrast Tomography (ACT). Taking advantage of the plane strain condition, the evolution of the internal strain field is measured by projection-DIC (P-DIC) within the material bulk, using the natural speckle pattern provided by intermetallic particles. The strain measurements reveal a heterogeneous field with early, spatially stable slanted bands that coincide with the fracture location.

In parallel, 3D crystal plasticity finite element simulations (CP-FE) are performed using the meshed DCT-measured microstructure as input. The predicted strain fields from these simulations describe well the experimental measurements. Conversely, simulations using macroscopic anisotropic plasticity models or CP-FE with random grain orientations fail to reproduce the observed results. Besides, a strong statistical correlation is found between the experimentally measured and CP-FE-predicted average strain per grain along the loading direction. This finding supports the hypothesis that crystallographic effects are responsible for the initiation of early strain heterogeneities, which subsequently lead to localization and ultimately dictate the fracture path.

To characterize the strain heterogeneity bands with more precision, an *in situ* nanotomography experiment was performed on a dedicated plane strain tension specimen. P-DIC applied to the collected data at 100 nm resolution provided a far better spatial resolution that could be achieved thanks to the capture of a second population of smaller intermetallic particles. It was thus possible to measure the width of the deformation bands, which is of the order of the grain size of the material, confirming the role of the polycrystalline structure in the strain heterogeneity.

(1) N. Park, H. Huh, S. J. Lim, Y. Lou, Y. S. Kang, and M. H. Seo, "Fracture-based forming limit criteria for anisotropic materials in sheet metal forming," *Int. J. Plast.*, vol. 96, pp. 1–35, Sep. 2017, doi: 10.1016/j.ijplas.2016.04.014.
(2) F. Bachmann, H. Bale, N. Gueninchault, C. Holzner, and E. Lauridsen, "3D grain reconstruction from laboratory diffraction contrast tomography," *J. Appl. Crystallogr.*, vol. 52, Jun. 2019, doi: 10.1107/S1600576719005442.

In-situ synchrotron X-ray micro-diffraction investigation of the microstructure evolution during low strain deformation of laminated Ti-Al composites

Yu Tianbo (1)

1 - Danmarks Tekniske Universitet = Technical University of Denmark (Denmark)

Speaker: Yu Tianbo. Keynote. **Monday**. Start time: **16:00**. Room: Saint Clair 3B LVL2. Link to abstract.

Laminated metal composites offer a unique opportunity to combine the desired properties of different metals in one material, with a possible further benefit from the constraint of the layer interface. To explore this constraint effect, the microstructural evolution of a laminated Ti-Al composite was investigated by a synchrotron-based micro-diffraction technique, namely differential aperture X-ray microscopy (DAXM) of a very high angular resolution (0.01∘). An ultra-low-strain deformation microstructure was revealed non-destructively in the bulk interior in the "fully recrystallized" Al layer. This ultra-low-strain deformation microstructure was found to result from the thermal stress, induced during cooling after annealing, due to the different coefficients of thermal expansion for the Ti and Al layers. The annealed sample was subsequently tensile deformed to a strain of 1.66% and followed by in situ DAXM. The results pointed to the important effects of the initial microstructure and the interface constraint, as well as the grain size and crystal orientation, on the plastic deformation. A gradient in dislocation density from the layer interface to the center was found in the Al layer of the annealed sample, and this gradient increased slightly during tensile deformation. The variation of the dislocation density is discussed based on the activation and interaction of dislocations in grains of different sizes and orientations during plastic deformation. Moreover, deviatoric elastic strains were estimated based on polychromatic microbeam diffraction, while lattice strains along the normal direction of the tensile sample were directly measured using monochromatic microbeam diffraction. The estimated deviatoric strains show large spatial variations, and the mean values are consistent with the external loading conditions. The directly measured lattice strains also show large spatial variations, although the magnitude of this variation is smaller than that for the estimated deviatoric strain. It is discussed how the findings advance the understanding of constraint effects within laminated metal composites and may be used to design novel composite materials.

In-situ multimodal X-ray characterization of local strain distributions in the bulk of metallic samples

Juul Jensen Dorte (1)

1 - Danmarks Tekniske Universitet = Technical University of Denmark (Denmark)

Speaker: Juul Jensen Dorte. **Monday**. Start time: **16:40**. Room: Saint Clair 3B LVL2. Link to abstract.

By a combination of X-ray techniques, for example absorption contrast tomography (ACT) and diffraction contrast tomography (DCT) or 3D X-ray diffraction (3DXRD), it is possible to map the spatial distribution of plastic strains in the bulk of particle containing metals. The local strains are determined based on the relative change in position of the particles during straining, while the crystallographic orientations of the individual grains are quantified by the diffraction. In this presentation this possibility is illustrated by two examples: In the first example, laboratory X-ray ACT and DCT are combined to map the evolution in local strains during tensile deformation of an Al-Cu alloy. It is shown that there are large variations in the local strains, which to our surprise could not be directly related to neither grain orientation nor grain size. The experimental results are compared to crystal plasticity finite element (CPFEM) simulations, and while good agreement is obtained on the macro scale, there are significant differences on the local scale. This is discussed. In the second example, laboratory X-ray ACT are combined with synchrotron 3DXRD and beam scanning methods to map both the evolution in local strain as well as crystallographic orientations during tensile deformation of commercially pure Al (AA1015). After straining to near fracture, the sample is annealed and the nucleation sites are related to the microstructure and local strain. Most nucleation site are observed to be at grain triple or multi junctions, and it is discussed if the local strain distribution can explain which junctions become active nucleation sites and which do not.

In situ study of double yielding in PA11: Role of the amorphous and crystalline fractions

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1 - INSA Lyon, CNRS UMR 5223, Ingénierie des Matériaux Polymères, F-69621Villeurbanne, France (France)

Speaker: Gros Barthelemy. Invited. **Monday**. Start time: **17:00**. Room: Saint Clair 3B LVL2. Link to abstract.

It is shown that polyamide 11 (PA11), a semicrystalline polymer (SCP), exhibits two well-distinct successive yield points on its characteristic stress-strain curve during tensile deformation below Tg (cf. figure 1). This phenomenon, denoted as double yielding (DY), has been observed in other SCPs like PA6(1)(2). Previous work has demonstrated an intimate relationship between the first yield point σy1 and molecular dynamics in the amorphous phase. The second yield point σy2 is more sensitive to morphological changes in the crystalline phase(3). Studying the origin of DY is pivotal to provide more insights into the complex and hierarchical deformation mechanisms in SCPs.
The purpose of this work is to investigate more thoroughly the origin of such phenomenon and to relate it to the deformation mechanisms occurring in the amorphous and crystalline phases of PA11. Particularly, we wish to highlight the specific deformation scenario and the chronology of the deformation events happening between the two yield points. In that regard, we aim at understanding the specific roles both phases play in the onset of plastic (and thus permanent and heterogeneous) deformation and the initiation of damage mechanisms such as cavitation and/or lamellar fragmentation. A macroscopic mechanical analysis by the means of tensile, creep and recovery tests is carried out and supported by a microstructural examination using in situ USAXS/SAXS/WAXS techniques performed at ESRF. Such fine methods are necessary to monitor real-time microstructural evolution and damage mechanisms during tensile deformation at the scale of lamellar stacks and uncover the co-dependent involvement of crystalline lamellae and inter-lamellar amorphous regions in the appearance of DY.

On one hand, the main results demonstrate the connection between σy1 and the onset of plastic flow in the amorphous phase as modelled by a thermally activated process. On the other hand, σy2 marks the onset of crystalline lamellae de-structuration. Between the two yield points, deformation seems to be governed by both amorphous and crystalline mechanisms operating interdependently. In addition, we investigate the influence of the test temperature on DY and the underlining deformation and damage mechanisms. Finally, these findings address crucial comprehension elements regarding the onset of heterogenous and irreversible deformation in SCPs.

References:
1. Shan et al., Polymer Testing, 24, 704-711, 2005
2. Shan et al., Journal of Polymer Science Part B: Polymer Physics, 45, 1217-1225, 2007
3. Gros et al. (under submission), 2025

Ascertaining the plastic deformation mechanisms of polycrystalline Zn and Mg through in situ HRDIC and EBSD

Rezaei Alireza (1), Mollaei Nafiseh (1) (2), Sarebanzadeh Maral (1) (2), Yang Biaobiao (1) (2), Fatemi Seyed Mahmood (3), Llorca Javier (1) (2)

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Speaker: Mollaei Nafiseh. Keynote. **Tuesday**. Start time: **10:00**. Room: Saint Clair 3B LVL2. Link to abstract.

Hexagonal close-packed (HCP) metals, such as Mg and Zn, accommodate plastic deformation through different mechanisms that depend on c/a ratio of the HCP lattice as well as on the loading conditions (temperature, strain rate) and texture. They include dislocation slip along different slip systems (basal, prismatic and pyramidal, pyramidal), twinning across different planes ({10-12} and {10-11} as well as double twinning), grain boundary sliding and recrystallization. Moreover, their dominant mechanism also changes during deformation and may be different at the onset of yielding, during strain hardening region or after the maximum strength, when the deformation is localized. This information is relevant to design microstructures with improved mechanical properties (yield and ultimate tensile strength and ductility) but can only been obtained through in situ mechanical tests in which the deformation processes are monitored through electron back-scattered diffraction (EBSD) and high-resolution digital image correlation (HRDIC). In order to ascertain the activation of the different plastic deformation mechanisms, tensile tests were carried out within the scanning electron microscope in pure Zn and Mg samples manufactured by extrusion. Both materials exhibited a weak basal tetxure. Mechanical tests were stopped at different strain levels and the sample surfaces were analyzed by means of EBSD and HRDIC. In the case of Mg, deformation was accommodated by basal slip and {10-12} tensile twins, while traces of non-basal slip were not found due to the high critical resolved shear stress necessary to activate them. It was found that deformation of Mg was very heterogeneous, that the global Schmid factor was not suitable to predict the active basal slip system in 50% of the cases while no relation was found between the twinning Schmid factor and twin nucleation. Most twins were nucleated at grain boundaries and triple junctions and the active twin variants were found to be related with the angle between the twin shear strain and the grain boundary trace of the surface. The mechanical tests of the Zn samples revealed that initial plastic deformation was mainly accommodated by basal although pyramidal slip was also found in selected grains. {10-12} compression twins appeared at larger strains and the active twin variant followed the Schmid law, indicating that plastic deformation was more homogenous. Finally, grain boundary sliding was also detected at higher strains.

Residual stress measurement in microscopic steel wires by FIB hole drilling

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Speaker: Engel Raphaël. **Tuesday**. Start time: **10:40**. Room: Saint Clair 3B LVL2. Link to abstract.

Michelin produces the metallic reinforcements that are integrated in their tyres, guaranteeing exceptional resistance, durability and performance. The reinforcements consist of wires obtained by wire drawing, which leads to a complex microstructure and remarkable mechanical properties. The residual stress generated by the process impacts the mechanical behaviour and the reliability of the wires. It is therefore necessary to be able to measure the residual stress, which is challenging due to the very small diameter of the wires (about 200 μm). To characterize residual stress, the incremental hole drilling method is used, with a small hole (diameter 10 μm) machined with FIB (Focused Ion Beam) at the surface of the wire. A specialized digital image correlation (DIC) analysis is developed to measure the displacement due to stress relaxation from the SEM images at multiple hole drilling depths. Consecutively, an FE calculation is performed at each machining stage to link the surface displacement field to the relaxed internal stresses. The main measurement challenge is due to the low measurement signal (small strains) in contrast with a series of measurement artifacts: e.g., tilt of the specimen, SEM scanning errors, and positioning of the hole centre. Dedicated kinematic modes are included in the specialized DIC method to carefully handle each of these artifacts when measuring the displacement field. This method makes it possible to obtain several components of the residual stress tensor at multiple depths, which was not possible with the wire dissolution method (Boujnah 2023).

High resolution surface field measurements by tracking gold nanodroplets

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Speaker: Tanguy Döme. **Tuesday**. Start time: **11:00**. Room: Saint Clair 3B LVL2. Link to abstract.

Remodeling of surface films is a well known method to create a pattern that can be used during in situ straining to measure surface displacements by digital image correlation (DIC). Originally done by a thermal treatment, it can now be done with the deposition of low fusion alloys that remodel at low temperature. The deposition conditions can be varied to provide a wide range of size for the surface features, down to a few nanometers (Hoef). It can therefore be used to perform high resolution DIC from images obtained on strained samples within an SEM.
In this work, an alternative is explored where gold nanodroplets are formed by laser dewetting. Each droplet is tracked individually. The displacements are measured at two scales : from the variation of the position of the droplet itself and, in case of localized deformation, from the deformation of the droplet when it is crossed by the slip discontinuity (either slip band or grain boundary), if the displacement is not too much oriented out of the surface.

Laser induced dewetting has the flexibility to create different density and sizes of droplets by playing on the initial film thickness. The fluence is kept low, just above the threshold to melt the film. Literature shows that the film solidifies again after a few 100 ns and therefore the heat cannot alter the microstructure. The droplets are very adherent and deform with the substrate. Another advantage is that in between the droplets, the substrate is apparent. Therefore, zooming out and using the BSE mode of the SEM, the contour of the grains is still distinguishable. This is useful when positioning slip bands with respect to grain boundaries during deformation when the grains experience deformation and rotation.

The capability of the method is demonstrated on Eurofer97, a ferritic steel obtained from an annealed martensite. A density of tracked droplets of 300 / μm2 with diameters ranging from 10 to 60 nm (peak at 35 nm) was obtained, allowing a spatial resolution of 70 nm. A tensile test was conducted up to 15% true strain. Slip bands were identified by calculating the Von Mises strain from the displacement field, over a field of view of 40 x 40 μm. The deformation within the bands were measured (when well oriented) from the deformation of the droplets intersected by the bands either thick (wider than the droplets) or thin (cutting the droplets). Blockage and transmission of bands and fracture of nanometer scale carbides when impacted by slip bands were observed.

(Hoef) J.P.M. Hoefnagels et al. Strain 55 12330 (2019)

Experimental investigation of grain boundaries deformation behavior in austenitic stainless steels

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Speaker: Masset Thomas-Xavier. **Tuesday**. Start time: **11:20**. Room: Saint Clair 3B LVL2. Link to abstract.

InterGranular Stress Corrosion Cracking (IGSCC) is a common failure mode of metal alloys used in industrial applications. This phenomenon is for example observed in the internal structures of nuclear reactors, leading to the intergranular failure of austenitic stainless steel components (1). In the latter case, irradiation affects the mechanical and deformation behavior of the material, resulting in an increased susceptibility to IGSCC due to stronger slip incompatibilities at grain boundaries. In order to predict intergranular cracking, modelling grain boundaries deformation and mechanical behavior – such as slip (dis-)continuity, local stress / stress fields – are thus required. In this study, two experimental campaigns were conducted to gain insights and provide quantitative data relevant for (un)irradiated austenitic stainless grain boundaries for which data in the literature are scarce. First, in-situ Scanning Electron Microscope (SEM) high temperature (320∘C) tensile tests were performed on one unirradiated and two proton-irradiated polycrystalline 304L specimens in order to assess slip transfer at grain boundaries. Activated slip systems were determined by coupling Electron Back Scatter Diffraction (EBSD) and slip trace analysis and / or Digital Image Correlation (DIC) coupled with the recently developed Slip System based Identification of Local Plasticity (SSLIP) (2). Among the different model proposed in the literature, slip discontinuity is found to be well predicted considering Luster-Morris (LM) criterion coupled with Residual Burgers Vector (RBV) criterion. Interestingly, the range of parameters for which slip discontinuity occurs is found to be independent of both strain and irradiation levels, and consistent with the criteria reported in the literature for FCC materials (3). Second, in-situ SEM high temperature (320∘C) tensile tests were performed on millimeter-sized bicrystalline and oligocrystalline specimens. The material used is a FeCr12Ni26Si3 (wt %) austenitic stainless steel subjected to a high temperature heat treatment promoting grain growth. DIC was used to assess local displacement fields at grain boundary, along with stress – strain curves. The effect of grain boundary type and applied strain was assessed thoroughly on both slip (dis-)continuity and local strain fields. Finally, crystal plasticity constitutive equations accounting for the presence of grain boundaries were used to perform numerical simulations of the experiments, and calibrated using the experimental data. These constitutive equations are then used to perform polycrystalline aggregates simulations aiming at predicting intergranular stresses and thus obtaining an IGSCC fracture criterion for (un)irradiated austenitic stainless steels.

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Coupled experimental and numerical investigations of microscale plastic deformation of friction-stirred high-strength aluminum alloys.

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Speaker: Girault Florian. Invited. **Tuesday**. Start time: **11:40**. Room: Saint Clair 3B LVL2. Link to abstract.

7xxx-series aluminum alloys are widely used in the industry, particularly in the aerospace sector, notably due to their high strength-weight ratio. However, their use in additive manufacturing (AM) poses specific challenges owing to their inherent metallurgical characteristics. To mitigate these AM-specific defects, several solutions have been implemented, and innovative processes have been introduced, such as additive friction stir deposition. Enhancing these alternative methods necessitates an in-depth understanding of the deformation mechanisms within these alloys. Yet, their mechanical behavior is controlled by local plasticity at the microstructural level: cnsequently, achieving a detailed comprehension of the deformation of these alloys requires a micro-scale investigation of plasticity.
The methodology is the following. First, optical and scanning electronic microscopy are performed to analyze the structure of the deposited material. Then, in situ SEM tensile tests are performed, coupled with digital image correlation analysis based on lithography and speckle patterns to access the local strain fields. The impact of several microstructural features in plastic deformation localization is investigated and extensive post processing methods are presented. Coarsest intermetallic compounds are demonstrated to be fragile, triggering high strain concentration in their vicinity before early cracking. However, no particle-cluster effects are exhibited for this specific microstructure. In addition, multiple crystallographic parameters are correlated with grains' mean deformation, resulting in very low correlation coefficients, even for the Schmid factor. Finally, the impact of grain boundaries on strain localization is addressed, exploring several slip-blocking criteria proposed in the literature.
In parallel, simulations are performed at the scale of the grains aggregate. A Meric-Cailletaud law is used to model the behavior of digital twins of experimental specimens. Its calibration is based on results from tensile tests, nano-hardness tests, and data from the literature. By comparing the simulation and experiment results, the relevance of hypotheses regarding the localization of plastic deformation is addressed. This analysis is extended to more complex microstructure, including the interface between friction-stirred aluminum and the initial substrate. Finally, the limits of such micro mechanical experiments and simulations are discussed.

Tailoring Mechanical Properties and Deformation Behavior in amorphous/crystalline Zr40Cu60/Fe Nanolaminates

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Speaker: Ezequiel Marco. Keynote. **Tuesday**. Start time: **14:15**. Room: Saint Clair 3B LVL2. Link to abstract.

Key Words: In-situ testing; amorphous/crystalline nanolaminates; local deformation; nanoindentation; micropillar compression

Amorphous/crystalline nanolaminates are known for their tailored mechanical properties by adjusting the microstructure, density of interfaces, and bilayer period (L), leading to large yield strength and plasticity (1). For instance, in amorphous/crystalline CuZr/Cu nanolaminates, tuning the thickness of the amorphous layer leads to enhanced plasticity by suppressing shear band instability, achieving a maximum tensile strength of 2.5 GPa and ≈4% strain at failure (2). Similarly, adjusting the crystalline layer thickness can suppress the catastrophic propagation of shear bands by promoting a homogeneous deformation and achieving a yield strength of 2.6 GPa and plasticity of 40% in compression (3).

However, critical questions remain regarding the effect of amorphous/crystalline interfaces on the mechanical properties and how they affect the deformation mechanisms (2). In addition, it is critical to gain insight into the critical layer thickness required to initiate plasticity and effectively suppress shear band formation, as well as to understand the deformation mechanisms in the amorphous/crystalline nanolaminates (1). Moreover, the use of BCC crystalline layers remains less explored.

In this study, we synthesized 2μm-thick Zr40Cu60/Fe-BCC nanolaminates by magnetron co-sputtering. Nanocrystalline Fe has been selected for its high mechanical resistance and positive mixing enthalpy with Cu, which limits intermixing, to form well-defined interfaces to block shear band propagation effectively. First, we varied the Zr40Cu60 layer thickness (from 10 up to 90 nm), keeping the Fe layer equal to 10 nm, to investigate the transition from localized plastic to homogeneous deformation in the amorphous layer. In a second approach, we kept the same volume fraction of Zr40Cu60 and Fe layers, varying the bilayer period (L), from 20 up to 80 nm, effectively tuning the density of interfaces (2/L). The atomic and microstructure have been investigated by transmission electron microscopy and x-ray diffraction. Optoacoustic techniques, nanoindentation, and in-situ micropillar compression tests were carried out to achieve a complete understanding of their mechanical properties under different loading conditions.

Regardless of the architecture, the elastic modulus of the nanolaminates closely follows rule-of-mixture predictions (2), while the hardness is significantly higher than that of the individual layers. Notably, the hardness increases with higher interface densities, reaching 9.6 GPa in the 10/10 nm Zr40Cu60/Fe nanolaminate (2/L = 0.1 nm-1) due to shear bands blocking at the interfaces and dislocation pile-up. In-situ micropillar compression tests reveal that nanolaminates with 90 nm Zr40Cu60 layers undergo localized deformation with percolative shear bands similar to monolithic Zr40Cu60. In contrast, nanolaminates with thinner Zr40Cu60 layers exhibit delayed shear band propagation and achieve yield strengths of up to 2.5 GPa. Nanolaminates with a 40 nm bilayer period demonstrate a delocalized shear band distribution effectively blocked by Fe layers, enabling compressive plastic deformation up to 45% and a yield strength of 2 GPa.

These findings highlight the potential of amorphous/BCC-crystalline Zr40Cu60/Fe nanolaminates as high-performance materials, offering tailored mechanical properties and a unique combination of exceptional strength and plasticity.

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CoCrNi and FexCoCrNi(100-x) complex compositional alloy thin films: Defect-induced microstructural evolution and microscale mechanical behavior

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Speaker: Curam Arjun Bharath. **Tuesday**. Start time: **14:55**. Room: Saint Clair 3B LVL2. Link to abstract.

Keywords: Complex compositional alloys, thin films, nanolaminates, micromechanics, stacking faults, nanotwins

Complex compositional alloys (CCAs) are recent materials characterised by a high number of atomic constituents, which are gaining interest due to the possibility of finely tuning their mechanical behaviour by adjusting their composition, potentially leading to large strength/ductility balance, especially for FCC nanocrystalline alloys (1). From the CoCrFeMnNi "Cantor" alloy, one of the frequently studied ternary compositions is CoCrNi, which reported hardness (H) and elastic modulus (E) values up to 9 and 180 GPa, respectively, due to a columnar structure with planar defects (2). The addition of Fe to form FeCoCrNi stabilised the FCC phase with a small grain size of _~20 nm, affecting H mildly up to _~10 GPa (3). These studies, however, were mainly conducted on bulk alloys, and research on complex compositional alloys thin films (CCAs-TF) is still in its early stages, particularly concerning the relationship between compositional variation, microstructural evolution, and their effect on mechanical behaviour, requiring the need of advanced characterisation techniques capable of probing the mechanical behaviour of sub-micrometre scale materials. Moreover, a nanoengineered approach to developing new multilayered thin film nanoarchitectures consisting of alternating layers and phase structures with boosted mechanical properties remains an open field.

Here, we synthesised CoCrNi and Fex(CoCrNi)100-x CCA-TFs by magnetron sputtering, in which the thicknesses were controlled from 15 nm up to 730 nm, and the Fe content was varied from 13 up to 29 % at. For each of the four compositions, using HRTEM, we investigated the evolution of the microstructure and phase structure as the thickness increased. With the help of nanoindentation (CSM), we analysed how the increasing Fe content affected the mechanical behaviour. Thick CoCrNi film shows a columnar structure with an average grain size of _~26 nm and a (111) textured FCC structure with a minor HCP (100) phase segregation. Additionally, we observed a transition from HCP to co-existing HCP/FCC upon increasing thickness from 15 to 40 nm. The presence of the minor HCP structure was attributed to a high density of Intrinsic Stacking Faults (ISF) and twinning within the FCC structure, which was responsible for a high H = 9.7 GPa and E=204.4 GPa as reported by nanoindentation and optoacoustic techniques.

With the addition of Fe, we retained the columnar structure while stabilising the FCC phase, reporting a preferred (111) orientation without phase segregation due to good miscibility of Fe within CoCrNi. With no segregation of Fe, and fewer defects like stacking faults owing to a higher stacking fault energy 32.5 mJ m–2 (4), H and E decrease down to 7.6 and 185 GPa.

While the FCC phase was stabilised in FeCoCrNi, individual layers of CoCrNi and Fe can lead to different phases and potential Fe segregation to obtain strong interfaces. For this reason, we synthesised _~1.4 μm thick CoCrNi/Fe (FCC/BCC) nanolaminates with bi-layer periods (Λ) of 70 and 35 nm, featuring incoherent interfaces aimed at blocking dislocations and crack propagation. We show high adhesion at the interfaces with limited crack formation during indentation, while compression of micropillars resulted in high yield strengths (2.5 GPa) without fracture up to 12%. Owing to a high density of interfaces and thickness confinement, a high plasticity of up to 40% was obtained.

Overall, our study shed light on the microstructure–mechanical properties of CoCrNi, Fex(CoCrNi)100-x

thin films, and CoCrNi/Fe nanolaminates, with potential applications in hard coatings and microelectronics.

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X-ray tomography characterization of the impact of compression on the microstructural properties of a packing of hemp shiv particles

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Speaker: Chekai Tinhinane. **Tuesday**. Start time: **15:15**. Room: Saint Clair 3B LVL2. Link to abstract.

The use of sustainable materials like bio-based building materials is a significant step toward carbon neutrality by reducing CO_2 emissions. Given that their performances are closely tied to their microstructure, it is essential to understand and link microstructural properties to the multiphysical behaviors of these materials.

This study aims to analyze the microstructural evolution of a hemp shiv packing under varying compression states. X-ray tomography images were acquired at the Soleil Synchrotron facility (Anatomix beamline), providing valuable information into the three-dimensional structure of the particles and their internal pore network that cannot be obtained using other techniques.

Scans were performed on cylindrical samples measuring 40mm in diameter and 40mm in height. The scans were performed in a loose state and under four compression states (sample density ranging from 130 to 844 kg/m3).

In addition to classical absorption reconstruction of the tomography data, a phase-enhancement Paganin (1) filter was used to improve the contrast of the images of this low attenuating material. However, the image analysis still faced several challenges: (i) high intra- and inter-particle porosity reduced image contrast, particularly at particle boundaries, which are critical for the individual segmentation of the shiv particles; (ii) the complex morphology of hemp shiv particles displays diverse shapes and sizes, (iii) the application of the Paganin filter accentuated artifacts in the images; and (iv) the large dataset size required using high-performance computational resources for efficient analysis.

Thus, convolutional neural networks were used to segment the hemp shiv packing. Semantic segmentation was achieved using deep learning, with training data generated by manually labelling the particles and assigning distinct labels to the surrounding sample (air). The "generic U-Net dl-7 ifc32" model, of the Dragonfly ORS software (2), was employed for this task. After training, in all 3 directions of space, the model was successfully inferred on the whole volume.

The individual segmentation of hemp shiv particles was based on their structural and spatial properties. Initial separation was performed by applying a threshold to eigenvalues derived from the structure tensor of the particle packing. These eigenvalues generated markers for a watershed algorithm. Further local separation was needed for wrongly merged particles, using a distance map and applying a local watershed algorithm. The initial labels were refined iteratively to ensure accurate particle separation.

The porous volume of the sample was analyzed using Dragonfly ORS, with the OpenPNM (3) plugin implementing PoreSpy's SNOW algorithm. This allowed modelling pores as spheres and throats as cylinders which resulted in the assessment of pore size, volume, position, and connectivity.

Finally, the local density of hemp shiv particles was examined with the help of calibration scans performed on materials with known densities. Assuming a linear relationship between X-ray attenuation and material density (Beer-Lambert's law), the density of hemp shiv particles was determined by correlating grey values with known densities from calibration data (4).

Despite the data's complexity, both qualitative and quantitative information were obtained, filling gaps in the literature and accentuating the value of X-ray tomography for studying such materials. The image

analysis techniques developed for these granular media are not only applicable to bio-based materials but can also be extended to study other granular materials, especially those with complex geometries and challenging contrast conditions.

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In-situ microscopic and macroscopic mechanics of flexible silica aerogels

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Speaker: Zinke Max. Invited. **Tuesday**. Start time: **15:35**. Room: Saint Clair 3B LVL2. Link to abstract.

Aerogels are lightweight, open-porous materials, that exhibit high specific surface area and low thermal conductivity (1). Among the different types of aerogels, the super flexible silica aerogels exhibit advantageous material characteristics with regards to their mechanical behaviour for practical applications (2). Moreover, a modification of the density of flexible silica aerogels allows for increased lightweight characteristics without a considerable reduction in heat insulation efficacy (3). However, there is a lack of knowledge regarding the mechanical behaviour and damping properties of flexible silica aerogels, particularly with regard to their suitability for low-temperature insulation necessary for aerospace and hydrogen applications.
In order to address these challenges, this study aims to provide insights into the micro- and macroscopic behaviour of flexible silica aerogels using computer tomography (CT) and dynamic mechanical analysis (DMA). Flexible silica aerogels of different densities were developed using moulds and shaping of geometries needed for testing was facilitated by the use of razor blades. Resulting geometries were scanned and measured using 3D-scanning technology. In-situ CT is employed while the aerogels undergo compressive loading to track the variation in pore size distribution across the aerogels specimen as a function of compressive strain. Additionally, compression tests were conducted using DMA, which has been employed for non-flexible silica composites previously (4, 5), to examine the mechanical and damping characteristics as a function of temperature and frequency. These combined findings have the potential to accelerate the advancement of flexible aerogel development and facilitate their practical implementation in low-temperature aerospace and insulation applications.

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Multi-instrumented in-situ measurement of strain induced martensitic transformation in medium Mn stainless steels

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Speaker: Lagorce Gwendal. **Tuesday**. Start time: **15:55**. Room: Saint Clair 3B LVL2. Link to abstract.

Keywords: Stainless Steels, Strain induced martensitic transformation, In-situ magnetic measurements modeling, Digital image correlation, Thermal imaging

The existence of an austenite-martensite phase transformation while undergoing plasticity gives excellent properties to unstable stainless steels (e.g. AISI 301 grades). Understanding and monitoring this phenomenon is essential for the development/validation of constitutive laws. Since austenite is paramagnetic whereas martensite is ferromagnetic, magnetic measurements allow for the estimation of martensite content. Well-suited in-situ systems usually involve permeameters to perform such measurements where a primary coil ensures magnetization, and a pick-up coil measures the material magnetic response. However, those systems forbid deformation and thermal full field measurements. On the other hand, previous work has shown that a non-contact fluxgate magnetometer can be used to monitor magnetic behavior variations without magnetization coils (1). It is a lightweight system that gives access to surfaces and therefore allows field measurements. Given the exothermic nature of the phase transformation, measuring temperature field could provide additional knowledge allowing for more accurate modeling. The present study aims to evaluate feasibility of using a non-contact fluxgate sensor to measure martensite volume fraction variations and make a correlation with mechanical and thermal fields.

Three grades of 1.5mm thick medium Mn stainless steel sheets have been considered exhibiting different austenite stabilities (thanks to variable compositions). Monotonic tensile tests have been then performed at a low strain rate (10–4 s–1) at room temperature using a hydraulic testing machine. Full field displacement and temperature measurements have been carried out using Digital Image Correlation (DIC) and Infrared Thermography (IRT). The magnetic response of the material and its environment has been evaluated during the tests using a 1D-axis fluxgate magnetometer designed for weak magnetic field measurements with a range of $\pm$ 200 μT.

Both DIC and IRT captured the propagation of Lüders and Portevin-le-Châtelier bands, associated with oscillations of the tensile stress. The higher the austenite stability the higher the strain threshold at which bands propagation begins. The magnetic measurements showed a global increase of the magnetic signal at increasing deformation, in accordance with previous experiments (2). Field measurements allowed to demonstrate a clear correlation between bands propagation and martensite content. Results will be used as validation tests of a fully coupled thermomechanical modeling of these materials.

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Characterization of Oil Paints Through An In-Situ Experimental Micro-Mechanics Approach : Linking Deformation Behavior to Chemistry

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Speaker: Bagheri Behboud Ali. Invited. **Tuesday**. Start time: **16:35**. Room: Saint Clair 3B LVL2. Link to abstract.

Historical oil paintings represent an invaluable cultural heritage. At the same time, however, from an engineering perspective, oil paintings are also complex, multi-phase systems, in which the mechanical properties of oil paint are influenced by several factors, including composition, pigment-to-binder ratio, environmental conditions (temperature and humidity), and the age of the paint. These factors crucially affect the paint stiffness, ductility, and fracture response.
This study aims to investigate the mechanical behavior of oil paint through a novel integration of real-time microscopic inspection and micro-mechanical testing. Using advanced micro-mechanics techniques, based on micro-tensile testing (1), we conduct a detailed experimental analysis of stress-deformation responses in oil paint samples. Departing from profilometry images taken with a profilometer, Digital Image Correlation (DIC) is employed to obtain local strain maps of the paint samples during testing (2). The thickness of the samples can also be accurately measured before mechanical testing by correlating the top and back surface height profiles of the paint samples from the profilometry images. After the micro-tensile experiments, based on the obtained strain maps and force values for each step of loading and knowing the thickness of samples, stress-strain curves can be constructed, providing information about the mechanical properties of oil paints such as ductility and stiffness at the micro-scale.

To validate the experimental methodology, model system titanium white samples are prepared on polyester substrates. The samples are then exposed to accelerated thermal aging for different periods under controlled temperature and humidity levels.

This in-situ experimental methodology additionally incorporates spectroscopic analyses to characterize the chemical properties of the paint. By combining mechanical and chemical analyses, we gain a deeper understanding of the correlation between the chemistry and mechanical behavior of oil paints over time. This approach offers a versatile framework for studying a range of oil paint samples, linking their micro-structure to micro-mechanical properties, and shedding new light on the long-term behavior of oil paints.

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Identification of the damage mechanism in a ceramic matrix composite / protection CMC-EBC system under tensile test.

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Speaker: Lancrenon Victor. **Tuesday**. Start time: **16:55**. Room: Saint Clair 3B LVL2. Link to abstract.

Ceramic matrix composites (CMC) are used in the aeronautic field for extreme thermomechanical conditions. Their low density and high refractory properties make them relevant materials for critical parts such as turbine blades. To prevent the CMC degradation for long life duration in an oxidizing atmosphere at high temperature into the engine, the material has to be coated with an environmental barrier coating (EBC). The EBC is a two-layer material composed of a silicon bond coat and a rare earth disilicate top coat. CMC and EBC are well-identified components: elaboration and deposition method, main failure mechanisms under various environment. However, only little researches deal with the synergic effect of the EBC and the CMC (1).
The {CMC-EBC} system performance in the engine is leaned on chemical compatibility, effectiveness of the EBC and mechanical resistance. Moreover, the initiation and the propagation of cracks between the CMC and the EBC are key information to predict the lifetime of the system in the engine environment. Indeed, under thermomechanical loadings, several factors have to be investigated to predict the stress distribution and damage evolution of {CMC-EBC}: interfaces, morphologies of the EBC and of the CMC, thermal properties and the part geometry. First works were carried out with tensile test at room temperature (2). These authors highlight the dissimilar behavior between CMC and {CMC-EBC}, especially depending on the substrate condition (degree of surface roughness).

This work focuses on the understanding of the cracking of a SiCf/SiCm CMC coated with an ytterbium disilicate (DSYb) top coat for turbine blade application. The different thermomechanical parameters are identified and considered separately in order to quantify their impact on the system in the engine. Furthermore, owing to damage closure phenomenon, a direct in-situ analysis is required to characterize the initiation and the propagation of first cracks through the CMC and the EBC. Specific instrumentations are set up for each test: image correlation, direct microscopy, acoustic emission.

Before the introduction of thermomechanical factors, an initial behavior has to be established. Tensile tests on {CMC-EBC} are performed at room temperature to determine the original crack path. The effect of different surface states of the substrate is also explored. Such a test allows direct observation of the surface by microscopy. A digital microscope maps a polished surface at several level of strain. Coupled with Digital Image Correlation (DIC) on other faces, a comprehension of the cracking between the CMC and the EBC is permitted. Elsewhere, these experiments are supported by tomographic test campaigns. Experiments are reproduced directly in the micro-computed tomography device. These acquisitions are challenging because of the low SiC/SiC contrast and the high absorbance of the top coat. It is necessary to work at high energy with phase contrast. Thereby, the crack behavior in the {CMC-EBC} at room temperature will be described in the volume.

This work paves the way for a full understanding of the behavior under thermomechanical loadings of a {CMC-EBC} system and for determining whether the EBC can enhance the lifetime of the aeronautical part if its damage threshold is greater than that of the CMC.

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In-situ imaging for the strain-engineering of deformable electrodes

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Speaker: Amiot Fabien. **Tuesday**. Start time: **17:15**. Room: Saint Clair 3B LVL2. Link to abstract.

Hydrogen is today mainly obtained by hydrocarbon steam reforming, which produces large CO2 quantities. Because of the rising concern about greenhouse gas emissions, the widespread use of hydrogen as an energy carrier requires the development of a carbon-free production chain. In case it makes use of renewable electricity sources, hydrogen production by electrolysis may be the key to trigger the expansion of this promising sector. However, only a few percent of the total hydrogen production comes today from water electrolysis, mainly because of its cost, which is about four times higher than the cost of hydrogen obtained by steam reforming. Electrolysis requires an electrocatalyst, typically platinum, which is rare and expensive.

Electrolytic production of H2 is thus handicapped by its dependence on platinum and by the adverse role played by the hydrogen bubbles produced at the electrode surface in the hydrogen production itself. It is therefore crucial, in order to minimize the cost and energy losses, to avoid materials like platinum as much as possible, and to limit the adverse effects of bubbles production.

It has already been demonstrated that elastic strains can modulate the electrocatalytic activity of metals (1-3), so that more abundant materials could be strained in order to compare with platinum in terms of electrocatalytic activity. The question of the optimal position in the 6-dimensional strain space is however open, and we propose an experimental approach based on an original imaging technique to address this issue.

This imaging technique is applied to monitor in-situ, in-operando the early stages of the hydrogen production at the surface of deformable micro-cantilevers made of much more abundant materials. This first reveals that the hydrogen production is very non-uniform along the cantilever. An initial deformation could also be imposed to the micro-cantilevers, so that the imaging technique has been applied to cantilevers with varied external mechanical loadings. This reveals that the hydrogen production is significantly altered on the surface under tension of the bent cantilever. Contrarily, the hydrogen production is enhanced when the surface is under compression.

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How chemistry influences the stiffness of fresh cement paste

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1 - Institute for Building Materials, ETH Zurich (Switzerland), 2 - Department of Microsystems Engineering [Freiburg] (Germany), 3 - Department of Civil, Environmental and Geomatic Engineering, Institute for Building Materials, ETH Zurich (Switzerland)

Speaker: Michel Luca. **Tuesday**. Start time: **17:35**. Room: Saint Clair 3B LVL2. Link to abstract.

When cement powder is mixed with water, attractive interactions between the cement grains result in the formation of a flocculated network. This network can withstand loads, and is at the origin of the macroscopic stiffness of fresh cement paste. Over time, the stiffness of the paste increases due to the chemical formation of hydration products that strengthen the flocculated network. High quality time-resolved stiffness data can be obtained with oscillatory shear measurements. However, such measurements do not directly capture the chemical reactions at the origin of the formation of hydration products. Thus, time-resolved rheology data only offer limited insights regarding the origin of stiffness increase in fresh cement paste. In this work, we perform oscillatory shear and isothermal calorimetry measurements to couple the chemical formation of hydration products with the stiffness evolution. Over our experimental window, we obtain a single exponential evolution of stiffness with heat of hydration, allowing to decouple the effects of chemical kinetics from the evolution of mechanical properties. We obtain evidence supporting that the stiffness evolution is governed by a strengthening of grain-to-grain contacts in the network, due to the formation of hydration products on the surface of the grains. We show that time-resolved rheology data is easily biased by different hydration kinetics across samples, which has led to a number of contradictory statements in the literature.

Fracture of Aluminum/steel welds imaged in 2D and 3D.

Dancette Sylvain (1), Suzuki Kiyoaki T. (2), Adrien Jérôme (3), Sato Yutaka S. (2)

1 - Matériaux, ingénierie et sciences [Villeurbanne] (France), 2 - School of Engineering [Tohoku Univ] (Japan), 3 - Matériaux, ingénierie et science [Villeurbanne] (France)

Speaker: Dancette Sylvain. Invited. **Tuesday**. Start time: **17:55**. Room: Saint Clair 3B LVL2. Link to abstract.

Dissimilar welding of aluminum (Al) alloy to steel suffers from the formation of a brittle intermetallic layer (IML) at the weld interface. The brittle interface limits the strength of the welded joints and their use in industrial applications. In this study, the mechanical behavior of Al/steel joints produced by TIG arc welding is investigated at different scales, from macroscopic tensile shear tests monitored *in situ* by Digital Image Correlation (DIC) to their miniature version under 3D X-ray tomography on top of local probing of the different weld zones. It is shown how the addition of selected alloying elements in the weld pool can improve the weld strength and affect crack propagation at the interface. Image-based finite element modeling using a Cohesive Zone Model (CZM) allows to clarify the contribution of the modified intermetallic layer at the interface on the fracture process.

MS4.3 - Non-invasive and Inverse Methods for Constitutive Parameter Identification

Organisers: S. Avril (SAINBIOSE-EMSE), S. Evans (Cardiff Univ) andJ. Réthoré (GEM-ECN)

Inverse Approaches to Dynamic Viscoelastic Material Identification

Lamberson Leslie (1), Matejunas Andrew (1), Koumlis Stylanios (1), Fletcher Lloyd (2)

1 - Colorado School of Mines (United States), 2 - UKAEA (United Kingdom)

Speaker: Lamberson Leslie. Keynote. **Thursday**. Start time: **10:00**. Room: Saint Clair 4 LVL2. Link to abstract.

Polymers are integral to various engineering applications, including defense, aerospace, automotive, and biomedical fields, where materials often experience high strain rates. Traditional high-rate material characterization techniques, such as the Kolsky bar (also known as the split-Hopkinson pressure bar), rely on assumptions like uniform loading and negligible inertial effects, which may not hold under all conditions. This presentation explores optical noninvasive and inverse methods for constitutive parameter identification, focusing on the dynamic behavior of both brittle and non-brittle polymers. The first segment examines open-cell polyurethane foams, commonly used in protective helmet liners, which exhibit significant rate-dependent behavior with low impedance. By employing quantitative microstructural characterization and a non-parametric formulation of the Virtual Fields Method (VFM), we analyze the compressive response of these foams across six orders of magnitude in strain rate, elucidating the relationship between microstructure and bulk mechanical properties as well as the validity of the experimental assumptions. The second segment addresses the viscoelastic behavior of brittle polymers, using polymethyl-methacrylate (PMMA) as a model material. Leveraging the Image-Based Inertial Impact Test (IBII) and numerical simulations based on a generalized Maxwell model, we are able to extract multiple viscoelastic parameters in a single experiment. Experimental validations confirm the method's efficacy in capturing viscoelastic properties across various time constants, offering a more robust approach to dynamic material characterization.

Relating local field fluctuations in composites with the sensitivity of their effective response to constitutive parameters: application to identification of elastic and viscoelastic materials.

Valmalette Robin (1), Bellis Cédric Hochard Christian Lahellec Noël

1 - Laboratoire de Mécanique et d'Acoustique [Marseille] (France)

Speaker: Valmalette Robin. Invited. **Thursday**. Start time: **10:40**. Room: Saint Clair 4 LVL2. Link to abstract.

In the study of the behaviour of composite materials, micromechanical models and homogenization methods make it possible to predict their effective macroscopic responses from the knowledge of their geometric and material properties at the micro-scale. The fundamental components of micromechanical homogenization models are the microstructure, phase properties, and the homogenization scheme itself. While advancements in tomographic imaging and image processing have made microstructural data more easily accessible, determining the constitutive properties of the constituents remains challenging in experimental conditions.
An alternative to in situ microscale experimentations is the inverse homogenization process, wherein microscale parameters are inferred from macroscale experimental data. Also referred to as reverse engineering or de-homogenization, this method revolves around minimizing, relative to the microscale properties, the discrepancy between measured macroscale data and simulated data so as to identify the former. Two types of macroscale data can be used: (i) In cases where the macroscale behaviour is homogeneous, average variables, such as effective elastic moduli, are employed (9). Alternatively, (ii) structural experiments, which inherently produce heterogeneous macroscale data, can be used (7). In these cases, displacement fields are typically measured via digital image correlation, and multiscale computational methods, such as FE2 techniques (2), are applied to account for the heterogeneities at both the macro and microscales. While this latter approach is efficient, as it generates a larger volume of data from a single test, it is often more complex to set up.

As highlighted by (4), inverse homogenization constitutes an ill-posed problem whose solution existence, uniqueness, and stability are not guaranteed. In this context, significant efforts have been made to analyse structural experiences in order to extract more information and therefore enhance the likelihood of successful parameter identification. Noticeably, some gradient-based algorithms for cost functionals minimization, using gradient approximations by finite differences, as well as semi-analytical methods have been developped (3). Given the cost of accurate gradient computations, gradient-free algorithms have also been explored (5), along with techniques related to model-reduction (6). Using a Monte Carlo approach, (8) examined the impact of noise in displacement fields on the identified properties, depending on the specific structural experiment. Both linear and nonlinear identified behaviours have been investigaed in the literature.

In the present work, we focus on the identification of a subset of constitutive parameters in a context where the macroscale heterogeneity is neglected. The unknown microscale parameters are to be identified from the effective response of the composite and the known microscale parameters. The solution is obtained by minimizing a cost function which compares the measured effective response to the one obtained numerically with guessed parameters and using full-fields homogenization computations. In order to use gradient-descent algorithms, the gradient and the Hessian matrix of the cost function need to be computed, through the derivatives of the effective reponse itself relatively to the microscale parameters. To this end, a second-order asymptotic expansion of the effective energy is proposed, building on the developements in (1). The first-order derivatives are shown to be directly computable from the strain fields generated by the homogenization simulations. However, a few additional simulations are required for the Hessian matrix. This approach is also particularized when the effective potential can be written as a function of effective parameters as for linear elastic or viscoelastic phases using the Laplace-Carson transform. In the general non-linear case, the method is described in terms of a stress- or energy-based formulation. We provide first an analytical example to highlight some key issues related to the inverse

method: the solution existence, uniqueness and stability. A second example consists in identifying the transversely isotropic elastic behaviour of carbon fibres embedded within an isotropic elastic matrix based on full-field simulations. The gradient and the Hessian matrix are computed, and a linearization of the uncertainties is performed to quantify the propagation of perturbations on each input parameter and thus determine the relevant experiments to be planned in order to improve the identification procedure. Finally, a last example concerns the identification of the viscoelastic behaviour of a matrix in a glass-fibre composite (isotropic elastic fibre), again, with full-field computations. All the examples presented here are based on synthetic data, while circumventing the so-called inverse crime, in order to illustrate the proposed approach. The satisfying performances of the latter will be illustrated quantitatively in terms of accuracy and numerical efficiency. In addition, the relevance of the linearized uncertainty quantification analysis will be highlighted.

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Mathematical and numerical analysis of Data-Driven Identification (DDI) method: the case of isotropic materials

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1 - Institut de Recherche en Génie Civil et Mécanique (France)

Speaker: Hachem Nour. Invited. **Thursday**. Start time: **11:00**. Room: Saint Clair 4 LVL2. Link to abstract.

Identifying the mechanical responses of materials is a fundamental challenge in solid mechanics. The constitutive equations close the boundary value problems of mechanics by establishing a relationship between kinematics (strain) and equilibrium (stress). This relationship can be identified through mechanical tests: simple tests (homogeneous isostatic tests) or complex tests. Simple tests on the material allow for direct calculation of the stress field from a force measurement. These tests are limited to simple deformation modes and often require multiple tests to obtain sufficient data for identifying the stress field. In contrast, complex tests involving heterogeneous strain fields provide more information in a single test, although the stress field cannot be determined directly using traditional methods.
Classically, the stress field is estimated using identification methods such as Finite Element Method Updating (FEMU), Virtual Field Method (VFM), among others. These methods rely on a postulated model a priori with its parameters adjusted to fit experimental data. However, the initial choice of the predefined model strongly influences the results and adds bias.

An alternative identification approach called Data-Driven Identification (DDI) was proposed by Leygue *et al.* (2018), allowing the estimation of stress fields from full-field kinematic measurements and applied net force without postulating a constitutive model. This method is based on Data-Driven Computational Mechanics (DDCM) introduced by Kirchdoerfer and Ortiz (2016), where a database of admissible strain-stress pairs samples the mechanical response of the material. DDI builds this database, which is used to regularize the stress estimation problem, but generally admits multiple solutions.

DDI has been successfully applied to synthetic and real data for various material behaviors, including elasticity, hyperelasticity, viscoelasticity, elastoplasticity, and large deformation. Although, a theoretical study of the method to validate the ability of DDI to accurately estimate and converge to the true mechanical stress is still missing.
In this work, we investigate numerically and algorithmically the preliminary work of Leygue (2024), where a criterion for the uniqueness of solutions was introduced. We propose three methods to characterize this criterion numerically and will evaluate their effectiveness, including a comparison of their computational costs. The DDI framework relies on algorithmic parameters that are often chosen empirically. As these parameters are adjusted to gain accuracy, the DDI becomes ill-posed. This study will help us select DDI parameters, reducing the risk of over-fitting. We extend the algebraic framework presented in Leygue (2024) to demonstrate how one can drive DDI to account for the possible isotropy of the materials. The consequences of this isotropic assumption are discussed.

Hetero-EUCLID: Simultaneously segmenting and discovering hyperelastic constitutive models of all components of a heterogeneous hyperelastic material using EUCLID.

Joshi Akshay (1), Dutta Saurav (1), Kumar Siddhant (2)

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Speaker: Joshi Akshay or Kumar Siddhant. Invited. **Thursday**. Start time: **11:20**. Room: Saint Clair 4 LVL2. Link to abstract.

In this work we build upon the Bayesian-EUCLID* framework to simultaneously segment, and characterize the full hyperelastic behavior of all constituents of a heterogeneous material. To achieve this, we make use of experimentally observable 3D surface displacements and boundary force data obtained from the finite element simulation of the biaxial tension test on the heterogenous sample. We make use of the derivatives of the strain-invariant field, as opposed to the invariants themselves, to segment the material with high-fidelity. The segmented material is then analyzed by an improved form of the EUCLID framework to simultaneously discover the material models of all constituent materials. We are able to achieve the segmentation and characterization of the material with data from a single experiment, thereby highlighting the ability of the hetero-EUCLID framework to be deployed in high-throughput characterization of heterogeneous elastic/hyperelastic materials. These settings include rapid characterization of composites and rapid characterization of selective tissue stiffening in medical conditions such as fibroatheroma/atherosclerosis or cancer.

*Bayesian-EUCLID: Discovering hyperelastic material laws with uncertainties (https://doi.org/10.1016/j.cma.2022.11522

A MATERIAL TESTING 2.0 METHODOLOGY FOR CORTICAL BONE

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Speaker: Pierron Fabrice. Invited. **Thursday**. Start time: **11:40**. Room: Saint Clair 4 LVL2. Link to abstract.

Background

Cortical bone mechanical properties (stiffness, damage, failure stress) are essential to understand the effects of osteoporosis or to predict accident-related trauma, for instance. Legacy mechanical testing rests on simple load configurations (uniaxial tension/compression, bending) and point deformation information (extensometer, strain gauges) (1), often even using the machine crosshead displacement to measure deformation, which is highly questionable. This leads to large dispersions in literature data for which it is hard to decide what is due to bone variability and what is caused by inaccurate testing procedures. Moreover, while cortical bone is generally assumed orthotropic or transversely isotropic, few studies address the full set of stiffness components and doing so requires different specimens which is a major difficulty for Human bone and adds to the scatter.

The advent of full-field deformation measurements like Digital Image Correlation (DIC, (2)) and inverse identification techniques like the Virtual Fields Method (VFM, (3)) has given rise to a new paradigm in mechanical testing of materials called Material Testing 2.0 (MT2.0) (5). This paper illustrates how this new paradigm can be used to identify the full set of orthotropic stiffness components of Human trabecular bone from a single test.

Experimental setup

Ten femoral and tibial cortical bone samples were sectioned from two elderly female donors (ethics reference: 19/YH/0184). The designed test configuration was a deep notched specimen mounted off-axis in the test machine. Speckle patterns of between 20 and 40 μm were transferred onto the samples using a stamp and the ink from a permanent marker. The samples were loaded in displacement control until 400 N (based on the linear region before failure from trial tests) and then unloaded. Each sample was tested repeatedly to assess repeatability and different speckle patterns. Back-to-back 2D DIC was used to extract the displacement and strain fields with the MatchID software.

Results

The four in-plane orthotropic stiffness components of each specimen were obtained using noise-optimized virtual fields (3). A thorough uncertainty analysis was conducted by simulating each individual test with its specific speckle pattern using synthetic image deformation (7). This allowed for the application of individual correction factor on the mean value identified for each stiffness component, as well as the prediction of uncertainty bounds due to the camera noise.

The results show that it is possible to identify the four orthotropic stiffness components of cortical bone on one single specimen (7). Thanks to the numerical simulation, it was found that the inter-specimen scatter was smaller than the inter-test scatter when the same specimen was tested several times. This suggests that in the literature on testing of biological materials, the large scatter generally reported may be partly caused by test scatter. This new methodology has great potential to produce higher quality data and will be extended to non-linear behaviour in the future.

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Combining continuous discrete lattice methods and Data Driven Identification to go beyond linear elasticity

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Speaker: Dandin Héloïse. Invited. **Thursday**. Start time: **14:15**. Room: Saint Clair 4 LVL2. Link to abstract.

In the field of isotropic elasticity and brittle fracture, the use of a discrete lattice network of mechanical bonds can be very useful to overcome issues from the continuum description in solid mechanics (Sage *et al.*, 2020; Longchamp *et al.*, 2024). Thus, in the field of the so-called 'discrete element methodology' (DEM), a Bernouilli beam kinematic can be chosen as a powerful link between nodes in a 3D space to bring out a continuous behaviour.
The cohesive beam model needs to be identified through an inverse method, also called calibration process, that aims to find the local parameters that best approximate the macroscopic behaviour (Girardot *et al.*, 2019). These parameters have different natures. On the one hand, the density of beams, defined by the number of discrete elements and by their connectivity, refers to the lattice structure. On the other hand, the local constitutive model relative to the cohesive beams form a second set of unknowns, especially if the target continuous behaviour needs to go beyond linear elasticity. In this case, the calibration step becomes tedious and requires to solve a high-dimensional problem that involves multiple parameters.

We suggest to improve this process by employing a model-free data-driven approach for the identification of the local behaviour of the mechanical bonds. The idea of model-free computing was first introduced by (Kirchdoerfer and Ortiz, 2016) with Data-Driven Computational Mechanics (DDCM), a method in which the constitutive model traditionally employed to solve initial-boundary-value problems is replaced by a discrete database that samples the material response. DDCM inspired Data-Driven Identification (DDI), which has been developped by (Leygue *et al.*, 2018) and further refined by (Leygue, 2024).

DDI is an inverse method that aims to find the balanced stress fields from heterogeneous strain fields without postulating any constitutive model. The algorithm requires displacements fields, for instance obtained from full-field measurements, and boundary conditions on a given geometry. In the end, it provides a discrete data set, called material database, that samples the material response in an appropriate space depending on the nature of the material behaviour (elastic, hyperelastic, etc.). DDI can be used to compute all kinds of linear or nonlinear elastic mechanical responses without further refinements. This property differentiates model-free from model-based methods, such as Finite Element Model Updating (FEMU), where testing several constitutive laws implies high computational costs while the relevance of the *a priori* chosen one is difficult to evaluate.

The idea is to implement DDI within a DEM framework to identify a local behaviour that provides a good approximation of a macroscopic material response obtained experimentally or generated artificially (in a way that mimics a real experiment), which is also the same framework to study the continuous emergence from a discrete network. In a first stage, we build a lattice structure following recommendations to ensure an isotropic network (Girardot *et al.*, 2019). When combined with the (pseudo-)experimental nodal displacements and reaction forces, performing DDI provides a discrete material database that describes the local material behaviour.

Preliminary results have been obtained with a truss kinematic, where each links corresponds to a bar in the 3D mesh. A Finite Element (FE) simulation conducted with a nonlinear elastic constitutive model provides nodal displacements and reaction forces. Then, DDI has been performed on the truss problem in the stress-strain space defined by the Cauchy stress tensor and the infinitesimal strain tensor. These quantities are scalar and represent the material behaviour of the bars.

To compute the mechanical response of the lattice, a constitutive model can be fitted a posteriori on the local material database, either in the stress-strain space or, following the recommendation of (Costecalde *et al.*, 2024), thanks to the strain energy density. The latter is computed from the material database

and provides a more accurate estimation of the parameters of the constitutive model.

Furthermore, a study of the influence of the lattice design on the material database obtained with DDI is led. We test different connectivities by linking the nodes to their n-first neighbours. Moreover, the truss is converted to a lattice beam model, which requires to define the adequate space for the description of the local behaviour.

The combination of DDI with DEM provides flexibility on the design of the lattice, since this operation is decorrelated from the identification of the local behaviour. DDI also allows to differentiate between several material behaviours with a single specimen (Valdés Alonzo *et al.*, 2022), which would make it possible to implement a complex network of bonds with varying properties.

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Diagonal compression of masonry panels : Identification of non-linear parameters via Digital Image Correlation

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Speaker: Collin Louis. Invited. **Thursday**. Start time: **14:35**. Room: Saint Clair 4 LVL2. Link to abstract.

During seismic events, masonry walls are subjected to in-plane loadings, which predominantly induce compression along the wall diagonals. The ASTM-standardized diagonal compression test simulates these conditions on a square masonry panel to analyze failure mechanisms and determine its compressive strength. This method has been widely applied to study both unreinforced and reinforced masonry, facilitating direct comparisons of their strength under identical loading conditions. Traditionally, deformations along the vertical and horizontal diagonals are measured using Linear Variable Differential Transducers (LVDTs). This measurement approach may limit the accuracy of strain analyses in heterogeneous materials like masonry.

To address this limitation, Digital Image Correlation (DIC) has been increasingly adopted for measuring displacement fields, providing a contactless method for tracking displacement fields and crack development. Studies have demonstrated that DIC enhances insight into displacement fields, strain distribution, and crack propagation. In diagonal compression tests on unreinforced masonry elements, cracking typically occurs along the mortar joints, forming a characteristic staircase pattern. To observe these mechanisms in greater detail, multi-view DIC is used, namely, two cameras are positioned at an angle to capture the overall 3D kinematics of the specimen, while three additional cameras focus on key regions. Specifically, two cameras monitor the upper and lower boundary conditions, and a third focuses on the specimen center, where initial cracking is expected to initiate and subsequently propagate across the sample. This approach reduces uncertainties in the zoomed regions, allowing for a more precise observation of localized phenomena (1).

Diagonal compression tests are simulated using the Finite Element Code Cast3M (https:// www-cast3m.cea.fr/). Two types of models are considered in this study, both are based on an isotropic damage model that incorporates friction and unilateral effects, namely, a macroscale law with a detailed representation of block and mortar elements using the nonlinear Vassaux et al. model (2), and a volumetric homogenized nonlinear model (3). Initial simulation results show that both models effectively replicate the expected behavior of a masonry panel. The objective, therefore, is to identify the parameters of these models

throughout the test. While extensive research has been conducted on diagonal compression tests, only few studies have considered full-field measurement techniques, such as DIC with the identification of nonlinear parameters. Transitioning from measured data to identifying meaningful physical parameters requires careful consideration of numerous variables. A recommended approach is to begin by virtually designing the experiment (4). This process involves initially positioning cameras in areas of interest, followed by conducting virtual tests in Blender (https://www.blender.org/) to simulate experimental conditions that closely approximate reality. In this virtual setup, a fully parameterized image correlation environment is created, integrating nonlinear Finite Element simulations with animation tools. Sensitivity analyses and uncertainty quantifications are then conducted to ensure that model parameters can be precisely calibrated prior to the actual experimental campaign.

The study proceeds with a description of the experimental campaign on individual block and mortar elements, followed by details of the diagonal compression test setup. Results, including force-displacement curves and post-processing of multi-view DIC data are then presented. Employing a Finite Element Model Updating (FEMU) approach, the objective is to use full-field displacement data from DIC to accurately define the boundary conditions within the simulations. By integrating this data with force measurements, the study seeks to identify and calibrate the nonlinear parameters of the masonry model

effectively.

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Different dynamic models for the study of ultrasonic wave dispersion for mechanical characterization of construction materials

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Speaker: De Fazio Nicola. Invited. **Thursday**. Start time: **14:55**. Room: Saint Clair 4 LVL2. Link to abstract.

In this study, we explore the dispersion relation, i.e. the dependence of the plane wave velocity with respect to the frequency, for longitudinal ultrasonic waves from both experimental and modeling points of view. For the modeling point of view, we start considering a 1D medium with different constitutive properties: from one hand we consider the non-dissipative strain-gradient elastic model and from the other hand the dissipative viscoelastic model.
1. **Dispersion stemming from material microstructure**: At low frequencies, the phase velocity correlates directly with material stiffness. Conversely, at higher frequencies (i.e. at low wavelengths), the phase velocity is influenced by the material's microstructure. The transition between these two velocity regimes occurs within a frequency range proportional to the characteristic length of the material.

2. **Dispersion arising from material internal viscosity**: Higher internal viscosity enhances material stiffening under dynamic loading, whereas lower viscosity necessitates higher frequencies to observe significant velocity variations.

We derive the governing equations for both cases with the extended Rayleigh-Hamilton principle. The analysis shows good agreement with the experiments and further experimental investigations are designed for a clear and quantitative identification of the dissipative contribution.
Moreover, the governing equations of motion, material constitutive relations, and boundary conditions are formulated and solved in both 2D and 3D domains to account for the real experimental conditions and reduce approximation errors. A time integration scheme is employed, coupled with variational formulations and finite element methods (FEM), to establish a relationship between wave velocity and material parameters, similar to the solutions for 1D models. We start with isotropic, homogeneous, and linearly elastic materials and then we add viscosity and microstructure as for 1D models. Validation was conducted using experimental data from concrete specimens tested in a controlled laboratory setting. The results confirmed the model's accuracy in predicting wave velocity and dynamics.

Neural networks methods for discovering multi-regional and biphasic hyperelastic properties

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Speaker: He Yiqian. Invited. **Thursday**. Start time: **15:15**. Room: Saint Clair 4 LVL2. Link to abstract.

Constitutive material modeling is an important basis for mechanical analysis. Machine learning methods based on neural networks have been extensively used for the discovery of material constitutive laws. Recently, Flaschel et al. (1) proposed a new *"unsupervised"* framework that does not need any stress labels, which are usually difficult to measure in experiments. However, there is no work on the application of the unsupervised machine learning models for multi-regional constitutive models of heterogeneous materials. To address this issue, this paper develops a new unsupervised multi-regional constitutive learning model. In the implementation of this machine learning model, two indicators, i.e., the residual nodal force indicator and the free energy indicator, are first defined to identify nonhomogeneous interfaces or material distributions. Then, the combined identification of multi-regional constitutive models is conducted by adding a *switch function* to the extended strain invariants layer of the neural network. Finally, multi-regional constitutive models can be trained in one neural network at the same time. Besides, the proposed method has also been applied into the discovery of biphasic hyperelastisc constitutive models, especially the equations of osmotic pressure. The effectiveness of the proposed model is verified through numerical simulation examples including an application to constitutive modeling of soft biological tissues undergoing regional damage.

Stochastic variational inference for myocardial constitutive models using heterogeneous displacement fields

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Speaker: Krijnen Rogier P.. Invited. **Thursday**. Start time: **15:35**. Room: Saint Clair 4 LVL2. Link to abstract.

The myocardium exhibits highly non-linear hyperelastic and orthotropic material behavior during passive deformation. Over the past few decades, many material models have been proposed, with one of the most popular ones being the microstructure-inspired constitutive model formulated by Holzapfel and Ogden (1). It has been shown that an accurate characterization of this material model based on homogeneous tissue experimentation is no easy task (2) and requires the excitation of multiple deformation modes, e.g. combined triaxial shear tests and biaxial stretch tests (3).
Inherently, such multimodal experimental protocols necessitate multiple tissue samples and extensive sample manipulations. Intrinsic inter-sample variability and manipulation-induced tissue damage might have an adverse effect on the inversely identified tissue behavior.

In this work, we aim to overcome this gap by focusing our attention to the use of heterogeneous deformation profiles in a parameter estimation problem. More specifically, we extend EUCLID, an unsupervised method for the automated discovery of constitutive models (4), towards highly non-linear, orthotropic materials using a Bayesian inference approach and three-dimensional continuum elements. We showcase its strength to qualitatively infer – with varying noise levels – the material model parameters of in-silico myocardial tissue slabs from a single heterogeneous biaxial stretch test. This method shows good agreement with the ground truth simulations and with corresponding credibility intervals for each parameter. Our work highlights the potential for characterizing highly nonlinear and orthotropic material models from a single biaxial stretch test - an approach long deemed to be infeasible.

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The Anisotropic Permeability of Skin Determined from Inverse Analysis of Centrifugal Draining Tests

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Speaker: Pulver Gabriel. Invited. **Thursday**. Start time: **15:55**. Room: Saint Clair 4 LVL2. Link to abstract.

Understanding the mechanical behaviour of human skin is crucial for medical applications such as wound healing (1), reconstructive surgery (2), automated planning of suture placement (3), skin growth using tissue expanders (4), formation of so-called stretch marks induced by abdominal skin tension during pregnancy (5), or intradermal and subcutaneous drug delivery (6). To rationalize in-vivo and ex-vivo experimental results and predict the mechanical behaviour of skin, several constitutive models were proposed. Recent studies rely on multi-layer and multiphasic modelling approaches (6), (7). In particular, quadriphasic models representing solid, liquid and ionic phases play a crucial role in modelling the biomechanics of soft biological tissue (6), (8). Thereby, tissue permeability is a crucial parameter to characterise the time-dependent mechanical behaviour of skin (9) or to analyse transport processes in drug delivery (6). Fluid permeability is often assumed to be isotropic, only accounting for changes in permeability due to volume changes (6), (7), (10). However, the collagen fibres in skin have a preferred in-plane orientation (11) which is expected to cause anisotropy of the permeability tensor. While modelling approaches accounting for anisotropic and deformation-dependent permeability properties were proposed (12), (13), there is a lack of experimental methods to accurately determine this crucial parameter and its dependence on flow direction. In fact, the range of the permeability values reported in the literature spans over a few orders of magnitude (14).
Our proposed experimental method exploits the body forces acting on all phases within a tissue sample when exposed to acceleration in a centrifuge. Centrifugal forces cause the liquid to flow out of the tissue at a rate that depends on tissue permeability. Using a porous support, liquid expelled from the tissue is rapidly transported away from the skin surface. This set of well-defined boundary conditions allows us to reliably simulate the experiment using the quadriphasic model (9) and conduct an inverse analysis, determining the permeability value based on the measured mass loss in the experiments. The new experimental setup allows us to quantify the skin's liquid flow in-plane and out-of-plane, depending on the orientation of the skin sample during the test.

First experiments were performed with porcine dermis and subcutis showing promising reproducibility. Further, the results indicate that there is indeed a measurable anisotropic permeability. Numerical sensitivity analyses were used to tune the experimental conditions and optimise the quantitative interpretation of the results. In particular, the computations showed that the transient phase of mass reduction in the experiments is mostly governed by the hydraulic permeability, while the long-term equilibrium mass is determined by the density of fixed charges, which determines the level of osmotic pressure within the tissue. The fibre and matrix stiffness parameters were found to play a subordinate role. The mean thickness of the samples was obtained from their planar cross-sectional area and the weight in the reference state. To determine the solid and liquid content within each tested sample, the weight of each sample was measured after it was dried out in an oven at the end of the centrifuge measurement, and compared to the reference initial weight. In conclusion, the results indicate that the new measurement procedure may provide a more reproducible and accurate method to determine the hydraulic permeability and its anisotropy in soft tissues.

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MS4.4 - Testing of materials and structures under extreme conditions or high-strain rate

Organisers: P. Longère (ISAE-SUPAERO/ICA), Daniel Rittel (Technion), Michel Coret (GEM-ECN) and Fabien Souris (CEA)

Durability Evaluation of Thermal Barrier Coating under Ultra-High Temperature for 1650°C Class Gas Turbine

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Speaker: Takeno Kazuma. **Wednesday**. Start time: **16:45**. Room: Saint Clair 5 LVL2. Link to abstract.

Rise of Turbine Inlet Temperature (TIT) plays a significant role to improve thermal efficiency of Gas Turbine Combined Cycle. Still, it is necessary to improve thermal barrier effect for hot parts to achieve higher TIT. Mitsubishi Heavy Industries, Ltd. has developed the advanced thermal barrier coating (TBC) which is capable of improving cooling efficiency of hot parts. and increased the thickness to satisfy the requirement. Although thicker TBC enhances its thermal protection capability, it is more likely to get buckling failure of TBC. This is caused by higher compressive thermal stress due to increase of a temperature differential between TBC surface and metal surface. This study introduces about advanced experimental techniques and methods to evaluate the durability of thick TBC under ultra-high temperature which simulated the severe environment of real gas turbine.

Crack propagation kinetics at the substrate/thermal barrier interface under complex thermomechanical loading

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Speaker: Coudon Florent. **Wednesday**. Start time: **17:05**. Room: Saint Clair 5 LVL2. Link to abstract.

Thermal barrier systems provide essential protection for the High-Pressure turbine blades of aircraft engines. Current engine development aims to increase the turbine's thermal efficiency, leading to a significant rise in the surface temperatures of turbine blades. During the design process, it is critical to ensure the durability of the thermal barrier coating under the extremely severe thermomechanical and environmental conditions applied. In particular, it is necessary to evaluate the adherence of the thermal barrier and its evolution during operation in order to estimate the number of cycles until spallation. Numerous tests for determining interface toughness exist in the literature (1), but they are destructive. This destructive aspect makes the characterization of interface toughness at various aging stages prohibitively expensive, thereby hindering the identification of clear trends and the isolation of inherent scatter in the thermal barrier spallation mechanism.
This study introduces a recent method for in-situ monitoring of crack propagation at the substrate/thermal barrier interface and called Laser Shock Damage Monitoring (LASDAM) (2-3). It leverages the ability to process a controlled-sized initial crack at the interface through a laser shock. Due to the evolution of the compressive stress level, the interfacial crack induces blistering of the ceramic layer. Subsequently, instrumentation of tests and analysis tools were developed to monitor, in a non-destructive manner, delamination and buckling of this blister during complex thermomechanical tests. The methodology has been validated under cyclic oxidation tests in furnace (homogeneous temperature), burner rig tests (with thermal gradients) (4) and in thermomechanical fatigue tests. More recently, this method has been applied to thermal gradient mechanical fatigue tests (TGMF). A synthesis of the results obtained in terms of delamination kinetics at the interface will be presented, as well as an analysis of the different regimes observed based on the applied loading conditions.

The cyclic evolution of the blister is modeled through finite element model accounting for nonlinear creep of metallic layer during thermomechanical cycles. This modeling is used to assess the local mechanical state at the crack tip. Then, equivalent quantities derived from fracture mechanics are calculated and analyzed to explain the stable delamination propagation during cycles. In a nutshell, the stable growth of a ceramic blister on a metallic surface can be studied for a large variety of load cases. It includes those where the viscoplastic behavior of the multi-layered system and progressive oxidation influence each other.

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In-situ observation of solid-solid phase transition in metals at high temperature

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Speaker: Fournier Alexandre. **Wednesday**. Start time: **17:25**. Room: Saint Clair 5 LVL2. Link to abstract.

Plasticity and phase transitions are among the main deformation mechanisms of metals. While each of them is understood separately, the coupling between them is less obvious. This coupling is challenging both for modeling (a multiscale model, from the atomic to the mesoscopic scale is needed) and experiments (one has to combine a good time resolution, adapted to the phase transition kinetics, and a good spatial resolution at the microstructure scale).This work focuses on solid-solid phase transitions in temperature. We present a device that allows for their in situ observation.

The sample is placed in the middle of a vacuum chamber, to avoid oxydation and to prevent the heat haze phenomenon (1). An electric current heats the sample by Joule effect. This allows for a wide range of temperature rates from no heating to several hundreds of degrees per second. Strain fields at one surface of the sample central zone are obtained thanks to an optical camera and the digital image correlation technique. The other side of the sample is used to measure the temperature of the sample using two pyrometers, one for low temperature and one for high, both focused at the center of the sample. A PID controller regulates the power intensity so that various temperature profiles can be imposed. A limit of the experimental procedure is that the temperature field is not perfectly homogeneous although it is supposed to be. The main temperature gradient is in the length of the sample, due to the grips acting as heat sinks.

In order to perform digital image correlation, it is necessary to have strong grey level textures on the images. To achieve this, a speckle pattern is applied on the studied surface of the sample. Its creation is a challenging because it must neither be too sparse nor too dense. In our case, the deposition is done thanks to an airbrush spraying a mixture of alcool and fine alumina particules (approximately 1μm in diameter).

In order to characterize the microstructure of the samples, the EBSD (for Electron Backscatter Diffraction) technique is used. It allows the measurement of crystals orientations on the sample surface, therefore detecting the grain sizes, positions and boundaries in a polycristal. Before performing the EBSD, the sample is polished in order to obtain a surface as flat as possible. The next step consists in making small marks around the soon-to-be mapped surface in order to be able to identify the area location later.

The sample is analysed by EBSD at ambient temperature before and after the transformation. Coupled with the digital image correlation data, an analysis of the sample in the high temperature phase can be made, and hence improving the understanding of phase transitions.

This procedure is illustrated on iron. The cristallographic structure of pure iron changes at 910◦C. Under Tt=910◦C, iron is in the so-called α phase, and has a body-centered cubic (or BCC) cristallographic structure. It is called ferrite iron. Above Tt, in the γ phase, it has a face-centered cubic (or FCC) structure and is called austenite iron.

The transformation from ferrite to austenite can be very different from the austenite to ferrite transformation. The first one is an atom diffusion-based nucleation and growth transformation (the transformation first occurs simultaneously on preferential sites, creating nuclei which then grow into the surrounding untransformed phase). The second one can be either a nucleation and growth transformation again, or a diffusionless martensitic transformation. As defined in (2) : "a martensitic transformation involves a cooperative movement of a set of atoms across an interface causing a shape change and sound". As no diffusion is involved, there exists orientation relationships between the orientation of the original grain and the orientation of the formed crystals. The transformation from austenite to ferrite can be approximated by the Bain mechanism (although it is never observed in practice for pure iron).

The main objective is to exploit experimental data obtained on the device to identify the phase transition mechanisms, coupled with the temperature and plasticity effects. In particular, the ambition is to identify the transition point between the nucleation and growth transformation and the martensitic transformation during cooling of the sample. To do so, a sample with a small number of big grains (500μm to a millimeter in diameter) is observed during the transformation through digital image observation. The effect of the loading conditions on the initiation and progress of the phase transition will also be studied.

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Instrumentation of the hot cracking phenomena in iron based hard facing weld NOREM02

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Speaker: Moor Maëlle. **Wednesday**. Start time: **17:45**. Room: Saint Clair 5 LVL2. Link to abstract.

NOREM02 is an iron based hard facing weld used in the nuclear industry as wear resistant hardfacing in replacement of StelliteTM. However, NOREM02, as other FCC alloys, can be susceptible to hot cracking phenomena caused by solidifications defects, a ductility drop and residual stress due to the welding process. The aim of the study is to develop a new grade using an inoculant to modify the chemical composition to inhibit the columnar network and to control ferrite content. Then its susceptibility to hot cracking with standard NOREM02 is compared. To do so, two mechanical tests, representative for welding classified in ISO standards, are fully instrumented to obtain coupled thermo - mechanical fields along the specimen with high precision. A first CMOS camera uses the near infrared thermography (NIRT) or a visible bichromatic measurement to image the thermal field. The second camera acquires images for digital image correlation (DIC) to measure the displacement and calculate the strain field on the surface of the specimen. The first test is a hot tensile test performed on a Gleeble® simulator to characterize the ductility dip cracking of the alloy. The second test is a PVR-test in which a flat tensile test is carried out simultaneously with a welding process at a linearly increasing speed. Microstructure on post mortem samples will be study to achieve a better comprehension of the hot cracking phenomenon. In the end, a hot cracking criterion based on the study results will be suggested for simulation.

Deformation-induced martensitic transformation at wide range of temperatures (4K, 77K, RT) in austenitic stainless steels fabricated by Fused Deposition Modeling Process (FDM)

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Speaker: Tabin Jakub. **Wednesday**. Start time: **18:05**. Room: Saint Clair 5 LVL2. Link to abstract.

Fused Deposition Modeling (FDM), a cost-effective additive manufacturing (AM) process for fabricating austenitic stainless steel components, has garnered significant attention. However, pore chains between filament strands and fabrication-induced ferrite can severely compromise mechanical properties and exacerbate anisotropy. This study investigates the deformation-induced phase transformation in additively manufactured and conventionally produced 316L stainless steel through tensile testing across a wide temperature range, complemented by detailed microstructural analysis (1,2). This study utilizes in-situ optical techniques (Digital Image Correlation), to investigate the evolution of strain fields and dissipative effects at cryogenic temperatures, including liquid helium (4 K) and liquid nitrogen (77 K). By offering a novel approach, the research provides valuable insights into the thermo-mechanical behaviour of FDM-processed austenitic stainless steels, focusing on deformation-induced phase transformations. These findings highlight the potential of FDM as a low-cost metal AM method capable of achieving mechanical properties comparable to those of other advanced AM processes.

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Shock energy attenuation of hydrogels: experiments and modeling

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Speaker: Rittel Daniel. **Thursday**. Start time: **10:00**. Room: Saint Clair 5 LVL2. Link to abstract.

It has been shown that methyl cellulose hydrogels are excellent candidates to attenuate shock energy. Methylcellulose hydrogels undergo a thermoreversible liquid to solid transition upon reaching a temperature of about 70C, while being cheap and totally innocuous health-wise, as they are routinely used in the food and pharma industries. In this presentation, we will show how we measured the frequency-dependent attenuation and implemented it in a simple 1D model. The next step was the development of a 3D model, implemented in a finite element code, which calculates the structural response for each frequency component, all being later recombined to generate the transmitted pulse. The 3D model was verified vs. the above-mentioned semi-analytical 1D model, and results of structural impact simulations will be shown that further illustrate the potential of those hydrogels to be part of a shock-mitigation assembly. This new development allows for the optimization of a gel-protective layer for any structure and type of impulsive load.

The Energy Absorption Behavior of Graphene Aerogels

Xie Jing (1), Rittel Daniel (2)

1 - Beijing Institute of Technology (China), 2 - Technion - Israel Institute of Technology [Haifa] (Israel)

Speaker: Xie Jing. **Thursday**. Start time: **10:20**. Room: Saint Clair 5 LVL2. Link to abstract.

The experimental investigation of the dynamic mechanical behavior of graphene aerogel is still challenging due to its low impendence. The classic one-dimensional stress wave theory for calculating the stress-strain curves and the strain rate data is, therefore, not applicable here. The energy analysis, however, does not require that the specimen be in a state of dynamic stress equilibrium or uniform deformation which are exactly the experimental challenges in the current study. Thus, the present work reports on the preliminary experimental characterization of the energy absorption characteristics of graphene aerogel by using the aluminum alloy (7075-T6) split Hopkinson pressure bar emphasizing the influence of the drying method. The graphene aerogels were synthesized by the sol-gel method and dried, either by supercritical CO2 drying (SD) or by freeze-drying methods (FD). It was observed that under dynamic uniaxial compression, the SD samples exhibited a negative Poisson's ratio throughout gradual compression. However, FD samples failed by radial shattering without this auxetic behavior. The energy dissipation ratios of SD samples increased from 41% to 73% as expected with the specimen thickness increasing from 3mm to 12mm, being overall higher in comparison with FD samples which rises from 35% to 43%. SD graphene aerogels have a large number of random pores (_~50nm), which is beneficial for absorbing the kinetic energy through plastic deformation and pore walls' collapse. By contrast, the FD graphene aerogels' pore walls buckle readily under the impact, and fail due to their ordered porous structure at the micron scale (_~1μm), which impairs their energy absorption capability.

High-throughput Characterization of five DP steels Plasticity and Fracture at slow, intermediate and high strain rates

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Speaker: Grolleau Vincent. **Thursday**. Start time: **10:40**. Room: Saint Clair 5 LVL2. Link to abstract.

Slow, intermediate and fast tensile experiments are carried out on five dual phase steel sheets, comprising DP590, DP780, DP980, DP1180 and DP1470. Each of the materials is characterized with uniaxial tension as well as notched, central hole and shear specimens in up to seven material orientations. To efficiently test the overall 675 specimens, an automated tensile testing system is used in conjunction with a novel high-throughput Split-Hopkinson Pressure Bar setup. An original specimen clamping mechanism along with fully automated bar positioning is presented. Together with a fully automated post-processing procedure this significantly decreases the testing overhead. Surface strain measurements are obtained from optical (high-speed) photography together with planar digital image correlation. High-speed infrared imaging is used to gain insight into the evolution of the surface temperature as a function of plastic deformation. To characterize the material response in a hybrid experimental-numerical manner, coupled thermo-mechanical finite element analyses are employed. The constitutive model comprises a non-associated quadratic yield function, a combined Swift–Voce strain hardening model, and a neural network-based strain rate hardening law. Integrated into a material user subroutine and calibrated using a combination of analytical formulas and a robust backpropagation algorithm, this machine-learning-enhanced plasticity model accurately predicts all experimental data, including force-displacement, local surface strain, and temperature measurements. Additionally, a neural network-based extension of the Hosford-Coulomb fracture initiation model is calibrated to capture the fracture behavior across a range of strain rates.

Deformation and failure mechanisms of architectured materials under impact

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Speaker: Weller Alexis. **Thursday**. Start time: **11:00**. Room: Saint Clair 5 LVL2. Link to abstract.

High-velocity impacts commonly referred to as ballistic threats, have evolved with advancing technology. Consequently, protective materials and systems have also steadily progressed. Over recent decades, additive manufacturing has seen remarkable advancements across various materials and has emerged as a promising technology for constructing customized, multi-scale materials designed for impact protection. Architectured materials, created through the periodic repetition of a lattice cell, have been promising candidates for impact protection. Several studies have proposed scenarios and models to understand the effects of intrinsic geometric and material parameters on the energy absorption and deformation behaviour of these architectured materials under ballistic impact. Let us recall the discussion on scale effects between the material scale of the protection system and that of the projectile, their dependency on the type of loading (1), as well as the influence of geometric parameters and fabrication-induced errors on global behaviour (2). Furthermore, precise studies on geometric parameters include, for example, the effects of dimensions such as strut thickness, relative density, and cell size (3); the shape of the elementary cell (4); and equivalent stochastic structures with varying connectivity and orientations (5). Other studies have explored the impact of structural arrangement, number of repetitions, progressive density, and the presence or absence of elements between layers, among other factors (6, 7). Understanding these effects benefits from a combination of experimental and numerical methods, such as compression characterization tests on Hopkinson bars (8), along with adapted modelling approaches (9). Despite numerous efforts, interactions between global, or local, dynamic loading and architectured materials remain poorly understood, and no precise or universally applicable solutions to these challenges have yet been found.

Thus, this study focuses on understanding the deformation and failure mechanisms in various geometries of architectured materials across a range of global and local dynamic loadings.

Specifically, the dynamic behaviour of Gyroid lattice structures is investigated through experimental techniques and finite element simulations. The Gyroid lattice structures studied, featuring 5x5x5 unit cell geometries and relative densities of approximately 20%, are manufactured from Inconel-718 using the Selective Laser Melting (SLM) process at the millimetre scale.

High strain-rate experiments are performed using a split-Hopkinson pressure bar (SHPB) system. The testing campaign combines compression and shear to determine mechanical properties and examine strain rate dependency across range up 0.001 /s to 1000 /s. This approach provides insights into deformation and failure mechanisms under high strain-rate loading through stereo correlation and strain gauges. Concurrently, a series of localized impact characterization tests is being carried out to evaluate and compare the effectiveness of different architectural structure geometries. In these tests, projectiles are launched at varying speeds, with high-speed cameras used to capture dynamic penetration depth in ballistic gelatin. This campaign aims to investigate the effect of very high strain-rate deformation (over 1000 /s) on the overall structural response.

Explicit finite element analysis using the Johnson-Cook constitutive model demonstrates good agreement with the mechanical failure trends and deformation modes observed in the experiments. The model enables a sensitivity analysis of parameters such as relative density and the number of unit cells, and supports prediction for future experimental campaigns.

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Capacitors at low temperatures revealed by cryo-synchrotron X-ray phase contrast microtomography

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Speaker: Vijayakumar Jaianth. **Thursday**. Start time: **11:20**. Room: Saint Clair 5 LVL2. Link to abstract.

Electronic devices are used in extreme conditions such as in outerspace, exposing them to extreme low temperatures. Understanding their behaviour is important for optimizing their functionality and to better design and manufacture individual electronic components. Capacitors are such electronic components sensitive to temperature. Low temperature electric characterization of capacitors typically has no spatial information. Here we combine synchrotron cryo-microtomography down to 77 K (carried out at beamline BM18), impedance and electrical characterization down to 20 K (carried out at beamline BM28), to correlate the electrical and structural properties of commercially available capacitors. We characterized multilayer ceramic, Ta2O5 and Al2O3 electrolytic capacitors. Our experiment reveals that a change in capacitance at low temperature is dominated by structural changes than from possible intrinsic changes such as in resistivity, crystal structure or dielectric permittivity. For example, in a tantalum oxide capacitor, we find that the porosity can increase by about 20% at 77K, and is resulting in a change of capacitance from 47 μF at 300K to 37 μF at 77K. Our result shows a new insight towards the functionality of commercial capacitors at low temperatures and provide important benchmark for developing and designing future capacitors for extreme environmental conditions.

Dynamic radial expansion and fragmentation of porous metal rings

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Speaker: Virazels Thomas. **Thursday**. Start time: **14:15**. Room: Saint Clair 5 LVL2. Link to abstract.

We have conducted dynamic ring expansion tests on 3D-printed AlSi10Mg porous samples utilizing both electromagnetic and mechanical testing techniques. The electromagnetic loading setup developed by Zhang and Ravi-Chandar (2006, 2008) is employed as a benchmark for evaluating and comparing the performance of the experimental configuration recently proposed by Nieto-Fuentes et al. (2023) to investigate the fragmentation of metallic rings using a pneumatic launcher. A total of 69 tests were conducted using expansion rates ranging from 2000 s-1 to 17000 s-1. The tests performed with both experimental techniques were filmed using high-speed cameras to obtain time-resolved information on the mechanics of sample deformation and fragmentation. The recorded data allowed us to determine the number of fragments, the elongation of the specimens at the onset of fracture, and the fragmentation time. Moreover, the fragments ejected from the samples have been soft recovered, measured and weighed. An excellent quantitative agreement has been achieved between the results obtained from electromagnetic and mechanical loading setups regarding the fragments size distribution and the evolution of the number of fragments with the loading rate. This agreement serves as a robust validation for the experimental configuration put forth by Nieto-Fuentes et al. (2023), which allowed reaching higher strain rates than the setup of Zhang and Ravi-Chandar (2006, 2008), and it is notable for its simplicity, fast operation, and quick assembly. The porous microstructure of the rings has been studied before and after testing through X-ray computed tomography unravelling the role of the voids in the dynamic failure of the specimen. Furthermore, the influence of the microstructure on the fragmentation mechanisms has been investigated through finite element simulations that incorporate the initial voids' size distribution of the specimens obtained from X-ray tomography analysis. The numerical calculations results have demonstrated both quantitative and qualitative agreement with the experiments, showing that large pores and clusters favor stress concentration and subsequent fracture initiation. Consistent with the statistical fragmentation theory of Mott (1947) for elastic-plastic materials that break without previous necking, the release waves emanating from the large pore defects and early fractures seem to play a critical role in determining the scale of the fragment size distribution in AlSi10Mg specimens.

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Development of an experimental set-up for the study of the dynamic damage of metals

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Speaker: Sicard Martin. **Thursday**. Start time: **14:35**. Room: Saint Clair 5 LVL2. Link to abstract.

Keywords: Ductile damage – High strain rate – Nonlinear constitutive modelling

Highly space- and time-resolved experimental data are needed for better understanding and further modelling the mechanisms that govern the damage and fracture of metallic materials and structures in a wide range of strain rates and stress triaxiality ratios.
For that purpose, a plate-impact-driven ring expansion test (PIDRET) set-up using a single-stage gas gun, PDV probes and ultra-high-speed cameras, see (1), is adapted to apply a tension-by-expansion loading to notched rings with achievable local strain rates of the order of 10^6 s^{-1}. Completed by (i) quasi-static tension tests carried out using a standard hydraulic machine and (ii) moderately dynamic tension tests using a split Hopkinson tension bar apparatus, the aim is to cover the strain rate range (10^{-3} s^{-1} , 10^6 s^{-1}) and the stress triaxiality range (0.3 , 1). Results obtained are intended to feed a coupled plasticity-ductile dynamic damage model, such as the GTN one, see (2).
Notch dimensions were designed by finite element analyses using the commercial computation code Abaqus-Exp. The feasibility of the dynamic tension-by-expansion test and the repeatability of the experimental results are investigated considering various metals and alloys.

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Analytical and Numerical Analysis of Necking in Dynamic Expansion of Thin Structures

Houire Ulrich (1), Xavier Mathieu (1), El Mai Skander (2), Mercier Sébastien (3), Czarnota Christophe (3)

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Speaker: Houire Ulrich. **Thursday**. Start time: **14:55**. Room: Saint Clair 5 LVL2. Link to abstract.

When exposed to high-velocity impacts or extreme dynamic stretching, thin structures made of aluminum, copper, and tantalum exhibit fragmentation behavior characterized by a range of fragment sizes and residual velocities (1). Since the 1940s (2), understanding the dynamic fragmentation of metallic structures under intense loading has been a major scientific challenge at the intersection of various military and civilian applications. Precisely predicting the fragment size distribution, fragment velocity, and the time to fracture remains an essential challenge in this domain.
To determine the characteristic dimensions of these fragments, we rely on Linear Stability Analysis (LSA) ((3-5)), which examines the response to small perturbations of a thin structure under extreme loading conditions. LSA enables the identification of the most unstable mode of perturbation. This analysis provides a foundational metric for predicting the scale of fragmentation patterns that emerge under dynamic loading.

In such a dynamic configuration, the combined effects of inertia and multiaxial stress within the neck region governs the instability development ((6-9)). Specifically, inertia stabilizes long-wavelength modes, while the multiaxiality of the flow stabilizes short-wavelength modes. Consequently, the most unstable mode has a wavelength that tends to fall within an intermediate range-a critical characteristic for accurately modeling fragmentation phenomena. Identifying and modeling this intermediate wavelength is essential for predicting fragmentation behavior, as it governs both the initiation and development of localized necking prior to complete material rupture.

Historically, Classical Linear Stability Analysis (CLSA) is based on the frozen coefficient theory and assumes an exponential growth of perturbations, facilitating the modeling of the early stages of instability under moderate dynamic loading conditions. However, this approach faces limitations in highly dynamic regimes. To overcome these limitations, an eXtended Linear Stability Analysis (XLSA) approach has been developed in (10-11) which relaxes the frozen coefficient approach and does not assume an exponential growth of instabilities. This model is expected to provide a more accurate and continuous description of the localization process. The XLSA allows us to follow the development of instabilities continuously over time, enabling the characterization of the most unstable mode and tracking the development of localized necking in thin metallic structures under dynamic extension.

In our research, the XLSA model is adopted to reproduce the local thinning development in cylindrical and annular metal structures (12). We supplement the XLSA approach with finite element simulations, providing a comparative basis for refining analytical predictions and validating model accuracy. Results indicate that both 1D and 2D-XLSA models produce reliable predictions for long-wavelength perturbations, while the 2D-XLSA model offers a more accurate evolution of short-wavelength instabilities. Leveraging insights from the 2D model, we propose to enhance the 1D model by modifying the multiaxial stress effects, thereby achieving predictions that align more closely with numerical observations. More precisely, a parametric study on the magnitude of the stress multiaxiality contribution is conducted showing that the Bridgman approach is not accurate for modes with intermediate to small wavelengths. While the most unstable wavelength remains largely not modified, the rate of development of the perturbation is highly sensitive to this contribution.

The combination of analytical modeling with finite element simulations, enables to improve the 1D approach, providing a more accurate description of the evolution of multiple necking during the early stages of the deformation.

This work was carried out in the framework of the joint Lab LRC FRAGDYN between French CEA

DAM, ISAE-SUPAERO, Université de Lorraine, IMT Mines Saint-Etienne and CNRS.

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In situ characterization and evolution of shear band microstructures at different shear strain rates

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Speaker: Schottstedt Luisa. **Thursday**. Start time: **15:15**. Room: Saint Clair 5 LVL2. Link to abstract.

The formation of adiabatic shear bands (ASBs) is a phenomenon of highly localized shear deformation in metallic materials that occurs especially at high shear strain rates. The conventional thermo-mechanical understanding focuses on the effect of thermal softening associated with energy dissipation during strongly localized plastic deformation; recent work however strongly indicates that microstructural softening, related to dynamic recrystallization, is the main mechanism that promotes ASB formation in most metals (1). Further experimental work is needed to substantiate these observations, and to clearly separate the contributions of microstructural and thermo-mechanical effects.
Several well-established shear test samples with different geometries (e.g. SCS0 (2), CFSS (3)) allow to experimentally trigger the formation of well-defined ASBs. However, an in-situ observation by digital image correlation (DIC), thermography and in-situ microstructural observations of the shear zone remains experimentally challenging due to the limited accessibility of the deformed area. In this contribution, we introduce a plane S-shaped sample made from a sheet material for the experimental investigation of ASB formation. The samples can be subjected to uniaxial compression, which leads to local simple shear deformation in a geometrically well-defined shear zone. The plane surface of this sample geometry considerably simplifies an in-situ observation of deformations by DIC as well as temperature variations by infra-red thermography during ASB formation.

We present in detail the potential of the sample geometry by considering quasi-static and dynamic experiments using both Ti-10V-2Fe-3Al and AA5754 alloys. Nominal quasi-static and dynamic strain rates up to 1000 1/s are used to produce different types of shear bands at local shear rates in the range of 0.02 1/s to 70000 1/s. Furthermore, our special experimental set-up allows to limit the deformation of the samples with low increments and high accuracy to investigate the evolution of shear band microstructures, even at high rates. We are therefore able to study the different deformation stages from initiation and propagation of shear banding to crack formation with in-situ techniques including DIC and thermography or post-mortem analyses like electron backscatter diffraction (EBSD) and micro-hardness mappings. Our experimental approach contributes to a deeper understanding of the rate-dependent mechanisms of shear bands in different metallic materials.

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Characterization of recovered iron samples after laser shock loading

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1 - CEA DAM (France), 2 - LMCE (France)

Speaker: Bruzy Nicolas. **Thursday**. Start time: **15:35**. Room: Saint Clair 5 LVL2. Link to abstract.

Many metals undergo solid-solid phase transitions under dynamic loading. Since post shock microstructures very often exhibit grain orientations that were not present in the initial microstructure, the analysis of recoverd samples is a promising way to investigate their transformation history. Twinning is also a frequent deformation mechanism under high strain rates and induces a change in lattice orientation. Reversion variants are then difficult to interpret because they can be induced by several sequences of phase transformations mediated by twinning. For instance, in the case where there is a single generic A-B transformation possible in pressure, one has to consider (if plausible) the scenarios :
- twinning of A ;

- A-B then B-A ;

- A-B then twinning of B then B-A.

We propose a software tool to handle such a large number of possible variants (1). Reaction Pathway Graphs (RPGs) (2) associated with each displacive transformation sequence are built, and all possible final crystal orientations are obtained as leaves of the graphs. These orientations are then compared with experimental ones to assess the most plausible transformation scenarios, if any. Iron was chosen as a test material to validate this approach. Iron transits from a body-centered cubic (bcc) phase to a hexagonal compact (hcp) phase around 15 GPa following the Burgers mechanism. Single crystal iron samples with a thickness of 100 micrometers were shock loaded above the alpha-epsilon transition pressure in the GCLT laser facility at CEA. A momentum trap apparatus was used to prevent damage within the regions of interest. After testing, the samples were cut and polished in their cross-section. Electron backscatter diffraction (EBSD) mappings of crystal orientations were then performed.

Reversion variants within the post mortem microstructure were further divided into two categories. First, variants for which bcc twinning and a transformation sequence involving the Burgers mechanism were the most plausible scenarios. Both are known to produce identical orientation relationships, preventing them to be distinguished from orientation data only. However, RPGs bear the information of transformation strains. An analysis based on Hadamard's compatibility conditions was then implemented to complement orientation analysis. It shows satisfactory results in the quick discrimination between twinning and Burgers variants.

Second, variants for which neither bcc twinning nor Burgers scenarios were plausible. We show that all these orientations can be accounted for when taking into account transformation scenarios mediated by twinning of the high pressure phase of iron. A twinning system is inferred from the analyses that is consistent with previous in situ observations, thus highlighting the richness of data on solid-solid phase transformations that can be gathered from recovered samples after shock loading.

(1) Bruzy et al., *Identification of diffusionless transformation sequences from crystal orientation data*, to be submitted, 2024
(2) Denoual and Vattré, A phase field approach with a reaction pathways-based potential to model reconstructive martensitic transformations with a large number of variants, JMPS **90** (91-107), 2016

Statistical analysis of ductile damage under impact loading

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Speaker: Thouénon Corentin. **Thursday**. Start time: **15:55**. Room: Saint Clair 5 LVL2. Link to abstract.

Spalling is a fundamental damage phenomenon observed in materials under dynamic loading. Experimental adjustments in strain rates and shock pressures, achieved through variations in shock generation methods (such as mechanical impact or laser shock), allow for modifications in fracture properties. In ductile materials, the microscopic mechanism behind spall cracks involves the nucleation, growth, and coalescence of pores in the plane intersected by relaxation waves. Many damage models assume independent collections of pores, overlooking potential collective effects among them. The proposed statistical approach aims to uncover correlations in the spatial distribution of pore sizes and investigate variations in pore areal density with strain rate. Employing scanning electron microscopy and stereo-imaging, this method enables statistical analysis of 3D reconstructions of post-mortem spall surfaces. The objective is to advance both damage models and our comprehension of the fundamental underlying mechanisms.

Multi-scale characterization of a high chromium hardfacing alloy for ballistic protection applications

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Speaker: Monnet Antoine. **Friday**. Start time: **10:00**. Room: Saint Clair 5 LVL2. Link to abstract.

Hardfacing process is currently widely used for the protection of materials and structures exposed to complex and severe environments **(1-2)**. This technique involves the fusion application of a protective coating onto a surface, significantly enhancing its resistance to wear, corrosion, and other forms of degradation. In sectors such as aerospace and automotive, hardfacing extends the lifespan of components and preserves their performance over time. However, its application in the field of ballistic protection remains relatively unexplored, even though research and development of new armor systems are crucial in light of the rapidly evolving current kinetic threats. The use of this technique could not only significantly increase the impact resistance of armor but also maintain the mobility of structures and the cost-effectiveness of deployed solutions. In this context, the work presented here focuses on the analysis of a bilayered passive protection composed of a S355MC steel substrate (C $<$ 0.2% by weight) with a thickness of 8 mm, onto which a material of the same thickness, equivalent to a highly alloyed chromium cast iron (Cr: 27-30% by weight; C: 4-6% by weight), is applied using flux-cored arc welding (FCAW). Impact tests were conducted on several units using a 7.62x51 mm caliber projectile, equivalent to the M61, on the instrumented ballistic testing facility of the Franco-German Research Institute of Saint-Louis (ISL). A comprehensive microstructural analysis of the composite is proposed and linked with target damage during impact. Additionally, a model of the welding deposit used is presented with a view to the numerical simulation of ballistic tests.

(1) Maria-Rosa ARDIGO-BESNARD, Arnold TELLIER, Aurélien BESNARD, Jean-Philippe CHATEAU-CORNU - Effect of the microstructure on the tribological properties of HIPed and PTAwelded Fe-based hardfacing alloy - Surface and Coatings Technology - Vol. 425, p.127691 - 2021
(2) Shibe, & Chawla, Vikas. (2013). Enhancement in wear resistance by hardfacing: a review. Mechanica Confab. 3.

Characterization of the mechanical behavior of fragmented ceramics under impact by using 3D tomographic-based numerical simulation confronted to experimental data

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Speaker: Francart Charles. **Friday**. Start time: **10:20**. Room: Saint Clair 5 LVL2. Link to abstract.

Ceramics are now widely used as front layer of armor configurations against high velocity threats. Indeed, the very high hardness of ceramics such as silicon carbide or boron carbide allows to shatter the projectile and then drastically reduce its perforation potential. A softer backing material (aluminum alloy or composite) is used to absorb the remaining energy through deformation. However, the ceramic under the projectile is a very brittle material that remains intact only during the first microseconds of the impact before fragmenting. Therefore, the mechanical behavior of the fragmented ceramic plays an important role in the performance of the armor.
However, the mechanical behavior of fragmented ceramic is not very well known and especially under impact due to the complexity of the experiments. The so-called tandem impact testing technique (1,2) was considered in the present study. It consists in impacting a ceramic tile two times successively, first, with a flat ended projectile to fragment it and, second, with a conical shaped projectile to perforate the fragmented ceramic tile while measuring the rear side velocity of a backing.

In this study, some SiC Hexoloy® (3,4) tiles were impacted using tandem impacts and some others were scanned using micro-tomography X after the first impact in order to use the obtained fragments distribution for numerical simulation of impact. The mechanical behavior of the fragments has been modeled using the intact behavior of the ceramic based on a JHB (5) constitutive model. The results were compared to data obtained with a homogeneous approach considering the JHB model for the ceramic in its fragmented state. This study should explain the link between the fragments distribution and the mechanical behavior of the ceramic in its fragmented state.

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(2) Zinszner, J. L., Forquin, P., & Rossiquet, G. (2015). Experimental and numerical analysis of the dynamic fragmentation in a SiC ceramic under impact. *International Journal of Impact Engineering*, *76*, 9-19.
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A multi-scale experimental assessment of the effects of crack propagation speed on mode I fracture properties of composite laminates

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Speaker: Stanek Alexis. **Friday**. Start time: **10:40**. Room: Saint Clair 5 LVL2. Link to abstract.

This work was motivated by the need for an accurate assessment of fracture properties of composite laminates over a wide range of crack propagation speeds. A review of the literature indeed reveals that rate-dependent fracture properties of composites have to be considered in order to accurately predict the behaviour of composite structures numerically (1), (2). However, composite materials can be manufactured with various processes and their specific microstructures play an important role in their multiscale damage mechanisms and, consequently, on their macroscopic responses (3), (4). Therefore, the microstructure's contribution needs to be accounted for in the comprehensive understanding of delamination in composite. Furthermore, the intrinsic nature of composite laminates makes them sensitive to manufacturing defects or impact damage (5), while their modularity makes them the perfect candidates for the design of "smart materials" with embedded sensors for structural health monitoring applications for example (6). These material discontinuities (damage, void, sewing yarns, embedded sensors) can locally influence the microstructure, further reinforcing the need for a comprehensive understanding of composite fracture properties as these discontinuities are likely to influence the crack propagation rate and therefore the material and structural responses. Such conclusions have already been drawn in the adhesive field, and it was proven that artificially generated defects along the crack propagation path can change the crack propagation speeds and the overall fracture scenario (7). As such, with the effect of the microstructure and its properties in mind, one is allowed to question the actual meaning of fracture standardized tests on composite laminates.
This communication, in response to these challenges, describes the experimental methods developed for the estimation of mode I fracture energies of composite laminates under different crack propagation rates. As such, specific mode I tests fixtures, based on Arcan fixtures (8) and meant to promote instabilities and rapid crack propagation, have been developed and compared to traditional DCB fixtures. In situ observations with an optical microscope mounted on a high-speed camera during crack propagation at speeds ranging from 10 m/s to 1000 m/s have been carried out. A multi-scale approach was used in an attempt to correlate the in-situ observations at small space-time scales to the macroscopic response of the specimens. Post mortem fractographic analyses, using both optical microscopy and SEM methods, were also conducted to reveal the evolution of damage at the microscopic scale with regards to crack propagation speed. Preliminary results indicate a decrease of fracture energies in mode I with increasing crack propagation speeds. These results are supported by the in-situ and post mortem analyses of the fracture process zone and consequent damages. These findings provide critical insights into the fracture properties of composites, further reinforcing the importance of considering microstructural effects in fracture analysis of composite structures.

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Mechanical Behavior of Interpenetrating Phases Composites under Dynamic Loadings

Jabin Echeveste Paul (1) (2) (3), Le Barbenchon Louise (2) (3), Héraud Lorène (2) (3), Coré Arthur (1), Viot Philipe (2) (3)

1 - CEA CESTA (France), 2 - Institut de Mécanique et d'Ingénierie (France), 3 - ENSAM TALENCE (France)

Speaker: Jabin Echeveste Paul. **Friday**. Start time: **11:00**. Room: Saint Clair 5 LVL2. Link to abstract.

In recent years, metamaterials such as IPCs (Interpenetrating Phase Composite) have come under increasing investigation, as their enhanced mechanical behavior makes them ideal candidates for applications such as shock and vibration absorption, as well as structural lightening. However, little is known about the causes of this improvement. This is why the aim of this investigation is to examine the effects of a secondary solid phase on the mechanical properties of TPMS and lattice architected metallic structures under quasi-static and dynamic loadings. The IPCs chosen in this study consist of a Stainless Steel 316L reinforcements made by LPBF process and a polymer filler matrix in epoxy or PDMS. The IPCs in this study are manufactured by vacuum infiltration of the liquid matrix through the reinforcements in moulds. They were subjected to mechanical tests at low speed (quasi-static regime, $\dot{\epsilon} = 0.007s--1$) and at high speeds (dynamic regime, $\dot{\epsilon} = 208s--1$). Quasi-static tests showed that the addition of an epoxy matrix improved the plateau stress and the absorbed energy. This improvement can be explained by the role of the matrix stabilising the struts in the structure. In the case of a TPMS Diamond reinforcement, the epoxy resin limits stage- by-stage collapse and homogenises the strain in the architected structure. In the case of the 3D auxetic Re-Entry geometry, the matrix stabilise the vertical beams, which are sensitive to buckling, in the loading axis over a wide range of loads. In the dynamic regime, the epoxy resin shows an exacerbated mechanical behaviour that is also present in IPC 316L/epoxy.

TOPIC: Computational Mechanics

MS5.1 - Computational microstructures

Organisers: Karam Sab (ENPC) and Simone Morganti (University of Pavia)

Impacts of polycrystalline microstructures on effective ionic conductivity of ceramic electrolytes: computational homogenization and machine learning

Peng Xiang-long (1), Xu Bai-xiang (2)

1 - Division Mechanics of Functional Materials, Technische Universität Darmstadt (Germany), 2 - Division Mechanics of Functional Materials, Technische Universität Darmstadt (Germany)

Speaker: Peng Xiang-Long. **Tuesday**. Start time: **10:00**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Polycrystalline ionic conducting oxide ceramics can be applied as solid electrolytes in all-solid-state batteries and solid fuel cells. In these application scenarios, high effective (macroscopic) ionic conductivity is demanded. Many oxide ceramics exhibit high intrinsic ionic conductivity in the grain bulk. However, the ionic conductivity at grain boundaries (GBs) is much lower than the bulk one, which results in low effective conductivity. In this contribution, we explore how to enhance ionic conductivity in these materials by microstructure engineering. To this end, we reveal the correlation between microstructural characteristics and ionic conductivity by investigating a large number of polycrystalline samples with different grain and GB features. Polycrystalline microstructures with controllable features represented by Voronoi diagrams are computationally generated. Theoretical models are proposed to characterize the ionic conducting behavior in the bulk and at GBs. Based on these models, the computational homogenization method is employed to calculate their macroscopic ionic conductivities. The influence of different microstructural features on the effective ionic conductivity is systematically studied. The revealed microstructure-property relationships are encapsulated into a graph neural network-based machine learning model. The ML model trained by the data from simulations can accurately predict the effective ionic conductivity for a given polycrystalline microstructure. This work provides crucial quantitative guidelines for optimizing the ionic conducting performance of oxide ceramics by tailoring microstructures.

Reconstructing polycrystalline 3D grain architectures from 2D image data by combining stochastic 3D modeling and generative AI

Furat Orkun (1), Fuchs Lukas (1), Finegan Donal (2), Smith Kandler (2), Schmidt Volker (1)

1 - Ulm University (Germany), 2 - National Renewable Energy Laboratory (United States)

Speaker: Furat Orkun. **Tuesday**. Start time: **10:20**. Room: Bureau Forum 2 LVL-2. Link to abstract.

This talk introduces a computational method for statistically reconstructing 3D grain architectures of (functional) materials from 2D image data using spatial stochastic modeling. We combine methods from generative adversarial networks (GANs) (1) with advanced stochastic geometry models, specifically random tessellation models (2). In particular, we use a generalization of Laguerre tessellations, namely, generalized balanced power diagrams (GBPDs) (3). The application of GBPDs in stochastic 3D models allows for a relatively low-parametric representation of 3D grain architectures, including those with curved grain boundaries. To achieve statistical reconstruction of 3D grain architectures from 2D image data, the parameters of the stochastic 3D models must be calibrated such that planar sections of the generated 3D grain architectures exhibit similar statistical properties to those observed in the 2D image data. The proposed calibration method uses convolutional neural networks, which act as so-called discriminators to differentiate between artificially generated and experimentally measured 2D image data. By tuning the parameters of the stochastic 3D model to make the generated planar sections indistinguishable by discriminators from the experimental ones, we obtain a statistically accurate reconstruction of the 3D grain architecture (3). In this talk, we apply the proposed method to reconstruct the 3D grain architecture of cathode particles in Li-ion batteries using 2D electron backscatter diffraction data. Furthermore, we combine the grain architecture model with a stochastic 3D model for the outer shell of non-spherical cathode particles. The latter model component, representing the outer particle shell, is calibrated using image data at a different length scale. Once calibrated, the stochastic 3D models can overcome the limitations of 2D imaging techniques by generating 3D morphologies that can be used as geometric input for spatially resolved numerical simulations of effective material properties (4). Additionally, by varying the model parameters, we can systematically explore different structural scenarios, creating a comprehensive database for establishing quantitative structure-property relationships (5). As a result, the presented method enables the generation of a wide range of virtual 3D morphologies, facilitating the identification of structures with optimized functional properties.

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FE prediction of microcracking in a 3D graphite polycrystal - evolution of the macroscopic response under temperature changes and irradiation

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1 - iMMC-UCLouvain (Belgium)

Speaker: Delannay Laurent. **Tuesday**. Start time: **10:40**. Room: Bureau Forum 2 LVL-2. Link to abstract.

The present study aims to predict the microscopic heterogeneity of stresses and strains inside a graphite polycrystalline aggregate. Graphite crystallites present a huge anisotropy in all regards: elastic stiffness, creep rates, thermal expansion and irradiation induced shape changes. As a result of the microscopic anisotropy, the cooperative (and geometrical compatible) deformation of adjacent crystallites in the bulk of a polycrystal induces high local stresses, which may trigger microcracking. The propagation of microcracks occurs both inside the crystallites (parallel to the basal planes) and along the grain boundaries. Once they are formed, microcracks are expected to decrease both the macroscopic Young modulus and the apparent coefficient of thermal expansion (CTE). They also affect the macroscopic creep rate. The phenomenon is simulated here using finite element modeling of a polycrystal made of Voronoi cells subjected periodic boundary conditions in 3D. Microcracking is accounted for by relying on user-defined cohesive-zone elements (UEL) whereas the response of individual graphite crystallites is computed based on a user-defined material law (UMAT). When compared to experimental trends, the predictions of the present model are shown to be more realistic than those obtained in a previous FEM study performed in 2D (1).

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Generative machine learning for accelerated modelling of microstructure evolution

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1 - Delft University of Technology (Netherlands), 2 - Tata Steel Europe, RD&T, Ceramic Research Centre, IJmuiden (Netherlands)

Speaker: Ramgopal Tarakram. **Tuesday**. Start time: **11:00**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Developing sustainable pathways for metal processing is increasingly critical. While recycling can contribute to sustainability, it also introduces variability in material composition, requiring on-demand optimization of processing conditions. Traditional computational models, such as Cellular Automata and Phase-Field methods, are effective for simulating microstructural evolution under specified processing conditions but often face computational bottlenecks, limiting their application in high-throughput and on-demand process optimization. To address this, we present a conditional generative machine learning (ML) framework leveraging GPU-accelerated denoising diffusion probabilistic models (DDPMs) to accelerate microstructural evolution simulations conditioned on processing parameters. Trained on a compact dataset of process–microstructure pairs, this framework first adds noise to microstructure images and then trains a neural network to progressively remove the noise, learning the underlying statistical patterns of the microstructure. We apply this model to predict the microstructural evolution during steel processing conditioned on cooling schedules and alloying element compositions. The model accurately predicts microstructures, capturing key physical features such as phase, carbon distribution, and grain morphology, along with statistical metrics like grain size distribution, phase fraction, and interface area distribution. This approach offers a promising avenue for intelligent, adaptive material design and process optimization across diverse material classes.

Learning textures via generative machine learning on SO(3) manifold

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Speaker: Nimmal Haribabu Gowtham. **Tuesday**. Start time: **11:20**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Microstructure analysis in polycrystalline materials is challenging due to the high dimensionality and non-Euclidean nature of crystallographic orientations (i.e., texture) and the stochastic, multiscale interactions driving microstructural evolution. To this end, we introduce a probabilistic machine learning framework, specifically, a continuous conditional generative machine learning framework, to analyze texture data in the SO(3) manifold. The framework leverages bidirectional transformations to map simple latent distributions to complex target distributions, making them well-suited for capturing the intricacies of high-dimensional texture data. By operating on the SO(3) manifold, the proposed approach directly incorporates crystallographic symmetries and efficiently represents rotational data. Our model captures the relationships between processing parameters and resulting microstructures by embedding them into a low-dimensional, orientation-aware latent space, enabling both process-structure linkage modelling and inverse design through optimization. Furthermore, the model generates microstructures with tailored textures, accurately capturing the distribution of orientations under various conditions. This framework underscores the potential of generative machine learning to advance materials design and microstructural analysis in non-Euclidean domains.

Computational characterization of nanowire network electrodes

Grazioli Davide (1), Ferliga Matteo (1), Nicola Lucia (1), Simone Angelo (1)

1 - University of Padova (Italy)

Speaker: Grazioli Davide. **Tuesday**. Start time: **14:15**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Transparent electrodes find applications in optoelectronic devices, solar cells, light emitting diodes, and transparent heaters. Indium tin oxide (ITO) is currently the most widely employed material for producing transparent electrodes due to its low sheet resistance and high transparency. Unfortunately, the scarcity of indium is making ITO too expensive to meet commercial requirements. Furthermore, ITO is intrinsically brittle and therefore inappropriate for deformable electronic devices. Electrodes based on metallic nanowire (NW) networks are nowadays the best alternative to ITO electrodes in terms of electrical conductivity and transparency, and their intrinsic mechanical flexibility makes them suitable for deformable electronic devices too.
Metal NW electrodes are planar arrangements of interconnected NWs that form a network capable of withstanding mechanical deformations and ensure electric current conduction. The electrode production process involves the synthesis, deposition, and welding of NWs. These steps affect network features at different characteristic lengths that range from tens of nanometers (nanowire scale) to hundreds of micrometers and above (network scale). More specifically, the synthesis process determines the crystallographic structure of the NWs, the welding process the morphological characteristic of the junctions (nanowire scale), whereas the deposition strategy determines nanowire density and arrangement (network scale). As the deposition process results in the random positioning of the NWs, the overall network properties are spatially not uniform (1). Consequently, mechanical stress and current density localizations take place causing NW and junctions breakages (local damage) (2). These occurrences negatively affect the macroscopic response of the network, eventually leading to failure.

To characterize these failure phenomena, we present a multiscale computational strategy that involves electrical and mechanical processes taking place in metallic nanowire networks. Molecular dynamics simulations are employed to identify the dependence of junction structure and properties on welding conditions, i.e., sintering temperature, time, and NWs relative orientation. Two-dimensional synthetic representations of electrode microstructures are converted into networks of beam and resistor elements to analyze the mechanical and electrical network responses, respectively.

We observe that the sintering process and the relative orientations between nanowires determines the microstructure of the junctions and their mechanical and electrical properties. Recommendations on welding parameters, nanowire arrangement and density are identified to limit the failure of electrodes based on metallic nanowire networks.

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Microstructural Characterization of Aerogel through Deep Symbolic Regression

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1 - Department of Continuum Mechanics, RWTH Aachen University (Germany)

Speaker: Chandrasekaran Rajesh. **Tuesday**. Start time: **14:35**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Aerogels are renowned for their unique properties, including low density, high surface area, and excellent thermal insulation. Two prominent modeling approaches-diffusion-limited cluster-cluster aggregation (DLCA) for silica aerogels and Laguerre-Voronoi tessellation for nanoporous open-cell aerogels-offer frameworks for studying the influence of fractal morphology and network structure on mechanical behavior. This contribution presents a novel methodology for advancing microstructural characterization in the modeling of aerogels using deep symbolic regression (DSR). Unlike black-box neural networks, DSR yields interpretable, algebraic expressions that elucidate the relationship between input parameters and structural outputs. Applying DSR in aerogel modeling enables a deeper understanding of how parameters such as particle radius and pore size distribution influence the material's structural and mechanical behavior. By integrating the microstructural insights, the proposed approach facilitates the development of material models that directly incorporate the structural effects within strain energy functions, providing a significant step forward in accurately modeling and optimizing aerogels for advanced applications.
Keywords: Microstructural characterization, Aerogel modeling, Particle radius, Pore size distribution, Deep symbolic regression

In-silico Evaluation of Structure-Function Relationship in Biopolymer Networks

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1 - dept. BioMechanical Engineering, Delft University of Technology (Netherlands)

Speaker: Cardona Sara. **Tuesday**. Start time: **14:55**. Room: Bureau Forum 2 LVL-2. Link to abstract.

The fields of mechanobiology and biomechanics are advancing our understanding of the complex behavior of soft tissues across multiple scales. A current challenge is linking tissue microstructure to its functional role. While traditional methods like in-vitro studies and mechanical testing remain vital, the significance of computational techniques is growing. Early imaging methods were less sophisticated than current methods, leading to histology-inspired models (1) that primarily focused on dominant fiber directions and overlooked the complex 3D architecture of soft biological tissues. Recent advances in imaging and topology extraction workflows have revolutionized tissue microstructure models, conceptualized as discrete fiber networks (DFNs) of load-bearing components. Given the computational challenge of full-scale modeling, Representative Volume Elements (RVEs) are used as statistically representative mesoscale (μm) units to derive tissue behavior at the macroscale (mm) (2-6). Establishing the reliability of RVE models is critical for upscaling to the tissue level. However, a direct connection between in-silico and in-vitro mesoscale nonlinear mechanics remains underexplored, with validation limited to macroscale tissue behavior.
Jansen et al. (7) analyzed the role of network architecture in the nonlinear mechanics of collagen. Their in-silico comparisons with mesoscale rheological testing data on collagen networks polymerized at varying temperatures, resulting in differing structural properties, offered insights into the structure-function relationship. Their model, however, is limited to 2D, with the network represented as a triangular lattice. While this approach represents a significant advancement, it fails to capture the complexity of the 3D environment critical for understanding the localized mechanical properties of the extracellular matrix surrounding cells. Experimental evidence highlights that macroscopic deformation gradients cannot fully predict fiber reorientation and arrangement during loading. Instead, localized processes play a significant role in shaping the global tissue response (8). To capture these processes, models must account for the 3D structural arrangement of biological networks.

In this work, we build upon previous generative algorithms (4, 9) to develop topologically controlled DFNs, and we incorporate them in RVEs of load-bearing elements that exhibit softening under compression (10) and are bending resistant. To ensure Hill-Mandel energy consistency, we impose periodicity on the micro-fluctuation field using periodic boundary conditions (PBCs) implemented in Abaqus Standard (2024). We evaluate the robustness of our method by replicating the same structural conditions, including fiber volume fraction, cross-link concentration, and length distribution of reconstituted collagen I networks as in (7). Specifically, we analyze the evolution of the differential modulus as the temperature of polymerization varies and find consistency between the computational and in-vitro results. We observe that collagen networks exhibit a two-phase stiffening response as the applied load increases. Initially, fibers undergo reorientation, aligning with the loading direction and contributing to geometrical stiffening. This is followed by an affine stretching of fiber chains, producing a linear elastic response with stiffness increased by an order of magnitude compared to the initial modulus. Our novel framework provides a robust platform for investigating the impact that varying microscale tissue configurations have on the tissue's mesoscale mechanical behavior.

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Mesoscale modelling and experimental validation of lightweight concrete mechanical behaviour

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Speaker: Brana-Linares Marcos. **Tuesday**. Start time: **15:15**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Lightweight concrete (LWC), characterized by its lower density achieved through lightweight aggregates, is an excellent material for improving sustainability in the construction industry. Compared to conventional concrete, LWC production generates fewer greenhouse gas emissions and requires less transportation energy. Constructions using this material may be an eco-friendly alternative to reduce environmental impact without compromising mechanical strength and durability. However, LWC exhibits complex behaviours at microscopic, mesoscopic, and macroscopic scales, requiring advanced analysis for better understanding and complete optimization of its performance.

This study assesses the mechanical performance of LWC at the mesoscopic scale, where it is modelled as a heterogeneous material consisting of mortar and lightweight aggregates. Using a MATLAB script, lightweight aggregates different in diameter are randomly positioned using Representative Volume Elements (RVEs) with the take-and-place method. This random distribution is based on the mix proportions used in the fabrication process of laboratory samples and the granulometry of the employed aggregates. Several geometries are generated to analyse different spherical aggregate distributions on a cubic specimen of 50x50x50 mm. The compressive strength of these geometries is evaluated using the Finite Element Method (FEM). Distinct material properties are defined for the mortar and the lightweight aggregates, applying a combined mathematical concrete model. This nonlinear model incorporates the Drucker-Prager material model for compression stresses and the Willam-Warnke material model for tension stresses to predict cracking and crushing failure modes. The developed numerical approach is validated with laboratory compression tests.

This advanced mesoscopic numerical model establishes a new methodology to assess LWC mechanical response, including deformation and fracture mechanisms, bridging the gap between mesoscopic and macroscopic scales. The applied hybrid methodology, combining numerical and experimental techniques, reduces costs and carbon footprint by optimizing the number of tests. The progressive replacement of laboratory tests by numerical simulations will enhance the sustainability of mesoscopic concrete behaviour studies, leading to more efficient and environmentally friendly research practices in the field.

Understanding nanoindentation statistical dispersion in ceramic – metal cemented carbides by numerical simulation and FIB tomography

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Speaker: Cruañes-González Diego. **Tuesday**. Start time: **15:35**. Room: Bureau Forum 2 LVL-2. Link to abstract.

WC-Co composites are metal-ceramic composites that have a dual-phase structure composed of a hard carbide phase (WC) and a metallic binder phase (usually Co). When characterized using high-speed nanoindentation, these contrasting phases lead to significant variability in hardness measurements of each phase. Such variability is influenced by the interaction between the phases and the contribution of subsurface microstructural features. To better understand and quantify this phenomenon, this study integrates simulated nanoindentations, based on three-dimensional reconstructions from FIB tomography, with experimental data to correlate hardness values with the microstructural characteristics of the composite.
The given approach seeks to relate the percentage of binder present in the zone near the contact point versus the hardness given in the simulation. This binder percentage gives information of the local microstructural surroundings influencing the indentation response. This is possible because the subsurface microstructure is fully characterized in the simulations. When performing experimental data, where this cannot be observed, the expected results are expected to be different. The percentage of binder present on the surface near the contact point will also be studied to know the importance of the material under the visible surface.

Once the nanoindentation conditions have been determined, a first approximation to the study area is determined by looking for the distance of affectation in the direction normal to the surface. This is done using a simpler model of thin layer and observing the evolution of the hardness as the thickness of the layer of the surface material is reduced. Next, meshes with the real microstructure are generated using three-dimensional reconstruction after FIB tomography. For each indented zone, the percentage of three-dimensional and two-dimensional binder is obtained using the distance previously obtained. The hardness is plotted with respect to the percentage of binder and the relationship that follows is analyzed. Other studies regarding the shape of the curve can be made.

Experimental tests are then performed. A small indentation map is made and a SEM image is made in order to obtain the two-dimensional binder percentage. The correlation between the data obtained by simulation and the experimental data is studied. For the three-dimensional study, a FIB tomography of the nanoindentations is performed.
Results show a good simulated force-displacement curve from which the hardness can be obtained. It has also been possible to plot hardness maps equivalent to those seen experimentally. A very clear relationship can also be seen between the percentage of volumetric binder and the recorded hardness. The dispersion of the data increases when the percentage of surface binder is used, showing that it is not possible to relate in a direct way what is seen on the surface with the expected mechanical properties. This study shows the importance to use statistical analysis and numerical simulations to correctly extract mechanical properties of different phases in high speed nanoindentations maps.

A variationally consistent and asymptotically convergent phase-field model for precipitation and dissolution

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Speaker: Lamperti Andrea. Invited. **Tuesday**. Start time: **16:35**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Available phase-field models for precipitation and dissolution (1, 2) are not variationally consistent, i.e. their governing equations are not derived starting from a free-energy functional, and do not incorporate nucleation. On the other hand, they fulfill the requirement that, as the regularization parameter tends to zero, convergence to an appropriate sharp-interface model is achieved. In this work, we develop a variational phase-field framework to model precipitation and dissolution. Our model features a closed-form expression of the free-energy functional, starting from which the non-linear coupled evolution equations of phase indicator and total ion concentration are obtained. The non-conserved phase indicator is assumed to be equal to the local solid volume fraction, and its evolution is governed by the Allen-Cahn equation. On the other hand, the conserved total ion concentration obeys the Cahn-Hilliard evolution law. In addition to being variationally consistent, our set of equations is also proved to converge to the appropriate sharp-interface model by applying the method of matched asymptotic expansions (3). The variational nature of our proposed model, beside offering a clearer physical interpretation and computational advantages, is also useful to incorporate nucleation of new precipitates, for which we propose a first possible approach.

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FFT based accelerated fatigue computation using wavelet transformation based

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Speaker: Kesmia Nassim. **Tuesday**. Start time: **16:55**. Room: Bureau Forum 2 LVL-2. Link to abstract.

The context of our study is to numerically quantify the influence of the microstructure on the fatigue life dispersion (Pineau et al. 2016) for a metal or an alloy for regimes ranging from low-cycle fatigue to lifetimes of the order of *10^5*, *10^6* cycles. One of main obstacles, is the computational cost. Solving numerically a fatigue problem, considering high-cycle fatigue, could yield a huge computational cost if not impossible. An accelerated approach has to be considered and it is the main object of the present work. In the literature, the most efficient fatigue simulation acceleration method is the "WATMUS" algorithm (Wavelet Transformation based Multi-time Scaling) (Ghosh et al. 2021). It is based on the combination of two approaches: (1) cycle jump and (2) wavelets transformation (a temporal transformation).
The concept of the cycle jump is to perform an incremental calculation (fine timescale) on one cycle, then skip a certain number of cycles (through an extrapolation scheme) instead of proceeding directly to the next one. It means that the evolution of internal state variables needs to be expressed as a function of the cycle number (cycle timescale). The wavelets transformation (Walker 2008) intervenes in the incremental calculation of each cycle. It provides an orthogonal basis that, in a cycle, separates the different timescales. Applied on the displacement, the so-called "coefficients of displacement" (coefficients of the wavelet transformation) allows expressing the variation of the displacement in cycle timescale. The equilibrium equations will be projected in this basis. The resolution is performed with respect to the "evolving coefficients". In other words, the solution is established considering Nc coefficients in wavelet basis instead of considering Nt solutions in time (where $Nc < Nt$) which could lead to gain in computing efficiency. This is possible because, from one cycle to the next, the solution does not evolve on certain timescales. The results obtained in the literature show that a high number of cycles, up to cycles, can be achieved at a reasonable computational cost.

The WATMUS approach has been applied so far exclusively within the framework of the finite element method (FEM). In the present study, WATMUS is implemented in FFT framework (Moulinec et al. 1994). Indeed, FFT methods have become a fundamental tool (Lucarini et al. 2021) for micromechanics due to the numerical efficiency of these solvers. Until now, it has gained a lot of maturity by becoming more precise and more versatile for several applications. In the context of this study, the performance of spectral methods may provide better efficiency than with FEM. Using the basic scheme of Moulinec & Suquet, we show that the equations are established in a more straight-forward manner comparing to FEM. The efficiency and reliability of the approach will be tested on several examples: a simple 1D elasto-visco-plastic problem and a more complicated 3D problem for polycrystalline aggregates where the Meric-Cailletaud crystal plasticity model (Méric et al. 1991) is used.

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Nonfolding Origami lattice for energy dissipation and strength

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Speaker: Dalaq Ahmed. **Tuesday**. Start time: **17:15**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Origami, an ancient art primarily used in festivities in East Asian cultures, has found new applications in engineering over the past three decades. Among these, triangulated Origami (also known as Kresling springs) stands out due to its unique uniaxial and rotational coupling (1). In fact, there has been a surge of studies delineating the fundamental aspects of making this Origami, analyzing its underlying mechanics, and applying it in real-world engineering contexts. However, many of the proposed, particularly niche, solutions remain in the conceptual or proof-of-concept stages at best, often utilizing primitive paper-based designs. Recently, a two-phase material version of the Kresling spring has proven effective, making it functional, robust, and reliable while maintaining the behavior of its paper-based counterpart (2). In this study, we focus on a unique region within the design space (3) of the Kresling spring (the top right corner of Fig 1A, indicated in blue, at a foldable width of $w = 0$), where the edges of the Origami are not easily foldable, and the entire structure is instead made from a single-phase flexible material. This design induces a spring-like behavior that can exhibit either a linear or nonlinear response. The exact response can be fully customized via the geometric parameters (uo$/R$, ϕo), as shown in Fig. 1B and 1C. We propose using this stiffer and less foldable version of the Kresling spring to create a cubic anisotropic unit cell, which forms a three-dimensional (3D) lattice material. The strength and energy absorption and dissipation are determined by the twisting action of the spring under uniaxial compression, which results in stiff contact friction between the panels. The intersection of these springs forms an intentional jagged core. When the extended panels reach the end of their rotational range, the jagged core (Fig. 1D) of adjacent unit cells interlocks, providing an additional strengthening and toughening mechanism.

Application of the Lippmann-Schwinger equation to the propagation of acoustic Bloch waves

Dolbeau Martin (1), Margerit Pierre (2), Sab Karam (1), Bleyer Jérémy (1)

1 - École des Ponts ParisTech (France), 2 - Laboratoire Procédés et Ingénierie en Mécanique et Matériaux (France)

Speaker: Dolbeau Martin. **Tuesday**. Start time: **17:35**. Room: Bureau Forum 2 LVL-2. Link to abstract.

FFT methods offer a number of advantages for the homogenization of periodic and random media, such as low memory cost and fast computation, making it possible to study larger systems than the finite element method.
Since the work of Segurado and Lebehnson (2021), FFT methods have been applied to calculating the acoustic properties (dispersion diagram) of arbitrary periodic materials. The calculation of frequencies and wave numbers involves solving an eigenvalue problem, in which the smallest eigenvalues are sought, which requires the inversion of a stiffness-type operator. The disadvantage of their method is that the inversion of this operator requires many iterations when the micro-structure presents high contrasts in mechanical properties. This method is therefore limited to low-contrast systems such as polycrystals.

In this presentation, we propose an alternative FFT method based on the Bloch theorem and the Lippmann-Schwinger equation. We solve it using the work of Sab et al (2024), who introduced an algorithm that is unconditionally convergent, even in the presence of infinitely rigid pores and phases. This makes it possible to extend the calculation of dispersion diagrams by FFT to highly contrasted structures, with a low calculation time.

The VE2 method: the Virtual Element Method for Multiscale Computational Analyses with Polycrystalline Microstructures

Böhm Christoph Hudobvinik Blaz Marino Michele (1), Wriggers Peter (2)

1 - University of Rome "Tor Vergata" (Italy), 2 - Leibniz University of Hannover (Germany)

Speaker: Marino Michele. Invited. **Tuesday**. Start time: **17:55**. Room: Bureau Forum 2 LVL-2. Link to abstract.

The efficient integration of micromechanical relationships into macroscopic modeling is crucial for accurately capturing micromechanical effects under macroscopic load conditions. However, achieving the desired level of accuracy often requires increased discretization, which in turn raises computational costs in real-world material analyses. This talk investigates the performance of the Virtual Element Method (VEM) in multiscale computational analyses of structures characterized by crystalline microstructures. VEM's inherent flexibility in accommodating arbitrary element shapes allows for direct discretization of existing (crystalline or composite) microstructures using element-to-grain approaches.
The discussion begins with an exploration of some advantages of employing VEM-based formulations in staggered schemes based on numerical homogenization schemes. These advantages are demonstrated by addressing a broad range of material responses, from nonlinear elasticity and dissipative processes to complex multi-physics phenomena. It then shifts focus to monolithic formulations, which integrate microscopic response calculations based on VEM directly into macroscopic boundary value problems solved either through FEM or VEM. Analogously to FE2, these are denoted as VE2 or FE-VE schemes. The multiscale integration is achieved through a consistent sensitivity analysis approach tailored to virtual elements and developed for various stabilization schemes.
Results demonstrate that VEM-based monolithic schemes enable fully multiscale simulations at just 10% of the computational cost of corresponding FE2 simulations. This significant cost reduction arises from enhanced flexibility in mesh generation, improved solution space properties, and the inherent low order integration of the method. These advantages firmly establish VEM as a highly promising tool for multiscale computational analyses in real engineering contexts.

MS5.2 - Computational methods for manufacturing and forming processes

Organisers: Lukasz Madej (TU Krakow) and Katia Mocellin (CEMEF, Mines Paris)

Original Eigenstrain Framework Combined with Machine Learning for Fast Residual Stress and Distortion Prediction in LPBF Parts

Markovic Patrik (1) (2), Mazza Edoardo (1) (2), Hosseini Ehsan (1)

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Speaker: Markovic Patrik. **Tuesday**. Start time: **10:00**. Room: Rhône 5 LVL1. Link to abstract.

Laser powder bed fusion (LPBF) is a popular additive manufacturing process for creating intricate metal components. However, this process is notorious for generating residual stresses that can cause distortion and cracking of the part, which poses a significant challenge to the desire of first-time-right high-quality manufacturing. High-fidelity thermomechanical simulations are an effective way to analyse residual stress development and optimize LPBF process conditions to ensure the quality of the final product but are restricted to very small domains due to the computational cost. To enable simulation of residual stresses and distortion for real-size LPBF components, approximate alternatives such as the inherent strain method (IS) have been proposed. Besides the known limitation of the method in terms of accuracy (1), the duration required for a single run based on IS spans hours or even days and is sub-optimal for the efficient design and optimization process of components manufactured through LPBF.
This research activity aims to extend the applicability of the original eigenstrain framework (2) for LPBF. Instead of applying a homogenized inherent strain tensor in a layer-wise fashion (as done in the IS method for LPBF), artificial neural networks (ANN) are trained and employed to approximate the distribution of the final inhomogeneous eigenstrain field (i.e. the sum of all incompatible permanent strains that are the cause for the residual stresses), for the entire component. Accordingly, the residual stress state and distortion is calculated through a single linear elastic finite element calculation.

In this study, eigenstrain fields of a set of geometries were calculated through the block dump method (3) and used for training the ANN. Performance assessment of the established machine learning-assisted (MLA) eigenstrain method was conducted on unseen geometries. The MLA eigenstrain method eliminates the need for layer-by-layer calculations compared to traditional simulation methods for LPBF and brings new opportunities for design and optimization procedures for real-size LPBF components through a drastic reduction in the computational cost.

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Cold Rolling Process Simulation: Analyzing Mechanical and Microstructural Development in Electrical Steels

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1 - Laboratoire des Sciences des Procédés et des Matériaux (France), 2 - Thyssenkrupp Electrical Steel UGO (France)

Speaker: Herard Laura. **Tuesday**. Start time: **10:20**. Room: Rhône 5 LVL1. Link to abstract.

Electrical steels are the primary soft ferromagnetic materials used in the electrical industry, especially for applications such as magnetic cores made of thin laminates in transformers. Their magnetic properties are closely tied to a specific crystallographic texture characterized by centimetre-sized grains aligned along the Goss orientation. This texture is the result of recrystallization mechanisms and abnormal grain growth during the final annealing stage, also affected by the texture from prior cold deformation (1).
Despite the importance of this process, the factors within the deformed state which control recrystallization and abnormal grain growth mechanisms remain not fully understood due to its complexity and heterogeneity (2). To bridge this knowledge gap, this work models the cold rolling stage to better characterize the mechanical and microstructural evolution of electrical steels. The aim is to improve our understanding of the intricate interplay between cold deformation and the resulting material properties in Fe-Si steels. A methodology has been developed to better simulate the deformation experienced at both the surface and core of the material. Using a macroscopic finite element modelling of the rolling process, the velocity gradient tensor associated with the deformation was extracted and used as input data for a self-consistent polycrystalline simulation, using a newly integrated dislocation-based hardening model (3). Mechanical tests, including tensile and shear loading at various angles relative to the rolling direction, were performed on both initial and deformed states to validate the model. Additionally, texture evolution was monitored both experimentally and through simulations, offering a comprehensive view of the material's response throughout the deformation process.
The study focuses on the early passes of industrial cold rolling to assess the impact of industrial parameters such as rolling speed, roll geometry, or temperature, and to capture the texture-dependent microstructural and mechanical properties.

Key words: VPSC, Finite elements, Texture, Dislocations, Mechanical Behavior

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Computation of residual stress development in boron steels and experimental assessment with X-ray and neutron diffraction.

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Speaker: Morel Xavier. **Tuesday**. Start time: **10:40**. Room: Rhône 5 LVL1. Link to abstract.

The hot stamping process has been deployed in the automotive industry to improve the lightweight design and security of body in whites, as detailed in the review of Karbasian and Tekkaya (2010). The latest generations of boron steels have a higher carbon content, resulting in improved mechanical properties, useful for crash-components such as B-pillars (see Merklein et al. (2016)). However, increasing carbon contents favour the potential risk of detrimental residual stresses. Two competing mechanisms are involved: the martensitic transformation, which redistributes stresses within the martensitic steel, as highlighted by Bok et al. (2015) and Neumann et al. (2019), and the coating-substrate interaction, as stated by Morel (2023). Boron steels are usually protected with an aluminised coating, which contributes to the development of residual stresses due to the difference of mechanical properties, by enhancing strain incompatibilities within the blank.
Harnessing residual stresses is thus of prime importance and can be achieved through both modelling and experimental characterisation. A micromechanical model has been developed by Morel (2023), which encompasses both martensitic substrate and Al-Si coating descriptions from the end of the austenitising step to the complete cooling of the blank. The substrate phase transformation from austenite to martensite is central to the model, as it is pivotal into the stress development during the hot stamping process. Finite element simulations have been performed on a representative layer of the omega-shaped parts to reduce the required computation time. At the end of the simulation, the stress tensor has been compared to experimentally determined residual stresses in both planar directions.

Two different ways have been considered to determine residual stresses: laboratory X-ray diffraction (XRD) and neutron diffraction (ND), performed on the top and on the fillet of an omega-shaped hot-stamped part. Having a lower energy, XRD is unable to diffract through the coating and requires successive matter layer removal to frame a stress profile within the substrate. This has been performed with electrolytical etching by successive 50 μm removed layers. However, ND experiments, performed on the SALSA beamline at the Institut Laue-Langevin, access the martensitic substrate through the coating and offers an in-depth complete stress profile without any matter removal. Both XRD and ND experiments are in line and yield similar levels of residual stresses within the substrate. Within the near-coating zone, stresses are in compression around -200 MPa and slowly decrease further away in the substrate. A comparison between numerical and experimental stress profiles displays satisfying results in both planar directions through the whole thickness of the part.

To conclude, ND experiments validate that the electrolytical etching required for XRD measurements do not distort residual stress profiles. It also furthers the comparison between XRD and finite element simulations as many part geometries have exiguous areas inaccessible to XRD measurements. Besides, these results tend to confirm the leading role of the coating into the development of residual stresses during the hot stamping process of boron steels.

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Towards a thermo-mechanical metallurgical model for TMCP of structural steel for offshore wind turbines

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Speaker: Parandavar Pedram. **Tuesday**. Start time: **11:00**. Room: Rhône 5 LVL1. Link to abstract.

Engineers face a significant challenge in meeting the growing demand for renewable energy to reduce fossil fuel consumption and to lower air pollution. The offshore wind energy sector, both fixed and floating, is currently experiencing significant growth. A key challenge is the need to scale up support structures, such as towers and monopiles, to handle greater load-carrying capacities required by larger nacelle sizes. A key limiting factor is the size dependence of rolled steel plates, particularly when welding. Thermo-mechanical control processing (TMCP) is a well-known technique for enhancing the mechanical properties and microstructure of metallic materials during hot rolling. This paper presents the development of a finite element thermal-metallurgical model as a key driver for the thermal-mechanical model to study the mechanical behaviour and metallurgical mechanism of the steel plate in multi-pass TMCP. Of specific interest is the well-known thickness effect and rate effect on yield and fatigue of rolled steel plate. The model is designed to account for metallurgical phenomena occurring during TMCP, including static and dynamic recovery, dislocation density evolution, static recrystallization, and grain structure evolution, to predict the mechanical behaviour during and after TMCP. A unified physically-based viscoplastic constitutive equation is adopted to model the thermo-mechanical behaviour of the material, incorporating key process parameters, including the number of thermo-mechanical passes, heating- and cooling-rates, dwell times and maximum temperatures on the resulting microstructure, including size and dispersion of the formed fine particles, are determined in this study. The study of the impact of process parameters on the mechanical behaviour of structural steel has been conducted to investigate the effects of TMCP on homogeneity of grain size and texture with respect to large steel plate thicknesses in TMCP. The work also facilitates identification of representative TMCP stress-strain histories for designing Gleeble simulation tests and understanding and analysing of TMCP-induced residual stresses.

Numerical framework for evaluation of distortions in bearing rings.

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Speaker: Sankaran Harihara Krishnan or Cazes Fabien. **Tuesday**. Start time: **11:20**. Room: Rhône 5 LVL1. Link to abstract.

High precision ball bearings produced by ADR-ALCEN has specific applications in aerospace and defense sectors. One such specialised bearings are slender bearings whose diameter is far greater than its thickness. The formation of residual stresses during turning creates distortions at each step of material removal process. If the turning process is not tightly controlled, further material processing could deform the rings beyond tolerance limits. This creates a need for accurate determination of residual stresses and distortions and associated uncertainities along the spatial coordinates.
In this work a 4 step approach is used to determine the distortions in bearing rings:

- Analytical estimation of cutting forces using Merchant theory (1) and equivalent thermo mechanical loads are estimated using the formulas proposed in (2).
- Simulation of the turning process using the previously equivalent thermo mechanical loads using Salome-Meca (3).
- Extraction of eigenstrain profiles as function of depth from the surface and fitting using spline interpolation.
- Application of the obtained eigenstrain profiles (4) on the real geometry of the ring to obtain distortions and residual stresses. This step only involves elasticity calculations with eigenstrains that are performed either using appropriate beam theory or finite elements simulations or full 3D simulation using Finite Element Analysis package FEniCS (5).

The distortions of the rings obtained from step 4 which corresponds to the industrial problem are of the order of microns which can be very difficult to measure with sufficient precision using conventional measurement techniques. Also by perfoming simulation of the ring that is cut along the radius at one part of the ring, we can obtain larger values of distortion that are easier to measure experimentally. This kind of experimental approach for cut parts of tubular shape is similar to existing Slitting method (6) that are widely used in tubing community. In addition to existing slitting method, the specific geometry of the rings investigated pushed us to consider not only in plane variation of the radius of the rings but also their out of plane displacements.

Numerical results obtained will be compared to experimental results obtained from the cutting of rings composed of AISI440C provided by the industrial partner. The cut of the rings is performed using Electro-discharge machining and displacements measurements are performed using contact sensors with Coordinate Mesuring Maching (CMM). The results of non-contact measurement of displacement using the non contact measurement setup composed of motorized translation and rotation stages and a laser triangulation sensor may be presented, if available at the time of conference.

Key words : bearing rings , turning simulation, distortions, residual stress, Slitting method, relaxation method, numerical simulation.

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Integration of numericaly computed residual stresses into fatigue life model for lifetime optimisation of machined parts

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Speaker: Valiorgue Frédéric. Keynote. **Tuesday**. Start time: **14:15**. Room: Rhône 5 LVL1. Link to abstract.

This communication concerns the optimization of the fatigue life of machined surfaces. Since 2005, the LTDS laboratory has developed a scientific simulation method to predict the state of residual stresses generated by cutting operations on the surface of parts. This simulation method is based on determining and applying thermomechanical loadings representative of the cutting process, calibrated using experimental data. This method has reached an industrial maturity level both technologically and scientifically. It is now available as a commercial software, MISULAB, which predicts the three-dimensional residual stress fields resulting from a finishing machining operation. The goal of this communication is to demonstrate how these numerical three-dimensional residual stress fields can be used in fatigue strength calculations. It also shows how MISULAB can be connected to the NCode DesignLife software to more accurately estimate the fatigue life of a rotating shaft by optimizing machining conditions and/or tool geometries.

Prediction of the recrystallisation defect in Nickel-based single-crystal parts following cooling after a casting operation.

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Speaker: Roche Louis. **Tuesday**. Start time: **14:55**. Room: Rhône 5 LVL1. Link to abstract.

Background

The lost wax casting process is used to manufacture single-crystal nickel-based parts. During solidification and cooling, this process generates a high level of stress, due to the different coefficients of thermal expansion of the various components (mould, alloy and core). This state of stress can lead to the nucleation and germination of highly misorientated grains, resulting in a significant deterioration in the mechanical properties of the part. This recrystallisation defect therefore leads to the part being systematically scrapped, which is why predicting this potential defect upstream of manufacture is becoming crucial, especially with the arrival of increasingly complex geometries and new generations of alloy, which could tend to favour the appearance of this phenomenon.

Procedure

A methodology was set up to predict the potential areas subject to recrystallisation. To do this, a complete numerical model was developed to simulate the cooling of a single-crystal nickel-based part over a temperature range from 1500∘C to 700∘C. This study presents the general methodology (1), which can be subdivided into 3 major stages. The first one consists of simulating the casting operation in a purely thermal manner on ProCAST. The resolution of the mechanical equilibrium is then decoupled from the resolution of the heat equation. A spatial and temporal distribution of the temperature at each point of the structure is extracted, serving as input data for the mechanical calculation. The second stage simulates and predicts the mechanical behaviour of the part at the end of the cooling process. A classical behaviour model was developed, taking into account Voce isotropic hardening and a modified Norton-Hoff potential. During solidification, there is a transition between the liquid and solid phases, in which stresses and strains are generated. This phase, which is often neglected due to a lack of information and data, has been considered by introducing the 1st stress invariant in the construction of the equivalent stress, as well as transition function from the work of (2,3). The last stage uses recrystallisation criteria to determine the zones that are potentially sensitive to recrystallisation. Using various tests, Safran has developed recrystallisation charts (4) to establish whether or not recrystallisation is present by means of two physical quantities determined by mechanical calculation: cumulative viscoplastic deformation and viscoplastic dissipation energies. This methodology is applied to an industrial case involving recrystallisation.

Key findings

- Formulation and identification of a macroscopic behaviour model taking into account the liquid-solid transition state
- Good correlation between experimental and numerical results on a cast test piece

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simulation methodology for prediction of recrystallization in Ni-based. Journal of Materials Processing Tech. 306 (2022). https://doi.org/10.1016/j.jmatprotec.2022.117624

Incorporating grain boundary curvature-driven growth mechanisms into the random cellular automata dynamic recrystallization model

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Speaker: Madej Łukasz. **Tuesday**. Start time: **15:15**. Room: Rhône 5 LVL1. Link to abstract.

Numerical simulations can help predict microstructure morphology evolution under hot forming conditions and support the determination of final material properties. In the case of microstructure evolution occurring under high deformation degrees, especially during dynamic recrystallization (DRX), the full-field random cellular automata method (RCA) can be successfully used (1). As is known, grain boundary curvature plays a certain role in determining the driving energy of microstructural evolution processes that involve grain boundary migration under grain growth. Similar mechanisms should also be considered in the DRX process to make the predictions more reliable.
However, unlike in the classical cellular automata, the random arrangement of CA cells in the RCA method makes curvature determination more complex and requires a series of sophisticated numerical approaches. This challenge is further compounded by the need for an in-depth analysis of the stability of proposed solutions, which must account for varying cell arrangements and discretization levels of the investigated computational domain. Such analyses are essential to ensure accuracy and consistency in curvature estimation across diverse configurations.

In this study, established methods for curvature determination (i.e., Kremeyer (2), Mason (3)) were adapted to the RCA method, and an original approach based on the convex hull algorithm was also developed. The implemented solutions were evaluated using custom software designed to simulate microstructure evolution during the DRX process, with particular attention to examine the influence of discretization and deformation levels on the results. The results of the implemented algorithms and their computational efficiency were also analysed and compared.

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Investigation of the fracture mechanics in TiN thin films deposited on different substrates based on the digital material representation concept.

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Speaker: Perzynski Konrad. **Tuesday**. Start time: **15:35**. Room: Rhône 5 LVL1. Link to abstract.

Titanium nitride (TiN) thin films are widely used materials for products with a high degree of biocompatibility and high strength resistance at the same time (e.g., implants). Therefore, TiN films are often used in implantology, from knee joint replacements to valve protection in the artificial human heart (1). However, electron and scanning electron microscopy analysis revealed the frequent occurrence of a complex columnar nanostructure in these materials resulting from the specific nature of the PLD (Pulsed Laser Deposition) (2) process. The morphology of such nanostructure is one of the main reasons for uncontrolled delamination and fracture observed in thin films under loading conditions. Accurate investigation of thin film fracture requires a series of very sophisticated laboratory experiments, which are time-consuming and expensive.
Therefore, this paper presents a new approach to the numerical analysis of crack evolution in TiN thin films deposited by PLD, taking into account the morphology of the thin film in an explicit manner with the digital material representation concept. The mechanical properties of the thin film and the substrate were determined with the nanoindentation tests conducted in laboratory conditions to provide flow stress models for numerical simulations. Then, the plugin for Abaqus software was implemented to generate 2D and 3D digital material representation models of the investigated thin film based on the microstructural characteristics. Finally, the crack propagation model was developed within the finite element method considering the cohesive type elements (CEs), eXtended Finite Element Method (XFEM) and brittle fracture criteria. The obtained numerical results were validated against a series of experimental data. The study proved that the model based on digital material representation (3) could be used for reliable predictions of local crack development in thin films deposited by the PLD method.

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Nonlinear Analysis of Functionally Graded Materials Using Linear and Quadratic Solid–Shell Finite Elements

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Speaker: Younas Nabeel. **Tuesday**. Start time: **16:35**. Room: Rhône 5 LVL1. Link to abstract.

This work presents the development and evaluation of prismatic and hexahedral solid–shell (SHB) finite elements, formulated in both linear and quadratic versions, for the nonlinear geometric analysis of thin structures composed of functionally graded materials (FGMs). These elements are constructed within a fully three-dimensional framework, where only displacement degrees of freedom are employed. To address common numerical challenges, a combination of in-plane reduced integration and the assumed-strain method is utilized, effectively countering locking issues. The through-thickness material variation in FGMs is represented by strategically placing integration points across the element's thickness, enabling precise modeling of gradation effects. The SHB elements are integrated with a material model that captures the functional gradation of mechanical properties, assuming a continuous variation of Young's modulus along the thickness according to a specified volume fraction distribution. Implementation is carried out within the ABAQUS/Standard finite element platform under quasi-static conditions, accommodating large deformation scenarios. A series of nonlinear benchmark problems, including those frequently cited in the literature, are used to validate the performance of these elements. The results highlight the accuracy and computational efficiency of both linear and quadratic SHB elements in simulating the complex behavior of thin FGM plates, demonstrating their suitability for advanced engineering applications.

Defining mechanical boundary conditions representatives of the frictional tool-part interaction when modelling the cure-induced deformations of thermoset-based composite parts

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Speaker: Parmentier Antoine. **Tuesday**. Start time: **16:55**. Room: Rhône 5 LVL1. Link to abstract.

The polymerisation reaction of curing of the resin brings the material from the liquid to the glassy state. During this change of state, the part experiences deformations due to thermal expansion and chemical shrinkage of the resin. These deformations are constrained from developing freely due to the frictional tool-part interaction and internal stresses build up. Upon demoulding, those internal stresses are released and the part deforms. Previous studies have shown the important influence the frictional tool-part interaction during curing has on the final part deformation (1). Modelling the frictional interaction between the part and the mould increases dramatically the cost of the curing simulations. With the increase of the composite part and mould complexity, the curing simulation time explodes. However, the industry need is to shorten the restitution time in order, for instance, to include the computations in a mould compensation strategy which requires several iterations. This brings the interest of being able to predict the cure-induced distortions of complex composite parts while limiting the increase of computation complexity.
The present study aims at defining mechanical boundary conditions representatives of the frictional tool-part interaction in order to avoid the costly frictional contact interaction in numerical computation.

The numerical methodology consists in performing a first thermo-mechanical finite elements (FE) simulation on the mould using Abaqus. The temperature evolution applied is the Manufacturer Recommended Curing Cycle (MRCC) for the prepreg of interest. The node displacements evolution at the mould cavity surface is extracted, mapped on the composite part mesh and defined as mechanical boundary conditions on the node displacements of the composite part surface during the subsequent curing simulation. The curing simulation consists in performing coupled chemical-thermal-mechanical FE calculations using Abaqus and a user subroutine UMAT. The details of the model implemented in the UMAT follow the approach suggested by Svanberg and Holmberg (2) which considers a simplified linear viscoelastic behaviour of the material where time-temperature-degree of cure superposition is applied.

The geometry of interest for the present study is L-shaped part with a gusset in order to have a spring-in angle evolution along the part length (Fig. 1). The spring-in angle is the difference in angle between the nominal geometry (before curing) and the cured part. L-parts are 550mm long with 150mm long flangesand made of a symmetric stacking sequence of 10 plies of woven carbon fibres AS4/8552 prepreg

Experimental data was generated manufacturing the parts using SQRTM process in an aluminium closed-mould and measuring the angle evolution along the part length. The angle was measured using a Nikon MMx100 laser scanner mounted on a 7-axis Metrology-grade MCA II arm. The declared accuracy is 54μm which lead to an uncertainty of 0.1$\circ$ on the spring-in angle post-processed from the angle measurement.

The experimental measurements were compared to the spring-in angle predictions of different numerical models:

- the mould was modeled as a deformable body with aluminum properties and the frictional tool-part interaction was defined. The curing simulation of the part inside the mould was performed and the results, in term of spring-in angle, serve as a reference case to evaluate the accuracy of the "mapping" method;

- the mould displacement evolution extracted from the thermo-mechanical simulation was mapped on the composite part surface for the curing simulation until the part reached the glassy state from which a sliding contact was therefore considered.

Results have shown that the methodology set up allows to approximate the frictional tool-part interaction by mechanical boundary conditions on the node displacements. Further developments will focus on improving the method to better reflect the experimental behaviour during processing, especially the transition between sticking and sliding contact which strongly influence the mould deformation transferred to the part. Imposing a maximum shear stress the interface can carry before entering in sliding contact is a mean to account for the transition. The method will also be validated on larger parts where the computation time reduction is of great interest

This work has been accomplished in WP 5.2.3.1 of the WINGS project, and also benefited from computational resources made available on Lucia, the Tier-1 supercomputer, both funded by the Walloon Region.

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Numerical simulation of the welding of thermoplastic parts using a level-set method

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Speaker: Jezequel Yohann. **Tuesday**. Start time: **17:15**. Room: Rhône 5 LVL1. Link to abstract.

The hydrogen tank liner constitutes the innermost layer of a hydrogen tank. The principal function of this polymer component is to restrict the diffusion of hydrogen particles. The aforementioned liners can be manufactured via extrusion blow molding, a manufacturing process comprising three distinct steps: extrusion, mold closure, and blowing.

This study seeks to employ numerical simulation of the mold closure step to gain deeper insight, adopting a macroscopic approach. The primary objective is to gain a comprehensive understanding of the welding that occurs during the mold closure, which is challenging to study experimentally.

This work employs a numerical approach, using a finite element method based on an anisotropic mesh, which has been refined through an immersed boundary approach based on a level-set method. This method allows for the combination of multiple physical approaches, thereby facilitating the identification of critical variables and the optimization of the quality of the conduction welding process.

The proposed model and numerical simulation approach will be presented and discussed with reference to several application examples. To verify the methodology, a two-dimensional model of the mold closure will be examined initially, with a multi-phase problem involving the polymer/air interface being simulated. Once validated, the simulation of the mold closure will be extended to a three-dimensional model.

MS5.3 - Computational nonlinear materials and couplings

Organisers: Andreas Menzel (TU Dortmund) and Julien Yvonnet (Université Gustave Eiffel)

A full-field model for dynamic recrystallization

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Speaker: Ask Anna. **Wednesday**. Start time: **16:45**. Room: Saint Clair 3A LVL2. Link to abstract.

The macroscopic properties of metals and metallic alloys are strongly influenced by the crystalline microstructure. It is natural then that thermomechanical processing to control the microstructure is an important aspect of metal manufacturing. One such process is recrystallization, whereby an existing microstructural arrangement is replaced by another one. This can be a sequential process, typically including a first step of plastic deformation such as cold rolling, and then a second step of annealing where the elevated temperature allows a release of the stored deformation energy by grain boundary rearrangement. Concurrent recrystallization processes may also take place during deformation at elevated temperature. In the latter case, a typical feature is the nucleation of new grains along existing high angle grain boundaries or deformation bands. These newly nucleated grains are not work hardened and a temporary softening can therefore be observed in the macroscopic stress-strain curve as the new grains grow. Recrystallization, whether static (sequential) or dynamic (concurrent), changes the morphology of the microstructure in terms of grain shape and size, and also the crystalline orientation distribution. Both of these microscopic properties strongly influence the macroscopic mechanical response.
Many approaches have been proposed to model recrystallization. At the scale of a polycrystal, the most common approach seems to be to combine a continuum model of crystal plasticity with some method that can account for grain boundary migration. In recent years both level-set and phase-field models have been used successfully to model grain boundary migration in polycrystals. In this study, a phase-field model is favored due to the straight-forward way to integrate it together with the crystal plasticity model in one thermodynamically consistent formulation. Specifically, an orientation-based phase-field model, originally proposed by (1,2), is used because this gives a great degree of freedom for heterogeneous evolution of the crystal orientation everywhere in the microstructure including in the interior of existing grains. The crystal orientation is also an important descriptor of the microstructure and in crystal plasticity simulations must be considered when the resolved shear stress is calculated in a material point. In standard crystal plasticity the grain orientation is however not a degree of freedom but a tabular quantity that is updated as deformation produces elastic reorientation of the crystal lattice. The model used in this work is formulated in a Cosserat continuum description which does contain local orientation as a degree of freedom. This local Cosserat rotation is associated with the crystalline orientation in the constitutive model by a penalty approach.

Earlier, a small deformation version of the model has been implemented in two (3) and three (4) dimensions. However, a small deformation formulation is not in general adequate to model recrystallization since the deformations that are involved are large. Furthermore, the small deformation model is also restricted to small misorientations and this is not representative of general crystalline microstructures. A large deformation model (5) is therefore necessary but numerically challenging both to the inherent nonlinearity of the coupled equations and also because large rotations are involved. Unlike the displacement degrees of freedom, the rotational degrees of freedom do not belong to a vector space and cannot be added incrementally in the finite element treatment. A dedicated numerical treatment is therefore necessary that (a) correctly handles the rotational degrees of freedom and (b) adopts high performance computing methods. In this work, a staggered scheme that partly decouples the mechanical part from the phase-field part is adopted. Parallelization of the resulting systems of equation is performed using AMPFETI (Adaptive MultiPreconditioned Finite Element Tearing and Interconnecting) (5).

The large deformation coupled crystal plasticity and phase-field model allows the study of polycrystalline systems. The focus here is not on very large polycrystals where other models already exist that can predict average properties such as grain size distribution and orientation texture with good precision, but rather on smaller systems and a quantitative prediction of the microstructure evolution.

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A Crystallization-Enhanced Thermo-mechanically Coupled Visco-hyperelastic-plastic Model for Thermoplastics Overmolding Processes

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Speaker: Liu Tiansheng or Simon Jaan-Willem. **Wednesday**. Start time: **17:05**. Room: Saint Clair 3A LVL2. Link to abstract.

The overmolding process, where thermoplastic compounds are joined with continuous fiber-reinforced thermoplastic tapes, is a critical technique in industries such as automotive, aerospace and energy. While widely adopted, this process often suffers from poor interfacial adhesion, leading to premature part failure, overdesign, and reliance on trial-and-error practices. The underlying challenges stem from the interplay of multiple spatial and temporal scales, as well as from the influence of diverse process-morphology interactions which remain poorly understood. Addressing these challenges requires advanced modeling approaches to predict and optimize the performance of thermoplastic materials in industrial applications. To this end, this study is part of an NSF-DFG collaborative project focusing on thermoplastic overmolding processes. The project aims to develop advanced material models to investigate and understand the process-dependent material morphology characterized by crystallinity, resulting mechanical performance and failure behavior of tape reinforced thermoplastic parts produced, thereby optimizing design reliability.

In the current work, we develop a material model for semi-crystalline thermoplastics based on the co-rotated intermediate configuration (CIC) theory which integrates elastoplastic and viscoelastic components to capture the time-dependent, nonlinear thermo-mechanical responses of the material. It features bidirectional thermal-displacement coupling to describe self-heating effects during deformation and unidirectional coupling of crystallinity to the displacement field. Using this model, we can predict the spatiotemporal evolution of the stress state, heat generation, and temperature of overmolded thermoplastic parts under different crystallinity, loading rates and thermal conditions, thereby establishing a clear cause-and-effect relationship between process control and interfacial bond strength. This approach aims to address key challenges in manufacturing, such as insufficient bonding strength and premature failure, while unlocking the potential of UD tape reinforcements to minimize material usage and emissions, promoting more sustainable and efficient engineering practices.

A Solid-State Phase Transformation Model for Multiphase Alloys – Application to Laser Powder Bed Fusion

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Speaker: Noll Isabelle. **Wednesday**. Start time: **17:25**. Room: Saint Clair 3A LVL2. Link to abstract.

Titanium-aluminum alloys, particularly multiphase α-β-alloys like Ti6Al4V (titanium grade 5), are widely used across industries due to their excellent mechanical properties. These properties are highly sensitive to thermal history, as cooling and heating rates strongly influence solid-state phase transitions, resulting microstructures, and potential (undesired) deformations. This sensitivity results in challenges for manufacturing processes with high thermal input, such as heat treatment and additive manufacturing techniques like Powder Bed Fusion – Laser Beam / Metals (PBF-LB/M). Accurate modelling of such processes requires precise representation of phase transformations, including melt-solid and solid-solid transformations between β- and (multiple) α-phases.

This work introduces a novel, thermodynamically consistent phase transformation framework tailored for multiphase alloys. In contrast to conventional empirical models such as the Johnson-Mehl-Avrami-Kolmogorov (JMAK) or Koistinen-Marburger (KM) approach, the proposed model uses energy densities and evolution equations based on physical principles. The framework incorporates thermomechanical coupling and thermodynamically consistent evolution equations to describe the varying material compositions. Phase evolution is governed by specifically constructed dissipation functions, with incorporated coefficients being determined by parameter identification using limited experimental data or continuous cooling temperature (CCT) diagrams. This approach enables the numerical reproduction of CCT diagrams consistent with experimental observations. Unlike empirical formulations, this thermodynamically consistent and physically sound material model offers flexibility, supporting extension to additional phase fractions and different materials. It allows the prediction of both microstructural evolution and the development of strains and stresses throughout and at the end of the process.

The model's ability to capture the effects of varying cooling and heating rates on material composition makes it particularly suited for high-temperature gradient processes like PBF-LB/M. Numerical examples with the widely used alloy Ti6Al4V demonstrate the framework's capability to handle the spatial and temporal heterogeneity of thermal conditions. Simulations using LPBF-derived temperature profiles highlight the model's potential to advance modeling in additive manufacturing by improving predictions of microsctructure, residual stresses, and warpage.

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Numerical Investigation of Glass Phase Transformations: An Implementation of Kinetic Models Using ANSYS and Neighbor Element Method

Rudolf Tobias (1) (2) (3)

1 - Meisam Soleimani (Germany), 2 - Tobias Bode (Germany), 3 - Philipp Junker (Germany)

Speaker: Rudolf Tobias. **Wednesday**. Start time: **17:45**. Room: Saint Clair 3A LVL2. Link to abstract.

The manufacturing processes of high-quality glass components, however, require precise control and understanding of phase transformation mechanisms, particularly during thermal processing stages.
This research introduces an advanced numerical framework for modeling glass phase transformations, incorporating both thermal and mechanical coupling effects. The implementation utilizes the commercial finite element software ANSYS, enhanced with a specialized Neighbor Element Method (NEM) approach. Our methodology focuses on capturing the kinetic aspects of phase transitions, providing a comprehensive tool for analyzing the complex material behavior during processing.

The developed model incorporates time-dependent phase transformation kinetics, enabling detailed investigation of structural changes during thermal processing. By implementing the NEM algorithm, we achieve improved representation of local material interactions and transformation phenomena. The numerical framework addresses the challenges of modeling glass transition behavior, including the complex interplay between thermal gradients and mechanical stress development.
A distinctive feature of this approach is its ability to capture the non-linear behavior during phase transitions while maintaining computational efficiency. The framework incorporates critical aspects such as structural relaxation mechanisms and temperature-dependent material properties, providing a robust platform for investigating various processing conditions. This computational tool is particularly promising for industrial applications where precise control of thermal processing and resulting material properties is essential.

Phase-field modelling of twinning in magnesium: microstructure evolution and size effects in nano-indentation

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Speaker: Stupkiewicz Stanislaw. **Wednesday**. Start time: **18:05**. Room: Saint Clair 3A LVL2. Link to abstract.

Plastic slip in magnesium and its alloys is accompanied by deformation twinning which is an important deformation mechanism due to the lack of easily-activated slip systems. Twinning is associated with microstructure evolution, including nucleation, propagation and annihilation of twin boundaries, which significantly impacts the plastic slip due to the lattice rotation induced by twinning. To model the related phenomena, we have developed a finite-strain phase-field model of deformation twinning coupled with crystal plasticity. In contrast to the common approach, twinning is treated as a volume-preserving stretch so that a single order parameter can be used to describe two conjugate twinning systems. Our finite-element implementation relies on the micromorphic approach so that the complex constitutive equations of crystal plasticity can be effectively included in the phase-field framework. We have recently extended the model by incorporating a simple description of slip-gradient effects. As a result, the model is capable of describing size effects introduced by the interfacial energy of twin boundaries within the phase-field framework and by the slip-gradient effects within the gradient crystal plasticity. The related effects are illustrated by modelling the nano-indentation of a magnesium single crystal. We show that the interfacial energy governs the microstructure, i.e., the morphology of twins, while its impact on the mechanical response is limited. Opposite dependencies are observed in the case of slip-gradient effects.

Interplay of martensitic phase transformation and plasticity in shape memory polycrystalline alloys: energetic considerations-based constitutive modeling

Frost Miroslav (1), Moskovka Alexej (1), Benešová Barbora (2), Sedlák Petr (1), Seiner Hanuš (1)

1 - Institute of Thermomechanics (Prague, Czech Republic) (Czech Republic), 2 - Faculty of Mathematics and Physics [Praha/Prague] (Czech Republic)

Speaker: Frost Miroslav. **Wednesday**. Start time: **18:25**. Room: Saint Clair 3A LVL2. Link to abstract.

Due to the possible concurrent activation of multiple inelastic deformation mechanisms, shape memory alloys exhibit a strongly nonlinear mechanical response. Recent experimental and theoretical findings shed new light on the plastic processes running in NiTi alloys and their interplay with martensitic phase transformation. Based on this we have formulated a novel constitutive model that carefully addresses such phenomena via a thermodynamically consistent variational formulation. Its core consists of conventional stored energy and a tailored dissipation function/potential. The model has been validated on a comprehensive set of experimental data and has been implemented in a finite element code to enable simulations of engineering structures.

Understanding grain boundary resistivity – A multiscale approach for electrical conductors

Güzel Dilek (1), Kaiser Tobias (1), Bishara Hanna (2), Dehm Gerhard (3), Menzel Andreas (1) (4)

1 - TU Dortmund University (Germany), 2 - Tel Aviv University (Israel), 3 - Max-Planck-Institute for sustainable materials (Germany), 4 - Lund University (Sweden)

Speaker: Güzel Dilek. **Thursday**. Start time: **10:00**. Room: Saint Clair 3A LVL2. Link to abstract.

The macroscopic electrical properties of metals are significantly influenced by the underlying microstructure, with grain boundaries being one of the key factors in determining electrical conductivity. Accordingly, various phenomenological models, such as the Andrews method (1), have been developed over the past decades to evaluate grain boundary resistivity in experiments. While these models offer simplified approaches, they often rely on ad-hoc assumptions that may not fully capture the intricate relationship between microstructure and conductivity.
To address these limitations, this work employs computational homogenisation techniques to systematically analyse the Andrews method, building on recent developments of computational multiscale methods for electrical conductors with material interfaces (2). In particular, we derive the governing multiscale relations for microstructures with cohesive-type interfaces, and demonstrate that the effective macroscopic conductivity tensor can be extracted from the underlying microstructure.
By a systematic comparison between the Andrews method and the proposed homogenisation approach, we show the fundamental connection between them (3). To this end, one-dimensional analytical expressions are examined, first, so as to uncover the underlying physics. The investigation of primitive anisotropic and isotropic microstructures highlights the importance of grain alignment and morphology influence resistivity in a second step. This crucial understanding of the microstructure-property-relation eventually manifests itself in scaling laws for the effective macroscopic resistivity that are derived thereafter. Finally, the analysis extends to polycrystalline microstructures and is validated against the experimental data.

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Derivation of a macroscopic nonlinear beam model for cables using homogenization

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1 - Institut de Recherche en Génie Civil et Mécanique (France)

Speaker: Zeidan Lara. **Thursday**. Start time: **10:20**. Room: Saint Clair 3A LVL2. Link to abstract.

Floating wind turbines represent a significant innovation in renewable energy, by addressing the global demand for sustainable electricity while reducing carbon emissions. These turbines transmit the generated electricity to offshore locations through dynamic cables, which are subjected to complex environmental loading conditions including platform movements, hydrodynamic forces from ocean currents, and aerodynamic pressures from wave action. Accurate simulation results are essential to ensure the structural integrity and operational reliability of these cables.
The dynamic cable under investigation typically measures 100 meters in length and 10 centimeters in diameter. Its complex geometry and heterogeneous structure arise from multiple components such as metallic layers composed of wires with helical configurations. This cable exhibits nonlinear bending behavior as a result of contact nonlinearities. To predict its mechanical behavior accurately, a multiscale study is required to link the complex interactions occurring at the microscale to the resulting macroscopic beam-like behavior of the cable.

The solution to homogenization problems performed at the microscale reveals that the macroscopic behavior of the cable is hysteretic, which can be effectively captured using a rheological model, specifically the Bouc-Wen model (1, 2). Using this macroscopic model avoids the computational complexity associated with numerical strategies that couple microscale and macroscale analyses, such as FE^2 approaches, while maintaining reliable predictions of the mechanical response of the cable under a range of loading conditions.

The aim of this study is to introduce a reduced macroscopic model based on the Bouc-Wen framework, estimate its parameters using solutions from homogenization problems, and demonstrate the accuracy of this macroscopic model by comparing it with detailed finite element models.

To determine the parameters of the Bouc-Wen model, an initial microscale analysis is performed on a representative volume element of a cable corresponding to an axial period subjected to tension and uniaxial bending under periodic boundary conditions (3). This analysis captures the structural behavior during the critical stick-slip phases, enabling the determination of both stick and slip stiffness, as well as the threshold for transitioning between these phases. The parameter identification process requires only a limited set of computations corresponding to a series of uniaxial bending tests under a constant axial force.

The Bouc-Wen model, formulated with parameters derived from microscale analysis, accurately captures the nonlinear hysteretic behavior associated with cyclic loading. This reduced rheological model, initially developed for uniaxial bending conditions, is then extended to account for multiaxial bending loads following the approach introduced by Saadat (4). This extension involves discretizing the three-dimensional bending space into n
theta equally spaced uniaxial systems. In each system, the uniaxial response is captured in a distinct plane where the loads and deflections are projected. The Bouc-Wen model, previously identified under uniaxial conditions, is used to represent the bending response of the cable in each plane. By combining these forces into the global system, the extended multiaxial model is able to accurately simulate the full 3D bending behavior of the cable, offering a comprehensive description of its mechanical properties.

The validation of the multiaxial rheological model begins with multiaxial loading conditions that vary over time according to the loading history. These loads are applied at the microscale on a 3D finite element model of a representative volume element within a homogenization framework. The results demonstrate that the macroscopic behavior is accurately predicted by the multiaxial rheological model. Furthermore, a structural analysis is performed. The extended multiaxial Bouc-Wen model is used for the macroscopic beam behavior, and its solution is compared with that of a detailed 3D finite element model of the entire cable, showing excellent agreement, even for multiaxial and multilayered cables with complex geometries.

These findings validate the ability of the proposed model to replicate high-fidelity simulations and confirm its accuracy in capturing the cable's complex mechanical behavior.

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A transfer function package-modeling approach for speeding up multi-scale MEMS sensor drop simulations

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Speaker: Plavecz Lambert. **Thursday**. Start time: **10:40**. Room: Saint Clair 3A LVL2. Link to abstract.

Drop robustness of MEMS (micro-electromechanical system) sensors becomes increasingly important. More and more devices utilize sensors, while at the same time, the industrial trend requires even smaller, and thus weaker, sensing structures. To evaluate the impact resistance of these devices, long and computationally demanding finite element simulations are conducted. In this contribution, a more efficient way of modeling MEMS sensor drop is proposed. Significant speedup can be achieved by using a discrete transfer function of the package, while the MEMS sensor structure and the carrier device are still simulated with an explicit finite element method (FEM).
The typical way of simulating drop tests or accidental drop of MEMS devices is following a multi-scale finite element approach (1)(2), where the typical length scales (or simulation levels) are that of the package, the MEMS sensor structure, and the microstructure of the polysilicon. These levels can be simulated separately because of the order of magnitude difference in the masses corresponding to each scale. Similar approaches are also common for MEMS gyroscopes, and microphones, even including carrier device level (e.g., a printed circuit board) (3)(4). However, to map the robustness characteristics of the MEMS sensor in a package drop event, many simulations need to be run. To speed up this process a novel transfer-function-based package model is proposed.

A computationally efficient package model can provide a large number of input load curves for structure robustness simulations. The ability to evaluate many drop situations may reveal previously unknown weaknesses in the structure, which can then be adequately addressed. Another strength of the discrete transfer function approach is its relative simplicity compared to e.g., a reduced-order model of the package. The latter is a more complex representation and can only support linear elastic materials, whereas e.g., polymer materials of the package would need a viscoelastic representation. With the transfer function, taking the average velocity of the package as input, the velocity of the anchor is output. This, in turn, can be used in the FEM simulation of the structure as a kinematic constraint.

To obtain an adequate transfer function of the package, the drop of a small number of representative carrier devices should be simulated with a fully modeled package in an explicit FEM model. In the next step, these simulations are used for fitting the package transfer function. Then, for further carrier devices only a homogenous package needs to be included, that is, a single solid brick with averaged material model. From this, the necessary input can be extracted, and via the transfer function, the anchor velocity is obtained which is the constraint of the sensor structure simulation. Similarly, for a package drop without a carrier device, a transfer function can be used together with a discrete package impact model to obtain the anchor movement.

The transfer function is shown to be able to approximate the anchor velocity in case of drops with different simplified carrier devices. Moreover, drop of the package onto a smooth floor can also be adequately modeled with the proposed transfer function method even for different drop heights and floor materials.

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Interplay of elastic and chemical driving forces for phase separation in biphasic media at large strains

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Speaker: Gomero Soria Andrea. **Thursday**. Start time: **11:00**. Room: Saint Clair 3A LVL2. Link to abstract.

Various polymeric structures, such as microporous membranes, thin films, hydrogels and electrospun fibers, can be engineered through phase separation into solvent and polymer-rich domains under suitable physical and chemical conditions. Tuning the microarchitecture of these structures through the adjustment of material and process parameters allows their use in a wide variety of applications (1). Lately, computational models simulating phase separation induced by different stimuli have been used to avoid or at least supplement extensive combinatorial trial-and-error experimental investigations, as they enable the tracking of microstructure formation in silico (2).
In chemoelastic polymer solutions and gels, the mechanical behavior of the constituent phases significantly influences the microstructural evolution and thus the macroscopic mechanical behavior of the system. In general, phase mixing and separation are associated with deformations of the solution and the evolving phases. When these deformations lead to non-negligible mechanical work, the latter can alter the free energy landscape, shift the binodal points of the phase diagram, and hence affect the phase separation process (3). In the present contribution, we investigate the role of these mechanical effects, focusing on cases involving large deformations, such as drastic volume loss due to external mechanical loads or solvent evaporation. Notably, in solvent evaporation scenarios, traditional models often rely on a rescaling approach rather than explicitly coupling with deformation mechanics (4). We show that the associated changes in geometry can lead to local alterations in composition that trigger and govern microstructure formation.

To this end, a chemomechanical, coupled theory based on the phase-field approach was developed (5), where the mixture is modelled as a single continuous body with diffusing liquid components (6, 7). Within this theory, the chemical (interfacial and mixing) energetic contributions of the original Cahn-Hilliard and Flory-Huggins theories, respectively, were consistently reformulated to account for large deformations in a Lagrangean framework. Special attention is given to the interfacial energy representation, where the fully consistent form implies strong non-linear dependence on deformation, distinct from the common model in literature (c.f. (6, 8)). The governing equations were numerically implemented using FEniCSx and assessed with regard to their predictions of microstructure formation. Through two and three-dimensional simulations, we highlight the importance of the constitutive model specifying the free energy density associated with the formation of interfaces in the geometrically non-linear regime. Finally, the model is used to explore the influence of the different material and process parameters on the predicted morphology.

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Phase-Field Modeling of High-Temperature Oxidation Corrosion in Multi-Chemical Component Systems

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Speaker: Löps Paul. **Thursday**. Start time: **11:20**. Room: Saint Clair 3A LVL2. Link to abstract.

For many materials, and particularly metals, corrosion is one of the most significant mechanisms regarding the chemical degradation of structural integrity. Therein, a chemical component diffuses to the surface of a structure and reacts with atmospheric elements to form a corrosive layer. The resulting products and their formation rates depend significantly on the material and atmospheric composition, as well as the operating temperature. Elevated temperatures accelerate this detrimental process, making it a key factor in estimating the lifespan of high-temperature electrolysis plants. In the "H2GIGA – HTEL" project, the influence and impact of corrosion are studied at temperature levels of up to 900 ∘C under dominant process atmospheres, such as those containing significant levels of hydrogen or high oxygen content.
Current state-of-the-art models allow the prediction of diffusion and reaction mechanisms using electrical or chemical potentials, see (1), but they are typically limited to solid or solid-liquid systems, where the system density remains nearly constant. Technological applications include ceramic filters used to purify molten steel by removing non-metallic inclusions, as in (2), or the reduction of iron oxide, see (3). To address oxidation processes involving changes in density due to reaction, diffusion, and phase transition mechanisms, a multi-phase, multi-component phase-field model is employed here, which is based on the work of Svendsen et al., cf. (4). This approach uses mixture theory to conserve the mass of all components in the system, as well as for the total mixture. The current mixture density is calculated using the molar mass and molar volume of each component. The chemical potential of each component contributes to the material point state, driving the diffusion in the sense of a generalized Cahn-Hilliard equation and enabling accurate modeling of mixing and separation processes via an Allen-Cahn framework. Following a phase-field approach, diffuse phase boundaries are implemented using spatial gradient terms in the free energy function, combined with contributions from components and phases. Reactions are defined by linear chemical equations and stoichiometric coefficients for all components according to (5). This work focuses on high-temperature oxidation processes in which chromium (Cr) plays a dominant role. Acting as a sacrificial anode, Cr oxidizes to form chromium(III) oxide (Cr2O3), protecting the underlying material until its concentration falls below a critical level, allowing other oxides to form. Experimental studies typically measure the weight change of specimens at discrete time intervals, even though cooling from high temperatures can cause mechanical stresses and delamination of the oxide layer. These factors complicate precise measurements. Another method involves microscopic imaging of cut specimens to directly evaluate layer thicknesses, capturing geometrical influences, such as variations in diffusion near corners. These spatially inhomogeneous effects are of high importance for the lifetime of a component and thus require an implementation of the model in a multi-dimensional framework, performed here in the finite element software Abaqus.

The proposed model simulates the reaction between chromium and oxygen to form Cr2O3 on the surface of a solid two-dimensional structure. To this end, the system comprises five components (Cr, O2, Cr2O3, air, and steel) and two phases (solid and gaseous). The reaction occurs at the interfaces, with the newly formed oxide adding to the solid phase, thereby expanding it. The model captures oxide layer growth on the surface and chromium depletion beneath it, while tracking phase interface movement due to Cr2O3 growth. Simulations also reveal differences in oxide formation at corners: outer corners are poorly supplied with chromium, resulting in thin oxide layers, whereas inner corners benefit from enhanced diffusion. Finally, we validated our model by comparing simulated results with experimental data, demonstrating its ability to replicate layer growth in real-world applications.

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Keywords: Chemical Reactions, High-Temperature Oxidation, Finite Element Method

Modeling of Hysteretic Behavior of Shape Memory Alloys Using a Rate-Independent Phase-Field Framework

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Speaker: El Khatib Omar. **Thursday**. Start time: **14:15**. Room: Saint Clair 3A LVL2. Link to abstract.

Shape memory alloys (SMAs) are a prominent class of multifunctional materials with remarkable thermomechanical properties, offering significant potential for engineering applications. Their behavior is characterized by stress- and temperature-induced phase transformations between austenite and multi-variant martensite, enabling unique functionalities such as superelasticity and shape recovery. These transformations are accompanied by energy dissipation, which is the origin of hysteretic behavior under cyclic thermo-mechanical loading. Experiments reveal that the majority of SMAs exhibit rate-independent responses under quasi-static conditions, maintaining finite-width hysteresis loops even at extremely low loading rates. The phase-field method has emerged as a powerful modeling framework for capturing the evolution of complex interface topologies in SMAs. Despite numerous important contributions addressing the continuum mechanical description of SMAs, see (1) and the references therein, most existing models employ rate-dependent dissipation formulations, limiting their ability to replicate the thermo-elastic hysteresis loops with finite width, as observed in experiments under quasi-static conditions.
To address this gap, this study extends a thermomechanically coupled and variationally consistent phase-field approach that integrates both rate-dependent and rate-independent driving force formulations, as detailed in (2). Additionally, it incorporates temperature dependent local energetic minima within the free energy landscape to accurately model sigmoidal undercooling hysteresis as welll as stress- and temperature-induced martensite pattern formation. Two-dimensional finite element simulations demonstrate the applicability of the proposed framework in analyzing microstructure evolution in twinned martensite, remanent microstructure formation under cyclic loading, as well as hysteresis behavior. These studies involve the influence of driving force related thresholds and the calibration of model parameters using experimentally observed martensite start and finish temperatures. Moreover, the introduction of nonlinearly weighted averaging operators further enhances the macroscopic characterization of microstructural features (see (3)). Future extensions of the framework to multi-phase and multi-variant alloy systems are also outlined, underscoring its applicability.

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Kwinking as the plastic forming mechanism of B19' NiTi martensite

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Speaker: Sedlak Petr. **Thursday**. Start time: **14:35**. Room: Saint Clair 3A LVL2. Link to abstract.

Recent experimental findings from thermomechanical testing and microstructural analysis of NiTi polycrystalline shape memory alloy have brought a qualitatively new picture of plastic deformation mechanisms of this most common shape memory material (1). In particular, they challenge the widely accepted paradigm that austenite is a phase more susceptible to dislocation slip and plastic deformation in NiTi than B19' martensite, despite the fact that only a single (100)(001)M dislocation slip system is observed in martensite.
In this contribution, we show that if the plastic slip of (100)(001)M and reorientation of martensite between two variants sharing the (010)M plane are active simultaneously, a new deformation mechanism arises that combines kink banding and twinning forming the so-called "kwink bands" (2). A model describing the formation of kwink bands developed based on the tools of nonlinear elasticity theory of martensite and crystal plasticity will be presented and it will be shown how the monoclinic martensite lattice can accommodate large prescribed macroscopic plastic deformations despite the activation of a single dislocation slip system.

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Two-way coupled modeling of dislocation substructure sensitive crystal plasticity and hydrogen diffusion at the crack tip of FCC single crystals

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Speaker: Gu Tang. **Thursday**. Start time: **14:55**. Room: Saint Clair 3A LVL2. Link to abstract.

Dislocation substructure-sensitive crystal plasticity (DSS-CP) modeling accounts for the evolution of mesoscale structures using dislocation-based parameters informed by experiments and computation at various lower length scales. To a first-order approximation, DSS-CP model parameters are affected by hydrogen (H) concentration, accounting for both H-dependent yield strength and strain hardening rate. This H-affected DSS-CP model is two-way coupled with H-diffusion to explore both effects of plastic deformation on H-diffusion and effects of H on yield strength and strain hardening in the DSS-CP model. Crack tip simulations are performed for face-centered cubic (FCC) metals under monotonic loading conditions with and without H. Enhanced maximum plastic deformation in the vicinity of the crack tip (i.e., localization or intensification of plastic strain) and crack tip opening displacement (CTOD) are predicted in the presence of H, consistent with experimental observations. In spite of increased initial strength due to H, subsequent reduction of the rate of strain hardening in the presence of H is shown to enhance localization of crack tip plasticity. Furthermore, this modeling framework predicts that higher H-diffusivity (leading to a larger H-affected zone) will enhance the crack tip plasticity, making use of the two-way coupling algorithm implemented in this work. On the other hand, we find that the H-sensitivity of crack tip strain localization response, based only on modification of model parameters, is too weak to explain typical experimental observations. This points to the need to develop more advanced DSS-CP constitutive relations that consider highly complex dislocation interactions with point defects.

Consistent Eulerian and Lagrangian variational formulations of non-linear kinematic hardening

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Speaker: Heuzé Thomas. **Thursday**. Start time: **15:15**. Room: Saint Clair 3A LVL2. Link to abstract.

Numerical simulation of impacts on solids generally consider a constitutive response that embeds, amongst others, an elastic-plastic contribution with a sole isotropic hardening. Indeed, the latter is sufficient in case of monotonic loadings. However, various engineering applications may also involve repeated impacts, like Laser Shock Peening used for instance for mitigating back stresses in rolled stainless sheets (1), or cyclic impacts sequentially applied in forward and reverse directions. In these cases, eventual local cyclic loadings can yield Bauschinger and/or ratchetting effects, such that considering non-linear kinematic hardening in the constitutive response becomes important.
Two Eulerian and Lagrangian hyperbolic modelings of thermo-hyperelastic-plastic solids coupled with a non-linear kinematic hardening in finite strains are proposed in this work (2). Constitutive equations are written in a consistent manner between both kinematical descriptions, first via the definition of back stresses, second thanks to plastic evolutions laws written in the respective settings, rather than in the intermediate one. The constitutive equations in the two settings are coupled with their respective multi-field first order systems of balance equations, so that the well-posedness of the Eulerian and Lagrangian hyperbolic modelings are ensured.

The structure of the constitutive modelings then naturally allows to build variational formulations of the dissipative thermo-mechanical local constitutive problem written in both Eulerian and Lagrangian descriptions. First order accurate variational constitutive updates are then derived from their continuous counterparts. Following the framework developed in (3), they admit updated values of specific internal energy as input data in place of the temperature. This makes these integrators naturally compatible with the solution of the conservation of total energy. However, constitutive equations written in initial and current settings now require a novel writing of discrete Euler-Lagrange equations, and a new parameterization of the flow direction.

Space discretization of balance equations is here performed via the second order accurate flux difference splitting finite volume method, embedding non-conservative fluxes arising in the Eulerian formulation. A sequence of test cases performed at one material point, then on 1D and 2D examples allow to show on the one hand the good agreement between solutions computed with the two descriptions, and on the other hand the truly different predicted solutions when accounting for kinematic or isotropic hardenings in case of a cyclic loading.

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Modelling the thermomechanical behaviour of high strength steel beams exposed to the fire resistance test using microplane approach.

Mundó Tijeras Ignasi (1), Cem Caner Ferhun (1), Mateo Garcia Antonio (1)

1 - Universitat Politècnica de Catalunya (Spain)

Speaker: Mundó Tijeras Ignasi. **Thursday**. Start time: **15:35**. Room: Saint Clair 3A LVL2. Link to abstract.

The computational simulation of high strength steel structures exposed to high temperatures provides valuable insights into the failure mechanisms of buildings in case of fire. To achieve this, precise methods are essential to evaluate various changes in the stress state of the steel, cyclic loads, and non-proportional loading paths that simulate the effects of impacts, blasts, or earthquakes. Conventional constitutive models for ductile metals fall short in predicting these effects; thus, alternative models are necessary, as presented herein.

In this study, the mechanical behavior of Q690 high strength steel is first calibrated with experimental data of tensile tests under different stress states and its response at elevated temperatures is optimally fitted with experimental data of transient-state temperature tensile tests. Subsequently, the thermo-mechanical simulation is performed on a loaded beam of the same steel subjected to the fire resistance test. During the test, the specimen is subjected to a constant load and increasing temperature according to the ISO 834 fire curve. The thermo-mechanical simulations are based on the calibration of two models: (1) The microplane-J2 constitutive model (MPJ2), and (2) the microplane model for metals (MPM) that employs strain-dependent yield functions. The microplane approach effectively reproduces the average response of physical phenomena occurring on various slip planes during plastic deformation and allows for a higher predictability under complex loading conditions. The temperature dependence of mechanical behaviour and the thermal expansion are introduced based on the measured experimental data. The results represent insight into the digitalization of fire resistance tests and predictive analysis of steel structures failure under fire, and open up new strategies for more accurate predictions under complex loading scenarios.

Finite element estimation of internal stresses induced by the carburizing quenching process.

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Speaker: Ben Ayed Salim. **Thursday**. Start time: **15:55**. Room: Saint Clair 3A LVL2. Link to abstract.

Carburizing-quenching is a thermochemical surface aimed at hardening the surface of steels and making them more resistant to friction, wear and corrosion (1). It consists in carbon atoms diffusion at high temperature, followed by a rapid cooling to obtain a martensitic microstructure. This process generates residual compressive stresses at the subsurface of the sample, which play a major role in the final mechanical properties (2).
This work aims to estimate the spatiotemporal evolution of the residual stress profile, to predict the mechanical behavior and evaluates the impact of the quenching process. It is based on the use of Abaqus software and user-defined subroutines to account for the coupling of the different physics involved in this Metallo-thermo-mechanical coupled problem (3).
Especially, several mechanical contribution were considered in the carburizing-quenching process modelling: elastic, plastic and thermal strain, transformation strain due to martensitic transformation, transformation plasticity strain for the plasticity due to phase transformation, and the expansion strain rate linked to carbon diffusion. The importance of taking transformation plasticity into account in order to correctly predict internal stress profiles was elucidate, as shown by several studies. (4)

(1) X. Li *et al.*, " Effect of Transformation Plasticity on Gear Distortion and Residual Stresses in Carburizing Quenching Simulation ", *Coatings*, vol. 11, no10, p. 1224, 2021, doi: 10.3390/coatings11101224.
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Foundational aspects of an hybrid equilibrium element for finite poroelasticity

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Speaker: Lo Franco Simona. **Friday**. Start time: **10:00**. Room: Saint Clair 3A LVL2. Link to abstract.

Computational modeling of coupled diffusion problems in the finite strain regime represents an area of considerable complexity arising from the intricate interplay between the deformation of a porous solid matrix and the fluid flow permeating the interconnected pore network. A significant amount of literature covers a wide range of finite element formulations, most of which are based on two-field discretization – typically incorporating solid displacements and pore pressures – or a more complex three-field discretization incorporating solid displacements, which commonly remain a primary variable (1, 2).
From a variational perspective, these methodologies lead to saddle point problems that require the implementation of stabilization techniques to ensure accurate and reliable solutions. A basic requirement to infer the well-posedness of these formulations is adherence with the inf-sup condition (3). However, even if this criterion is met, substantial challenges can arise in the numerical solution, especially in low permeability or small time step scenarios. In such cases, the use of stabilization strategies or highly refined meshes is essential to mitigate instabilities such as spurious pressure oscillations, which can significantly affect the accuracy of the solution even for seemingly simple benchmark problems.

An alternative paradigm (4, 5) involves adopting a specific set of state variables that inherently preserves mass balance at the local level and allows the derivation of a variational minimization principle. By satisfying the inf-sup condition a priori, the latter approach yields an element with superior intrinsic stability. Nevertheless, the development of a conforming and computationally efficient element capable of locally enforcing the mass balance depends on the adoption of an appropriately reduced numerical integration scheme for the volumetric coupling term. Recently, a related stress-pressure formulation (6) in the small deformation regime has led to the development of a hybrid equilibrium element that does not rely on stabilization techniques to cope with spurious pressure oscillations.

Building on these advances, the present work presents a novel hybrid equilibrium finite element formulation to address the nonlinear coupled problem of fluid transport in porous media. By exploiting the intrinsic properties of hybrid elements, the proposed approach facilitates the enforcement of fundamental balance laws within the discretized framework. This property not only increases the theoretical rigor of the formulation but also avoids numerical artifacts, thereby eliminating the dependence on external stabilization techniques and providing a robust tool for accurate computational modeling of complex poroelastic systems. The related finite element implementation details are shown and finally the obtained numerical results for a few basic poroelastic problems are discussed.

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Fluid-Structure Interaction Model for Actuation of Immersed Light-Responsive Liquid Crystal Elastomer (LCE) Beams

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Speaker: Norouzikudiani Reza. **Friday**. Start time: **10:20**. Room: Saint Clair 3A LVL2. Link to abstract.

Liquid Crystal Elastomers (LCEs) are a class of smart materials capable of undergoing large, reversible deformations when exposed to external stimuli such as light, heat, or humidity. Among these stimuli, light is particularly appealing as it enables precise, non-contact control over LCE properties, leading to complex deformations and dynamic behaviors. Recent experimental researches have demonstrated the potential of light-actuated LCE beams immersed in fluid environments. For example, one study reported self-oscillation in a planar LCE beam immersed in water, driven by the self-shadowing effect under constant illumination (1). Another study described a light-powered micro-swimmer inspired by the anatomy and motion of ephyras, composed of four beam and demonstrated its propulsion capabilities (2). The actuation of LCE beams under light involves a complex interplay of multiple physical processes spanning structural mechanics, heat transfer, light absorption, chemical reactions, and, when submerged in a fluid, fluid dynamics. This multi-disciplinary nature makes it essential to understand the underlying physics governing these interactions to enhance the performance and functionality of LCE systems. In particular, the dynamic response of LCEs in fluidic environments, including phenomena such as self-oscillation and light-driven swimming, is an area of growing interest. In this work, we developed a multi-physics fluid-structure interaction model using COMSOL software to investigate the dynamic behavior of LCE beams immersed in a fluid and subjected to light. Our model integrates several phenomena, including nonlinear structural mechanics, fluid mechanics, heat transfer, and chemical reactions, while incorporating the Beer-Lambert law to capture light absorption. Deformations and bending of the LCE beam are driven by either thermal or chemical effects, depending on the specific problem and light stimulus.
Inspired by the experimental study in (1), we applied the model to study the self-oscillation of an immersed LCE beam under steady illumination. Self-oscillation occurs due to a feedback loop driven by the self-shadowing effect, where the beam's deformation alters the light intensity distribution along its surface, causing periodic motion. We conducted a detailed parametric analysis to understand how various factors influence the oscillation behavior, including beam length, and light intensity. The results highlight the impact of these parameters on the amplitude and frequency of oscillation, offering valuable insights for optimizing the design and functionality of LCE-based devices.

In addition to investigating self-oscillation, we extended our model to simulate a two-dimensional (2D) light-powered swimmer inspired by the ephyra, as described in (2). In this model, a thin LCE beam is considered as the swimmer, with its propulsion and steering controlled by modulating two light sources with independently adjustable illumination periods. The actuation mechanism relies on the photochemical reactions of azobenzene molecules embedded in the LCE. Specifically, under light exposure, the azobenzene undergoes a trans-to-cis isomerization, causing a localized contraction in the LCE material and bending towards the light source. This deformation drives the actuation of the swimmer. A second light source is used to facilitate relaxation by reversing the isomerization process or redistributing the molecular configuration to allow recovery of the original shape. The interplay between these two light sources creates a dynamic cycle of deformation and relaxation, enabling control of the swimmer's motion. Our simulations explore the impact of this light-modulated actuation-relaxation process on the swimmer's propulsion, stability, and steering. This approach highlights the potential of chemically-driven light-responsive mechanisms for achieving controlled navigation in fluidic environments.

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Advanced Dynamic X-Mesh Interface Modeling for Yield-stress fluid application

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Speaker: Hun Darith Anthony. **Friday**. Start time: **10:40**. Room: Saint Clair 3A LVL2. Link to abstract.

Abstract

Precise representation of interfaces is crucial for improving the accuracy of numerical simulations in fluid and solid mechanics. Within the scope of the X-Mesh project, this study aims to develop advanced dynamic and automatic meshing method for modeling complex interfaces (1), here with a specific focus on yield stress fluids as the application.

The X-Mesh framework explores two complementary approaches. The first approach, well adapted for fluid flows (2), involves placing mesh nodes directly on the fluid interface to enhance precision in transitional zones, such as those between solid and shear flow phases for the yield stress application. The second approach presented here, particularly tailored for solid mechanics problem, relies on an adaptive redistribution of nodes across the entire domain and based on minimization of a specific energy. Concerning the computational method, the numerical optimizer plays a critical role and must be well-suited to the specific problem. These both aspects will be detailed. Results show that node redistribution notably improves the quality of numerical solutions and enhances simulation convergence, particularly in regions with significant variations in physical fields.

This research advances mesh optimization techniques can be adapted to others multiphysics interfaces, offering a robust solution to reduce simulation errors, relevant for both industrial and academic applications.

Keywords : adaptive meshing, complex interfaces, fluid mechanics, multi-physics simulations.

(1) Moës, N., Remacle, J. F., Lambrechts, J., Lé, B., Chevaugeon, N. (2023). The eXtreme Mesh deformation approach (X-MESH) for the Stefan phase change model. Journal of Computational Physics, 477, 111878.

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MS5.4 - Computational methods for damage and fracture

Organisers: Nicolas Moes (UC Louvain) and Jean-François Molinari (EPFL)

State of the art of the Lip-field approach

Chevaugeon Nicolas (1), Moes Nicolas (2)

1 - GeM, Institut de Recherche en Génie Civil et Mécanique, UMR6183 (France), 2 - iMMC, Institut de recherche en mécanique, matériau et génie civil Université Catholique de Louvain. (Belgium)

Speaker: Chevaugeon Nicolas. **Wednesday**. Start time: **10:00**. Room: Roseraie 1 LVL3. Link to abstract.

The Lip-field approach is a regularization method for softening material models. It was applied to damage and softening (visco)-plasticity models both in 1D and 2D scenarii.
The incremental potential used in the Lip-field approach is the nonregularized one. The regularization comes from the addition of a Lipschitz constraint on the damage field (or adequate (visco)-plastic quantities). In other words, the free energy does not depend on the damage gradient. The search of the displacement and damage fields from one time-step to the next is based on an iterative staggered scheme. The displacement field is sought for a given damage field. Then, a Lipschitz continuous damage field is sought for a given displacement field. Both problems are convex. The solution to the latter benefits from bounds proven in (1). The implementation of the Lipschitz regularity constraint on a finite element mesh and details of the overall solution scheme will be presented. Numerical examples will demonstrate the capability of the approach (2).

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(2) Nicolas Chevaugeon, Nicolas Moes. Lipschitz regularization for fracture: The Lip-field approach. Computer Methods in Applied Mechanics and Engineering, 2022, 402, pp.115644. ⟨10.1016/j.cma.2022.115644⟩. ⟨hal-03927211⟩

Sharp cracks in continuous damage models using the eXtreme Mesh deformation approach (X-Mesh) : a 1D study

Moës Nicolas (1) (2), Lé Benoît (3), Chevaugeon Nicolas (4), Remacle Jean-françois (1) (2)

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Speaker: Moës Nicolas. **Wednesday**. Start time: **10:20**. Room: Roseraie 1 LVL3. Link to abstract.

Continuous damage models are widely used to model the propagation of cracks, since they can handle complex cracking processes, from nucleation to coalescence and branching. However, these approaches do not explicitely model cracks opening, which is necessary to avoid numerical issues when the damage variable d tends to 1, or to model contact phenomenon between cracks lips for instance. In this work, we will see how to use the eXtreme Mesh deformation approach (X-Mesh) introduced in (1) to insert macro-cracks opening inside a continuous damage model. In particular, we will consider two continuous approaches to fracture: the Phase-field approach which has been widely used to model the failure of material since the last few years, and a more recent one, the Lip-field approach. Both formulate the mechanical problem to be solved as the minimization problem of an incremental potential, and introduce a characteristic length parameter lc to avoid mesh dependency, the main difference being how this parameter lc is taken into account.

The main idea of X-Mesh as it is presented in (1) is to move the nodes of a finite element mesh to have a time continuous, sharp representation of a moving front (for instance in (1), a phase-change front). These nodes movements allow to model topological changes of the front, including coalescence and splitting. Note that only the position of the mesh element nodes changes, the topology of the mesh being fixed (that is, the connectivity between the nodes), which is easier than full remeshing. For fronts where only the derivative of the quantity of interest if discontinuous, having only a line/surface of nodes in 2D/3D on the front is enough; however, in the case of cracks where the displacement field is discontinuous, the key idea will be to move nodes to create zero measure elements at the cracks location.

Since both Phase-Field and Lip-field formulate the mechanical problem to be solved as an optimisation problem, where the unknown are the displacement and damage fields, it is natural in the X-Mesh framework to consider the mesh nodes position as an additional unknown. In this work, we will show on a 1D bar example that by optimising the mesh nodes position, zero measure elements appear when the damage variable tends to 1, allowing jumps of the displacement solution.

(1) Moës, N. and Remacle, J.F. and Lambrechts, J. and Lé, B. and Chevaugeon, N. (2023). The eXtreme Mesh deformation approach (X-MESH) for the Stefan phase change model. Journal of Computational Physics, 477: 111878.

A Griffith description of fracture for non-monotonic loading conditions and its phase-field implementation

Saha Subhrangsu (1), Dolbow John (2), Lopez-pamies Oscar (3)

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Speaker: Saha Subhrangsu. **Wednesday**. Start time: **10:40**. Room: Roseraie 1 LVL3. Link to abstract.

In the first part of this talk, I will present a generalization of the classical Griffith energy competition for crack growth in nominally elastic brittle materials to arbitrary *non-monotonic* quasistatic loading conditions, which include monotonic and cyclic loadings as special cases. Centered around experimental observations, the idea consists in: i) viewing the critical energy release rate Gc *not* as a material constant but rather as a material function of both space $\mathbf{X}$ and time t, ii) one that decreases in value as the loading progresses, this solely within a small region around crack fronts, with the characteristic size l of such a region being material specific, and iii) with the decrease in value of Gc being dependent on the history of the elastic fields in said small region. By construction, the proposed Griffith formulation is able to describe any Paris-law behavior of the growth of large cracks in nominally elastic brittle materials for the limiting case when the loading is cyclic. For the opposite limiting case when the loading is monotonic, the formulation reduces to the classical Griffith formulation. I will illustrate additional properties of the proposed formulation via a parametric analysis and direct comparisons with representative fatigue fracture experiments on a ceramic, mortar, and PMMA. In the second part of the talk, I will present the formulation of a phase-field theory of nucleation and propagation of fracture that is consistent with the new Griffith description of crack growth.

Constitutive modelling of viscoelastic materials coupling damage and healing

Samal Priyanka (1), Mulay Shantanu S. (1)

1 - Indian Institute of Technology Madras (India)

Speaker: Samal Priyanka. **Wednesday**. Start time: **11:00**. Room: Roseraie 1 LVL3. Link to abstract.

Viscoelastic (VE) materials are widely used in many engineering applications, such as aerospace, civil, automobile and medical fields (human skin and bone behave as VE material). These materials show change in their stress response with time, often termed as ageing, due to micro-structural changes. Such changes have a considerable effect on the subsequent degradation and macro-scale failure of the material. Recently, self-healing materials have been developed that can decrease or sometimes completely remove the local damage thereby recovering the original material stiffness (intrinsic and extrinsic self-healing approaches in the absence of material ageing). A damaged VE material, when undergoes healing over a long period of time, the final material properties are influenced by the combined effect of ageing and healing, thus resulting in a stiffness not exactly equal to the virgin material. A broader VE material constitutive model is thus required to capture the combined effects of damage, healing, and ageing. However, at present a model that accurately captures all the said effects is unavailable.
An irreversible thermodynamics-based formulation is adopted in this work to obtain the constitutive response of VE material. A novel form of Helmholtz free energy is proposed (motivated by Simo's approach) accounting viscoelasticity, damage, healing, and ageing effects. Strain energy equivalence for VE material, from continuum damage mechanics (CDM), is employed to relate the current and effective configurations in the presence of damage, ageing, and healing. The stress field in the current configuration thus relates with the corresponding field in the effective configuration through the damage effect tensor. The proposed formulation is also amenable to characterise the damage evolution parameters (capturing hardening, softening, and tertiary creep) from an experimental stress history.

The healing can occur both in the presence and absence of stress. There are several works in literature to model healing in the former case. In this work, the model for the latter case is motivated by the diffusion-based mechanism of healing agent, in the presence of micro-capsules (extrinsic healing) containing the healing agent, present in a material. Coupling of stress-free healing with the proposed VE formulation is able to capture the healing process happening in the damaged VE material during rest periods. The resulting VE constitutive and evolution equations are numerically discretized into an incremental form and implemented in the *in-house* developed nonlinear finite element method (FEM) code while solving several boundary value problems (e.g., uniaxial and bi-axial tension, creep test and open hole tests). Physically realistic macro-scale diffused crack paths are thus obtained under various loading and boundary conditions.

The developed model is also applied to simulate the stress-free healing in the presence of an existing damage (localized damage). The developed model will also be extended in future to study the failures in polymer-based composite (aged and unaged).

Description of thermal shocks using micromorphic damage gradient models

Nava Soto Pedro (1) (2), Jamond Olivier (3), Fandeur Olivier (3), Siedel David (2), Helfer Thomas (1), Besson Jacques (2)

1 - CEA/ DES/ IRESNE/ DEC/ SESC/ LMCP (France), 2 - Centre des matériaux (France), 3 - CEA- Saclay (France)

Speaker: Nava Soto Pedro. **Wednesday**. Start time: **14:30**. Room: Roseraie 1 LVL3. Link to abstract.

A nuclear fuel rod in Pressurized Water Reactors (PWR) is a stack of cylindrical pellets enclosed in a metallic cladding. The fuel material is made of uranium dioxide, a brittle ceramic. During the reactor start-up, a complex network of crakcs develops in the fuel material. This crack network has important consequences on the overall thermomechanical evolution of the fuel rod during normal and off-normal operating conditions.
This contribution describe some micromorphic damage gradient models and their applications to describe the crack network generated by thermal shocks.
The micromorphic framework has several key advantages:
• Micromorphic behaviours are grounded on the rigorous thermodynamic bases of standard generalized materials allowing to express the evolution of the structure as a minimization principle.
• The irreversibility constraint is treated exactly at integration points.
• Micromorphic behaviours are versatile allowing to describe complex coupled behaviours. They are also able to approximate classical phase-field models (AT1 and AT2).
• Their numerical implementation is straightforward and efficient.
This contribution illustrates those advantages on several examples of thermal shocks from the litterature using the newly developed HPC solver Manta, developed by the French Alternative Energies and Atomic Energy Commission (CEA).
Micromorphic behaviours is then applied to the simulation of the crack network in the fuel pellet during the reactor start-up.

Discrete Element Method to predict cracks initiation and propagation in plasma-sprayed Thermal Barrier Coatings during a thermal cycle

Bensemmane Ilyes (1), Leclerc Willy (1), Ferguen Nabil (2), Guessasma Mohamed (1)

1 - Laboratoire des technologies innovantes (France), 2 - Centre de développement des technologies Avancées (Algeria)

Speaker: Leclerc Willy. **Wednesday**. Start time: **14:50**. Room: Roseraie 1 LVL3. Link to abstract.

Thermal barrier coatings (TBCs) are advanced materials used in many industrial fields (aircraft engines, gas turbines, marine propulsion, etc.) to protect metal components from high operating temperatures. TBCs are multilayer materials consisting of a ceramic Top-Coat (TC) thermal barrier layer, a metal Bond-Coat (BC) intermediate layer between a superalloy substrate and the TC, and an oxidation-resistant layer called Thermally Grown Oxide (TGO). Predicting interface delamination and failure of the TBC under thermomechanical loading is quite complex due to the severity of the thermal conditions and the complexity of their microstructure, which includes microcracks, pores and heterogeneities. In addition, the lifetime of these systems is affected by several factors, including thermal expansion mismatch, oxidation, interface roughness and creep, which play a major role in the premature failure of TBC. In the present work, we consider a plasma-sprayed TC ceramic deposited on a NiCrAlY BC. Our main objective is to numerically simulate and reproduce the fracture mechanisms occurring during a three-stage thermal cycle comprising a heating phase from 25∘C to 1100∘C, a rest phase at 1100∘C and a cooling phase from 1100∘C to 25∘C. For the numerical method, due to the heterogeneity of the TC ceramic layer and the complex cracks typically observed in TBCs, we opted for the discrete element method (DEM) which is a promising approach to simulate the mechanical and multiphysical properties of heterogeneous materials and predict their failure modes, including the propagation of complex cracks with coalescence and branching effects. First, an original visco-plastic creep model based on Norton's law is proposed. Then, the thermomechanical stresses induced by the combined effects of creep and thermal expansion coefficient mismatch are evaluated and compared with finite element method (FEM) calculations in the reference case of a TBC model with a sinusoidal profile. The effects of TGO thickness and amplitude are also investigated. Thirdly, the same study is applied to a realistic TBC model obtained by image processing and including defects such as pores, microcracks and an irregular TBC interface. Finally, the initiation and propagation of cracks occurring during thermal cycling are simulated in this context and the results are discussed in relation to experimental observations of the literature.

On a hybrid simulation using a phase-field approach for predicting the concrete behavior under fire

Kandekar Chaitanya (1), Rottmann Max (1), Palani Arulnambi (2), Breuer Michael (2), Weber Wolfgang E. (1)

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Speaker: Kandekar Chaitanya. **Wednesday**. Start time: **15:10**. Room: Roseraie 1 LVL3. Link to abstract.

Concrete exhibits a highly non-linear material behavior, especially under non-isothermal conditions like fire exposure. At elevated temperatures, the interaction between heat and mass transfer can lead to a specific mode of concrete degradation, also called thermal spalling, affecting substructural components such as walls and columns. Spalling can be explosive, resulting in a substantial reduction in the load-bearing capacity at structural scale such as buildings. Extreme temperature gradients and moisture clogs play an important role in understanding the cracking and subsequent spalling of the fire-exposed substructural concrete components. Recently, the phase-field method has been proposed to address this challenge and simulate fire-induced concrete spalling (1). This approach facilitates a straightforward numerical setting to simulate complicated phenomena at the component level, e. g., the initiation and development of cracks. Drastic reduction in the load bearing capacity of one substructural component results in a redistribution of the internal forces and coordination of deformations between all substructures. Furthermore, simulations of the structural scale necessitate damage simulations of each component and a computational framework, which can deal with scale transition during fire-structure interactions. However, simulating these multiphysics phenomena at structural scale is numerically very challenging.
The objective of this contribution is to provide a computational framework for fire-structure simulations to elucidate the interplay between local damage of the concrete due to fire and its effects on load-bearing capacity on the building scale. In this simulation framework, the temperature distributions and the evolution of the fire exposed components are taken from the simulation results of the real fire scenario using the open-source software *Fire Dynamics Simulator* (2). It is a computational fluid dynamics code relying on the large-eddy simulation technique to account for the instantaneous turbulent flow and heat transfer including combustion and radiation. Furthermore, the substructural model treats concrete components as a porous material locally exposed to the fire, whereas the structural model simulates load-bearing capacity on the building scale. Thus, in the proposed computational setup, two additional softwares are used to simulate material damage and the resulting load redistribution of an exemplary structure under fire. The substructural-scale model uses a *FEniCS*-based solver for the concrete material. Herein, the concrete damage such as cracks and subsequent spalling is computed using a unified phase-field method. The structural-scale model uses *ABAQUS* for mechanical simulations. These solvers exchange information on the damage and the resulting changes in geometry across scales through the open-source coupling library *preCICE* (3). The proposed model is illustrated by an example case that forecasts the fire-induced damage caused by the thermal spalling of the concrete substructure and its effects on the global scale.

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On the thermo-mechanical modeling of crack propagation and healing in a brittle solid

Salmon Lucas (1) (2), Lejeunes Stéphane (3), Gărăjeu Mihail (2), Adrien Socie (1), Blanc Victor (1), Helfer Thomas (1)

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Speaker: Salmon Lucas or Lejeunes Stéphane. **Wednesday**. Start time: **15:30**. Room: Roseraie 1 LVL3. Link to abstract.

In this communication we consider the case of a brittle, isotropic elastic solid exhibiting cracking and healing mechanisms when subjected to cyclic thermo-mechanical loadings. More precisely, we focus on the case of oxyde fuel materials for which the mechanical state impacts core reactivity. The healing process is related to a welding phenomenon of primary cracks that occurs under specific irradiation conditons and can be considered on the macroscopic scale as a chemo-physical process driven by the thermodynamic state. We developed a local model within the framework of the cohesive zone approach (CZM). This model incorporates the damage and healing mechanisms with the help of two scalar internal variables that are coupled and allow the cracks to propagate and heal. The healing variable can be viewed as a healing reserve and thus naturally incorporates a limited number of cracking/healing cycles. We show that the model is thermodynamically consistent and permits to account for the reciprocal impact of the cracks upon the heat diffusion. The CZM is implemented into a finite-element code and we insert cohesive elements between the edges or surfaces of each volumic element of the structure. We discuss the comparison with a phase-field approach towards crack propagation, in particular for the calibration of CZM material parameters. We consider a few numerical examples to illustrate the interest of such an approach, while showing the limitations and drawbacks inherent in this type of modeling. As a perspective we will depict an investigation of introducing a healing phenomena into a non local damage model.

Bridging variational and perturbation approaches in brittle fracture: application to shear crack in heterogeneous media

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1 - Laboratoire Navier (France), 2 - Institute for Building Materials, ETH Zurich (Switzerland), 3 - University of Freiburg (Germany)

Speaker: Egorov Serafim. **Wednesday**. Start time: **16:45**. Room: Roseraie 1 LVL3. Link to abstract.

Modeling three-dimensional crack propagation in perfectly brittle materials is challenging due to the distribution of strong stress concentrations localized in the vicinity of a propagating crack front. In the presence of heterogeneities, crack propagation has been shown to be highly intermittent and to display multi-scale behavior, spanning from the heterogeneity size up to the size of the structure (Bonamy and Bouchaud, Phys. Rep., 2011). The numerical modeling of fracture processes is usually conducted using XFEM (Moës et al., IJNME, 1999) or the phase-field method (Bourdin et al., J. Elast., 2008). Both methods effectively address a wide range of scientific problems: while XFEM helps to handle complex (viscoplastic, hydromechanical, etc.) material behavior using enriched elements around the crack front, the phase-field method provides a variational framework capable of modeling fracture processes, from crack initiation to multiple crack interactions. These methods are computationally intensive, making 3D simulations of composites with numerous heterogeneities impractical without high-performance computing.
The perturbation approach of LEFM, initiated by Rice (J. Appl. Mech., 1985), has proven to be relevant to solving this class of problems because the 3D fracture process is modeled from the meshing of the sole 1D crack front. However, these studies rely on ad-hoc viscous regularization of Griffith's criterion, which may impact the fracture process itself and the apparent fracture behavior (Barés et al., PRL, 2014). In addition, simulations are often conducted for semi-infinite cracks propagating in tensile mode I (Patinet et al., PRL, 2013). Yet, cracks are often of finite size, and they can be loaded in mixed (tensile and shear) modes I+II+III. As a result, the influence of heterogeneities, size effects, and mode mixity on three-dimensional crack is not yet fully understood.

In this work, we consider an isotropic linear elastic body with an initial circular crack embedded within a plane. To model the coplanar propagation of a *sharp* crack, we propose to bridge the variational approach of Francfort and Marigo (JMPS, 1998) and the perturbation theory of Gao (IJSS, 1988) within a unified energetic framework. In this method, equilibrium positions are computed by minimizing the sum of the potential energy of the system, which relates to the crack geometry, and the dissipated energy, determined by the (heterogeneous) fracture energy field. Unlike previous approaches based on the resolution of Griffith's criterion through asymptotic estimates of the energy release rate, our energetic method instead builds on the asymptotic estimates of the potential energy of an arbitrarily perturbed configuration. The latter is efficiently computed by meshing only the crack front and using FFT to accelerate calculations. However, the physics of the rupture process imposes three strong constraints on the minimization process: namely (i) crack irreversibility, (ii) the existence of long-range (non-local) elastic forces, and (iii) the inability of the crack to overcome fracture energy barriers larger than its instantaneous energy release rate. To address these constraints, we implemented a (i) *bounded* Newton conjugate gradient method with (ii) *matrix-free* implementation and (iii) *trust region*, using PETSc and its Python wrapper petsc4py. Further speed-up is achieved by *preconditioning* the Hessian matrix with the inverse of the Hessian of a circular penny-shaped crack, propagating in a homogeneous medium, and (ii) leveraging JAX for *automatic differentiation* and *just-in-time compilation*. The final code is benchmarked on simple problems, for which analytical solutions can be derived. It displays remarkable numerical efficiency when applied to randomly heterogeneous problems.

Using our newly developed method, we have conducted 36,000 large-scale simulations of shear crack propagation in several weeks. The largest simulation has been performed on a field with high fracture energy contrast, with a seed crack starting below the heterogeneity scale and extending over three orders of magnitude with a time stepping corresponding to the crack propagation along 1/100 of heterogeneity.

It typically requires 8 hours on a single core computer. We demonstrate how modes II+III coupling affects front deformations and apparent fracture energy, depending on heterogeneity properties and Poisson's ratio. Simulations reveal material weakening or strengthening based on disorder intensity and crack size: small heterogeneity contrasts weaken the material, while larger disorder intensities strengthen it, possibly due to front instabilities during crack propagation at higher disorder intensities and larger crack sizes.

FE-FFT multiscale model of damage in hydroelectric dams under alkali-silica reaction

Fourel Lucas (1), Molinari Jean-françois (1)

1 - EPFL (Switzerland)

Speaker: Fourel Lucas. **Wednesday**. Start time: **17:05**. Room: Roseraie 1 LVL3. Link to abstract.

Hydroelectric dams are susceptible to Alkali-Silica Reaction (ASR), a concrete degradation mechanism that leads to structural expansion and cracking. ASR spans multiple length and time scales, from chemical reactions at the atomic level to the deterioration of structures over 200 meters tall. The Swiss Committee on Dams (1) emphasizes the critical need for representative numerical models to understand and predict dam deterioration. Current multiscale numerical models of dams under ASR are limited to 2D due to the computational cost of conventional methods such as Finite Elements (FE) (2, 3). However, 3D modeling is crucial, since dams are almost systematically composed of 3D features such as arches and corners.
This study proposes a 3D multiscale approach that integrates Fast Fourier Transform (FFT)-based solvers at the mesoscopic scale with FE method at the dam scale. The mesostructure of concrete is represented by three phases including aggregates, cement paste, and expanding ASR gel pockets. A non-local damage model is employed to simulate crack initiation and propagation within periodic Representative Volume Elements (RVEs). These RVEs are loaded with macroscopic strains derived from dam-scale loading conditions, such as structural weight and hydraulic pressures. This 3D FE-FFT approach allows to derive key structural parameters, including homogenized stiffness and displacements at the dam crest. These outputs are compared with those from the existing 2D FE^2 model (3) and validated against field data from the Illsee dam in Switzerland.

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Identification of Phase-Field Fracture Models from Molecular Simulations on Silicon

Denzer Ralf (1), Hiremath Praveenkumar (1)

1 - Lund University (Sweden)

Speaker: Denzer Ralf. **Wednesday**. Start time: **17:25**. Room: Roseraie 1 LVL3. Link to abstract.

Understanding fracture behavior in silicon is crucial for the development of reliable semiconductor devices. This work aims to identify parameters for different phase-field fracture models using molecular simulations. We conducted molecular static and dynamics simulations to observe fracture processes at the atomic level, focusing on crack initiation and propagation in silicon. The simulation data is then used to calibrate the phase-field fracture model parameters, ensuring accurate representation of fracture mechanics. Our results demonstrate that the calibrated model can predict the fracture path and energy release rates for different crystal orientations. This approach bridges the gap between atomic-scale simulations and continuum-scale modeling, providing a robust framework for predicting fracture behavior in silicon-based materials.

Micromechanical simulations of coalescence in a random porous material

Cadet Clément (1), Ferhi Ouali (1)

1 - CEA DAM DIF (France)

Speaker: Cadet Clément. **Wednesday**. Start time: **17:45**. Room: Roseraie 1 LVL3. Link to abstract.

For ductile materials, the failure process is commonly divided in three stages: void nucleation, growth and coalescence. In the widely-used Gurson-Tvergaard-Needlemann (1) model for ductile materials, coalescence is represented by a phenomenological effective porosity higher than the real porosity. This effective porosity allows to account for a quicker damage increase than predicted by the sole growth model, only relevant for an isolated void. The difference between the effective and real porosity values thus represents the effect of void interactions. We focus on pressure-dominated loading (typical of shock loading), for which experimental studies on tantalum (2) have shown that coalescence takes place by a direct impingement mechanism rather than plastic localization. As for percolation phenomena, in this situation, the geometry of the void distribution plays a key role and the concept of effective porosity has a clearer physical basis.
In this study, coalescence and especially the effect of void interactions are investigated using micromechanical analyses explicitly considering multiple voids. The objective is to suggest a physically justified expression for the effective porosity (instead of the classical purely phenomenological piecewise-linear expression of the GTN model). As for previous studies on the yield surface (3) or the onset of coalescence (4) of random porous materials, finite element simulations are carried out on a representative volume element consisting of a population of randomly dispersed spherical voids in an elastoplastic matrix. Simulations are analyzed after the onset of coalescence ; by comparison with the GTN model, an expression for the effective porosity can be deduced from the stress-porosity relation. Furthermore, the comparison between multi-void simulations and single-void analytical models can also be performed for a purely elastic model. We thus also investigate the difference in effective porosity between the elastic and elastoplastic cases.

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The covariogram: the link between a heterogeneous medium microstructure and its non-local damage behavior.

El Mansouri Hicham (1), Gueguen Mikaël (1), Halm Damien (1), Azdine Nait-ali (1)

1 - Pprime Institute, (France)

Speaker: El Mansouri Hicham. **Wednesday**. Start time: **18:05**. Room: Roseraie 1 LVL3. Link to abstract.

The main interest here is to create for composite -e.g. fiber reinforced composites and porous materials- a macro-scale damage model enriched with the micro-scale mechanical behavior field at the initial state, considering for each point and its neighborhood its local microstructure. For this concern, the model must describe precisely the microstructure, including the non-local interactions between the phases due to the local distribution of the inclusions. This description fully summarizes the local morphology, which gives the micro-scale mechanical behavior field when combined with a homogenization method. By consequence, the macro-scale behavior is enriched by the mechanical behavior field, without any hypothesis at the macro-scale, enabling damage simulations on the plain microstructure.
The covariogram is utilized in the process of describing the local morphology by considering the neighborhood around each point. A key point of this process is the neighborhood scale, called meso-scale, which is the location of the non-local interactions: greater scales tend to classic homogenization methods, giving only the mean non-local interaction, and smaller scales tend to full field methods, hiding the non-local interactions at the meso-scale. The scale transition is directly linked to this meso-scale, the dimensions of which are defined by the covariogram on the entire studied medium. The main local informations are the inclusions volume fraction, and the quadratic moments of the local covariogram, reflecting the local morphology.

By incorporating this information to a homogenization method, the mechanical behavior now depends on the local features: the meso-scale is larger than the phase inclusions scale, then it is possible to use classic Eshelby homogenization schemes, by precising on each point the real local microstructure, instead of a homogenized equivalent medium. The result is the actual mechanical behavior field of the studied composite material: full field methods only give the mechanical behavior corresponding to the phase in which the point is located.

In damage simulations for composites, at the initial state, local heterogeneities -e.g. local geometry, mesh or boundary condition- are set arbitrary to initiate a crack where it is supposed to happen. The covariogram approach naturally introduces these stress heterogeneities without resort to these local heterogeneities, thanks to the micro-scale behavior field -which means that they are also quantitative.
In practice, the mechanical behavior field serves as the initial state for a FEM tensile test performed on an isoparametric square mesh. To simulate the composite damage, the 2D Hashin model which considers independent damage modes -i.e. fiber failure and matrix damage- is used here. The damage values soften the initial mechanical behavior of the composite. Results show cracks initiation, propagation and coalescence at the weak points of the studied medium, in a smeared way, enlightening the role of the non-local interactions.

The role of the organic matrix for the compressive strength of nacre

Vigliotti Andrea (1)

1 - Centro Italiano Ricerche Aerospaziali (Italy)

Speaker: Vigliotti Andrea. **Wednesday**. Start time: **18:25**. Room: Roseraie 1 LVL3. Link to abstract.

Nacre, a natural composite with a brick-and-mortar microstructure of aragonite platelets embedded in an organic matrix, exhibits an intriguing mechanical response. Notably, its high compressive strength contrasts sharply with its relatively lower tensile resistance, an observation often attributed to asperities between the platelets and calcitic bridges ensuring a direct mechanical connection. Numerous studies have investigated nacre's morphology and mechanical properties, both at the macroscopic and microscopic levels, providing detailed analytical and numerical analyses. However, the mechanical origin of its properties remains somewhat elusive. This study proposes an alternative explanation focused solely on the hyperelastic nature of the organic matrix.

We incorporate a phase-field damage model for both the matrix and the platelets within a multiscale framework. This approach allows us to apply boundary conditions in terms of components of a remote macroscopic deformation field, effectively analyzing a single representative volume element (RVE) of nacre to reproduce experimental uniaxial test results. By focusing on a limited-sized RVE, we are able to understand the origin and development of damage within the material. Our findings demonstrate that the hyperelastic behavior of the organic matrix is sufficient to explain the observed disparity between compressive and tensile strengths. The model predicts the material's strength accurately, both qualitatively and quantitatively, aligning well with existing experimental data.

This three-dimensional micromechanical model offers a new perspective on the mechanical properties of nacre, emphasizing the significant role of the hyperelastic matrix. It provides an alternative to the conventional explanation based on platelet asperities and bridges, deepening our understanding of the underlying mechanisms that contribute to the material's remarkable mechanical behavior.

Hyperbolic formulation of gradient damage models and finite volume simulations of dynamic brittle fracture

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Speaker: Renaud Adrien. **Thursday**. Start time: **10:00**. Room: Roseraie 1 LVL3. Link to abstract.

In the context of "phase-field" approaches for brittle fracture based on a scalar damage internal variable, the well-posedness of mathematical formulations is in general ensured by means of geometrical or constitutive regularizations. The techniques of the former family such as the Thick Level Set or the Lip-field consist in constrain the damage variable geometrically while those of the latter are based on the introduction of the damage gradient in the internal energy. In both cases, however, the problem associated with damage evolution is governed by an elliptic partial differential equation whose numerical solution requires the solution of a global optimization problem. For dynamics applications (impact fragmentation, high-speed forming processes, etc.), the derived formulation prevents from using Godunov-type finite volume methods, which apply to hyperbolic PDEs and allow embedding some amount of the analytical solution within the numerical solution scheme in order to accurately track waves. Moreover, the global optimization problem of damage evolution may lead to prohibitive computational cost in any explicit scheme since it must be solved at each time step.

In this work, both previous points are addressed and a fully local hyperbolic formulation of gradient damage, well-suited to efficient explicit finite volumes computations, is proposed. The derivation of the governing equations under small strains is based on Hamilton's variational principle in which the solid internal energy is taken as a function of strains, the damage variable and the gradient of an additional non-dissipative damage variable. The latter, which can be seen as a micromorphic variable, is on the other hand involved in a 'microinertia term' associated with microvoids - following Frémond's model proposed in the 90s - that contributes to the kinetic energy of the solid. Therefore, non-local effects are carried by an auxiliary damage variable in a two-field formulation which makes a first significant difference with the already existing approaches to model dynamic brittle failure.

Hamilton's variational principle yields a set of conservative partial differential equations that does not account for irreversible effects. This system of first-order PDEs is hyperbolic providing that the second-order acoustic tensor has positive eigenvalues - the so-called strong ellipticity condition -, which is not automatically satisfied in presence of unilateral damage with total recovery of the elastic modulii due to microcracks closure.
However, the use of a deviatoric/hydrostatic additive decomposition of the fourth-order elasticity tensor in which a distinction between tension and compression stiffnesses is only made on the hydrostatic part allows ensuring hyperbolicity of the model. Finally, assuming the existence of a convex dual dissipation pseudo-potential, a rate-dependent damage evolution law is then derived as a Perzyna-like model and introduced as a source term in the governing system. The "default" formulation is non-dissipative, though irreversible, but the ratio between dissipation and storage of energy can be controled depending on the forms chosen for the internal energy and the yield function.

The explicit numerical solution of the derived hyperbolic system with source term can be made using a fractional-step method composed of the following steps in a staggered fashion:
1/ Solve the homogeneous part by means of a Godunov-type finite volume scheme. This part can actually be split into two uncoupled problems related to a purely elastic part on the one hand, and the transport of the microdamage on the other hand.
2/ Solve an ordinary differential equation system associated with the source term and for which initial conditions result of the homogenous problem. It is worth noticing that in order to avoid any influence on the CFL condition, a backward Euler discretization coupled with a Newton–Raphson method may be preferred.
Such a procedure can be seen as a predictor–corrector approach in which damage flow can only occur in the ODE.

Several numerical results show very promising features of the formulation.
First, good convergence properties are exhibited on a one-dimensional multifragmentation test. Namely, the number of fragments with respect to the strain rate imposed to a one-dimensional domain for a given mesh as well as the number of fragments with respect to the number of elements for a given imposed strain rate. In addition, the complexity of the numerical scheme used is of the order of the square of the elements length, which cannot be achieved with the other existing nonlocal formulation of damage.
Second, consistent crack paths are observed for the two-dimensional Kalthoff–Winkler test.
At last, the model allows capturing crack branching in perfectly symmetrical two-dimensional settings.

A length-scale insensitive cohesive phase-field interface model: application to concurrent bulk and interface fracture simulation in Lithium-ion battery materials

Chen Wanxin (1), Xu Bai-xiang (1)

1 - Technische Universität Darmstadt - Technical University of Darmstadt (Germany)

Speaker: Chen Wanxin. **Thursday**. Start time: **10:20**. Room: Roseraie 1 LVL3. Link to abstract.

A new cohesive phase-field (CPF) interface fracture model is proposed in this paper. It employs an exponential function for the interpolation of fracture energy between the bulk phase and the interface, and its effective interface fracture energy is solved based on the Euler-Lagrange equation of the phase-field theory and the consistency to the cohesive zone model (CZM) in the sharp interface concept. Comparison to other interface models in the literature clearly shows that the above energy consistency is essential to ensure the insensitivity of the results to the length-scale parameters for regularization of the crack surface and of the interface. The proposed interface model can be conveniently implemented via the relaxation solution of an Allen-Cahn equation, which offers high flexibility in handling structures of complicated interface topology. The proposed CPF interface model is employed further to derive a thermodynamically consistent chemo-mechanical model relevant to Lithium-ion battery materials. Finite-element simulations confirm the model's ability to recapture the competition between bulk and interface fractures, while also demonstrate its merits of length-scale insensitivity and consistency with CZM results. The model is eventually applied in polycrystalline electrode particles, which are reconstructed from images with segmented interfaces, confirming the expected computational advantages and the length-scale insensitivity in multi-physical context.

A multi-field decomposed model order reduction approach for thermo-mechanically coupled gradient-extended damage simulations

Zhang Qinghua (1), Brepols Tim Reese Stefanie

1 - Institute of Applied Mechanics [Aachen] (Germany)

Speaker: Zhang Qinghua. **Thursday**. Start time: **10:40**. Room: Roseraie 1 LVL3. Link to abstract.

The analysis and prediction of damage onset and propagation within ductile materials under thermo-mechanical scenarios play an essential role in both research and industry. Many models in the literature concentrate solely on fracture and damage mechanisms while neglecting the influence of temperature. Therefore, simulations based on such models are often suitable only for some special cases that deviate far from true manufacturing conditions. On the other hand, multiphysics damage modeling considering temperature-dependent plastic flow is not only a challenging task, but also usually leads to computationally expensive simulations. This is mainly due to an increased number of degrees of freedom (in the case of nonlocal damage) and the coupling between the damage, plasticity, and temperature. Consequently, incorporating efficient model order reduction techniques into multiphysics models is an interesting and promising field of research, particularly for industries focusing on real-time simulations.

The first objective of this work is to develop a multi-field decomposed model order reduction approach (1) and combine it with the gradient-extended damage-plasticity formulation for finite strains by Brepols et al. (2) and to study its effect on reducing computational costs. In the second step, the multi-field decomposed model order reduction approach is integrated into the thermo-mechanically extended version of the aforementioned model (see Felder et al. (3)) to enable fast multiphysics damage-plasticity simulations. Finally, the new approach is investigated in several numerical benchmark tests to evaluate its advantages and disadvantages.

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A tri-dimensional model for the numerical treatment of ductile fracture in dynamics using the Extended Finite Element Method

Scheidt Louis (1) (2), Crété Jean-philippe (2), Longère Patrice (1)

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Speaker: Scheidt Louis. **Thursday**. Start time: **11:00**. Room: Roseraie 1 LVL3. Link to abstract.

Summary
The purpose of this work is to extend the tri-dimensional unified methodology used to reproduce the different phases of ductile fracture proposed by (1) in order to solve transient dynamic problems while treating the effects linked to large deformation. A particular attention will be paid to the mass matrix definition in the context of the extended finite element method (XFEM) as well as the way high strain rates effects are taken into account in the material constitutive behavior. Exemples of simulations using both implicit and explicit integration schemes are presented.

Introduction
It is generally accepted that the ductile fracture process that is initiated within a material more or less lately after the plastic flow start can be divided into 3 phases : (i) diffuse damage by nucleation and growth of voids, (ii) strain localization in a narrow band and (iii) initiation and propagation of a macro-crack. The strain localization process is tentatively put aside in this work, a direct transition between diffuse damage and crack propagation is indeed considered. Such a scenario of the ductile fracture process is similar to the one proposed by (2). The material is supposed to obey to the micro-porous plasticity model proposed by Gurson and modified by Tvergaard and Needleman (3) and its hardening is represented by a Voce type law. The extended finite element method (XFEM) is used for the numerical treatment of the crack. A lumped mass matrix is generally used to solve dynamic problems, allowing to minimize the computation time by, notably, increasing the stable time increment (4). A lumping scheme of the mass matrix in the context of the shifted basis of the XFEM (5) is presented with the aim of ensuring the kinetic energy conservation (6).

Validation of the model
The proposed model was implemented via a user element in the commercial finite element computation software Abaqus (UEL or VUEL depending on the integration scheme) and used to carry dynamic tests on CT specimens using both time integration schemes. The results are then compared in term of crack profiles, porosity fields, stiffness evolution and energy balance.

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Dynamic fragmentation using phase-field modelling of fracture

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Speaker: Durussel Shad. **Thursday**. Start time: **11:20**. Room: Roseraie 1 LVL3. Link to abstract.

Dynamic fragmentation is a process during which a material or structure subjected to intense loads fails catastrophically through the initiation, propagation and coalescence of a multitude of cracks. It is a key topic in many fields of engineering, as for instance in aerospace industry, where the outcome of destructive re-entry is of great concern. Robust numerical models are direly needed to develop a fundamental understanding of such events, in particular to be able to predict the statistical distributions of fragment sizes, shapes and velocities resulting from destructive events.

A well established way to address this problem is to use finite elements solid mechanics models coupled with cohesive elements (1). Cohesive cracks give an explicit representation of crack surfaces and simplify the treatment of contacts between fragments, a crucial factor to predict debris velocities. However, the cohesive approach is known to suffer from mesh dependency, with crack paths that depend on the underlying mesh, resulting in non-robust predictions of fragments shapes.

Phase-field modelling of fracture belongs to another family of methods using diffuse crack approaches and, as opposed to cohesive models, where the fracture paths are not dependent on the underlying mesh. Phase-field has been shown to lead to promising results in many problems, not only in quasi-static but also in dynamics where different mechanisms such as branching can be observed (2).

Moreover, the multiplicity of possible crack patterns obtained with phase-field for a single loading case in quasi-static has been discussed in (3) where different simulation outcomes can be associated with probabilities. This study is yet to be extended to dynamic cases, where the evolution of statistics on fracture paths with the loading rate can be explored. This stochastic approach is of great interest in the context of dynamic fragmentation to enrich statistical data of fragment sizes and shapes in light of material heterogeneity.

In addition to the conventional stiffness degradation associated with damage, certain models also account for a reduction in mass density in damaged zones, as proposed in (4). It is particularly pertinent to examine the influence of this mass loss on key fracture characteristics, including crack tip velocity, damage band width, and the branching mechanism, as well as its broader impact on fragmentation outcomes predicted by phase-field simulations.

The phase-field approach to fracture will be evaluated in the context of dynamic fragmentation, with numerical results compared against available analytical models and the predictions of cohesive crack models. Furthermore, the influence of mass loss will be investigated, and the sensitivity of debris distributions to minor variations in material parameters or model geometry will be analysed.

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A coarse-grained molecular dynamics study of damage localization during the fracture of double polymer networks

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Speaker: Ortellado Laureano. **Thursday**. Start time: **14:15**. Room: Roseraie 1 LVL3. Link to abstract.

Double network (DN) materials, made by consecutively polymerizing two interpenetrated networks (a first sacrificial network and a second matrix network), have attracted an increasing interest due to their remarkable properties, combining high stiffness, large reversible deformation and high fracture toughness (1-3). Although an important effort has been put into engineering tough hydrogels and elastomers by tuning the network architecture (2), a detailed understanding of the molecular mechanisms explaining the large increase in fracture energy of double networks is still lacking.
In this work, we investigate, using coarse-grained molecular dynamics simulations, the molecular-scale mechanisms at the origin of the increase toughness of DNs, focusing mainly on the interplay between load sharing between the interpenetrated networks and the localization of damage.

By performing large strain uniaxial deformation simulations of single networks (SNs) and DNs, we first show that damage propagation in DNs occurs as a two-stages process, with a first regime mainly governed by the properties of the sacrificial network and a second regime governed by inter-network interactions (4). While a growing damaged region quickly leads to macroscopic fracture in SNs, several damaged regions can be stabilized by the presence of the matrix in DNs and macroscopic fracture is delayed to larger strain values.

We rationalize these findings by investigating the response to single bond breaking events in these different regimes, showing that, even at small strain, a more anisotropic stress response can favor damage localization in SNs (compared to DNs) by loading neighouring strands. At larger strain, we further evidence load sharing and dissipation in the matrix network upon bond breaking in the sacrificial network, thus proposing a mechanism for the increased fracture energy of DNs.

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Computational modelling of biodegradable bone implants

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Speaker: Zoboli Lorenzo. **Thursday**. Start time: **14:35**. Room: Roseraie 1 LVL3. Link to abstract.

Bio-resorbable bone implants represent a recent advancement proposed for orthopedic surgery, as they have the capability of gradually dissolving while feeding the bone with nutrients which sustain its growth and remodeling. If properly designed, the degradation time of an implant can be tailored to match the parallel healing process of the bone, thus ideally eliminating the need for secondary removal surgery. Magnesium alloys have emerged as most promising constituent materials for orthopedic screws, given their proven balance between mechanical resistance and the effectiveness in providing essential nutrients to the surrounding tissue.

Modeling the simultaneous processes of implant degradation and bone healing is not a trivial task from a computational standpoint, not only since the boundary between the two changes over time but also because the grow-back feedback mechanism of the nurtured bone must be accounted for. To tackle these aspects, in the present work advanced techniques such as phase – field formulations and peridynamics have been employed, given their intrinsic proficiency in capturing evolving boundaries and non – local effects. These modeling approaches can also be linked to classical Finite Element formulations for the evaluation of the mechanical performance of the screw over time. The implemented modeling strategy aims at capturing the biological feedback mechanisms and mechanical environment, providing a comprehensive view of the implant's performance over time.

Preliminary results demonstrate the potential of Magnesium implants to support bone regeneration while maintaining structural integrity during degradation. These findings pave the way for further optimization and clinical application, highlighting the transformative potential of this technology in enhancing patient outcomes.

On the finite strain phase field fracture of nearly incompressible hyperelastic material

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Speaker: George Deepak. **Thursday**. Start time: **14:55**. Room: Roseraie 1 LVL3. Link to abstract.

Rubber-like materials have become integral to the modern society due to their unique properties, such as stretchability, fracture resistance, low cost, ease of manufacture etc. However, predicting the behaviour of such materials especially in fracture becomes inevitable in deciding its suitability for various engineering applications. Thus, some notable studies (1, 2) have already explored the fracture modelling of hyperelastic materials using phase field models. However, the incompressibility of such materials makes the fracture modelling challenging due to the inability of the damaged elements to undergo volume changes. Moreover, the use of the staggered scheme to solve the coupled problem, makes the solution process expensive. The study presented here overcomes both the difficulties while using a mixed displacement-pressure-damage formulation (3) along with a quasi-Newton monolithic solver based on the Broyden–Fletcher–Goldfarb–Shanno (BFGS) technique. The phase field formulation involves the AT2 scheme and the Neo-Hookean hyperelastic constitutive law which decouples the volumetric and isochoric deformation for nearly incompressibility is used here. The algorithm is implemented using a user-defined element subroutine (UEL) in the commercial finite element software ABAQUS. The robustness of the scheme illustrated with the help of three numerical examples, where the results are compared to experiments. Further, the cumulative iteration and computing time of the BFGS solver is compared to that of the staggered solver. The results illustrate a significant reduction in the computing time while requiring a smaller number of iterations to solve the coupled problem. Thus, for the first time we establish the suitability of the BFGS scheme to solve the phase field damage problem of nearly incompressible hyperelastic materials at finite strain.

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MS5.5 - Mechanical challenges in Energy Production/Harvesting/Storage

Organisers: Alberto Salvadori (University of Pavia) and Alejandro Franco (Université de Picardie Jules Verne)

Modeling the phase transformations in tin-based anodes for sodium-ion batteries

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Speaker: Bastanfar Marzieh. **Monday**. Start time: **13:40**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Keywords: Sodium-ion batteries, Phase transformation, Cahn-Hilliard theory.

Sodium-ion batteries (NaBs) have risen as a viable alternative to lithium-ion batteries, driven by the widespread availability of sodium and their potential for sustainable, high-capacity energy storage. This work primarily concerns conversion type tin-based anodes for NaBs, which hold considerable potential. Tin forms binary alloys with sodium, thereby generating compounds with enhanced capacity. In contrast to carbon anodes, tin's alloying interaction with sodium induces phase transformations that can favor electrode degradation (1,2), mostly due to the expansion and subsequent fragmentation of electrode materials.

We aim at formulating a model that captures the mechanical and chemical properties of these phase transformations. To this end, we adopt a dual approach that combines visco-plasticity to account for mechanical stresses and strains, and the Cahn-Hilliard equation (3) to manage the chemical diffusion dynamics. The complexity of the coupled and uncoupled versions of the fourth-order Cahn-Hilliard equation necessitates the use of a split-method approach and a penalty term to simplify it into manageable second-order PDEs (4,5).

Numerically approximated phase diagrams and segregation metrics effectively demonstrate the dynamics of phase segregation over time, highlighting the model's alignment with experimental validations and its relevance to understanding the mechanisms of material behavior in sodium-ion batteries.

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Void evolution in the lithium anode of a solid state battery

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Speaker: Roach Ashley. **Monday**. Start time: **14:00**. Room: Bureau Forum 2 LVL-2. Link to abstract.

The growth and collapse of voids within the Li anode of a solid state battery has direct relevance to two commonly observed failure modes: dendrite/filament formation within the ceramic electrolyte and a large increase in Li flux resistance at the Li/electrolyte interface. Thus, there is a need to explore experimentally the collapse of voids within the Li anode of a solid state battery due to the application of a pressure and a superimposed electrical current that drives a Li flux from the Li anode into the underlying ceramic electrolyte. Circular cylindrical specimens of Li were sandwiched between a top layer of copper sheet and a bottom layer of LLZO ceramic. Additionally, a circular cylindrical void was generated within the Li layer but adjacent to the LLZO interface; this was achieved by withdrawing a niobium wire of diameter 0.2 mm from the Li during its manufacture. The collapse of this void was tracked visually under a prescribed pressure on the faces of the sandwich specimen. The sensitivity of void collapse to applied pressure was determined by varying the radius to height of the Li pancake-layer and by varying the applied load. The evolution of specimen height with time is consistent with power law creep of the Li, and the rate of closure of the voids also supports the mechanism of power law creep. An additional set of experiments was performed whereby the Li was forced to migrate into the LLZO substrate by the imposition of a constant electrical current. It was found that the void shrinks at a rate consistent with rigid body motion of the Li layer into the LLZO, with negligible flux focussing in the vicinity of the void. The study has direct relevance to the effect of a stack pressure upon void evolution in a solid state Li battery.

A Fracture Mechanics-Based Model of Lithium Dendrite Growth in Partially Filled Cracks of Solid Electrolytes

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Speaker: Esmizadeh Sahar. **Monday**. Start time: **14:20**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Solid-state batteries represent a transformative advancement in energy storage, offering enhanced safety and higher energy density compared to traditional liquid-electrolyte Li-ion batteries. These benefits arise from the solid electrolyte's ability to suppress flammability, enable the use of lithium-metal anodes, and increase battery cell energy density. However, lithium dendrite penetration remains a significant challenge in solid electrolytes, often causing short circuits and battery failure. Internal defects, such as cracks and grain boundaries, are known to trigger lithium dendrite formation in solid electrolytes. Understanding the interplay between lithium transport and internal defects is therefore critical to suppress dendrite formation and prolong battery life.

While significant progress has been made in understanding dendrite propagation within filled cracks, recent studies reveal that dendrites can initiate and drive crack propagation even before the crack is completely filled. Here, we develop a computational model coupling solid electrolyte deformation, stress-driven lithium diffusion along the dendrite-electrolyte interface, and stress-dependent Butler-Volmer kinetics of Li deposition into the crack. Using this model, we examine how interfacial diffusivity, interfacial resistance, and applied current density influence dendrite-driven crack growth. Our results show that dendrite thickening, rather than lengthening, promotes early fracture, particularly under conditions of low interfacial diffusivity and high current density.

These findings provide valuable insights into the mechanical and electrochemical interactions within solid-state batteries, offering critical guidance for designing more robust solid electrolytes and creating safer, longer-lasting energy storage systems.

Micromechanics of lithium dendrite growth in solid electrolytes

Leronni Alessandro (1)

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Speaker: Leronni Alessandro. **Monday**. Start time: **14:40**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Lithium-ion batteries with solid electrolytes are transforming electric vehicles by enabling faster charging, extended driving range, and enhanced safety compared to conventional batteries with liquid electrolytes. However, solid electrolytes are prone to cracking near the anode during operation. Lithium deposition into these cracks during charging can lead to dendritic structures that propagate across the electrolyte, potentially causing short circuit.
Despite extensive efforts to understand and mitigate lithium dendrite growth in solid electrolytes, the influence of size effects, that is, the increased strength of lithium at dendritic length scales, has been completely overlooked. Recent experiments on compressed lithium layers between ceramic substrates have quantified these size effects, which can now be incorporated into multiphysics models of dendrite growth.

This study develops a comprehensive model that integrates the transport of lithium ions within the solid electrolyte, the deposition of ions into cracks, the viscoplastic flow of lithium within the cracks, the pressure exerted on crack walls, and the fracture mechanics of the electrolyte. Size effects are included by accounting for strain rate gradients in the energetics of lithium.
A parametric analysis is conducted to determine how the ratio of dendrite thickness to viscoplastic length scale influences crack propagation rates and dendrite growth dynamics. These findings provide a basis for future operando experiments, where advanced imaging techniques can monitor the evolving morphology and crystallography of dendrites in real time.

Modeling the effect of electrode geometry, and interface properties in solid-state batteries

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Speaker: Bucci Giovanna. **Monday**. Start time: **15:00**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Electrodes with three-dimensional (3D) architectures offer significant advantages in overcoming capacity and rate performance trade-offs in batteries. These designs can enable higher active material loading while maintaining fixed transport pathways and improving material utilization. Architected electrodes may also help manage the chemical expansion that battery materials experience during charge and discharge cycles. Our models and experiments demonstrate that the benefits of 3D electrode shapes become more pronounced under extreme conditions, such as low temperature operation and high charge/discharge rates. In this talk, we first focus on the influence of electrode shape on the chemo-mechanical response of battery materials, particularly in all-solid-state batteries. We analyze the stresses generated by intercalation-driven volume expansion and show that, while shaped electrodes significantly reduce ion-transport resistance, they also give rise to unfavorable stress concentrations. Overall, we find that fully interdigitated electrode designs strike the best balance between minimizing resistance and managing mechanical stress. In the second part of the talk, we explore the impact of interface patterning on the cycling stability of lithium-metal anodes. To systematically investigate failure mechanisms in solid-state batteries, we introduce a controlled population of defects, in the form of islands or nuclei. In cell fabrication/operation, nonuniformities in current density and mechanical stress can be caused by material defects, limited wetting or contact, void-formation during Li-stripping, and Li-nucleation in anode-free configurations. By introducing defined defects at smaller length scales (≤ 1 μm), we develop model systems to study electro-chemo-mechanical coupling at various stages of metal electrodeposition.

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Phase-field fracture predictions for composite solid-state battery cathode microstructures

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Speaker: Boyce Adam. **Monday**. Start time: **15:20**. Room: Bureau Forum 2 LVL-2. Link to abstract.

The solid-state lithium-ion battery (SSB) is an emerging technology with the potential to provide significant improvements in energy storage capacity relative to the ubiquitous liquid-based (LIB) equivalent. Mass adoption of SSB technology will have enormous benefit on myriad industries, i.e. automotive and aerospace, and is critical to mitigate climate change via reduction of CO2 emissions (1). SSBs normally comprise a multi-material composite cathode, a high-capacity lithium-metal anode, and a ceramic electrolyte separator. The limiting lithium-dendrite problem at the anode has received significant attention and remains a key challenge. Comparatively, the composite cathode has received limited focus despite its equally restrictive issues, specifically the understanding and mitigation of fracture-based degradation mechanisms during cycling – this is the focus of the present study.
An SSB cathode is a heterogeneous structure with transition metal oxide ceramic active particles, ionically conductive oxide or sulphide ceramic electrolyte and a polymer binder containing carbon particulate for electrical conductivity. Poor interfacial contact and active particle volume changes during charge transfer reactions lead to interfacial fracture of the active material-electrolyte interface. This reduces battery power, capacity, and ultimately leads to complete failure.

Predictions of microstructural fracture in a solid-state battery (SSB) or lithium-ion battery (LIB) using the phase field approach are usually made for a single active particle (2) or within a group of particles across an electrode subvolume (3). The present study takes a significant step forward by capturing degradation in the multi-material composite structure of an image-based SSB electrode microstructure obtained through a combination of focused ion beam and scanning electron microscopy. This study simultaneously predicts the fracture of active particles, the solid-electrolyte, and the particle-electrolyte interface using a coupled chemo-mechanical model of a realistic composite electrode structure. This framework offers a deep mechanistic understanding of heterogeneous SSB microstructural degradation. Furthermore it serves as a valuable tool for SSB electrode design to mitigate fracture-induced degradation through careful selection of particle, electrolyte and conductive additive distributions.

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Exploring Deformation-Driven Short-Circuit Mechanisms in Li-Ion Pouch Cells Using In-Situ Synchrotron Laminography

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Speaker: Tancogne-Dejean Thomas. **Monday**. Start time: **16:00**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Lithium-ion cells are complex mechanical systems with poorly understood failure mechanisms under mechanical loading. Independent of their application (e.g. portable electronics or automotive), all cells are made of the same repetitive layers of anode, cathode and separator. Both electrodes are made of metallic foils coated on both sides with a granular media. A liquid electrolyte ensures ion transfer through a porous polymeric separator. From postmortem investigations it is known that under out-of-plane indentation, localization bands are formed below the indenter. Failure of the separator leads to a short circuit and thermal runaway. At the same time, ductile failure of the individual current collectors is also reported. In this study, we investigate and quantify the failure mechanisms in commercial small-format pouch cells (4Ah capacity with NMC/graphite chemistry) using in-situ synchrotron laminography. A newly-developed dedicated loading frame enables performing macroscopic hemispherical indentations. Two in-situ indentations are performed, one with high-quality and one with high field of view. Both comprises more than ten loading steps. In both cases, the voxel size is 3.25μm. The failure in each component is then assessed and quantified through phase segmentation. This insight will help develop numerical model of lithium-ion cell and further enable the design of safe battery system.

Intergranular cracking of polycrystalline particles during electrochemical cycling of Lithium-ion batteries

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Speaker: Pinot Clémence. **Monday**. Start time: **16:20**. Room: Bureau Forum 2 LVL-2. Link to abstract.

With the electrification of vehicles and the widespread use of portable digital devices, lithium-ion batteries are experiencing significant growth. Since lithium and cobalt mineral resources are limited and under pressure, it is essential to maximize the lifespan of these devices. For these batteries, the migration of lithium ions from the negative electrode to the positive electrode enables the flow of electrons in the circuit. Therefore, electrode materials have been selected based on their ability to store and release Li+ ions under the influence of an external voltage. The positive electrode studied here is manufactured from micron-sized polycrystalline particles of lithium, nickel, manganese, and cobalt oxide (NMC). These crystals have a layered structure in which lithium atoms can intercalate. While this layered structure is advantageous for storing atoms, it results in anisotropic volume changes during the charging and discharging cycles of the battery. This phenomenon is believed to be the cause of cracking in the positive electrode polycrystalline particles. Indeed, the cracks appear to localize at the grain boundaries as a consequence of the strain mismatch between the grains of differing crystal orientations (Mao et al., 2024). This intergranular fracture is considered one of the key factors behind battery aging and the reduction of capacity over charge/discharge cycles, particularly at high charge rates (Xia et al., 2018).
To understand this phenomenon, it is necessary to establish a link between the microstructure and the damage mechanisms in these particles through multiphysics numerical simulations. There are several examples from the literature which use a model coupling mechanics, diffusion, and damage to simulate this phenomenon at the microstructure scale, using a finite element model (Allen et al., 2021)(Singh et al. 2022) or discrete element method (Sun et al., 2022). In (Allen et al., 2021) and (Sun et al., 2022), synthetic microstructures are used which might influence the simulated results compared to the real microstructures. In (Allen et al., 2021), a synthetic microstructure is generated based on statistics from experimental data for the grain morphology and particle shape, but an assumption is made that the grains are randomly oriented. However, according to (Quinn et al., 2020), there seems to be a texture of the grain orientation which is probably relative to the particle center. Moreover, this texture is expected to influence the performance and fracture of the particle and should therefore be integrated in the simulation. In addition, in the previously cited models the material properties data used, like the elasticity coefficients, are taken from density functional theory (DFT) simulations without being compared to experimental measurements.

In this work, a finite element model coupling mechanics, diffusion, and damage is developed. A linear elasticity assumption is made, similarly to the existing models of the literature. For damage, a phase-field model is used. The originality of this work, compared to existing literature, lies in feeding and validating this model through detailed characterizations of the microstructure, and mechanical property measurements. Initially, the model uses as an input a mesh generated from an electron backscatter diffraction (EBSD) map of a particle and elasticity coefficient data obtained from Resonant Ultrasound Spectroscopy (RUS) measurement on a single crystal. Ultimately, the developed model is applied for the simulation of optimized microstructures to mitigate this degradation phenomenon.

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Effect of Stresses with Different Triaxiality Ratios on the Electrochemical Response of Silicon Electrodes

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Speaker: Le Anh Tuan. **Monday**. Start time: **16:40**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Silicon as a material for the negative electrode of lithium-ion batteries has ten times the capacity of the traditionally used graphite. Lithiation (resp. delithiation) refers to the mechanism of inserting of lithium into (resp. extracting from) silicon, two processes inherent to the functioning of a battery. With a volume expansion of 300% when fully lithiated, the integration of silicon into commercial batteries is still a challenge. During lithiation and delithiation, silicon experiences large stresses that in turn affect its electrode potential and as a result the voltage of the battery. This study investigates the effect of stresses of different triaxiality ratios on the electrochemical response of silicon electrodes using experimental and modeling approaches. A 50-nm thick amorphous silicon (a-Si) layer is deposited on a stainless steel substrate as the positive electrode, with lithium metal as the counter electrode. The stainless steel substrate is subjected to *operando* uniaxial and equibiaxial tensile loading, while the silicon thin film is subjected to galvanostatic lithiation and delithiation cycles. Since this study focuses on low-strain conditions and the a-Si exhibits strong adhesion to the stainless-steel substrate, the strain in the a-Si thin film is equal to that of the stainless steel during tensile loading. From the experimental results of the coupled lithiation-tensile tests, the electrical potential undergoes changes of the order of 2 mV when subjected to uniaxial strain of ϵ_xx = 2.2× 10^(-3) and changes of _~ 4 mV for equibiaxial strain of ϵ_xx=ϵ_yy=1.5× 10^(-3).
These experimental results of stress-induced changes in electrode potential are rationalized using a chemo-mechanical model that describes the interplay between species diffusion and mechanics. The model is based on irreversible continuum thermodynamics, the Larché-Cahn theory (1), and in particular its extensions to inelastic materials (2), describing the lithium-silicon alloy as a viscoplastic material. We also show how our coupled experiments allow an indirect quantification of the mechanical properties of the lithium-silicon alloy, which are otherwise difficult to measure. On the one hand, the stress-induced changes in electrical potential measured during tensile tests allow us to determine the Young's modulus and the viscoplastic properties of the lithium-silicon alloy. On the other hand, similar measurements under different states of biaxial stress conditions allow us to determine its Poisson ratio as a function of lithium content, a parameter that has not been previously accessible to measurement.

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A variational continuum model for the 'adsorption-intercalation-pore filling'-type Na storage in hard carbon anode particles of sodium ion batteries

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Speaker: Mukherjee Dipayan. **Monday**. Start time: **17:00**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Sodium-ion batteries (SIBs) are currently under intense research focus for their possible application in developing commercial batteries to address the worldwide green energy challenge. SIBs, as opposed to lithium-ion batteries (LIBs), use amorphous hard carbon (HC) particles as the anode material for storing Na ions during charging. The narrower interlayer spacing in graphite-based LIB anode particles leaves it unable to intercalate Na ions due to a greater ionic radius of Na+. Nonetheless, the HC particles having randomly oriented graphite layers and nanopores are observed to be a good material holding Na ions during the charging of SIBs. However, several experiments reveal that the Na storage in HC particles occurs via the 'adsorption-intercalation-pore filling' mechanism (1,2). The nanopore filling with Na metal during charging leads to a low voltage plateau (_~ 0.1 V) in the voltage-capacity response of SIB anodes. Such low voltage plateaus are unique to the HC-based SIB anodes and are not observed in the conventional graphite particle-based LIB anodes.
We propose a coupled chemo-mechanical variational continuum theory that models the pore filling by Na metal in HC nanoparticles during the charging of SIBs. In the proposed model, the HC anode particles are idealized to be a combination of spherical HC nanoparticles, each having a central void. Each of these nanoparticles is assumed to be sodiating/desodiating uniformly at a given rate. Besides providing the bulk governing equations for the intercalated Na concentration and mechanical displacement fields in the HC particle, the variational principle also yields the expression for Na metal influx into the nanopore. This influx depends on the difference between the chemical potentials of Na in the HC bulk and the nanopore and the adsorption energy of Na atoms on the HC surface. Moreover, the expression of Na influx dictates that the pore pressure developed after its complete filling reduces the Na influx, exhausting the capacity to store more Na in the HC particles.

Excellent agreement between the measured and computed specific capacity versus voltage response of HC anodes is obtained for different pore volume fractions. Moreover, the low voltage plateau capacity of HC particles is found to be directly proportional to the pore volume fraction of the HC nanoparticles. A quantitative agreement between the model-predicted porosity-capacity variation and measured ones (2) is obtained. The adsorption energy of Na atoms on the HC closed pore surfaces plays a pivotal role in controlling the pore-filling phenomena during sodiation. A higher number of defect atoms in HC increases the adsorption energy of Na. Consequently, the Na metal influx into the nanopores becomes less viable, leading to an 'adsorption-intercalation'-type sodiation mechanism. The model predicted regimes of pore filling and no pore filling match comprehensively with the experimental observations.

Stress developed in the HC anodes bounded with polymer-based (PVDF) binders is computed next by considering a representative volume element (RVE) containing one HC nanoparticle surrounded by the PVDF matrix. Numerically computed variation of compressive nominal anode stress with the specific capacity matches comprehensively with that reported recently in the literature (3). Per the experiments, the model also predicts a plateau in the anode stress during the pore-filling regime.

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Structural analysis of solid-state transformers using the inductive power transfer technology through a multiphysics computational framework

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Speaker: Rogkas Nikolaos. **Monday**. Start time: **17:20**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Solid-State Transformers (SSTs) are power electronic systems that are increasingly seen as replacements for conventional grid transformers, offering improved adaptability for the demands of smart grids and the integration of renewable energy sources. A critical aspect of SST design is efficiently modeling thermal behavior to assess potential material degradation. Achieving this requires a multiphysics approach that couples electromagnetic, thermal, and fluid dynamics models, particularly when forced cooling is involved. Building on the authors' previous works (1,2), this study assesses the structural aspects of high-frequency, high-voltage SSTs employing inductive power transfer (IPT) technology, within SSTAR, a Horizon Europe research project (3). To achieve this, a one-way coupled simulation strategy is developed that integrates electromagnetic, thermal, computational fluid dynamics (CFD), and mechanical models. This approach initially calculates the power loss distribution and the associated temperature fields within transformer components. The obtained results are used to calculate thermal stress and strain by using the Finite Element Method (FEM) in order to evaluate the mechanical performance and structural integrity of the system. A key focus is the design and optimization of the supporting structures for the primary and secondary systems (shield, core, and windings). Various configurations of these structures are being evaluated to ensure structural integrity. Furthermore, fatigue analysis is performed to estimate the operational lifespan of the SST, providing insights into its long-term performance and durability. In conclusion, this research provides a comprehensive framework for assessing the thermal, mechanical, and structural performance of SSTs, ensuring that they meet the demanding requirements of modern power grids.

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MS5.6 - Model reduction and machine learning

Organisers: David Ryckelynk (Ecole des Mines de Paris) and Francisco Chinesta (ENSAM)

A multifidelity deep learning model for predicting the internal excitation sources in geared systems

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Speaker: Mouton Valentin. **Tuesday**. Start time: **10:00**. Room: Roseraie 1 LVL3. Link to abstract.

Gears are an essential component of kinematic chains used in many mechanical systems and a wide range of technical applications. However, they may cause noise pollution. Accurately predicting vibroacoustic response is of paramount importance for the design, optimization and health monitoring of gear transmission systems. System identification is therefore needed to reach a sufficiently high level of accuracy. However, this usually comes at the cost of high computational burden.
It is widely accepted the dynamic and vibroacoustic response of geared systems is mainly induced by the gear static transmission error (STE) and time-varying mesh stiffness. These physical quantities are governed by the local contact conditions between the gear teeth. An accurate computation of these physical quantities is therefore crucial. However, this is a difficult problem as gear contact resolution is intrinsically nonlinear and multiscale.

Classical approaches rely on semi-analytical computation methods, which are computationally efficient due to their reliance on simplifying assumptions. However, this efficiency is achieved at the cost of reduced accuracy. To overcome the limitations of these assumptions, a direct finite element (FE) contact resolution can be implemented, capturing the full flexibility of the gearbox. While this method provides higher accuracy by minimizing assumptions, it results in significantly higher computational costs, often requiring several hours or even days to complete.
To address this drawback, this work introduces a novel framework based on a multifidelity deep learning approach for predicting static gear contact conditions. The proposed method involves training multiple neural networks using extensive numerical data generated by a semi-analytical approach. Additionally, a transfer learning (TL) method is employed to incorporate supplementary data from a limited number of full FE simulations into neural networks built from semi-analytical data. The developed multifidelity model offers a significant computational speedup, enabling near real-time predictions compared to FE analysis. It enables further dynamic optimization tasks that fully integrate the flexibility of the gearbox.

Achieving universal approximations with a novel neural network framework for isotropic polyconvex hyperelasticity

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Speaker: Kurzeja Patrick. **Tuesday**. Start time: **10:20**. Room: Roseraie 1 LVL3. Link to abstract.

Incorporating physical principles and constraints into artificial neural networks can significantly enhance their ability to accurately capture the behavior of materials. This promising combination, however, comes with substantial challenges (1,2). Principles such as objectivity, polyconvexity and isotropy may interfere with each other and naive implementations can become too restrictive for the solution space. This work hence introduces a novel neural network framework for hyperelasticity that inherently satisfies these fundamental constraints while maintaining flexibility. Unlike previous approaches, the proposed framework is based on the universal approximation theorem, ensuring the ability to approximate any objective, polyconvex and isotropic energy with arbitrary accuracy within this function space. Moreover, the approach enables the approximation of polyconvex hulls.

Numerical examples validate the effectiveness of the proposed framework and demonstrate its ability to approximate energy functions that were previously unattainable using other neural networks. Additionally, the computation of polyconvex hulls for non-polyconvex energies is demonstrated.

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The determination method of supplement training condition for neural network model fusing real data and virtual data

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Speaker: Lu Songsong. **Tuesday**. Start time: **10:40**. Room: Roseraie 1 LVL3. Link to abstract.

Real calibration tests can obtain high accuracy data, but data amount is limited due to costs. Virtual simulations can obtain rich enough data to cover each required application range, but data accuracy is lower. To achieve win-win results, many researchers investigated how to take fully advantages of real-calibration-tests data and virtual-simulation data in training of neural network (NN) model. Various real-virtual fusion neural network (FNN) models with high predicted accuracy in wider application range were therefore putforwad. However, these FNN models are difficult to be applied in engineering field. It is because their prediction errors for some conditions in required application range is relatively low (stated as lower cognitive (LC) conditions) and these LC conditions are hard to be identified without conducting corresponding comparative tests.
To address above issue, investigations were conducted in this research with scale-down aircraft wing strain-load FNN model serving as research object. A method coarsely identifying LC conditions of FNN model without conducting extra real calibration tests was established first. In this method, various sub-learners are embedded into the FNN model to obtain various predicted results for one condition; variance of predicted results corresponding to different sub-learners are calculated and conditions with higher calculated variance value were classified as LC conditions. This coarse method was verified by comparative study, where a significant LC condition with around 46% error is identified as its remarkable higher (over 7 times) variance than that of other conditions with error below 5%.

This coarse method was then further developed into an improved method, which can accurately identify LC conditions not ensuring a specified accuracy requirement. This improvement was achieved by micropertubation training on FNN model with various embedded sub-learners, especially by taking fully advantages of different evolution characterization of variance for different types of conditions at early stage of micropertubation training (the variance decreases for LC conditions but increases for other conditions with the increase of iteration steps). The procedure of this method is listed as follows: 1) using the virtual simulation data at a specific condition to train the FNN model with micropertubation; 2) adjusting the number of iteration steps of micropertubation training to obtain the smallest percentage of conditions with decreased variance; 3) determining conditions with decreased variance at this iteration step as most remarkable LC conditions; 4) excluding these most significantly LC conditions from all predicted conditions and calculated variance of each remaining condition; 5) checking whether these variance ensures the specified predicition accuracy requirement and repeat the step 1)-4) until these variance ensuring the specified requirement; 6) determining all excluded significant LC conditions as the identified LC conditions not ensuring the specified predicition accuracy requirement.
The improved LC condition identifying method in this research is meaningful. Conducting supplementary tests under these conditions and retraining the FNN model after adding these supplementary data in training dataset will helps to effectively improve both accuracy and application range of FNN model.

Parametric Physics-Informed Neural Networks (PINNs) for Solving Inverse Problems in Mechanics: Viscoplastic Constitutive Model Calibration

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Speaker: Xu Haotian. **Tuesday**. Start time: **11:00**. Room: Roseraie 1 LVL3. Link to abstract.

Recent advancements in machine learning have transformed numerous fields, including mechanical engineering, by offering powerful tools for data analysis, prediction, and optimisation. In mechanical engineering, constitutive models serve as numerical tools to represent the mechanical behaviour of materials. However, calibrating advanced constitutive models remains a challenging and computationally intensive task. This study leverages Physics-Informed Neural Networks (PINNs) to significantly reduce the computational cost of such calibrations, demonstrated through a case study focused on the Chaboche viscoplastic constitutive model and the prediction to the constitutive response for cyclic tensile tests.
The Chaboche model is recognised for its capability to represent the complex, temperature-dependent mechanical response of metals, capturing phenomena such as viscoplasticity and isotropic-kinematic hardening. Calibrating the model and determining its relatively large number of parameters from experimental time-strain-stress data necessitates the adoption of an inverse analysis approach (1). This typically involves incrementally integrating the evolution equations characteristic for the state variables of the Chaboche model across the experimental loading profile and exploring various combinations of model parameters to achieve the best fit to the available experimental data, thereby identifying the most representative model parameter set by least-squares optimization. This process is computationally expensive, particularly when the model must be calibrated over a wide range of temperatures, based on outcomes from a large number of experiments.

This study utilises PINNs to streamline the calibration process, thereby effectively reducing the computational burden associated with constitutive model calibration. Initially, the Chaboche model formulation is directly incorporated into the neural network framework, and the resulting PINN is trained to construct a parametric solution for the Chaboche model, representing the material deformation behaviour across different loading conditions and various combinations of model parameters. Once the parametric solution is obtained, the trained PINN is employed as a fast surrogate for the Chaboche model in inverse analysis to determine the optimal set of model parameters. This integration enables efficient inverse analysis by leveraging the computational power of GPUs, benefiting from automatic differentiation for calculating required gradients for inverse analysis, and enabling one-shot forward evaluation of PINNs, in contrast to the incremental numerical integration required when using the Chaboche model in traditional methods.

In the present contribution, we show that after training the PINNs surrogate model for the typical ranges of the material constants (unsupervised), the Chaboche model parameter identification from a set of synthetic material stress-strain-time curves is successfully completed within an order of 30s. This is a factor of 1000 faster than the traditional approach, based on a numerical integration of the evolution equations within inverse analysis. We hence demonstrate that despite known limitations (2,3), rapid parameter identification for continuum mechanical models of complex, time-dependent material behaviour represents a domain where PINNs can realise their full potential.

Keywords: Physics Informed Neural Networks; Constitutive model calibration; Inverse problem; Chaboche model; Parametric solution

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Machine Learned Interatomic Potential for Shock Response of B4C

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Speaker: Subhash Ghatu. **Tuesday**. Start time: **11:20**. Room: Roseraie 1 LVL3. Link to abstract.

A neural network (NN) - based machine learned interatomic potential (MLIP) was developed for simulating the shock response of boron carbide (B4C). The training data set consisted of atomic species and coordinates of four different polymorphs, their associated total energy, forces, and virial stresses for a broad range of atomic configurations (e.g., various strain levels in tension, compression, and shear loading as well as atomic configurations in different material phases). This data was generated with ab initio methods to maximize accuracy. The MLIP was validated using a three-stage material-agnostic procedure for stability (e.g., energy, force, virial stresses) static property prediction (e.g., elastic constants, equation of state, lattice constants), and dynamic property prediction (e.g., melting point, phase transition and high-pressure response). Shock simulations were then performed at a range of impact velocities to determine the Hugoniot elastic limit (HEL). The evolution of amorphous bands in different polymorphs at different orientation was systematically investigated. It is shown that amorphization causes local increase in the volume and hence causes significant compressive stress within the surrounding crystalline region thus revealing the mechanism for the lack of cracking which has been observed in numerous microscopic observations.

Hyper-reduction by statistically corrected clustering

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Speaker: Wulfinghoff Stephan. **Tuesday**. Start time: **14:15**. Room: Roseraie 1 LVL3. Link to abstract.

The efficiency of projection-based reduced order models hinges on numerically robust and accurate hyper-reduction methods. Recently, statistically compatible hyper-reduction has been introduced as one possible pathway to construct integration points for the reduced-order model (1). For example, second-order statistical compatibility means that the average strain (i.e. the 1st statistical moment) of the full field representation (based on the modes) is exactly met by the reduced integration points and, in addition, the second moment is also exactly preserved. This idea is taken from more analytical homogenization methods, in particular developed by Pedro Ponte-Castaneda (e.g., 2). The recent approach (1) shows good results with small numbers of integration points, often in the order of 10-20, as long as the degree of nonlinearity of field fluctuations is moderate. However, it suffers from a major limitation, namely that the maximum number of reduced integration points is limited. Up to now, it was thus impossible to increase the number of integration points for highly nonlinear problems, where a higher amount would be necessary to reach a good accuracy. In this work, this limitation is overcome by combining the method with a kmeans-based clustering procedure in a generalized strain space, such that the number of integration points can be further increased and convergence to the FEM-solution is achieved even in strongly nonlinear cases.

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Component wise hyperreduction in nonlinear mechanics

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Speaker: Ritzert Stephan. **Tuesday**. Start time: **14:35**. Room: Roseraie 1 LVL3. Link to abstract.

Many mechanical systems consist of substructures. This holds the potential for model order reduction, if these substructures are used multiple times in different mechanical systems, or are repeated in the same structure. In our method, we reduce the number of degrees of freedom of each substructure independent of the other substructures and assemble them to the global reduced mechanical system.
The model order reduction method consists of two parts. The first part is the hyperreduction of the substructures, where we use energy conserving sampling and weighting (ECSW) with a projection matrix computed by proper orthogonal decomposition (POD). The second part is the connection of the components to form a global system. Here we use a mortar tied contact formulation, which enables us to connect components with non-matching meshes. A further advantage is that the Lagrange multipliers can be removed from the equation system by static condensation, by choosing dual shape functions for the Lagrange multipliers.
The substructure projection matrices are computed from snapshots of the substructure. The snapshots can be computed directly with the substructure or with a small subsystem that includes the substructure to be trained. The computed projection matrices are stored and can be used in different mechanical systems under varying loading conditions.
We apply the method to nonlinear mechanical simulations involving plasticity, viscoelasticity, and geometric nonlinearities.

REDUCED ORDER MODEL FOR DRAINAGE COMPUTATION IN LOWER LIMB LYMPHEDEMA

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1 - Mines Saint Etienne (France), 2 - Universitat Politecnica de Catalunya (Spain), 3 - Mines Saint Etienne (France)

Speaker: Garcia-Llona Aratz. **Tuesday**. Start time: **14:55**. Room: Roseraie 1 LVL3. Link to abstract.

The lymphatic system is formed by a series of vessels and glands that collect and filter excess fluid, proteins and toxins (lymph) from cells and tissues, next, return them to the bloodstream. When the lymphatic system is damaged, the body is unable to drain it and the lymph tends to accumulate (1). Lymphedema is usually treated with compression therapy through compression stockings. Compression therapy raises the interstitial fluid pressure, which increases the pumping capacity of the lymphatic vessels. The aim of the treatment is to regress to an edema-free stage or at least to decrease swelling.
Patient-specific compression stocking applies personalized pressure over the lower-limb increasing the effectiveness of the treatment. Computer-aided approach can model the behaviour of lower-limb lymphedema and it supposes a digital replica to try different compression pressure. The behaviour of soft-tissues is usually simplified and it is modeled as an elastic or hyperplastic material (2). However, the fluid phase plays an important role regarding the interstitial fluid pressure. Soft-tissues are modeled as a poroelastic material to consider the interstitial pressure due to the lymph.

The digital-twin of the lower lymph (poro-elastic model) is built to model the impaired fluid drainage. The proposed digital-twin is based on reduced order model (ROM) (3). In this study non-intrusive ROM are applied to compute the drainage effect in the lower-limb. The ROM is carried out through the solution computed by several finite element (FE) model or high-fidelity model defined by a set of patient-specific parameters. This is carried out through Proper Orthogonal Decomposition (POD), which decomposes the high-fidelity solution in a linear combination of a set of coefficients and modes. In order to reconstruct the approximated solution, the POD coefficients should be predicted using surrogate models. This method is known as Proper Orthogonal Decomposition with Interpolation (PODI). The proposed algorithm reduces the computational cost and enables to estimate the desired features to evaluate the effects of the compression therapy in real time such as lymph velocity, drained volume, morphology etc.

The digital-twin of the lower-limb enables to foresee the effects of the applied compression therapy. It will suppose a step forward in the treatment of lymphedema moving from off-the-shelf stocking to patient-specific compression stocking.

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Efficient cooling time optimization in Wire Arc Additive Manufacturing using a multi-layer reduced order model

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Speaker: Robens-Radermacher Annika. **Tuesday**. Start time: **15:15**. Room: Roseraie 1 LVL3. Link to abstract.

Additive manufacturing (AM) has transformed the industry by enabling the production of complex geometries and parts with customized properties. Among various AM techniques, wire arc additive manufacturing (WAAM) stands out due to its high deposition rate and low equipment cost. However, WAAM's complex thermal history poses challenges for real-time simulation, essential for online process control and optimization. Consequently, experimental optimization remains the state-of-the-art approach. A critical parameter to optimize is the cooling phase duration, which prevents structural overheating, controls the molten pool size, and influences the mechanical properties of the final product.
For efficient cooling time optimization, a fast-to-evaluate model of the temperature field during multi-layer deposition is necessary. This study proposes a reduced order model (ROM) using the proper generalized decomposition (PGD) method (1) as a powerful tool to minimize computational effort. Given the moving heat source in WAAM processes, a mapping approach (2,3) is employed to achieve a fully separated representation of the temperature field. Building on the authors' previous one-layer approach (4), this contribution extends the model to multiple layers through enhanced mapping and compression techniques. The compression reduces the total number of PGD modes as the number of layers increases. The extended mapping allows computations with a fixed mesh over the simulation time, in contrast to standard methods such as the element birth technique.

For cooling time optimization, the cooling duration of each layer is incorporated as PGD variables, enabling time-efficient computation of the temperature field for varying cooling times. The developed ROM is applied to optimize the cooling time of a multiple layer example. Therefore a 5-10 layer wall structure is investigated using the austenitic stainless steel 1.4404 (AISI 316 L). The resulting cooling times and the efficiency of the approach are discussed.

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Physics-Informed Surrogate Model for Forward and Inverse Problems in 3D Polycrystalline Elastostatics

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Speaker: Monteiro Fernandes Lucas. **Tuesday**. Start time: **15:35**. Room: Roseraie 1 LVL3. Link to abstract.

We develop a physics-informed neural network pipeline for explicitly solving linear elastic micromechanics in three dimensions, on heterogeneous media with periodic geometry. Our main application is a representative volume element of a polycrystalline material. Our approach combines a convolutional neural network with residual connections and non-learnable layers. The latter are introduced to enforce the fields admissibility and constitutive law in a way consistent with so-called Fast Fourier Transform (FFT) algorithms. More precisely, differential operators are discretized by finite differences in accordance with the Green operator used in FFT computations and treated as convolutions with fixed kernels. The deterministic relation between crystalline orientations and stiffness tensors is transferred to the network by a non-trainable layer. A loss function dependent on the divergence of the predicted stress field allows to update the network parameters without further supervision by ground truth fields. The neural network is trained on untextured synthetic polycrystals with periodic boundary conditions, realized from a stochastic 3D microstructure model based on random tessellations. Once trained, the network is able to predict the periodic part of the displacement field from the set of crystalline orientation field (represented as unit quaternions) of an artificial volume element. The proposed self-supervised pipeline is compared to a similar model trained with a data-driven loss function. Furthermore, we analyze the accuracy of the predictions of both models over microstructures larger than the ones used for training, as well as over polycrystals generated with different parameters of the stochastic 3D microstructure model. Finally, we show how the trained neural network can be employed to perform an optimization by gradient descent of the crystal orientations of a polycrystalline microstructure. In our optimization procedure, we minimize the local equivalent Von Mises stress field with an isotropy constraint on the overall mechanical response.

An open-source scalable architecture for finite elements with neural network based constitutive models (FENN)

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Speaker: Alheit Benjamin. **Tuesday**. Start time: **16:35**. Room: Roseraie 1 LVL3. Link to abstract.

Significant progress has been made in the development of neural networks (NNs) for the constitutive modeling of (anisotropic) hyperelastic solids, with wide-ranging applications ranging from biomechanics to soft robotics. Some examples of these include constitutive artificial neural networks (CANNs) (1), input convex neural networks (ICNNs) (2, 3), and neural ordinary differential equations (NODEs) (4). These neural networks based constitutive models (NNCMs) are far more flexible than traditional constitutive models whilst maintaining important attributes such as objectivity, material symmetry, and polyconvexity. The ultimate goal of these constitutive models is to be deployed in a scalable finite element method (FEM) framework for analyzing large-scale mechanical boundary value problems.

We, however, demonstrate that the integration of NNCMs in a conventional FEM framework destroys their respective compute scalability due to mismatch in how NNCMs and FEM capitalize on hardware parallelization. To address this, we reimagine a scalable FEM architecture that takes synergistic advantage of the single instruction multiple data architecture of NN frameworks to maintain computational performance despite the additional floating-point operations that NNCMs introduce relative to traditional constitutive models. We demonstrate efficient compute-scaling of the framework with increasing size and complexity of mechanical boundary value problems. The architecture is realized in C++ using the deal.II finite element library (5) and torch deep learning library (6) and featuring distributed memory parallelism. With the launch of an open-source codebase of the algorithm, we invite the solid mechanics community to adopt our code, and finally start harnessing the power of NNCMS in their research and work.

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Implicit automatic differentiation and implicit layers for constitutive modeling

Bleyer Jérémy (1)

1 - Laboratoire Navier (France)

Speaker: Bleyer Jérémy. **Tuesday**. Start time: **16:55**. Room: Roseraie 1 LVL3. Link to abstract.

The intersection of computational mechanics and machine learning is advancing rapidly, particularly in the domain of constitutive modeling. Constitutive models, being inherently data-driven, share structural similarities with neural network layers. Beyond data-driven learning, there is significant potential in adapting traditional constitutive models for seamless integration with machine learning frameworks. Automatic differentiation (AD) has revolutionized machine learning by enabling the computation of derivatives for complex functions constructed from simpler operations. In this talk, we will explore how AD can enhance constitutive modeling, focusing on two critical applications: efficient tangent operator computation and material parameter sensitivity.

First, AD can automate the derivation of consistent tangent operators, which are crucial for the efficient integration of constitutive models into large-scale simulations. We will examine strategies for obtaining these operators, including directly applying AD to unrolled algorithms and leveraging implicit differentiation for greater efficiency. Additionally, AD enables the computation of material parameter sensitivities, facilitating more effective model calibration and optimization.
Finally, we will discuss a novel architecture for data-driven constitutive models that employs implicit layers. This approach departs from conventional large-scale feed-forward neural networks, aiming to develop machine-learning-based constitutive models that adhere to thermodynamic principles, integrate domain knowledge, and demonstrate superior performance on unseen data. These models not only align with established theoretical frameworks but are also easier to train and generalize effectively.

On the role of interpretability of data-driven constitutive modeling by constitutive artificial neural networks

Abdolazizi Kian (1), Cyron Christian (1) (2), Linka Kevin (1)

1 - Hamburg University of Technology (Germany), 2 - Helmholtz- Zentrum Hereon (Germany)

Speaker: Abdolazizi Kian. **Tuesday**. Start time: **17:15**. Room: Roseraie 1 LVL3. Link to abstract.

The classical theory-driven approach to describe the deformation of a material body is based on the formulation of constitutive equations relating strains and stresses. A drawback of this approach is the effort typically required to develop appropriate functional relations and to identify material parameters. These efforts are not required in data-driven approaches to constitutive modeling. To combine the advantages and overcome the disadvantages of both theory-driven and data-driven constitutive modeling, we have developed the novel concept of Constitutive Artificial Neural Networks (CANNs) (1, 2). This machine learning approach to data-driven constitutive modeling does not require any major a priori assumptions about the constitutive law, but still incorporates substantial theoretical knowledge of continuum mechanics and constitutive theory. In this way, CANNs are able to learn the constitutive law of a material from relatively small amounts of stress-strain data. Moreover, our results suggest that CANNs can robustly discover different flavors of material models from data and, by design, have a clear physical interpretation. These capabilities are illustrated using different data collected from arterial and brain tissue.

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The Prediction of Cellular Materials Properties Through Deep Learning and Semantic Segmentation

Sadia Haleema (1), Alam Parvez (2)

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Speaker: Sadia Haleema or Alam Parvez. **Tuesday**. Start time: **17:35**. Room: Roseraie 1 LVL3. Link to abstract.

Predicting the properties of cellular materials is important in engineering design as they are used ubiquitously in a broad range of applications. Here, we propose a **deep learning-based approach** for the prediction of materials properties directly from 2D images, offering a fast and scalable alternative to conventional simulation techniques. Our framework is to train **Convolutional Neural Networks (CNNs)** by high-resolution image datasets generated using FEA simulation outputs. By using **semantic segmentation,** class labels are assigned to individual pixels based on the stress and strain associated with that pixel. It enables precise identification of material behavior and can thus learn spatial and hierarchical patterns in a cellular material structure under various loading conditions. By using deep neural networks to automatically extract complex features from raw data, the model will accurately predict cellular material responses, aiding designers in the virtual characterisation of cellular material structures. We apply **transfer learning** techniques to further enhance CNN model performance, by leveraging pre-trained CNN architectures, such as **U-Net**, **DeepLab**, **Segnet, EfficientNet,** and **ResNet**, and fine-tuning them for the task of predicting cellular material properties. This not only accelerates training, but also improves the model's ability to generalize from limited data. The results show that the deep learning model outperforms traditional methods in terms of speed, and scalability, and can be used to predict cellular material properties applicable to a diverse range of engineering applications.

Modelling of pulsed laser interaction with stainless steel for laser ablation.

Hardman Christopher (1)

1 - University of Bristol [Bristol] (United Kingdom)

Speaker: Hardman Christopher. **Tuesday**. Start time: **17:55**. Room: Roseraie 1 LVL3. Link to abstract.

The decommissioning and disposal of structural materials exposed to radiation is especially difficult for very large components. Removing the highly active outer surface, so that the remainder can be treated as low-level waste, is desirable and several methods are being investigated. One option is laser ablation, where laser pulses cause melting and local damage causing material to spall off. However, the interaction of high-power pulsed lasers with steel surfaces is a complex phenomenon, involving an interplay of optical, thermal, fluid, and material processes. These interactions are inherently non-linear, making the precise control and prediction of outcomes challenging. To address these complexities, computational modelling emerges as a cost-effective and powerful tool for enhancing laser treatment procedures.
As part of this work, the Finite Volume Method (FVM) has been employed to simulate the dynamic behaviour of the laser-induced molten pool, as well as the resulting crater formation, material ejection and plasma generation. The FVM allowed for the detailed capture of the transient and spatially varying phenomena associated with pulsed laser heating. By varying the material composition and laser parameters, particularly laser power and pulse duration, their effects on the time-temperature profiles and the resulting crater dimensions were investigated. This is in addition to model specific criteria such as the heat source type and viscosity model used.

The thermal model has been calibrated against thermal camera measurements during laser pulse testing. The resulting material response - such as molten zone shape, transformation boundaries and phase fractions at locations during the pulse - have been validated with microscopy and synchrotron X-ray data. Allowing for direct comparison with model outputs.
Much of the work is performed using the open-source software package OpenFOAM, it is hoped that producing an accessible model for such work will allow facilitate future research with other data sets.

MS5.7 - Data driven approaches of materials structures and processes

Organisers: Laurent Stainier (EC Nantes), Michael Ortiz (Caltech) and Benjamin Klusemann (Leuphana University)

Discovering New Constitutive Models for Soft Materials by Symbolic Regression

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Speaker: Itskov Mikhail. Keynote. **Thursday**. Start time: **10:00**. Room: Rhône 2 LVL1. Link to abstract.

Soft materials can undergo large deformations, demonstrate not only elastic but also inelastic and often anisotropic response, which makes their constitutive modeling very challenging. Traditionally, it was mostly driven by expert knowledge whereas attention was focused in particular to elastomers, soft biological tissues and fabrics. Symbolic regression represents an interesting method of machine learning which allows an unbiased automatized generation of constitutive models for such materials. In comparison to other data-driven methods symbolic regression reproduces a mathematical expression of a strain energy, damage or other desired function which can be analyzed, interpreted und easily implemented into a finite element code. In this contribution, we present some applications of symbolic regression demonstrating how effective it can be for example in modeling elastic and inelastic response of elastomers. The proposed procedure also grants new insights into many established and well-known material models.

Optimization of TFA homogenization based on data-driven approach

Alaimo Gianluca (1), Rotini Francesca (1), Auricchio Ferdinando (1), Marfia Sonia (2), Sacco Elio (3)

1 - Department of Civil Engineering and Architecture, University of Pavia (Italy), 2 - Department of Civil, Computer Science and Aeronautical Technologies Engineering, Roma Tre University (Italy), 3 - Department of Structures for Engineering and Architecture, University of Naples Federico II (Italy)

Speaker: Marfia Sonia. Invited. **Thursday**. Start time: **10:40**. Room: Rhône 2 LVL1. Link to abstract.

Composite materials are increasingly used in various fields of engineering. A large number of composite materials exhibit nonlinear behaviour due to the intrinsic mechanical response of the constituents and the topological complexity of the internal periodic structures at the micro level. The mechanical behaviour at the micro level can be determined by studying the Representative Volume Element (RVE) using appropriate constitutive models. However, the computational effort usually associated with the RVE study by the Finite Element (FE) method is very high.
An effective approach that can significantly reduce the computational effort is Transformation Field Analysis (TFA), introduced by Dvorak (1). TFA is based on the idea that it is possible to divide the RVE into subdomains or clusters within which a uniform distribution of microscopic strain fields is assumed. Such an assumption drastically reduces the number of internal variables required to solve the micromechanical problem and consequently the computational time. Accordingly, in TFA, the total macroscopic strain prescribed on the RVE is mapped onto each cluster by elastic and inelastic strain localisation tensors, which are generally a function of the position within the cluster. Uniform localisation tensors are obtained during the offline stage by averaging the localisation tensors within each cluster.

This paper presents an optimisation procedure based on a data-driven approach that leads to the evaluation of strain localisation tensors. The choice of uniform localisation tensors is obtained through a training stage consisting of a two-step optimisation process aimed at minimising a total stress error measure between TFA and an FE reference solution during some pre-analyses. Such a training stage is performed during the offline stage so that it does not affect the computation time of the online TFA procedure. Several benchmark strain histories are used during the online stage as a verification test to validate the optimised strain localisation tensors. The results show that the total strain errors are reduced by at least two orders of magnitude in all cases considered.

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HyperCAN: Hypernetwork-driven deep parameterized constitutive models for metamaterials

Zheng Li (1), Kochmann Dennis (1), Kumar Siddhant (2)

1 - Eidgenössische Technische Hochschule - Swiss Federal Institute of Technology [Zürich] (Switzerland), 2 - Delft University of Technology (Netherlands)

Speaker: Zheng Li. Invited. **Thursday**. Start time: **11:00**. Room: Rhône 2 LVL1. Link to abstract.

We introduce HyperCAN, a machine learning framework that utilizes hypernetworks to construct adaptable constitutive artificial neural networks for a wide range of beam-based metamaterials exhibiting diverse mechanical behavior under finite deformations. HyperCAN integrates an input convex neural network that models the nonlinear stress–strain map of a truss lattice, while ensuring adherence to fundamental mechanics principles, along with a hypernetwork that dynamically adjusts the parameters of the convex network as a function of the lattice topology and geometry. This unified framework demonstrates robust generalization in predicting the mechanical behavior of previously unseen metamaterial designs and loading scenarios well beyond the training domain. We show how HyperCAN can be integrated into multiscale simulations to accurately capture the highly nonlinear responses of large-scale truss metamaterials, closely matching fully resolved simulations while significantly reducing computational costs. This offers new efficient opportunities for the multiscale design and optimization of truss metamaterials.

Nonlinear two-scale beam simulations accelerated by thermodynamics-informed neural networks

Leclezio Helen (1), Karapiperis Konstantinos (2), Kochmann Dennis M. (1)

1 - Mechanics and Materials Laboratory, ETH Zürich (Switzerland), 2 - Data-Driven Mechanics Laboratory, EPFL (Switzerland)

Speaker: Leclezio Helen. Invited. **Thursday**. Start time: **11:20**. Room: Rhône 2 LVL1. Link to abstract.

Beam-based architected materials can be subjected to large strains in a range of applications such as shock absorption or soft robotics. Finding efficient and accurate models for these materials at finite strains is a challenging task as their microstructures consist of many individual slender beam members that exhibit nonlinear effects due to their geometry (large rotations) and behavior (e.g., hyperelastic materials). Classical 1D models ignore nonlinearities due to hyperelastic constitutive laws and full 3D finite element analysis comes at a prohibitive computational cost. Therefore, there is a need for an efficient modeling approach capable of accurately capturing the physics of these large, complex systems. Following a formal asymptotic dimension reduction approach, we decompose the problem into an efficient macroscale simulation of the beam's centerline and a finite elasticity problem on the cross-section (microscale) at each point along the beam. From the solution on the microscale, an effective energy is passed to the macroscale simulation, where it serves as the material model. However, this two-scale approach comes at a high computational cost. To leverage the efficiency of the macroscale beam simulation, we therefore introduce a Sobolev-trained thermodynamics-informed neural network, which serves as a surrogate model for the costly microscale simulations. We compare three different neural network architectures, viz. two well-established Multi-Layer Perceptron based approaches as well as a recently proposed Kolmogorov-Arnold (KAN) network, and we evaluate their suitability. The models are trained on varying cross-sectional geometries, all of varying sizes and degrees of hollowness. Based on its smooth and accurate prediction of the energy landscape, which allows for automatic differentiation, the KAN model was chosen as the surrogate material model, whose effectiveness we demonstrate in a suite of examples, ranging from cantilever beams to 3D beam networks.

Morphing As-Designed Databases for Lattice Materials with Image-Based Models to Capture Manufacturing-Induced Effects

Court Clément (1)

1 - Institut Clément Ader (France)

Speaker: Court Clément. Invited. **Thursday**. Start time: **11:40**. Room: Rhône 2 LVL1. Link to abstract.

With the advent of metal additive manufacturing, lattice materials - valued for their high stiffness-to-weight ratio - have become increasingly accessible for industrial applications. The inherently multiscale nature of these materials requires the use of specialized methods to study their mechanical behavior at the macroscopic scale. Data-driven methods have demonstrated improved efficiency compared to the FE^2 method, primarily due to their ability to capitalize on precomputed simulation results at the mesoscopic scale rather than recomputing them repeatedly. However, despite this advantage, building dense databases remains computationally expensive due to the 6-dimensionality of the strain space.
Furthermore, it has been shown in the literature, and confirmed by previous work through the use of image-based models (often referred to as "as-manufactured" cell configuration), that the mechanical behavior of lattice materials is influenced by manufacturing variability.
To account for these effects without performing a full design of experiments (DOE) on image-based RVEs, we propose leveraging the rich database generated from the "as-designed" CAD-based RVEs as a foundation. A morphing process will be explored, based on a lighter DOE conducted on image-based RVEs, to approximate the mechanical behavior of the as-manufactured material. By using interpolation techniques, such as radial basis functions (RBFs) or other methods, with a limited number of simulations, we aim to approximate databases that account for geometric variations caused by manufacturing. This approach may reduce computational costs by avoiding exhaustive (and numerically unaffordable) recomputation.

Physics augmented neural network model for simple isotropic damage in hyperelasticity

Zlatić Martin (1), Čanađija Marko (1)

1 - Faculty of Engineering, University of Rijeka (Croatia)

Speaker: Zlatić Martin. Invited. **Thursday**. Start time: **14:15**. Room: Rhône 2 LVL1. Link to abstract.

Neural networks in solid mechanics have come a long way from simple black-box models that fulfil a specific role. With the increasing number of different implementations, the knowledge of physics is brought into the modelling, either through the loss functions, keeping the properties of a classical neural network, or through the construction of new architectures and the implementation of new activation functions. The aim of this work is to develop a neural network model for simple isotropic damage that occurs in natural rubber and is known as the Mullins effect. In this work, a neural network architecture with a custom activation function was implemented in a specialised framework. The neural network architecture was adapted to satisfy some conditions such as the normalisation condition for energy, thermodynamic consistency, objectivity and polyconvexity. It was tested on several numerical examples with different variations of the architecture to find the best version. The result is a general approach to modelling damage in hyperelastic materials with a novel training framework for neural networks that is independent of the underlying neural network model.

Data-driven finite element computations for materials with an open-cell microstructure

Weinberg Kerstin (1)

1 - Universität Siegen (Germany)

Speaker: Weinberg Kerstin. Invited. **Thursday**. Start time: **14:35**. Room: Rhône 2 LVL1. Link to abstract.

In the data-driven finite element analysis the constitutive material modeling is eluded and instead data are directly employed as an input for computational analysis. This model-free description allows to implement arbitrary behaviors. It can be especially beneficial when you want to easily change the microstructural material design avoiding to start a new fitting process every time you make a change.

Our contribution focuses on the question of how we can use the data-driven finite element analysis for cellular materials. Since experimental data acquisition can be tedious, we suggest using numerical computations of representative volumes. In that way, the micromechanical behavior of the material can be employed to deduce homogenized data points.

Specifically we consider lattice-like materials and foam made of polyurethane. Dependent on the manufacturing process and the composition of the constituents, the material properties such as relative density, strut thickness, cell distribution, and general structure of the material vary. To map these different microstructures, we use regular or/and stochastic representative volume elements (RVEs) to generate the data basis. A generator produces the RVEs with the desired properties which are then subjected to some test loads to deduce homogenized data points. For illustration, the database is used in a finite element simulation of a compression experiment.

Phase-space iterative solvers

Joaquin Garcia-suarez (1), Cortes Gaetan (1)

1 - Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Speaker: Joaquin Garcia-Suarez. Invited. **Thursday**. Start time: **14:55**. Room: Rhône 2 LVL1. Link to abstract.

We introduce an iterative method to solve problems in small-strain non-linear elasticity. The method is inspired by recent work in data-driven computational mechanics, which reformulated the classic boundary value problem of continuum mechanics using the concept of "phase space". The latter is an abstract metric space, whose coordinates are indexed by strains and stress components, where each possible state of the discretized body corresponds to a point. Two subsets are then defined: an affine space termed "physically-admissible set" made up by those points that satisfy equilibrium and a "materially-admissible set" containing points that satisfy the constitutive law. Solving the boundary-value problem amounts to finding the intersection between these two subdomains. Our iterative method consists on projecting points alternatively from one set to the other, until convergence. The method is similar in spirit to the "method of alternative projections" and to the "method of projections onto convex sets", for which there is a solid mathematical foundation that furnishes conditions for existence of solutions and convergence. Its aptitude to deal with constitutive laws based on neural network is also discussed.

Efficient and noise-resilient nonlinear elastic simulations via a continuous data-driven framework

Karaca Kaan (1), Peerlings Ron (1), Geers Marc (1)

1 - Eindhoven University of Technology [Eindhoven] (Netherlands)

Speaker: Karaca Kaan. Invited. **Thursday**. Start time: **15:15**. Room: Rhône 2 LVL1. Link to abstract.

This work introduces a computational data-driven mechanics framework based on a continuous dataspace, improving upon the traditional data-driven methodology (1). Conventional data-driven computational mechanics methodology relies on finite, discrete datasets as the dataspace and iterative projections between the dataspace and the constraint space defined by the problem setting. However, using discrete datasets as the dataspace introduces drawbacks such as reduced accuracy due to noise and outliers in the dataspace (2), and high computational cost needed for locating optimal datapoints within the large and multidimensional datasets (3). The proposed framework addresses these issues by replacing the discrete dataset with a continuous dataspace extracted via Gaussian mixture modelling. This continuous dataspace acts as a data density field that is a sum of a finite number of Gaussian kernels and can be used to assess the likelihood of points attaining the material behaviour. Consequently, it mitigates the effect of noise and outliers on the solution accuracy. Hence it has been observed that the proposed framework outperforms the conventional one in terms of accuracy for varying noise levels. Moreover, the framework streamlines data-to-constraint space projections by utilizing a search direction derived from the continuous dataspace, therefore significantly reduces the computational cost by eliminating the need for search queries in discrete datasets as the computational cost of the conventional framework is shown to scale exponentially with respect to that of the newly introduced framework with increasing dataset size. Numerical experiments in both one and two dimensional problems validate the framework's ability to improve both accuracy and computational efficiency.

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An Efficient Multiscale Method for Modelling Anisotropic Fracture in Heterogeneous Structures Based on Data-Driven Approach

Chafia Zakaria (1), Yvonnet Julien (1), Bleyer Jérémy (2)

1 - Laboratoire Modélisation et Simulation Multi-Echelle (France), 2 - Laboratoire Navier (France)

Speaker: Chafia Zakaria. Invited. **Thursday**. Start time: **15:35**. Room: Rhône 2 LVL1. Link to abstract.

An efficient data-driven multiscale framework for modelling anisotropic damage in heterogeneous structures is proposed, where the anisotropic damage model at the macro scale is constructed purely on the knowledge of Representative Volume Elements (RVE) of the material microstructure. The technique involves three main steps: the construction of a database, obtained by performing off-line calculations of crack propagation on Representative Volume Elements (RVE); the construction of an anisotropic damage model constructed from the database using Harmonic Analysis of Damage and off-line calculations, where damage is computed using the constructed model in tandem with a strain-gradient regularization technique. Using Harmonic Analysis of Damage, an anisotropic damage model defining the evolution of the macroscopic elastic tensor as a function of macro internal variables is provided without specific assumptions about the anisotropy related to the RVE geometry. A surrogate model is constructed to define their evolution. The macroscopic problem uses the constructed anisotropic damage model, and a modified strain-gradient regularization is applied to guarantee mesh-independence. The technique accuracy and robustness has been assessed on several structural problems with different microstructures, involving a strong initial and induced anisotropic fracture behavior, and compared with direct crack numerical simulations (DNS) of heterogeneous structures. Very good accuracy has been obtained both regarding the force-displacement curves as well as crack paths, while keeping the efficiency of classical Finite Element simulations.

Neural simulation of plastic phenomena using MeshGraphNets

Iparraguirre Mikel M (1), Cueto Elias (1), Alfaro Iciar (1), Chinesta Francisco (2) (3)

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Speaker: Iparraguirre Mikel M. Invited. **Thursday**. Start time: **16:30**. Room: Rhône 2 LVL1. Link to abstract.

This work investigates the use of MeshGraphNets, a deep learning framework, to simulate plastic forming processes. Our database consists of synthetic data coming from high-fidelity finite element simulations. The deep learning model accurately captures the complex behavior of plastic phenomena for non-monothonic loading trajectories. Examples will be provided that demonstrate the robustness and accuracy of our approach in out-of-distribution cases, thus proving the feasibility of neural simulators for industrial use.

Graph neural network modeling of time-dependent materials under indentation

Secchi Paolo (1), Balint Daniel (1)

1 - Department of Mechanical Engineering [Imperial College London] (United Kingdom)

Speaker: Secchi Paolo. Invited. **Thursday**. Start time: **16:50**. Room: Rhône 2 LVL1. Link to abstract.

Indentation offers advantages over other tests, being non-destructive, requiring minimal material, and adaptable to multi-layered samples like polymer-coated steel plates. However, calibrating constitutive models by iteratively matching experimental indentation force-displacement curves via FEM simulations is computationally intensive. This study addresses the indentation curve matching problem by using a Graph Neural Network (GNN)-based surrogate model to reduce calibration time for viscoelastic materials. By combining GNN with Gated Recurrent Units (GRUs) to capture the material temporal dependency, the model can infer stress-displacement fields as well as the corresponding force-displacement curves using both synthetic and experimental data for training. Performing calibration through an indentation test on a polymer-coated steel panel, the model demonstrates a significant reduction in computational time compared to traditional FEM methods while accurately inferring stress and displacement fields. The surrogate model reliably predicts material behavior within the training range of the parameters, making the trained GNN well-suited for materials that can be described by the same constitutive model used to generate the synthetic data. This study, by improving existing GNN architectures, develops the first surrogate model of a 2D FEM model that includes viscoelasticity and contact. Additionally, a novel procedure for calibrating viscoelastic materials through indentation testing is presented, suitable for samples like thin polymer layer coatings on steel panels. The generality of this procedure highlights its potential applicability to manufacturing processes, such as optimizing the indenting pattern applied to soft coatings on metal sheet in a roll-to-roll hot embossing process.

Hybrid modeling via machine learning corrections of numerical process simulations towards experimental measurements for friction surfacing

Campos Pedro (1), Frederic Bock (1), Elbossily Ahmed (2), Kallien Zina (1) (2), Klusemann Benjamin (1) (2)

1 - Helmholtz- Zentrum Hereon (Germany), 2 - Leuphana Universität Lüneburg (Germany)

Speaker: Campos Pedro. Invited. **Thursday**. Start time: **17:10**. Room: Rhône 2 LVL1. Link to abstract.

The combination of data-driven and physics-based modeling can enable the consideration of validated engineering knowledge to increase physical consistency while performing machine learning (ML) regression tasks. A hybrid framework consisting of a physics-based process model for friction surfacing (FS) that shows errors compared to the targeted experimental solution due to inherent simplifications and assumptions is corrected by an ML model to reach that solution. In this presentation, a hybrid framework has been applied to the solid-state processing technique of FS, which produces fine grained coatings with superior corrosion and wear properties. In this regard, a Smoothed-particle hydrodynamics (SPH) model served as the physics based model and a scarce experimental data set based on a Box-Behncken Design of Experiment (DOE) was used to train the ML correction model. This correction task can require less data compared to mapping the complete problem since the correction is often less complex when fundamental relationships are already represented in the physics-based model that is corrected. As a result, the required number of experiments is reduced upon the effective exploitation of the available physics-based model, leading to savings of resources such as materials, energy and time. The development of the correction model is based on dimensionless inputs according to the Buckingham Pi theorem to reduce prediction inaccuracies and increase model generalization. The force, rotation and traverse speed as well as maximum process temperature, feed rate and other parameters are used as dimensionless inputs to train the ML model. The deposition has two dimensions, namely thickness and width. Both dimensions from both experiments and simulations are used to calculate a correction factor k that is the target solution of the ML model. The model was trained to learn the k and the predicted correction factors ^k is used to correct the simulation thickness and width. A consecutive goal was to replace the SPH simulation model with a data-driven model since it would provide results at a fraction of the time and with a substantial cut in computation cost. These predictions were also corrected to achieve the anticipated results. In that way, a hybrid model composed of a physics-based numerical model and a data-driven ML model is able to predict results that are in very good agreement with experimental measurements of deposition thickness and width.

A data-based derivation of internal stress and material microstructure characteristics

Schulz Katrin (1) (2)

1 - Karlsruhe Institute of Technology = Karlsruher Institut für Technologie (Germany), 2 - Karlsruhe University of Applied Sciences (Germany)

Speaker: Schulz Katrin. Keynote. **Friday**. Start time: **10:00**. Room: Rhône 2 LVL1. Link to abstract.

In this presentation, we introduce a framework for the derivation of the internal stress terms based on the statistical analysis of data from microscale dislocation simulations. By investigating the dislocation structure formation within the coarse graining benchmark systems under various combinations of numerical and microstructure conditions, e.g. element size, initial dislocation density, and the gradient of geometrically necessary dislocations, the heterogeneous dislocation structures formation within an element is identified. The resulting structure can be further predicted by the collected data base statistically or by a machine learning approach. We derive the near field correction stress within a coarse-grained system according to the uneven stress field induced by the heterogeneous dislocation structure formation. This stress terms are again used to set up a surrogate model to find meaningful correlations between experimental and simulation results.

A Neural Network-Based Framework for Data-Driven Inelasticity in Two Dimensions

Harnisch Marius (1), Bartel Thorsten (1), Schweizer Ben (2), Menzel Andreas (1) (3)

1 - Institute of Mechanics, TU Dortmund (Germany), 2 - Chair I (Analysis), TU Dortmund (Germany), 3 - Division of solid mechanics, Lund University (Sweden)

Speaker: Harnisch Marius. Invited. **Friday**. Start time: **10:40**. Room: Rhône 2 LVL1. Link to abstract.

Ongoing research in computational mechanics has led to the development of numerous data-driven methods. Within this class of methods, Kirchdoerfer and Ortiz (1) introduced data-driven mechanics, which substitutes traditional material models with data sets containing discrete pairs of stress and strain. The solution to boundary value problems is then derived by minimizing a distance between these pairs, referred to as material states, and mechanical states, which satisfy equilibrium and kinematic compatibility conditions.

While originally formulated for elastic materials, extending this framework to inelastic material responses is necessary but non-trivial due to the path-dependent behavior of such materials. In our extension (2) we utilize a history surrogate, a quantity designed to store essential information of stress and strain paths. This surrogate works in conjunction with a propagator, which updates the history surrogate at the end of each time step. The path-dependent behavior is embedded into the framework by introducing the history surrogate to both the material and mechanical states as an additional quantity. By doing so, our framework preserves the key characteristics of the original method.

For truss structures, as demonstrated in (3), finding an appropriate history surrogate can be achieved intuitively. However, for two-dimensional problems, the increased complexity of stress and strain paths also makes this task substantially more challenging. To address this, we use a neural network as propagator. The neural network autonomously handles the task of defining and updating the history surrogate based solely on discrete stress and strain data, thereby eliminating the need for explicit update rules or user intervention.

In this contribution, we provide a detailed analysis of our framework's capabilities, beginning with truss structures, which include inelastic material behavior, and results are presented for both an intuitive and neural network propagator. We further extend the discussion to two-dimensional problems, presenting results for the framework using the neural network propagator. Additionally, we examine the challenges associated with a higher-dimensional setting and offer insights into potential strategies for overcoming related issues.

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A Thermodynamic-Consistent Reduced-Order Machine Learning Model for Non-Equilibrium Materials Response

Huang Shenglin (1), Gao Huajian (2)

1 - Nanyang Technological University [Singapour] (Singapore), 2 - Tsinghua University [Beijing] (China)

Speaker: Huang Shenglin. Invited. **Friday**. Start time: **11:00**. Room: Rhône 2 LVL1. Link to abstract.

The materials loading response beyond elastic region usually exhibit a complex history dependency rising from its heterogeneity and the nature of plasticity, rendering huge modeling difficulties in both theoretical and computational aspects. In order to avoid such history dependency, a reduced-order model can be developed by introducing extra internal variables such that the materials loading response can be fully determined by the loading condition and internal variables at current step. However, despite of the model simplicity, internal variables usually cannot be measured directly from experiment. In this work, we propose a thermodynamic-consistent machine learning architecture to learn this reduced-order model from the materials loading responses (such as stress-strain curves) without any knowledge of internal variables. Such a model was verified on various examples including viscoelasticity and crystal plasticity. It can also be utilized as a constitutive law for doing simulation in a larger scale.

TOPIC: Dynamics, Waves and Metamaterials

MS6.1 - Nonlinear Dynamics in Mechanical and Structural Systems

Organisers: Sergey Sorokin (Aalborg University) and Daniele Zulli (University Aquila)

Nonlinear damping in large-amplitude vibrations

Amabili Marco (1)

1 - Westlake Univerity (China)

Speaker: Amabili Marco. Keynote. **Monday**. Start time: **10:10**. Room: Rhône 4 LVL1. Link to abstract.

An increase in damping is relevant for the passive control of vibrations and noise; therefore, it is very significant in design. Experimental data shows a strong and nonlinear dependence of damping on the vibration amplitude for beams, plates, and shells of different sizes and made of different materials (metal, composite materials, silicone rubber, and graphene). While the frequency shift of resonances due to stiffness nonlinearity is commonly 10 to 25 % at most for common structural elements, a damping value up to several times larger than the linear one can be obtained for vibrations of thin plates when the vibration amplitude is about twice the thickness. This is a huge change in the damping value! Therefore, the nonlinear nature of damping affects structural vibrations much more than stiffness nonlinearity. Despite this experimental evidence, nonlinear damping has not been sufficiently studied yet. A model of nonlinear damping was derived from linear viscoelasticity for single-degree-of-freedom systems and for rectangular plates by introducing geometric nonlinearity. The resulting damping model was nonlinear and the model parameters were identified from experiments. Numerical results for forced vibration responses of different structural elements in large-amplitude (nonlinear) regimes were obtained and successfully compared to experimental results, validating the nonlinear damping model. Recently, the effect of nonlinear damping into one-to-one internal resonances was addressed. This type of resonance appears in the case of symmetry: circular cylindrical shells and square plates are examples, as well as beams with circular cross-section in the three-dimensional space. The results of this new development in the study of nonlinear damping are particularly interesting.

Dynamic Responses of Parameter-Tuned Nonlinear Oscillator Arrays Under Harmonic Excitation

Zaraza Espinosa Javier (1), Agarwal Vipin (1)

1 - Department of Mechanical Engineering, University of Memphis (United States)

Speaker: Zaraza Espinosa Javier or Agarwal Vipin. **Monday**. Start time: **10:50**. Room: Rhône 4 LVL1. Link to abstract.

This study investigates the dynamic complexities of a linear arrangement of 10 coupled nonlinear oscillators under harmonic excitation, examining how tailored structural properties affect both individual oscillators and collective behavior. Each oscillator is represented by a Duffing system, modeled experimentally with a cantilever beam fixed at one end and a magnet at the free end, positioned within the magnetic field of a second fixed magnet. By adjusting the relative orientation and distance between these magnets, we achieve precise control over linear and nonlinear stiffness properties. Leveraging recent advancements in material science and manufacturing, this research systematically explores an extensive range of parameters through analytical, numerical, and experimental methods. Our findings provide a deeper understanding of how tunable parameters influence the system's dynamic response, revealing complex behaviors, including energy localization and varied amplitude responses. Addressing a significant gap in nonlinear oscillator research, this study demonstrates how strategic parameter tuning enhances control over dynamic responses, with broad implications for developing adaptable and responsive systems in nonlinear dynamics.

Vibration-assisted friction modulation: theory and application for a slip joint connection

Cabboi Alessandro (1), Sulollari Enxhi (1)

1 - Delft University of Technology (Netherlands)

Speaker: Cabboi Alessandro. **Monday**. Start time: **11:10**. Room: Rhône 4 LVL1. Link to abstract.

In the last 5 years, TU Delft investigated the use of a slip joint to connect offshore structures, such as wind turbine towers to their corresponding support structure. The slip joint, also sporadically used for telecommunication towers, is a direct steel-to-steel connection obtained by overlapping two identical conical sections over each other. The connection solely depends on the geometry and contact mechanism between the two steel surfaces, and the load transfer depends on the frictional stress between the surfaces in contact. Hence, the key challenge for such connection is to guarantee a proper fit and sound contact. To either enforce the fit and the sound contact or to loosen it, a vibration-assisted technique was explored at TU Delft.
The goal of this technique is to take advantage of the interaction between friction and an imposed high-frequency vibratory load, to control and facilitate the initiation of sliding between the surfaces in contact. At first, experimental evidences of the developed methodology will be shown, using a 1:10 scaled model of the slip-joint. Subsequently, unique results are showcased, obtained by applying the vibration-assisted technique to decommission a real slip joint assembled offshore, in the North Sea.
To explain the observed experimental data and the success of the applied technique, a slow-fast process is assumed, through a selection of simplified models (e.g. mass-spring systems, mass-rod systems). The slow process refers to the steady sliding state, while the fast process intends to encapsulate the vibratory load and includes its averaged effect on the slow process. Specifically, the slow-fast analysis enables the investigation of the interaction between the imposed high-frequency vibratory load and the friction force, which can facilitate the sliding process by means of an averaged reduction of the friction force. The simplified models and the assumed slow-fast process is solved through the method of direct separation of motion.

Linear and Nonlinear Vibration of a Beam with Constant Curvature

Firouzi Behnam (1), Sorokin Sergey (1)

1 - Department of Materials and Production [Aalborg] (Denmark)

Speaker: Firouzi Behnam. Invited. **Monday**. Start time: **11:30**. Room: Rhône 4 LVL1. Link to abstract.

This paper presents an analysis of approximate methods for the vibration analysis of curved panels, focusing on their accuracy and reliability compared to exact solutions. The primary approximate approach utilizes static condensation, based on the assumption that longitudinal inertia (stretch due to bending) is negligible. We investigate the influence of boundary conditions and geometric parameters on veering phenomena. Additionally, an alternative approximation method is introduced and assessed alongside the classic approach and exact solutions. Key parameters affecting accuracy are examined to determine each method's suitability under various conditions. The performance of approximate methods is evaluated in both linear and nonlinear cases, highlighting their practical applicability.

Utilizing Nonlinear Oscillator Arrays as Physical Reservoir Computers

Gupta Ayush (1), Agarwal Vipin (1)

1 - Department of Mechanical Engineering, University of Memphis (United States)

Speaker: Gupta Ayush Agarwal Vipin. **Monday**. Start time: **11:50**. Room: Rhône 4 LVL1. Link to abstract.

This work introduces a nonlinear multi-oscillator array as a physical reservoir computer, proposing a novel approach to computational tasks by leveraging the intrinsic dynamics of coupled oscillators. Unlike traditional reservoir computing, which relies on recurrent neural networks (RNNs) as computational reservoirs, a physical reservoir directly utilizes a physical system's inherent dynamics. The nonlinear behavior of oscillators makes them highly suitable as a computational medium, providing flexibility and depth for data processing. By adjusting parameters such as stiffness, damping coefficients, and inter-oscillator coupling, we can fine-tune the reservoir's properties, including vibration frequencies, amplitude, and equilibrium points, allowing precise control over its dynamic behavior. The interactions among oscillators introduce complexity, enabling synchronized and chaotic behaviors that capture intricate temporal dependencies in signal processing. Input signals are transformed into high-dimensional outputs through the oscillations of individual oscillators, where each oscillator represents a unique dimension within the state space. This high-dimensional representation is then utilized in neural network models for applications such as temporal data classification and time series prediction. The proposed multi-oscillator reservoir thus offers a versatile and customizable framework for advancing physical reservoir computing.

Hybrid Passive Seismic Protection Strategies of Rigid Blocks

Ferretti Manuel (1), Amoroso Lorenzo (1), Di Egidio Angelo (1)

1 - University of LÁquila [Italy] (Italy)

Speaker: Ferretti Manuel. Invited. **Monday**. Start time: **13:40**. Room: Rhône 4 LVL1. Link to abstract.

Many valuable artifacts and sensitive equipment respond to base excitations in a manner similar to rigid blocks. The economic and cultural significance of these objects is often comparable to that of the buildings housing them. Consequently, safeguarding such items against seismic events has become a crucial focus within civil engineering, comparable to the protection of entire structures.
Over the years, numerous strategies have been proposed to enhance the seismic resilience of rigid block-like objects. These methods generally fall into two broad categories: (i) coupling the objects with external systems, either in parallel or series (1,2,3), and (ii) employing seismic isolation techniques (4,5,6). Both approaches encompass passive and active solutions. Examples include pendulum mass dampers and tuned mass dampers directly attached to the objects, as well as hybrid configurations combining these techniques. More recent studies have explored advanced mechanisms, such as tuned mass damper inerters and actively controlled systems, to improve performance under seismic excitation.

Seismic isolation, the second major category, has been extensively applied to a variety of structures, leveraging devices like curved surface sliders and lead rubber bearings. This approach has also been adapted to non-structural components, such as equipment and artifacts, with experimental evaluations demonstrating its effectiveness. Analytical investigations into the application of seismic isolation to rocking blocks began approximately two decades ago. Early studies addressed the basic effectiveness of base isolation, later expanding to include factors like eccentricity and sliding. Tall and slender structures, such as ancient columns, were also studied, leading to the development of more sophisticated analytical and numerical models.

This study aims to develop a hybrid control strategy that combines seismic isolation and external nonlinear systems. Specifically, the research focuses on analyzing the effectiveness of horizontal isolation techniques coupled with arrays of oscillators, such as hysteretic tuned mass dampers and/or impact oscillators.

The study rigorously derives equations of motion, uplift and impact conditions, assuming that the protected objects cannot slide but may undergo rocking motions. Horizontal isolation is modeled using a hysteretic system characterized by the Bouc-Wen model, while coupled oscillators are represented either by the same Bouc-Wen model or by an appropriate impact system model.

Parametric analyses are performed using archetype objects subjected to recorded earthquake motions. The results, presented through rocking maps and overturning spectra, assess the performance of the proposed hybrid isolation approach. Comparisons with non-isolated systems further validate the findings and demonstrate the potential benefits of the combined methodology.

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On the dynamics of a collapsing set of blocks

Theresa Honein (1), O'reilly Oliver (2)

1 - American University of Beirut, Lebanon (United States), 2 - University of California [Berkeley] (United States)

Speaker: Theresa Honein. **Monday**. Start time: **14:00**. Room: Rhône 4 LVL1. Link to abstract.

The dynamics of a collapsing stack of rigid blocks is explored in the present paper. Stacks of this type are ubiquitous mechanical systems that can be used to model boxes stacked in warehouses, containers on ships, and stacks of boxes being transported by robots. While studies on the dynamics of a single block moving on a horizontal plane are well known to exhibit complex dynamics when the plane is subject to a harmonic motion, the dynamics of a stack of blocks proves to be far more complex in part because of frictional contacts and impacts between the blocks and the wide range of potential configurations. As analytical methods are untractable to study the dynamics of these systems, recourse to numerical methods is necessary. In the present paper, a non-smooth generalized-alpha method for systems with frictional contact and impact is used to compute the dynamics of the stack. From the simulations, it is shown that high-frequency excitation of the bottom block tends to stabilize a stack. The numerical analyses also reveal the existence of an abundance of distinct solutions stemming from a unique initial configuration when the lowest block in the stack is subject to a harmonic excitation. The abundance of solutions has application to robotics as it illuminates the challenges of controlling the motion of a robot so it can successfully transport a stack of blocks.

Horizontal and vertical base isolation for the seismic protection of non-symmetric rigid blocks

Amoroso Lorenzo (1), Ferretti Manuel (1), Di Egidio Angelo (1)

1 - University of LÁquila [Italy] (Italy)

Speaker: Amoroso Lorenzo. Invited. **Monday**. Start time: **14:20**. Room: Rhône 4 LVL1. Link to abstract.

In modern society, there is an increasing need to address the impact of catastrophic natural hazards. Among these, earthquakes and their economic and societal effects have been extensively studied. The devastation caused by numerous earthquakes has significantly deepened and expanded the understanding of the seismic vulnerability of structures, leading to the development of various seismic risk assessment methods.
Particular attention has been given to mitigating the seismic vulnerability of various objects within buildings. Many of these elements can be modeled as rigid blocks. The growing need to reduce seismic risk for these rigid block-like objects has spurred numerous studies proposing different protection methods. This diversity stems both from the distinct characteristics of rigid block structures, which impose specific constraints on protection strategies, and from the rapid technological advancements in protective devices, which offer new possibilities for more effective solutions. For example, objects such as artworks, storage racks, electrical cabinets, and certain hospital equipment can all be modeled as rigid blocks.

Base isolation is one of the most effective protection methods against earthquakes. In recent years, numerous studies have investigated the application of this technique to rigid block-like structures representing artworks. For example, studies (1) and (2) analyzed the effectiveness of horizontal base isolation in detail, focusing on moderately slender and highly slender rigid blocks, respectively. Most studies use a symmetric rigid block model to describe the seismic response of artworks. However, in reality, nearly all artworks are asymmetrical and require a non-symmetric rigid block model for accurate representation. Very few studies have examined the use of base isolation to protect non-symmetric rigid blocks from earthquakes, such as in (3). More recently, in (4), the effectiveness of base isolation acting in both horizontal and vertical directions was examined as a seismic protection method for symmetric rigid blocks. To the best of the authors' knowledge, horizontal and vertical base isolation has never been applied to non-symmetric rigid blocks. This paper aims to address this gap.

A mathematical model of a non-symmetric rigid block on a horizontally and vertically oscillating base was developed. The equations of motion were derived using a Lagrangian approach. Particular attention was given to formulating the impact conditions, which provide the velocities of both the oscillating base and the block after impact, based on their velocities before impact. The non-symmetric block was initially subjected to a horizontal impulsive one-sine excitation to generate classical overturning spectra and maps. The findings revealed several intriguing aspects of the behavior of the isolated non-symmetric block. Notably, unlike symmetric blocks, which exhibit only two overturning modes, non-symmetric blocks display additional distinct overturning modes. Additionally, the response of the isolated system under various recorded horizontal and vertical earthquake excitations was analyzed, highlighting the influence of block eccentricity.

The results demonstrated the effectiveness of horizontal and vertical seismic isolation in protecting non-symmetric rigid blocks, even when subjected to seismic excitations with very high vertical PGA (Peak Ground Acceleration).

Acknowledgement This work is funded by the European Union - Next Generation EU, Mission 4 Component 2 Investment 1.1, in the framework of the project PRIN 2022, "2022TH5HC2 - Engineered basements for vibration protection of artworks and strategic sensitive equipment" (CUP: E53D2300373 0006, University of L'Aquila).

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Longitudinal Seismic Isolation Strategies for Pipelines in Underground Utility Tunnels

Mancini Lorenzo (1), Ferretti Manuel (1), Di Egidio Angelo (1)

1 - University of LÁquila [Italy] (Italy)

Speaker: Mancini Lorenzo. Invited. **Monday**. Start time: **14:40**. Room: Rhône 4 LVL1. Link to abstract.

The increasing demand for urban infrastructure has driven a significant expansion of underground utility tunnels, which house essential pipelines for water, gas, electricity, and communications. While these tunnels reduce surface disruptions and simplify urban maintenance, they face unique challenges from seismic events due to their underground placement. During earthquakes, soil-structure interactions impose additional forces that directly affect the behavior of the tunnels and the pipelines they contain (1). Past assumptions about the inherent safety of underground structures have been challenged by significant damage observed in recent seismic events, such as the 1995 Kobe earthquake, where underground systems, including pipelines, suffered failures ranging from buckling to tensile rupture (2).
Existing research has primarily addressed the seismic behavior of tunnels as standalone structures, often neglecting the complex dynamics affecting internal pipelines, which differ in material properties and functions. The damage or failure of these pipelines can disrupt critical services, emphasizing the need for targeted protection strategies. Developing tailored solutions for pipeline seismic isolation within utility tunnels is crucial for maintaining functionality and ensuring public safety.

This work addresses the issue of vibration isolation for pipelines within utility tunnels, with a particular focus on isolation in the longitudinal direction of the tunnel (2). To tackle this problem, appropriate coupled one-dimensional models were developed to represent the interaction between the tunnel and the pipelines inside it, with the goal of evaluating the forces exchanged between the two structures. Special attention was given to the impact of different soil types on the pipelines' response. Following the analysis of the unprotected system's response, a vibration protection strategy based on seismic isolation techniques was proposed. This strategy combines hysteretic tuned mass dampers and impact oscillators with the pipelines to reduce the displacement demand on the isolated structure.

A significant emphasis was placed on studying the nonlinear dynamics of the system, exploring how coupling the isolated pipelines with nonlinear oscillators can beneficially reduce displacement demand. Finally, the proposed model was effectively validated against more refined finite element models, where the tunnel and pipelines were modeled as 3D assemblies of plates and one-dimensional elements. This validation confirmed the effectiveness of the seismic isolation techniques, thereby enhancing the resilience of pipelines housed in utility tunnels.

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Transverse seismic isolation of pipelines in underground utility tunnels for enhanced earthquake protection

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1 - Department of Civil, Construction-Architectural and Environmental Engineering, University of L'Aquila (Italy)

Speaker: Di Egidio Angelo. Invited. **Monday**. Start time: **15:00**. Room: Rhône 4 LVL1. Link to abstract.

The expansion of underground utility tunnels plays a vital role in consolidating essential infrastructure, such as water, gas, electricity, and communication pipelines, into centralized networks. This approach minimizes surface-level disruptions and facilitates easier maintenance, particularly in densely populated urban environments. Traditionally, underground structures were assumed to be inherently safer than their above-ground counterparts, but events like the 1995 Kobe earthquake have challenged this belief. Damage to underground tunnels and their internal systems during such seismic events has highlighted the need for more focused research into the vulnerabilities of these structures. While the resilience of tunnels themselves has been thoroughly investigated, studies addressing the seismic protection of the internal pipelines remain comparatively scarce.
Earthquakes pose significant risks to pipelines within utility tunnels through two primary mechanisms. The first mechanism involves longitudinal seismic effects, where forces act along the pipeline's length, as noted in previous research (1). The second mechanism involves transverse seismic effects, where seismic forces act perpendicular to the pipeline's length (2). This study concentrates on the latter, with a specific focus on vibration isolation strategies that enhance the transverse seismic resilience of pipelines housed within utility tunnels.

A simplified mechanical model is utilized to simulate the interaction between the tunnel and its contents under transverse seismic excitation. To streamline the analysis, the tunnel is modeled as infinitely long, limiting the investigation to a single representative cross-sectional plane. The tunnel's cross-section is assumed to be rigid, with its motion described by three displacement parameters: two translational and one rotational. The surrounding soil is treated as a compressive-only medium, reflecting its inability to sustain tensile forces.

Within the tunnel, the pipelines are mounted on an internal frame, also assumed to be rigid. This frame is connected to the tunnel via flexible connectors that permit only horizontal motion. As a result, the internal frame-pipeline system introduces an additional degree of freedom, requiring one more displacement parameter. To mitigate seismic impacts, a hysteretic mass damper, modeled as a one-dimensional mechanical system, is attached to the internal frame. This damper is designed to limit horizontal displacement between the internal frame and the tunnel, thereby enhancing the behaviour of the system. Overall, the mechanical model representing the tunnel-content system is five-dimensional, encompassing the combined dynamics of the tunnel, internal frame, and damper.

A comprehensive parametric study was conducted, utilizing various recorded earthquake excitations to assess the system's response. Absolute acceleration measurements were taken at critical points within the tunnel, both with and without the implementation of internal isolation mechanisms.

The results underscored the efficacy of the internal isolation strategy. Moreover, they demonstrated that the use of a nonlinear hysteretic mass damper significantly reduced the horizontal displacement of the internal frame structure. Further research into the optimization of damper characteristics could yield even greater resilience against seismic events.

This study contributes valuable insights into the field of seismic protection for underground utility tunnels, emphasizing the importance of considering the dynamic behavior of internal pipelines. It underscores the need for innovative isolation strategies to safeguard critical infrastructure in seismically active regions,

paving the way for more robust and resilient urban utility networks.

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Parameter identification of nonlinear dynamical systems through the Hilbert Huang Transform and the Multiple Scales Method

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Speaker: De Flaviis Andrea. Invited. **Monday**. Start time: **15:20**. Room: Rhône 4 LVL1. Link to abstract.

Keywords: Parameter identification, Nonlinear dynamics, Multiple Scales Method

The parameter identification of mechanical systems is an open issue, which has been largely addressed in the literature over the years. As great emphasis has been given to linear systems, literature applications on nonlinear problems are more recent (1). However, as nonlinearities can exhibit a predominant role in the response of dynamical systems, identification of the parameters ruling their contribution appears as a challenge in the field of inverse problems.

The idea behind this work takes its inspiration from (2), where a 2-d.o.f nonlinear mechanical system was considered and its parameters identified combining the Hilbert Huang Transform (HHT) with the Complexification Averaging (CX-A) (3).

Here the same problem has been tackled but combining HHT with Multiple Scales Method (MSM) (4). The procedure based on the combination of MSM and HHT is here roughly described: 1) System response time series are acquired after application of nonzero initial conditions (they are either taken from experimental tests or from numerical simulations); 2) the HHT is applied to the time series, performing the Empirical Mode Decomposition (EMD) to decompose the original signal in Intrinsic Mode Functions (IMF), i.e. mono-component functions in terms of frequency; 3) the inverse problem is therefore generated by using the Amplitude Modulation Equations (AME) evaluated by the MSM; 4) pseudo-inversion of the AME provides the identified system parameters.

It is found that the proposed method can suitably identify the system parameters for different case studies, ranging from 1-dof systems to continuous ones. As a benchmark, parameter identification through the SINDy algorithm (5) is carried out and comparisons with the proposed technique addressed.

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Theoretical and Experimental Analysis of Axial Wave Transmission in a Rod with a Nonlinear Absorber

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Speaker: Sorokin Vladislav. Invited. **Monday**. Start time: **16:00**. Room: Rhône 4 LVL1. Link to abstract.

Nonlinear vibration absorbers can feature benefits for vibration suppression as compared to their linear counterparts such as the high level of tunability and a wider frequency bandwidth of vibration suppression. While an active area of research, there is still a lack of comprehensive theoretical understanding of the dynamics of continuous systems, such as rods, beams and plates, when one or more nonlinear vibration absorber is attached. Analytical and numerical analysis has been completed that investigates elastic wave transmission through 1D structures with attached damped absorbers featuring Duffing-type nonlinearity. General equations for wave transmission through a rod with a single nonlinear absorber attached were derived via the wave approach and solved using the Method of Varying Amplitudes. Results from the theoretical analysis revealed that the fundamental harmonic dominates, softening and hardening nonlinearity imply qualitatively different responses, and the nonlinear absorber can feature a wider frequency band of effectively reduced vibration transmission as compared to the linear one. An experimental study has been completed to support the theoretical work.
Clamped-clamped beams offer a relatively simple realizable design to achieve stronger nonlinearity, therefore, a nonlinear vibration absorber of this type has been designed and built for experiments. The experimental prototype of the nonlinear resonator consists of an aluminium base frame to which a thin piece of steel shim is attached. Magnets placed at the center of the shim act as the displaced mass. The resonator can be tuned by adjusting the tension in the steel shim, changing the thickness of the shim and increasing the displaced mass. The nonlinearity is characterized by the backbone curve identification and analysis. The absorber is designed such that axial vibrations of the base structure will excite bending in the thin steel material, leading to hardening nonlinearity. The absorber is attached to a rod undergoing axial vibrations and transmissibility is determined by measuring accelerations of the base structure, to either side of the attached absorber.

On the role of 5-wave resonances in the nonlinear dynamics of the Fermi-Pasta-Ulam-Tsingou system

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Speaker: Lotriglia Matteo. **Monday**. Start time: **16:20**. Room: Rhône 4 LVL1. Link to abstract.

In this work we study, from the point of view of Wave Turbulence Theory, the celebrated Fermi-Pasta-Ulam-Tsingou (FPUT) lattice (Fermi *et al.* 1955) for an arbitrary number N of particles, with any number of nonlinear terms in a polynomial expansion ("alpha", "beta", etc.), and with either periodic or fixed boundary conditions.
By looking at the well-known wave dispersion relation of FPUT, relevant to the weakly-nonlinear case, in previous works it was established that 5-wave resonances are relevant to the FPUT dynamics when N $>$ 6 and N is divisible by 3 (Bustamante *et al.* 2019).

The wave-turbulence approach to this problem (Zakharov 1974) assumes that waves are weakly nonlinear, so that near-identity transformations can be performed sequentially to eliminate non-resonant interactions and produce so-called normal forms, where only resonant terms are present. These normal forms can be truncated up to a desired order M, representing M-wave resonant interactions, so that the equations of motion for the normal-form variables represent close approximations of the original equations of motion. Moreover, the original variables can be written in terms of the normal-form variables, so the structural features of the original system are preserved in the normal-form system: constants of motion, hyperchaos, etc.

There is a great advantage in using resonant normal forms. On the conceptual side, the problem reduces to just a number of terms (proportional to N) in the equations of motion, and it is straightforward to construct new independent quadratic invariants, based on previous results from (Harper *et al.* 2013). On the practical side, the timescales become slow, so that the time step can be increased significantly, without any loss of accuracy. This makes long-term behaviour studies feasible, such as energy equipartition phenomena or Lyapunov exponent calculations.

We carefully implement this approach to arrive at the normal-form equations of motion truncated up to 5-wave interactions. This is a new result, improving (Krasitskii 1994), as it even eliminates non-resonant terms within the classes of wave interactions converting 2 waves to 2 waves and also the classes converting 2 waves to 3 waves. When N is divisible by 3 and N $>$ 6, this normal form contains non-trivial resonances (Bustamante *et al.* 2019), and is thus generally non-integrable. This is in contrast to what happens with the normal form truncated up to 4-wave interactions, which is known to be integrable for all values of N (Rink 2006; Henrici and Kappeler 2008). Based on (Harper *et al.* 2013), we construct new independent quadratic invariants for the normal form truncated up to 5-wave interactions. We show that there is always a significant number of these invariants, no matter how large N is. We provide explicit examples for relatively small N cases.

We then proceed to compute numerically, for relatively small values of N, the number of positive Lyapunov exponents of our FPUT normal form truncated up to 5-wave interactions, and show that it is consistent with our result above on new independent invariants.
We then move on to construct a new thermalization theory (with constraints) for the normal-form energies, and validate it numerically, finding very good agreement.

Finally, we show numerically that at low enough nonlinearity the normal form truncated up to 5-wave resonances provides a good approximation to the original system. We do this by carefully evaluating numerically the scaling of the errors between the original variables and the variables mapped from the normal variables, and showing that the errors scale as the fifth power of the wave amplitudes. This is the first time, to our knowledge, that Krasitskii's tensor calculations are validated numerically.

In conclusion, our work "solves" the FPUT system, via Zakharov's method based on weakly-nonlinear

wave interactions to obtain a normal form at the order of 5-wave interactions. While the resulting normal form is resonant and not integrable in general, it has a number of extra quadratic invariants apart from the energy. Thus, the study of thermalization of the normal-form variables is not as simple as in the original system (Benettin and Ponno 2011; Pistone *et al.* 2019): a constrained entropy maximization problem must be introduced, which takes into account the various extra invariants. We tackle this problem using Gibbs' ideas and obtain a theory that predicts maximum entropies which are in good agreement with our numerical simulations. To demonstrate how our method is relevant to the study of the original FPUT system, we perform a direct comparison of the time evolutions of the original FPUT system versus the normal-form system (appropriately mapped) and show very good agreement.

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Bending edge waves on a thin functionally graded cylindrical shell

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Speaker: Som Rahul. **Monday**. Start time: **16:40**. Room: Rhône 4 LVL1. Link to abstract.

The development of the mathematical theory of the bending edge wave started with the work of Konenkov on the thin isotropic plate; after that, many researchers investigated the mechanical behaviour of the bending edge wave on different elastic material plates. Using the asymptotic theory, Kaplunov and his group investigated the behaviour of edge waves on thin elastic shells. This study examined the localized vibration of thin isotropic elastic shells. The kinematic of the shell is governed by the Kirchhoff-Love shell theory. An index grading of the material properties of the shell is considered and varies along the transverse direction of the shell. The surface elasticity theory proposed by Gurtin and Murdoch is included in the model to extract the effects of the mechanical properties of the surface element onto the dispersion of the bending wave on the shell structure. The dispersion relation is obtained by considering a sinusoidal wave propagating along the free edge of the thin semi-infinite shell and decaying exponentially along the longitudinal direction of the shell. The implementation of the asymptotic integration technique on the equation of motion and free edge boundary condition of a circular cylindrical shell enables the extraction of the dispersion of bending wave under a small value of thickness-to-curvature ratio. Analytical and numerical analysis of the resulting dispersion relation is performed, and the results are illustrated with their underlying physics.

Design and Experimental Validation of a Two-to-One Internally Resonant Point Wave Energy Harvester

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Speaker: Khasawneh Mohammad. Invited. **Monday**. Start time: **17:00**. Room: Rhône 4 LVL1. Link to abstract.

Point wave energy absorbers (PWAs) are widely regarded as the simplest and most efficient method for harnessing wave energy (1). Despite their advantages over other methods, PWAs still face a limitation rooted in their reliance on establishing resonance conditions between the sea waves (excitation) and the absorber (resonator). This necessitates the natural frequency of the absorber to align with one of the dominant frequencies in the wave energy spectrum. However, in reality achieving resonance is a challenging undertaking. First, the high stiffness of the hydrostatic restoring force resulting from buoyancy yields an absorber's natural frequency that is typically much higher than the dominant frequencies in the wave spectrum. Lowering this frequency often necessitates adding heavy submerged bodies or incorporating complex mechanical and control solutions. Second, even when the natural frequency is tuned to match the dominant wave frequency, much of the wave energy remains unharnessed because the resonant bandwidth of the PWA is significantly narrower than the broad wave energy spectrum. Finally, operating at linear resonance can induce large-amplitude motions in rough seas, which may compromise the structural integrity of the absorber.
In a previous study (2), we proposed a novel PWA design to overcome these limitations. This design features a broader bandwidth, reduced sensitivity to variations in excitation frequency, and the ability to respond to wave frequencies as low as half the fundamental frequency of the absorber. It also avoids the sharp resonance peak associated with the response of linear PWAs. The key innovation lies in incorporating an additional mass suspended inside the buoy via a nonlinear restoring force, creating an auxiliary oscillator. The natural frequency of this auxiliary oscillator is tuned to the dominant frequency of the wave spectrum and to half the natural frequency of the primary oscillator. When subjected to low-frequency wave excitation, the auxiliary oscillator resonates, transferring energy to the primary oscillator through a two-to-one internal resonance mechanism. This interaction generates a reasonably large-amplitude motion for the buoy over a wide frequency range, which can then be converted into electricity using Faraday's law of induction.

Our earlier work (2) validated this concept through numerical simulations under regular and random wave excitations, as well as tested it using an electrodynamical shaker. The present study focuses on advancing this concept by building a prototype and conducting experimental tests under real wave excitation in a laboratory-scale wave flume.

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Dynamics of axially traveling string with fluctuating speed and curved obstacles at both ends

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Speaker: Sharma Abhishek. **Monday**. Start time: **17:20**. Room: Rhône 4 LVL1. Link to abstract.

Abstract

This research investigates the transverse vibrations of an axially traveling string against curved obstacles at both ends. The axial velocity of the string is fluctuating, which makes the system parametrically excited and leads to fairly complex dynamics. Floquet theory is employed to conduct the linear stability analysis. Stability diagrams illustrate the regions in the operating parameter space where the straight configuration and the associated vibrations are stable/unstable. We also investigate the influence of the resulting non-uniform tension on the stability regions.

Introduction

Several engineering systems like band saw blades, threadlines, high-speed magnetic tapes, and pipes transporting fluids involve the transverse vibration of an axially moving continua. More specifically, our system is pertinent to applications like ropeways and conveyor belts, which have big pulleys at the ends. Due to their technological importance, various researchers have explored the dynamics of axially moving systems. Wickert and Mote (1,2) studied the free and forced linear dynamics of axially moving continua by employing an eigenfunction method specifically for discrete gyroscopic systems or the Green's function method to obtain the dynamic response of axially moving string subjected to a traveling mass. Pakdemirli and Ulsoy (3) used the method of multiple scales to get the stability boundaries for an axially accelerating string and found that instabilities were observed when the frequency of the velocity fluctuations approached twice the natural frequency of the system at the mean velocity. More detailed studies on axially traveling systems can be found in (4-6). However, these studies focused solely on the dynamics of axially traveling strings, with no obstacle present at the ends as well as ignored any axial variation in the tension due to velocity fluctuations. The incorporation of non-uniform tension introduces linear coupling, modifying the stability boundaries. Furthermore, interaction with the curved boundaries introduces complexity resulting in nonlinear effects and more intricate dynamic responses that have been incorporated into our study. A comprehensive linear stability analysis that incorporates both uniform and non-uniform tension offers new insights into the dynamic behaviour of the system.

The current study assumes that the string travels with harmonically fluctuating velocity about some mean velocity. The primary features of these systems consist of velocity-dependent natural frequencies and the existence of a critical speed at which divergence instability arises. The wrapping and unwrapping of the string around the obstacle introduces a moving boundary (7), which, with a suitable scaling, is converted into a fixed boundary problem at the expense of introducing nonlinearities in the governing equation of motion. The variational principle has been used to derive the governing equation of motion and the appropriate boundary conditions. This system comes under the category of parametrically excited systems because of the presence of time-dependent terms in the governing equations. Previous studies (1-6) used either the stationary or traveling modes to discretize the governing partial differential equation. Stationary modes have slow convergence, whereas projections of nonlinear terms with traveling modes in our study are quite tedious. Hence, we use the assumed mode method to get the reduced-order system of ordinary differential equations governing the transverse vibrations of our system. In this method, the Lagrangian of the system is obtained in terms of the assumed solution for the string displacement. Then, the application of the Euler-Lagrange equation provides the system of ordinary differential equations that govern the dynamics of our system. We validate our model by comparing the linear vibration characteristics against those obtained from the discretized system using the stationary and traveling modes.

This validated model is used for linear stability analysis wherein we linearize our system about the static configuration of the string and study the linearized system using Floquet theory. The absolute values of the eigenvalues of the monodromy matrix, termed Floquet multipliers, depict the stability of the system. If any floquet multiplier is greater than one, then the system is unstable; if it is less than one, the

system is stable. We plot the stability diagram between the forcing frequency and the fluctuating velocity amplitude for a fixed mean velocity value. We examine two cases, one in which tension remains uniform and the other where the tension varies spatially. In realistic cases, the tension typically changes due to the acceleration of the string, making it essential to consider non-uniform tension for a more accurate analysis.

Results and discussion

It is concluded that the dependence of the natural frequency on the traveling velocity is countered by the presence of the curved obstacles. It is observed that the discretization of the partial differential equation using the stationary modes shows slow convergence and involves some spurious roots. Discretization using the traveling modes is exact but complex. The assumed mode method is simple and gives fewer spurious roots than discretization using stationary modes. Linear stability analysis illustrates the influence of mean velocity, fluctuating velocity amplitude, and excitation frequency on the stability of the system. The spatial variation of tension influences the stability regimes. In contrast to the constant tension example, it enlarges the instability regime for lower mean velocity values while decreasing the number of unstable points in the parameter space at higher mean velocities.

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Nonspherical oscillations of an encapsulated magnetic microbubble

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Speaker: Krishna B J Arun. **Monday**. Start time: **17:40**. Room: Rhône 4 LVL1. Link to abstract.

Encapsulated microbubbles is used in biomedical applications, serving as drug delivery carriers and contrast agents for ultrasound imaging. Recent advancements have focused on developing magnetic microbubbles that integrate diagnostic and therapeutic functions. A key phenomenon in these systems is the resonant frequency of the bubbles. While resonance should be avoided in contrast agent applications to extend the carrier time, it is exploited in drug delivery to rupture the bubble and release the drug. Therefore, understanding and modeling the resonant frequency and the stability of these bubbles is essential.
The radial dynamics of encapsulated bubble is well understood by modifying the standard Rayleigh-Plessset equation to include the encapsulation effect. To understand about non-spherical oscillation of bubbles many papers assumed non-linear radial oscillations and linear shape mode oscillations. Using these assumptions by surface elasticity theory mode shape equations is derived and surface Instability of derived shape modes is obtained (1). But, these equations were not completly valid due to consideration of linear shape modes. Recent papers have modified the non-linear shape mode interactions of gas bubble models for an encapsulated bubble and found out that non-linearity saturates the instability from spherical oscillations in case of encapsulated bubbles also (2).

There are very few works on modelling non-spherical oscillations of encapsulated bubbles under magnetic fields. This is mainly due to the fact that surface magneto elasticity is not well developed to apply to bubble surfaces. Also, due to absence of magnetic monopoles purely radial magnetic field is impossible and it is at least axisymmetric and forces on the bubble surface have both radial and tangential components. This does not allow the use of potential flow assumption and restricts usage of energy methods to obtain mode shape equations.

In this work to model non-spherical oscillations of encapsulated magnetic bubbles, instead of interface theory a simple membrane theory for Finite deformation of magneto-elastic membranes developed by Steigmann and Barham (3) is used. The membrane theory is approximaing the three dimensional elasticity equation to two dimension by leading order approximation along thickness . The assumption involved in magneto-elasticity is that the membrane is a poymer coated with weakly magnetic particles. This allows to neglect induced magnetic fields and magnetic forcing is only througn applied magnetic field and field gradients created by coils symmetrically placed above and below the bubble. The bubble's deformed shape is expressed using radial and tangential shape modes and by using orthogonality of Legendre polynomials, individual shape mode equations is derived.

But, the derived equations encounter similar limitations as linear shape mode approximation of non-magnetic bubbles. The dynamics of bubble when nonlinear mode interaction is considered is unknown as our equations starts behaving exponentially when applied pressure reaches a critical value at given driving frequency which may or may not be actual behaviour of the bubble. However, there is a region in applied pressure amplitude-frequency plane in which our equations are valid. These regions are computationally found and it is observed that this region geneally increases with higher driving frequencies and some sudden dips in pressure amplitude is observed which may be caused due to standard as well as sub harmonic resonances. Using the approximation that toroidal vortex in the fluid is confined to a small boundary layer near bubble surface natural frequency of each modes is obtained computationally. Also, how the stability diagrams vary with various material parameters is computationally studied.

Despite its limitations, this model provides a foundational framework for analyzing the behavior of coated magnetic microbubbles Within the critical pressure amplitude and frequency ranges. This approach enables the study of their dynamics, paving the way for future research to address non-linear interactions and refine the model further.

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Energy exchange in a mass-in-mass meta cell with geometrically customized nonlinearity

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Speaker: Ture Savadkoohi Alireza. Keynote. **Tuesday**. Start time: **10:00**. Room: Rhône 4 LVL1. Link to abstract.

Vibration is a prevalent physical phenomenon encountered across various engineering applications. Understanding and controlling vibrations in mechanical systems are of key concern as they affect the serviceability and overall performance of these systems. Excessive vibrations can compromise operational efficiency and may pose risks to sensitive equipment or individuals. Effective vibration control is especially important when the vibrations occur within critical frequency ranges. To address this, various passive control techniques are available. One widely used method is the tuned mass damper (TMD), which involves attaching a secondary mass with a prescribed mass ratio to the primary structure using linear spring-damper elements. While conventional TMD systems are effective, they have the limitation of reducing vibrations within a narrow frequency range, typically addressing only a particular mode due to their linear springs. An alternative approach is to employ nonlinear energy sinks (NES), which incorporate a nonlinear spring and, therefore, have an energy-dependent natural frequency. This unique characteristic allows the NES to sequentially mitigate multi-modal vibrations from high to low frequencies through resonance capture, making NES notably advantageous over traditional TMDs in controlling multi-modal vibration.
Creating nonlinear stiffness is the core to dynamic design of NES, often tailored to specific requirements and application scenarios. Depending on material properties and geometric configurations, there are several ways to form nonlinear stiffness. NES can generate or adapt to specific nonlinear force profiles are increasingly valuable as they allow tailored responses in systems subjected to complex dynamic loads. Among nonlinear force profiles, cubic and piecewise nonlinearity have garnered particular interest due to their versatile applications in systems requiring energy dissipation or vibration isolation.

This study presents an analysis and experimental validation of energy exchange in a mas-in-mass meta cell with a tailored nonlinearity. In this regard, a device specifically engineered to customize pure cubic and piecewise nonlinear forces, with potential applications in vibration isolation, frequency tuning and dynamic response control in various systems. The device is designed using a combination of mechanical springs, and uniquely curved mechanical stops. These components are arranged in a configuration that allows adjustment of the force-displacement relationship, resulting in customizable nonlinear force characteristics. The primary mechanism enabling cubic nonlinearity involves a carefully tuned spring system. The spring stiffness and pre-compression are adjusted to achieve a cubic relationship between force and displacement over a desired operational range. To generate piecewise nonlinear force, the device utilizes adjustable stops or mechanical stops with curvature that engage at predetermined displacement thresholds. These stops introduce abrupt changes in stiffness, which results in a force profile that switches between different stiffness values as the displacement reaches specified points. By adjusting the position of the stops and the stiffness of the springs, the force-displacement profile can be customized.

An experimental setup is constructed to validate the numerical results. The device is mounted on a vibration testing platform capable of providing controlled displacements and loads. Sensors are attached to measure displacement, force, and acceleration, allowing precise monitoring of the device's response to various input conditions. The experimental protocol includes tests for both pure cubic and piecewise nonlinear configurations, with multiple trials conducted to ensure repeatability and accuracy. The device is subjected to harmonic excitation over a range of frequencies and amplitudes. The resulting force-displacement curves are recorded and compared with the numerical model predictions.

The designed NES has significant potential in fields that benefit from tailored nonlinear dynamics. For instance, in vibration isolation, the cubic nonlinearity allows for higher energy dissipation and improved isolation at specific frequency ranges. Similarly, the piecewise nonlinearity could be utilized in shock

absorbers, where a variable stiffness profile is necessary to handle impacts of varying magnitudes, ensuring efficient energy absorption over a wider frequency range. Additionally, this NES can be used in systems exposed to dynamic loads, such as bridges or buildings, where nonlinear damping mechanisms are beneficial for reducing resonance and prolonging structural life. Moreover, the proposed NES can be arranged in a chain of meta-cells to tailor wave propagation by creating periodic and non-periodic responses, enabling their use as vibro-acoustic filters. The device's ability to tailor force profiles makes it ideal for adaptive systems that require different force responses due to changing environmental conditions or operational demands.

This study successfully demonstrates the design, analysis, and experimental validation of a NES capable of generating pure cubic and piecewise nonlinear force profiles. The performance of the designed NES, particularly in terms of energy exchange, is verified through numerical modelling and experimental testing. This research establishes a foundation for developing advanced devices that leverage nonlinear dynamics for practical engineering applications, paving the way for more resilient and adaptable systems in various engineering fields. Furthermore, investigating the performance of the proposed NES under multi-directional or complex loading conditions presents a promising avenue for future research.

Design of a nonlinear energy sink with energy harvester

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Speaker: Dalroti Mohammad Huzefabhai. **Tuesday**. Start time: **10:40**. Room: Rhône 4 LVL1. Link to abstract.

Ambient vibrations are ubiquitous, arising from sources such as human motion, machinery, structures, and ocean waves. Most of their energy lies in wide spectra of low frequencies. In machinery and structural systems, mitigating these vibrations is crucial, making low-frequency vibration reduction a prominent research area. Structural health monitoring, which uses sensors to detect and quantify ambient vibrations, faces challenges with frequent battery replacements. To address this, energy harvesting mechanisms are integrated into sensors to capture ambient vibrations and power the sensors. As a result, both vibration mitigation and energy harvesting have become significant areas of study.

Linear tuned mass dampers (TMDs) have been widely used for vibration mitigation. These secondary attachments, tuned to match the resonance frequency of primary systems, effectively reduce vibrations and harvest energy near resonance points. However, their performance deteriorates outside these frequencies. This limitation has led to the development of nonlinear energy sinks (NES), which operate over broader frequency ranges, and arrays of TMDs for multiple resonance frequencies.

Nonlinear energy sinks are secondary attachments that dissipate vibration energy through nonlinear coupling with primary systems. They mitigate vibrations across wide frequency bands and, when combined with energy harvesters, enable simultaneous vibration reduction and energy harvesting. This study examines a system integrating a nonlinear energy sink with an electromagnetic energy harvester.

The investigated system comprises a primary oscillator subjected to harmonic base excitation and a secondary NES attachment that absorbs vibration energy. An electromagnetic energy harvester is attached to the secondary mass (NES) converts mechanical energy into electrical energy through magnetic levitation in a current-carrying coil attached to the primary oscillator. The electromotive force (EMF), generated through the relative motion between the coil and the magnet, depends on the rate of change of electromagnetic flux, a nonlinear function influenced by the magnet's position, orientation, and velocity. However, many studies simplify this phenomenon by treating flux changes as linearly dependent on magnet velocity. This analysis prioritizes the accurate representation of the magnet's position and velocity to quantify energy transfer between the mechanical system and the electrical circuit.

The energy dissipation of the system is quantified both with and without the NES. Additionally, the impact of the energy harvester on the system dynamics and energy dissipation is evaluated. A parametric analysis is performed to optimize the system's performance. The findings provide insights into designing efficient linar oscillator with nonlinear energy sink (LO-NES) systems for applications requiring both vibration mitigation and energy harvesting.

Elastic wave transmission in a 1D elastic structure with an attached nonlinear autoparametric pendulum absorber

Pan Junqi (1), Sorokin Vladislav (2)

1 - University of Auckland (New Zealand), 2 - University of Auckland (New Zealand)

Speaker: Pan Junqi. Invited. **Tuesday**. Start time: **11:00**. Room: Rhône 4 LVL1. Link to abstract.

Autoparametric pendulum absorber is an effective device for vibration suppression and has been widely employed in various engineering applications. However, most studies on pendulum absorbers are based on discrete systems. In this paper, the dynamics of a pendulum absorber attached to continuous structures, such as rods and beams, is studied. This is motivated by the fact that numerous real mechanical components and structures can be modeled as rods and beams. First, the simplest case is considered: a single pendulum absorber attached to an elastic rod. The wave transmission and reflection at the pendulum attachment point are determined. Then performance of a single autoparametric absorber attached to a beam is studied. The governing equations of motions for the pendulum attached to the rod and the beam are derived using elastic wave theory. Subsequently, the response of the systems is analyzed using the method of varying amplitudes, and the results are validated numerically. Due to the energy transfer from the hosting structure into the motion of the pendulum, it is shown that the transmitted wave can be reduced considerably. The system parameters affecting the reduction of the transmitted wave are investigated, and a comparison is made between the effectiveness of the autoparametric pendulum absorber and that of the conventional linear mass-spring-damper absorber. It was found that the nonlinear pendulum absorber can exhibit a wider bandwidth and superior vibration transmission reduction performance compared to the linear absorber.

Vibration attenuation on Tubular Telecommunications Towers using Non-Linear Energy Sink

Mbaki Zacarias (1) (2), Chénard Samuel (2), Langlois Sébastien (2), Ture Savadkoohi Alireza (1)

1 - LTDS (France), 2 - University of Sherbrooke (Canada)

Speaker: Mbaki Zacarias. Invited. **Tuesday**. Start time: **11:20**. Room: Rhône 4 LVL1. Link to abstract.

Telecommunication towers are a crucial component of modern communication infrastructure, facilitating the transmission and reception of signals for various communication forms such as mobile phones, radio, and television. However, the airflow around these structures may generate vortex shedding, which can lead to excessive vibrations, resulting in structural fatigue, reducing the tower's lifespan, and compromising its integrity

One commonly used solution by various manufacturers is the Tuned Liquid Dampers (TLDs) to mitigate vibrations. Tuned Liquid dampers uses a liquid confined in a container, to control vibrations of a primary structure, by dissipating the energy through the fluid damping inside the container. This damper offers the advantage of being cost effective. However, these solutions have several drawbacks: they are effective only at a specific frequency, involve complexity in reservoir sizing, and are highly dependent on the choice of fluid, among others.

Our study proposes the use of Nonlinear Energy Sinks (NES) as an alternative to TLDs. NES take advantage of nonlinearities to control vibrations across a broad frequency range while offering the benefits of simplicity in analysis and design compared to TLDs. This work focused on the application of this approach to control vibrations in steel tubular telecommunication towers. The simulations show promising results, demonstrating that this solution can effectively meet the requirements for vibration control in the studied structures.

Analysis of radiation efficiency and sound transmission loss of functionally graded plates using the state space method

Paital Chittaranjan (1), Gopal K. V. Nagendra (1)

1 - Indian Institute of Technology Madras, Chennai, 600036,India (India)

Speaker: Paital Chittaranjan. **Tuesday**. Start time: **11:40**. Room: Rhône 4 LVL1. Link to abstract.

This study examines the radiation efficiency (RE) and sound transmission loss (STL) of flexible finite functionally graded material (FGMs) plates in an infinite rigid baffle. FGMs are composite materials engineered to possess heterogeneity by continuously varying the composition of the constituent materials in a chosen direction. Such customization makes FGMs highly suitable for designing vibro-acoustically efficient structures. Accurate modeling analysis of the multiphysics response of FGM structures is challenging. First, the effective material properties of these materials have to be estimated by either using a simple rule-of-mixtures approach or more complex elasticity or numerical models. The radiation efficiency of FGM plates under harmonic force and sound transmission loss of the plate under oblique incident acoustic waves are analyzed. Acted load vibrates the plate and radiates sound. The state space formulations for plate vibrations are derived from the full three dimesional equations of motion, stress-strain, and strain-displacement relations (1). An elementary radiator approach solves the Rayleigh integral that links the plate velocity to the radiated pressure waves. Radiation efficiency represents the actual sound power radiated by the plate compared to an ideal vibrating piston. Sound transmission is quantified by the ratio of transmitted to incident sound power. Yang et al. (2) investigated only the sound power level for an FGM plate using the state space method. This implementation is validated through comparisons with existing literature.
The radiation efficiency (RE) and sound transmission loss (STL) of functionally graded (Al/Al2O3) plates simply supported on all edges is presented in this work for different power law variations of the material properties. As the FG layer's power law index rises, it is seen that the RE curves exhibit a declining tendency. The STL curve may have three separate stiffness, mass, and damping control areas, respectively. A detailed study of the effects of plate thickness, plate aspect ratio, damping, load type, and incident angle on RE and STL is presented.

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Data-driven Soft Robot Control using Adiabatic Spectral Submanifolds

Kaundinya Roshan (1), Matt Jonas (1), Alora John (2), Pabon Luis (2), Pavone Marco (2), Haller George (1)

1 - ETH Zurich (Switzerland), 2 - Stanford Univeristy (United States)

Speaker: Kaundinya Roshan. Invited. **Tuesday**. Start time: **14:15**. Room: Rhône 4 LVL1. Link to abstract.

Controlling soft robots is inherently challenging due to their flexible and dexterous design, which leads to highly nonlinear dynamics described by high-dimensional governing equations. These complexities make real-time control difficult, especially for dynamic trajectory tracking tasks. Additionally, in most real-world applications, data is typically limited to a few planned experiments conducted on the soft robot. Soft robots are primarily intended for use in environments such as surgical procedures, underwater deep explorations, and space satellite maintenance. In these contexts, precise control is crucial for safely executing dynamic trajectory tracking tasks. Notably, the speeds of soft robots are generally much slower than the intrinsic decay rates of their vibration modes. This observation can be leveraged by applying recent theory of temporal spectral submanifolds (SSMs) to identify a low-dimensional adiabatic spectral submanifold (aSSM) from data. By reducing the robot's dynamics to an aSSM, we obtain a non-autonomous reduced model that accurately captures the dominant slow dynamics of the system. Further an aSSM is typically normally hyperbolic, making it robust to fast, bounded control perturbations as well. These properties make the aSSM-reduced model well-suited for model predictive control. We demonstrate that a 5-dimensional aSSM-reduced model effectively captures the dynamics of a high-dimensional soft trunk robot. This model outperforms existing nonlinear and linear control methods across various 3D closed-loop target control tasks.

High codimension bifurcation in suspended cables under aerodynamic forces

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Speaker: Zulli Daniele. Invited. **Tuesday**. Start time: **14:35**. Room: Rhône 4 LVL1. Link to abstract.

Suspended cables are commonly used structures in many civil and industrial applications. In cold regions, where ice accretions can break the axial-symmetry of the cable cross-section, the occurrence of the galloping phenomenon is often observed, and cables experience high amplitude/low frequency oscillations, even for moderate and uniform wind (1). The phenomenon can be explained as a Hopf bifurcation happening at a certain critical wind velocity, and limit cycles occurring in post-critical conditions. In (2), a mechanical model of cable was proposed, where the wind was assumed to: (a) modify the equilibrium configuration initially occupied by the cable under self-weight, through the mean component; (b) induce the Hopf bifurcation from the modified equilibrium through the dynamic component. There it was observed that, besides the wind velocity which represents the main bifurcation parameter, a second parameter, namely the initial orientation of the ice accretion, was crucial to determine whether the critical mode was of symmetrical or anti-symmetrical shape. Furthermore, a third parameter, namely the initial sag-to-span ratio, was able to change the critical frequency of the symmetric mode.
It mean that there exist a critical value of the three parameters (wind mean velocity, initial orientation of the ice accretion and sag-to-span ratio) at which a 1:1 resonant double Hopf bifurcation occurs, i.e. where the symmetric and anti-symmetric modes have both the same critical wind velocity and frequency.

Here, the critical conditions for the occurrence of the mentioned codimension-three bifurcation are sought and the post-critical analysis is carried out, paying special attention to the transitions from non-resonant to resonant double Hopf bifurcation.

Acknowledgements
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Direct parametrisation of invariant manifold with shell finite element: nonlinear dynamics of thin structures using reduced order modeling

Xia Zixu (1), Cong Yu (1), Nedjar Boumediene (1), Lerbet Jean (1), Zahrouni Hamid (2), Gu Shuitao (3), Feng Zhi-qiang (1)

1 - Université d'Évry-Val-d'Essonne (France), 2 - Université de Lorraine (France), 3 - Chongqing University [Chongqing] (China)

Speaker: Xia Zixu. **Tuesday**. Start time: **14:55**. Room: Rhône 4 LVL1. Link to abstract.

The nonlinear dynamics of thin structures is a prominent research focus in modern mechanics. Compared to solid elements, shell elements are particularly attractive due to their reduced degrees of freedom and the straightforward application of displacement assumptions in the transverse direction. Despite having fewer degrees of freedom, shell elements still require considerable computational resources when used in nonlinear frequency domain analysis. As a result, developing an accurate and efficient Reduced Order Model (ROM) is critical for advancing the study of the dynamic behavior of thin structures. In this work, we propose the numerical framework of ROM incorporating the Direct parametrization of invariant manifold (DPIM) and 7-parameter solid-shell element to investigate the nonlinear dynamic behavior. Unlike traditional shell theories such as Kirchhoff-Love and Reissner-Mindlin, the solid-shell element directly applies three-dimensional constitutive relations without any modification. It inherently considers Enhanced Assumed Strain (EAS) through a mixed variational principle to prevent Poisson locking. Numerical examples demonstrate that our reduced-order model can accurately compare with the full-order model based on the Harmonic Balance (HB) method. Through this validation, we analyzed several cases to further explore nonlinear vibration behavior.

Utilizing Nonlinear Oscillator Arrays as Physical Reservoir Computers

Gupta Ayush (1), Agarwal Vipin (1)

1 - Department of Mechanical Engineering, University of Memphis (United States)

Speaker: Gupta Ayush Agarwal Vipin. **Tuesday**. Start time: **15:15**. Room: Rhône 4 LVL1. Link to abstract.

This work introduces a nonlinear multi-oscillator array as a physical reservoir computer, proposing a novel approach to computational tasks by leveraging the intrinsic dynamics of coupled oscillators. Unlike traditional reservoir computing, which relies on recurrent neural networks (RNNs) as computational reservoirs, a physical reservoir directly utilizes a physical system's inherent dynamics. The nonlinear behavior of oscillators makes them highly suitable as a computational medium, providing flexibility and depth for data processing. By adjusting parameters such as stiffness, damping coefficients, and inter-oscillator coupling, we can fine-tune the reservoir's properties, including vibration frequencies, amplitude, and equilibrium points, allowing precise control over its dynamic behavior. The interactions among oscillators introduce complexity, enabling synchronized and chaotic behaviors that capture intricate temporal dependencies in signal processing. Input signals are transformed into high-dimensional outputs through the oscillations of individual oscillators, where each oscillator represents a unique dimension within the state space. This high-dimensional representation is then utilized in neural network models for applications such as temporal data classification and time series prediction. The proposed multi-oscillator reservoir thus offers a versatile and customizable framework for advancing physical reservoir computing.

Stability and robustness assessment of self-synchronizing vibrating screens

Szabó Márton (1), Miklós Ákos (1), Habib Giuseppe (1)

1 - Budapest University of Technology and Economics, Department of Applied Mechanics (Hungary)

Speaker: Szabó Márton. Invited. **Tuesday**. Start time: **15:35**. Room: Rhône 4 LVL1. Link to abstract.

Since the early 20th century scientists have noticed the inclination of machines driven by two or more eccentric rotors towards self-synchronization. This means that rotors that are not otherwise connected mechanically, for example through gears, chains or drive belts, tend to synchronize their motion through the weak coupling of the machine body. One of the prime examples of industrial machines showing this phenomenon are linear vibrating screens, which have two unbalanced shafts rotating in the opposite direction, theoretically creating a unidirectional force excitation on the sieve body. Concerning this type of machine, the main goal of the present study is to investigate the global stability of the synchronized motion with respect to the difference between the driving torques acting on the rotors. In literature various analytical methods for the local stability estimation of the synchronized regime have already been established, from which the stability boundary of the system with respect to the driving torque can be obtained. The results from these analytical methods exhibit an excellent agreement with numerical simulations of the system dynamics. However, numerical simulations show a large regime where synchronous and non-synchronous motions for the same driving torque difference coexist, which indicate that the basin of attraction for the stable, synchronous motion is finite. To assess the safety of this region, the dynamical integrity of the synchronous state was computed; in particular, we estimated its local integrity measure by exploiting the algorithm proposed by Habib (Nonlinear Dynamics, Vol. 106, issue 3, (2021) p 2073-2096). Results indicate that a significant part of the investigated region has too small dynamical integrity for being of practical use. Which would mean that in practice, the driving torque difference of the two unbalanced rotors cannot be as large as previously calculated for the vibrating screen to retain its synchronous operation.

Nonlinear Modeling and Control of Artificial Muscles via Spectral Submanifolds

Bettini Leonardo (1), Kazemipour Amirhossein (1), Axås Joar (1), Katzschmann Robert (1), Haller George (1)

1 - ETH Zurich (Switzerland)

Speaker: Bettini Leonardo. Invited. **Tuesday**. Start time: **15:55**. Room: Rhône 4 LVL1. Link to abstract.

Advancements in robotics increasingly draw inspiration from the adaptability and versatility of biological systems. Artificial muscles, designed to mimic the force-generating functionality of biological muscles, play a crucial role in musculoskeletal robotics and prosthetics. Among various soft artificial muscles, Hydraulically Amplified Self-Healing Electrostatic (HASEL) actuators represent a promising solution that combines the benefits of soft fluidic and electrostatic actuation. They consist of oil-filled pouches partially covered with electrodes, that redistribute the oil upon activation through applied voltage and allow contraction. Modeling and controlling HASEL actuators poses significant difficulties due to their complex interplay between soft materials, electrostatic forces and frictional elements, which produce fundamental nonlinear dynamics and introduce memory effects and hysteretic behavior into the system. At the same time, capturing the essential dynamics is crucial for accurate system representation and effective control strategies, such as Model Predictive Control (MPC). The complexity of the problem prompts us to seek a reduced-order model directly from data. Among the numerous model reduction techniques, we employ the reduction to Spectral Submanifolds (SSMs). The theory of SSMs provides a mathematically justified method to capture the essential nonlinear dynamics on low-dimensional, attracting invariant manifolds in the phase space of the system. Nearby trajectories approach the SSMs and quickly synchronize with their internal dynamics, which then serve as accurate reduced models for the longer-term dynamics of the full system. The data-driven reconstruction of SSMs and their reduced dynamics have proven successful, not only in reconstructing the autonomous behavior, but also predicting the response under periodic and general external forcing. In particular, the setting of the adiabatic SSM under slow forcing lends itself well to control applications, wherein the internal time scale of the system dynamics is much faster than the targeted motion of the robot. We construct the SSM-based reduced order model of the HASEL actuator from a single observable, i.e. the vertical stroke, at different levels of voltage. With the inclusion of forcing into the model, we can then predict the robot's displacement given the commanded voltage or compute the voltage required for the robot to follow an envisioned trajectory.

MS6.2 - Elastic Metamaterials and Topological Aspects of Waves

Organisers: Agnès Maurel (ESPCI), Anastasiia O. Krushynska (Groningen, NL) and Régis Cottereau (CNRS Marseille, FR)

Programmable Surface Dimpling for Aerodynamic Textile Metamaterials

Farrell David (1), Mccann Connor (1), Forte Antonio Elia (2), Walsh Conor J. (1), Bertoldi Katia (1)

1 - Harvard John A. Paulson School of Engineering and Applied Sciences (United States), 2 - King's College London (United Kingdom)

Speaker: Farrell David. **Wednesday**. Start time: **14:30**. Room: Roseraie 2 LVL3. Link to abstract.

For high-speed sports, marginal differences in air resistance can have a compounding impact over time, making aerodynamics a critical factor in determining competitive success. Traditional textiles used in athletic apparel are characterized by fixed surface roughness and static aerodynamic properties, overlooking dynamic velocity profiles and varying environmental conditions. Here, we introduce textile metamaterials designed to promote and actively control mesoscale dimples on worn textiles. Our textile metamaterial consists of a stiff woven fabric bonded to a spandex knit. Guided by Finite Element simulations, we demonstrate that by varying the architecture of the woven fabric, we can significantly alter the shape, location, and depth of the dimples on the worn textile, as well as their evolution under applied deformation. Notably, by optimizing the dimples, we can selectively modulate the drag of a textile-wrapped cylindrical shape. More importantly, we show that by controlling the applied deformation, we can actively tune the dimples to maintain minimal drag force under varying wind speeds. These advancements open the door to a new generation of adaptable, aerodynamic textiles.

Surface impedance and topologically protected interface modes in one-dimensional phononic crystals for longitudinal and bending elastic waves

Coutant Antonin (1), Lombard Bruno (2), Rallu Antoine (3)

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Speaker: Rallu Antoine. **Wednesday**. Start time: **14:50**. Room: Roseraie 2 LVL3. Link to abstract.

When semi-infinite phononic crystals (PCs) are in contact, localized modes may exist at their boundary. The central question is generally to predict their existence and to determine their stability. With the rapid expansion of the field of topological insulators, powerful tools have been developed to address these questions. In particular, when applied to one-dimensional systems with mirror symmetry, the bulk-boundary correspondence claims that the existence of interface modes is given by a topological invariant computed from the bulk properties of the phononic crystal, which ensures strong stability properties. This one-dimensional bulk-boundary correspondence has been proven in various works. Recent attempts have exploited the notion of surface impedance, relying on analytical calculations of the transfer matrix. In the case of second-order operators describing longitudinal waves, we prove the monotonic evolution of surface impedance with frequency, for all one-dimensional phononic crystals with mirror-symmetry (1). This result allows us to establish a stronger version of the bulk-boundary correspondence that guarantees not only the existence but also the uniqueness of a topologically protected interface state. This correspondence is extended to a larger class of one-dimensional models that include imperfect interfaces, array of resonators, or dispersive media. Numerical simulations are proposed to illustrate the theoretical findings. Current extension to fourth-order operators describing bending waves in Euler-Bernoulli beams is also addressed. (1) A. Coutant, B. Lombard, "Surface impedance and topologically protected interface modes in one-dimensional phononic crystals", *Proceedings Royal Society London A* 480 (2024), 20230533

Design of interface states using canonical phononic waveguides

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Speaker: Morini Lorenzo. **Wednesday**. Start time: **15:10**. Room: Roseraie 2 LVL3. Link to abstract.

We propose a novel and rigorous method to predict the presence of localized modes at the interface between two dissimilar two-phases quasiperiodc phononic waveguides. The condition for the presence of an interface state between two one-dimensional structures, requiring that the sum of the surface impedances of the two waveguides that make up the system is zero and previously introduced for electromagnetice waves (1), is here applied to study mechanical localized modes. We show that, for systems composed of two quasiperiodic rods which elementary cell possesses particular layouts corresponding to a periodic frequency spectrum, the so-called *canonical* configurations (2), it is possible to determine exactly all the gaps of the spectrum where this condition is satisfied. The variation of the impedance inside each band gap is analyzed through the method of the universal toroidal manifold, recently introduced by the authors to describe the dynamical properties of this class of structures (3). In terms of prediction, the results obtained are identical to those derived by calculating the Zak phase of the bulk bands for both the waveguides composing the system (4). Considering two specific combinations of finite canonical rods and analyzing the associated reflection coefficients, we obtain exact equations to determine the frequency of the interface state. Our approach provides new insight to design and optimize systems where interface modes appear inside a prescribed gap avoiding the challenging numerical calculations normally required to estimate topological invariants such as the Zak phase.

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Designing elastic metasurfaces for Scholte-Stoneley wave control at solid-fluid Interfaces

Zeighami Farhad (1), Quqa Said (1), De Ponti Jacopo Maria (2), Ayyash Nadeen (1), Marzani Alessandro (1), Palermo Antonio (1)

1 - University of Bologna (Italy), 2 - Politecnico di Milano (Italy)

Speaker: Palermo Antonio. **Wednesday**. Start time: **15:30**. Room: Roseraie 2 LVL3. Link to abstract.

Scholte-Stoneley waves (SSWs) are interface waves propagating along solid-fluid boundaries, with significant potential for diverse engineering applications, such as microfluidics and lab-on-chip devices. However, achieving effective control over their propagation remains challenging. In this study, we propose a novel approach to manipulate SSWs using elastic metasurfaces, consisting of a periodic array of subwavelength mechanical resonators placed at the solid-fluid interface.
The solid and fluid media are chosen such that the velocity of the solid exceeds that of the fluid, cS> cF, ensuring that the standard SSW speed is close to the velocity of the fluid. The resonator is modeled as an equivalent boundary condition exerting a uniform vertical force on the solid medium, allowing for the derivation of analytical dispersion relations valid in the long-wavelength regime. Inspection of the dispersion curve reveals a strong interaction between the fundamental SSW mode and the collective resonances of the mechanical resonators. Unlike the typical behavior observed in surface Rayleigh waves interacting with elastic metasurfaces, this hybridization does not induce a frequency bandgap. Instead, the velocity and the degree of localization of the fundamental SSW mode can be finely tuned through careful design of the elastic metasurfaces.

To validate these theoretical predictions, we employ numerical finite element (FE) simulations and conduct eigenfrequency analyses. Subsequently, harmonic analyses are performed to delve deeper into the underlying physics of the problem. In particular, graded metasurface configurations are designed, featuring mass-spring resonators with spatially varying resonant frequencies along the metasurface array. This design approach enables two key phenomena: (i) rainbow effect, realized by gradually decreasing the metasurface resonance frequency along the array, and (ii) controlled conversion of SSWs into leaky fluid modes, achieved through a smooth increase in the resonance frequency along the array (1).

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Vibration bandgap of immersed periodic plates with fluid surface sloshing effect

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Speaker: Shen Nian. **Wednesday**. Start time: **15:50**. Room: Roseraie 2 LVL3. Link to abstract.

This article builds on previous work by implementing a unit cell-based symmetric fluid-structure formulation to predict vibration bandgaps of immersed periodic composite plates with the account for fluid surface sloshing effect. The significance of this study lies in integrating Bloch periodic boundary conditions into a symmetric hydro-elastic (u, η, ϕ) unit cell model with fluid-structure interaction (FSI). The unit cell comprises three subdomains: the immersed composite plate, the fluid domain and the fluid free surface. Bloch periodic conditions are applied simultaneously across all the three domains, allowing the prediction of vibration bandgaps that consider both fluid inertia and surface sloshing effects. This approach is applicable to immersed periodic structures across full-range immersion depths, whether distant from or approaching the fluid free surface. We conducted a study on the linear dynamics of periodic composite plates across various immersion depths and revealed a competitive relationship between the fluid inertial effect and the fluid surface sloshing effect. Specifically, for deeply immersed structures, the model converges to the classical added mass model, indicating that the fluid inertial effect dominates the influence on vibration bandgaps. While in shallow immersion scenarios, as structures approach the fluid surface, the free surface sloshing effect associated with fluid gravity becomes the dominant factor. The results are verified through comparison with the frequency response simulations that consider the same FSI conditions. The approach has also been applied to investigate the dispersive bandgaps for microstructures with anisotropic wave propagations. The results demonstrate the effectiveness of the proposed model in designing immersed meta-structures for vibration attenuation.

Non-local programmable floppy sequences in kagome chains

Azizi Pegah (1), Gonella Stefano (2)

1 - University of Minnesota (United States), 2 - University of Minnesota (United States)

Speaker: Gonella Stefano. Keynote. **Wednesday**. Start time: **16:45**. Room: Roseraie 2 LVL3. Link to abstract.

The kinematics of Kagome kagome lattices consist of unit cells comprising two triangles connected at a single vertex. The kinematics of the kagome family deformation are characterized profoundly dictatedby their twist angle. As we sweep the twist angle, we elicit a global soft mode that reconfigures the lattice from a fully deployed state, corresponding to the regular kagome lattice, to a fully folded state, where all the triangles de facto collapse and align to form a one-dimensional prismatic structure, whose kinematics are reminiscent of those of a torsional chain. We call this structure a kagome chain. Our study focuses on systematically exploresing the twist angle spectrum to investigate reveal potential exotic emergent phenomena behaviors directly emerging enabled by thisfrom its dimensional collapse mechanism. Of particular interest are the two extreme configurations of the spectrum (regular kagome and kagome chain), whose mechanics are mutually linked by duality mapping. Both these configurations shows promise forhave the capability of hosting bulk zero modes. Invoking the duality relations between the chain and its deployed lattice counterpart, we study how the floppy modes manifest in the chain. We document the emergence of non-local floppy twist sequences that are sensitive to the direction of loading and can therefore be programmed according to a variety of patterns. We validate our analysis via experiments conducted a physical kagome chain prototype.

A well-posed homogenized strain-gradient model for elastic waves in periodic media.

Cornaggia Rémi (1), Bonnet Marc (2), El Ouafa Saad (3), Rosi Giuseppe (3), Auffray Nicolas (4)

1 - Sorbonne Université, CNRS, Institut Jean Le Rond d'Alembert, F-75005 Paris, France (France), 2 - POEMS (CNRS, Inria, ENSTA Paris), France (France), 3 - CNRS, MSME, Univ Gustave Eiffel, F-77447 Marne-la-Vallée, France (France), 4 - Sorbonne Université, CNRS, Institut Jean Le Rond d'Alembert, F-75005 Paris, France (France)

Speaker: Cornaggia Rémi. **Wednesday**. Start time: **17:25**. Room: Roseraie 2 LVL3. Link to abstract.

This work focuses on low-to-medium frequency linear elastic waves in unbounded periodic media. In this context, we show how to obtain a well-posed strain-gradient model using the two-scale asymptotic homogenization method, pushed to the second-order.
We combine (i) classical formal asymptotic expansions in terms of the periodicity length-to-wavelength ratio (1) and (ii) original reciprocity identities between the so-called cell problems at various orders to obtain new relations between the higher-order homogenized tensors entering the model (2). The latter results allow to highlight the symmetry properties of those tensors and reduce the overall cost of their computation for a given periodicity cell.
An original "Boussinesq trick" is then proposed, which allows to ensure the positivity and (respectively) coercivity and ellipticity of the stiffness and inertial bilinear forms featured in the obtained strain-gradient wave equation. Those properties, in turn, are used to establish the well-posedness of initial-value problems in the free space featuring that equation.
Finally, numerical simulations show the expected second-order asymptotic accuracy of the model and its ability to reproduce key features of the wave propagation, notably higher-order anisotropic propagation that would not be captured by a classical, leading-order homogenized model (3) and demonstrate the practical advantages gained from the reciprocity identities.

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Improved direct mapping of acoustic waveguides to lattice models

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Speaker: Cheong Su Ho. **Wednesday**. Start time: **17:45**. Room: Roseraie 2 LVL3. Link to abstract.

The propagation of acoustic waves in waveguides provides an effective testbed for studying topological insulators and their properties. Recent studies have demonstrated how waveguides can be used to model the one-dimensional (1D) Su-Schrieffer-Heeger (SSH) model. In these works, it has been shown that an acoustic waveguide can be directly mapped to a 1D SSH, which supports the presence of edge modes through chiral symmetry and where the geometry of the waveguide plays the role of inter and intra-site hopping's. This 1D modelling approximates the 3D problem and it ignores near field effects at each change of cross-section of the waveguide. Here, by using an expression for the discontinuities at the cross-sections for the pressure and flux, which contains a so-called correction length, this improved discrete SSH model achieves a better alignment between the eigenfrequencies of the discrete SSH and those obtained from finite-element simulations. Furthermore, with the use of the improved discrete equations, it is possible to show that some robustness of the edge mode can be maintained.

Nonlinear harmonic generation in mechanical metamaterials

Yi Jianlin (1)

1 - Institute of Mechanics, Chinese Academy of Sciences (China)

Speaker: Yi Jianlin. **Wednesday**. Start time: **18:05**. Room: Roseraie 2 LVL3. Link to abstract.

Elastic wave propagation and control in solid materials and structures play a crucial role in the development of devices and technologies across various fields, including vibration control, damage detection, medical ultrasound imaging, and information processing. Mechanical metamaterials, composed of artificial microstructures, have garnered significant attention due to their remarkable capabilities in elastic wave manipulation. Nonlinear harmonic generation is a fundamental dynamic process and an essential mechanism for wave energy transfer in the frequency domain. However, studies on nonlinear harmonic wave propagation in mechanical metamaterials remain scarce. In this work, we systematically investigate nonlinear harmonic generation, propagation, enhancement, and control in mechanical metamaterials. Our findings reveal anomalous dispersion in a metamaterial exhibiting coupled translational and rotational motion, which can induce localized nonlinear harmonic generation. We also explore the influence of pre-strain on nonlinear harmonic generation, demonstrating significant tunability. Additionally, we propose tailoring the geometric asymmetry of the structure to enable both longitudinal and flexural second harmonic generation. This research offers new insights for the development of advanced elastic wave devices.

Dispersion and ellipticity of Rayleigh waves in a soil supporting resonant beams/plates

Marigo Jean-jacques (1), Pham Kim (2), Maurel Agnès (3), Guenneau Sébastien (4)

1 - LMS Ecole Polytechnique/Institut d'Alembert Sorbonne Université (France), 2 - LMI, ENSTA Paris, Institute Polytechnique de Paris (France), 3 - Institut Langevin/ESPCI (France), 4 - Imperial College (United Kingdom)

Speaker: Pham Kim. **Thursday**. Start time: **10:00**. Room: Roseraie 2 LVL3. Link to abstract.

Elastic surface waves can propagate in a soil substrate hosting a periodic array of resonant elements. While early studies primarily explored this phenomenon in the GHz regime with resonators on the micrometer scale, extending these concepts to meter-scale structures shifts the focus to seismic frequencies. In this context, a network of beams on a soil substrate serves as a canonical configuration in seismology to study "site-city interaction," first introduced in pioneering works.Theoretical models of resonators coupled to soil typically employ simplified resonant systems with one or more degrees of freedom, leading to effective Robin-type boundary conditions for the soil itself. These models have been instrumental in advancing seismic metasurfaces, capable of efficiently shielding Rayleigh waves and Love waves. Early investigations of specific resonators, such as elastic beams or plates, initially focused on compressional resonances, followed by flexural resonances. Recently, the simultaneous consideration of both resonance types has been addressed, and the resulting models have been validated through scattering simulations. Building on this foundation, we extend the analysis to surface waves in configurations involving three-dimensional beams and two-dimensional plates. Specifically, we demonstrate that the effect of resonant structures can be encapsulated in boundary conditions linking normal stress to displacements in the soil. These conditions depend on frequency and two dimensionless parameters: the slenderness of the elastic structures and a coupling parameter between these structures and the soil.The resulting dispersion relations reveal two types of surface waves. In the sagittal plane, hybridized Rayleigh waves emerge from the interplay of flexural and compressional resonances. Notably, within specific frequency ranges associated with flexural resonances, two Rayleigh waves can coexist, characterized by soil displacements exhibiting either high ellipticity or near-zero ellipticity. For three-dimensional beams, we also identify Love waves, associated with displacements perpendicular to the sagittal plane. These waves, sensitive only to flexural resonances, are the elastic analogs of plasmon polaritons in electromagnetism.

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Marigo, J. J., Pham, K., Maurel, A., & Guenneau, S. (2021). Effective model for elastic waves in a substrate supporting an array of plates/beams with flexural and longitudinal resonances. *Journal of Elasticity*, *146*, 143-177.
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Maurel, A., Marigo, J. J., Pham, K., & Guenneau, S. (2018). Conversion of Love waves in a forest of trees. *Physical Review B*, *98*(13), 134311.

Modeling Anthropogenic Cavities as Elastic Meta-Interfaces: Implications for Seismic Surface Displacements

Maurel Agnès (1)

1 - Institut Langevin - Ondes et Images (UMR7587) (ESPCI, 1 Rue Jussieu 75238 Paris Cedex 05 France)

Speaker: Maurel Agnès. **Thursday**. Start time: **10:20**. Room: Roseraie 2 LVL3. Link to abstract.

A. Maurel, K. Pham, S. Brulé & S. Guenneau,

Seismic design codes require accurate characterization of the elastic properties of soils down to depth of a few tens of meters below the Earth's surface. Indeed, at these depths, the sismic signal can be significantly modified by the heterogeneity of the geomaterials or the geometry of the U-shaped basins creating multiple wave reflections. For rocky terrains, there is no recommendations for wave propagation in the presence of cavities or networks of near-surface underground cavities, often of anthropogenic origin. For example, this may be buried quarries forming dense clusters of regularly spaced cavities. However, these "defect" networks can significantly influence surface displacements.

In order to identify the impact of these near-surface void structures on the dynamic response of buildings, it is necessary to develop a simple model that can be directly implemented in building displacement calculations. For example, it is crucial to study whether the H/V (horizontal/vertical) displacement ratio at the surface is amplified or reduced, and whether filling the cavities with a material or fluid could mitigate these displacements.

Building on recent advances in elastic meta-interfaces, we propose a two-scale homogenization approach to model a cavity network as an effective interface. We show that this seismic meta-interface introduces discontinuities in elastic displacements and normal stresses, involving effective parameters whose values explicitly depend on the geometry of the actual network. Initially applied to an infinite elastic medium (1), the method is extended here to an elastic half-space (the ground) with a free surface subjected to a zero normal stress condition. This analytical model, based on idealized assumptions (perfectly periodic quarry, homogeneous elastic ground), meets the simplicity requirement and demonstrates remarkable reliability when compared to numerical simulations of the full problem. The agreement is particularly good in the frequency range of interest for seismic waves in earthquake engineering ($<$ 50 Hz).

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Metamaterial Sandwich Structures: Boundary Effects and Performance Optimization

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1 - Institute of Structural Mechanics, Statics and Dynamics, TU Dortmund University (Germany), 2 - Laboratoire de Tribologie et de Dynamique des Systèmes (France)

Speaker: Hermann Svenja. **Thursday**. Start time: **10:40**. Room: Roseraie 2 LVL3. Link to abstract.

Mechanical metamaterials offer unique capabilities for wave control and vibration mitigation. Modeling infinite-sized metamaterials and optimizing their dispersive behavior has become a well-established practice that is generally approached using Bloch Floquet analysis. The performance in finite-sized structures, however, which is critical for practical applications, is less explored.
In this work, we analyze a metamaterial that is embedded in a so-called sandwich structure, where it is bounded by classical Cauchy-type materials. This configuration reflects common engineering applications like structural panels or vibration isolators. Numerical simulations coupled with experimental validation provide insights into the interplay of structural boundaries and metamaterial properties.
Our study reveals that the dynamic behavior of the metamaterial in the structure is highly sensitive to boundary conditions at the interfaces with the homogeneous outer layers. The free boundaries, where the structure is in contact with air, further influence the wave propagation in the metamaterial. We present strategies to increase the absorption capacity of the metamaterial by tailoring boundary conditions and geometry. To classify the vibration reduction capability of our sandwich structures, we consider mechanical as well as vibroacoustic aspects. The findings of our research contribute to advancing the practical implementation of metamaterials in engineered systems.

High Bulk Modulus Pentamodes: the Three-Dimensional Metal Water

Cominelli Sebastiano (1), Brambilla Giacomo (1), Verbicaro Marco (2), Cazzulani Gabriele (1), Braghin Francesco (1)

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Speaker: Cominelli Sebastiano. **Thursday**. Start time: **11:00**. Room: Roseraie 2 LVL3. Link to abstract.

Over the last two decades, considerable effort has been devoted to the development of acoustic metafluids: engineered solid structures that mimic the properties of fluids to manipulate sound waves. A key player in this field is the pentamode metamaterial, which mimics fluid behaviour due to its singular elasticity tensor. Designing a 3D version of these metamaterials that mimics the behaviour of water holds great promise for underwater applications such as perfect lenses and cloaking (1). Excellent results have been demonstrated for the 2D approximation (2), but existing 3D geometries face limitations in density and stiffness due to their lattice structures (3, 4, 5).
In this study, published in (0), we introduce a novel pentamode lattice that builds on existing mechanical networks. By extending the concept of double cones and addressing theoretical limitations related to bulk modulus, we propose an alternative shape for lattice links to overcome these constraints. A link based on parallel fibres, acting as an ideal slider, allows lower shear and higher axial stiffness to be achieved, effectively removing the upper limit on the ratio of bulk to shear modulus.
In this way, we model the primitive unit cell of 3D metallic water: using low-frequency homogenisation, we obtain an effective elastic solid with a satisfactory bulk modulus and minimal shear-to-bulk ratio. The dynamic behaviour of the lattice is also investigated, revealing two band gaps where only compressional waves propagate, further enhancing the potential of the material for practical applications.
The presentation will discuss preliminary fabrication results and experimental validations.

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Controlling wave propagation by modulating in time the parameters of imperfect interfaces

Darche Michaël (1), Assier Raphaël (2), Guenneau Sébastien (3), Lombard Bruno (1), Touboul Marie (4) (5)

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Speaker: Darche Michaël. **Thursday**. Start time: **14:15**. Room: Roseraie 2 LVL3. Link to abstract.

In many domains of engineering, it is useful to control waves in various ways. For example, spatially structured materials, which have experienced significant growth in recent years, can create forbidden frequency band gaps, and can be designed to cut-off frequencies where structural resonance occurs. A new frontier has now emerged: the temporal modulation of materials. Indeed, time-dependent materials lead to k-gap, bandgaps in wavenumbers (by analogy with the spatial case). However, the fact that waves cannot travel back in time (when they can travel back in space) changes the behavior of waves within the bandgaps. Consequently, wave propagation of the corresponding wavelengths corresponds to an unstable regime where the energy grows exponentially.

By modulating properties in both time and space, one of the other effects that can be obtained is non-reciprocity, which means that wave propagation depends not only on the direction of the wave vector but also on its orientation. From a practical standpoint, it is difficult to modulate both spatially and temporally in media. However, asymptotic homogenization of spatially architected materials shows that locally applied effects are transmitted to the bulk behavior of the material under certain conditions (notably at low frequencies). The idea is to replace volumetric modulation by imperfect interfaces whose properties depend on time. Experimentally, one could imagine a series of mechanical resonators whose mass and stiffness are modified. These interfaces are then governed by jump equations on the displacement field and the stress field. In this work, the modulation of the properties does not generate additional waves.

The evolution of the mechanical energy in the case of bulk and interface energy shows that the choice of modulation (relative to the considered parameters, properties, and initial state of the media) can attenuate or amplify the scattered waves by modifying the total amount of energy. Numerical studies are performed to understand acoustic wave propagation in 1D media separated by imperfect interfaces. The numerical scheme is based on finite differences with a velocity-stress formulation. The treatment of the jump conditions at the interfaces is handled using an immersed interface method, modified to account for the time dependence of the properties. The numerical methods have been validated thanks to a semi-analytical solution obtained in the case where either the inertia or the rigidity are modulated.

Moreover, a harmonic balance method is applied to this case in order to understand the generation of harmonics. Then, as one of the objectives is to obtain an effective bulk modulation through local application of the modulation, asymptotic homogenization is performed in the case where the microstructure is small compared to the considered wavelength. Based on the homogenized model, the propagation of waves in a time-laminated material (homogeneous in space) is studied to understand the possibilities and limitations that k-gaps offer. Finally, the study of a phase-shifted modulation of the interfaces is conducted. The analysis of such a medium, modulated in space and time, is analyzed in terms of the dispersion diagram, and in fact, the influence on the non-reciprocal features.

Non-reciprocity for the time-modulated wave equation and diffusion equation through the lens of high-order homogenization

Touboul Marie (1) (2) (3), Lombard Bruno (4), Assier Raphaël (5), Guenneau Sébastien (3) (6), Craster Richard V. (7) (8) (9)

1 - Department of Mathematics [Imperial College London] (United Kingdom), 2 - Propagation des Ondes : Étude Mathématique et Simulation (France), 3 - UMI 2004 Abraham de Moivre-CNRS, Imperial College London (United Kingdom), 4 - Laboratoire de Mécanique et d'Acoustique [Marseille] (4 impasse Nikola TeslaCS 4000613453 Marseille Cedex 13 France), 5 - University of Manchester [Manchester] (United Kingdom), 6 - Blackett Laboratory (United Kingdom), 7 - Department of Mathematics [Imperial College London] (Imperial College London, 180 Queen's Gate, London SW7 2AZ, United Kingdom United Kingdom), 8 - UMI 2004 Abraham de Moivre-CNRS [Imperial College London] (London SW7 2AZ, UK United Kingdom), 9 - Department of Mechanical Engineering [Imperial College London] (Imperial College London, London SW7 2AZ United Kingdom)

Speaker: Touboul Marie. **Thursday**. Start time: **14:35**. Room: Roseraie 2 LVL3. Link to abstract.

Time-modulated laminate for the wave equation
We first consider a 1D periodic elastic medium in the antiplane elasticity framework. Moreover, the physical parameters, i.e. the mass density and the shear modulus, are modulated in space and time in a wave-like fashion with modulation speed c.We further assume that the constant modulation speed is such that the configuration is in the subsonic or supersonic cases. The range of modulation speed considered here excludes the sonic case, where an effect similar to a sonic blow-up occurs (Cassedy, 1963).

Homogenized equation at the leading order
Assuming that the characteristic wavelength is much larger than the periodicity, we introduce a small parameter for the low-frequency setting. Using the two-scale asymptotic technique, homogenization can be applied. At the leading order, the effective equation is obtained, where three effective parameters appear: an effective mass density, an effective shear modulus, and an effective Willis coupling coefficient W0 due to the modulation. The associated dispersion relation describes the behavior of wave propagation in the modulated medium.

This effective equation implies that reciprocity is broken as soon as W0 is non-zero, as there is no longer symmetry between the wavevector k and -k. However, if only one physical parameter (either the shear modulus or the density) is modulated, the Willis coupling coefficient W0 vanishes and reciprocity is recovered. This is consistent with the literature (Nassar, 2017; Huidobro, 2021), but inconsistent with Bloch-Floquet analysis (Cassedy, 1963), which highlights a limitation of the leading-order homogenized model.

Homogenized equation at the second order
To correct the limitations of the leading-order model, we push the homogenization to the second order (Touboul, 2024a). When the density is constant, the effective dispersion relation for the second-order model developed in this work shows that non-reciprocity is ensured due to a non-zero term breaking the symmetry between k and -k. A similar result holds when the other parameter is constant.
The accuracy of this model is illustrated for a bilayered medium. The dispersion relation computed through a Bloch-Floquet analysis in a moving frame is compared to the one derived from the homogenized models. Time-domain simulations in the microstructured medium are also performed to illustrate non-reciprocity.

The case of the diffusion equation
This same methodology is applied to the diffusion equation. In this case, a time-modulation in a wave-like fashion leads to non-reciprocal behavior and propagation of the field, while it would be purely attenuated in a non-modulated medium. However, leading-order models (Torrent, 2018) or first-order models (Xu, 2022) fail to describe this phenomenon when only one parameter is modulated. As with the wave equation, this issue is corrected by considering second-order homogenization (Touboul, 2024b). The same

methodology is also applied to the case when the density is modulated in the heat equation, leading, therefore, to a corrective advective term (Li, 2022) that cancels out non-reciprocity at the leading order but not at the second order.

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NON-HERMITIAN DEGENERACIES AND PT SYMMETRIC SCATTERING IN ELASTIC METAMATERIALS

Amirkhizi Alireza (1), Alizadeh Vahidreza (1), Wang Weidi (1)

1 - University of Massachusetts Lowell (United States)

Speaker: Amirkhizi Alireza. **Thursday**. Start time: **14:55**. Room: Roseraie 2 LVL3. Link to abstract.

Mechanical metamaterials and phononic crystals, composed of periodic cellular unit cells, have attracted significant interest for their ability to exhibit unique behaviors, such as stop bands, negative effective parameters, and wave manipulation capabilities. The standard first step in the design and analysis of such systems is to perform eigen-frequency calculations based on Bloch-Floquet periodicity. This approach allows for the prediction of the material's response under various conditions by leveraging the periodic nature of the unit cells.

In this work, we explore the band structure and scattering of in-plane stress waves in these microstructured systems. Of particular interest is the emergence of exceptional points (EPs)-non-Hermitian degeneracies in the eigen-parameter space where the system operator becomes deficient. Remarkably, these EPs can appear in elastic (lossless) media when parameterized with real-valued frequencies and tangential wave vectors. These EP pairs are not confined to the original stop bands but can also emerge in all-mode pass bands, giving rise to new stop bands and scattering phenomena. When mechanical gain is theoretically introduced to balance loss in a parity-time symmetric structure, EP pairs also emerge in the scattering matrix spectrum. These pairs lead to striking effects such as amplification of transmission above unity and single-sided reflectivity, both indicating broken phase symmetry.

We show the appearance of such EPs in various cellular and layered metamaterials and analyze the scattering phenomena occurring near and at these points. The observed PT-symmetry broken phases and unidirectional reflectivity have significant implications for the design and application of metamaterials such as sensing devices. This study presents an efficient modeling approach, highlighting the importance of modal chirality and symmetry in the loss/gain-embedded mechanical metamaterials.

Single-Phase Phononic Crystals with 4-Fold Rotational Symmetry

Nadejde Ilaie (1), Galich Pavel (1)

1 - Technion - Israel Institute of Technology [Haifa] (Israel)

Speaker: Galich Pavel. **Thursday**. Start time: **15:15**. Room: Roseraie 2 LVL3. Link to abstract.

In this study, we investigate the mechanisms underlying bandgap (BG) formation in two-dimensional phononic crystals (PnCs) exhibiting 4-fold rotational symmetry. Our focus spans symmorphic symmetry groups, such as *p4* and *p4mm*, as well as the nonsymmorphic *p4gm* group. By introducing reproducible design families based on these symmetry groups, we enable systematic exploration of their acoustic properties.

Through detailed parametric analysis, we uncover the interplay between Bragg scattering and local resonance mechanisms, demonstrating their combined potential to yield exceptionally wide, complete omnidirectional BGs in single-phase PnCs. The study identifies nonlinear relationships between geometric parameters and BG size, revealing critical design principles for maximizing attenuation performance. Numerical simulations, complemented by experimental validation, confirm the emergence of strongly coupled BGs capable of attenuating both longitudinal (P-wave) and shear (S-wave) modes. Designs featuring large resonators interconnected by thin ligaments are particularly effective, achieving BGs up to 118% relative width with attenuation exceeding 80 dB within just three unit cell layers.

Our findings emphasize the crucial role of resonator-to-connector configurations, analogous to mass-spring systems, in facilitating the coupling of resonant and Bragg mechanisms. Remarkably, we demonstrate that simpler symmorphic symmetry designs can rival or exceed the BG performance of nonsymmorphic counterparts, challenging traditional design paradigms. These results not only deepen our understanding of BG formation in single-phase PnCs but also provide actionable insights for developing advanced vibration isolation and wave manipulation technologies.

Validity of radiative transfer approximations in bounded random media

De Abreu Correa Lucio (1), Fall Madou Khazaie Shahram (2), Gomez Christophe (3), Cottereau Régis (4)

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Speaker: Cottereau Régis. **Thursday**. Start time: **15:35**. Room: Roseraie 2 LVL3. Link to abstract.

This presentation focuses on the propagation of waves in a randomly-fluctuating heterogeneous medium. In general, the solution of such an equation in a given position displays two phases: (i) a coherent wave, somewhat similar to a wave propagating in a homogeneous medium, and (ii) an incoherent wave, seemingly more random. In some very heterogeneous media, like concrete, granular media or the Earth, that second phase of the solution is the most prominent, and the coherent wave almost vanishes. The amplitude of the solution can then be represented by a radiative transfer equation, obtained through an asymptotic expansion assuming random fluctuations of the properties in the appropriate regime. The RTE only models the amplitude of the solution, not its phase, but has the advantage of homogenizing all the rapid fluctuations of the properties and solution. It is similar in that respect with diffusion models, that are more widely used in the wave physics litterature, but has the enormous advantage of being capable of modeling both the coherent and incoherent waves, while diffusion models can only account for the coda. This presentation reports a series of numerical experiments comparing solutions of the 3D acoustic wave equation in a heterogeneous medium and of the radiative transfer equations. Parameters of the two equations are chosen such that the radiative transfer solution is expected to provide an accurate approximation of the energy of the wave in the weak scattering regime. The comparisons indicate that the radiative transfer provides accurate approximations even quite far from that regime. A particular attention is devoted to analyzing the results close to boundaries, where the accuracy of the radiative transfer equation has not been evaluated before.

Third-order exceptional points and frozen modes in planar elastic laminates

Fishman Ariel Elbaz Guy Varma Venkatesh Shmuel Gal (1)

1 - Technion - Israel Institute of Technology (Israel)

Speaker: Shmuel Gal. Keynote. **Friday**. Start time: **10:00**. Room: Roseraie 2 LVL3. Link to abstract.

Exceptional points (EPs) are degeneracies of two or more natural modes of open systems, which lead to unusual wave phenomena. Despite the robustness against imperfections of spatial EPs, they are less studied relative to temporal EPs, particularly in elastodynamics. However, elastic waves exhibit features not found in sound and light, which have proven useful for forming spatial EPs. Here, we harness these features to tune the coalescence of three eigenmodes in the Bloch spectrum of planar elastic laminates. We show that these third-order EPs give rise to axially frozen modes: anomalous transmitted waves with zero axial group velocity and finite transmittance. These modes, which were first reported in optics and required three-dimensional laminates, are achieved here in a planar setting thanks to elastodynamics tensorial structure, and expand the toolbox for elastic wave shaping.

Design and fabrication of 3D-printed composite metastructure with subwavelength and ultrawide bandgaps

Gulzari Muhammad (1)

1 - University College Dublin [Dublin] (Ireland)

Speaker: Gulzari Muhammad. **Friday**. Start time: **10:40**. Room: Roseraie 2 LVL3. Link to abstract.

Architected composite metastructures can exhibit a subwavelength ultrawide bandgap (BG) with prominent emerging applications in the structural vibration and noise control and, elastic wave manipulation. The present study implemented both forward and inverse design methods based on numerical simulations and machine learning (ML) methods, respectively to design and fabricate an architected composite metastructure exhibiting subwavelength and ultrawide BGs. The multilayer perceptron and radial basis function neural networks are developed for the inverse design of the composite metastructure and their accuracy and computation time are compared. The band structure revealed the presence of subwavelength and ultrawide BGs generated through local resonance and structural modes of the periodic composite lattice. Both in-plane and out-of-plane local resonant modes of the periodic lattice structure were responsible for inducing the BGs. The findings are confirmed by calculating numerical wave transmission curves and experiment tests on the fabricated supercell structures, utilizing 3D-printing technology. Both numerical and experimental results validate the ML prediction and the presence of subwavelength and ultrawide BG was observed. The design approach, research methodology and proposed composite metastructure will have a wide range of application in the structural vibration control and shock absorption.

Improvements to the PWE-based methods for analyzing 2D phononic crystals with complex geometries

Shen Wei (1)

1 - Navier, École nationale des ponts et chaussées, Univ Gustave Eiffel, CNRS, 77455, Marne-la-Vallée, France (France)

Speaker: Shen Wei. **Friday**. Start time: **11:00**. Room: Roseraie 2 LVL3. Link to abstract.

Analyzing the band structure of phononic crystals is essential for understanding their elastic wave propagation characteristics. The plane wave expansion method (PWEM) is highly efficient and accurate, making it a useful tool for analysis. However, the PWEM often encounters significant computational challenges when dealing with complex structures in phononic crystals. This work improves the computation of Fourier coefficients, enabling various versions of the PWEM to efficiently calculate the band structure of phononic crystals with complex geometries. By dividing the unit cell into multiple similar simple geometries, the complex integration domain of the Fourier coefficients can be transformed into a summation over several simpler domains. At the same time, this approach solves the problem of not having a unified formula for different geometries in the PWEM. The rasterized plane wave expansion method was developed by rasterizing the unit cell and integrating image processing techniques. The mesh based improved plane wave expansion method was introduced by dividing the geometry of the unit cell into triangles, similar to the finite element method. Extensive numerical computations validated that both improved strategies significantly reduce derivation costs while preserving the original computational efficiency and accuracy. Due to the integration of image processing techniques, the improved method provides significant advantages in applications such as training machine learning datasets and enhancing Digital Image Correlation (DIC) analyses. The improved method based on triangular meshes enables the efficient and accurate establishment of benchmarks for finite element-based approaches without requiring structural discretization. This strategy can be effectively integrated into certain commercial finite element software, enhancing their analysis capabilities. These improved methods considerably reduce the accessibility barrier and expand the range of potential applications.

Topology optimization of 2D lattice structures for target band gaps with continuity conditions

Gómez-silva Francisco (1), Huang Xiaodong (2)

1 - Carlos III University of Madrid (Spain), 2 - Swinburne University of Technology [Melbourne] (Australia)

Speaker: Gómez-Silva Francisco. **Friday**. Start time: **11:20**. Room: Roseraie 2 LVL3. Link to abstract.

Excessive vibrations in engineering systems can lead to significant challenges, including structural failure and decreased operational efficiency. This research addresses these issues by developing an innovative topology optimization algorithm to design 2D lattice structures that exhibit band gaps around a specified target frequency, specified by the user. Band gaps are frequency ranges within which wave propagation is prohibited, making them essential in vibration control and wave filtering applications. The methodology relies on analyzing a single unit cell using the Bloch-Floquet theorem, which significantly reduces computational complexity. The optimization employs the innovative method Floating Projection Topology Optimization (FPTO) method, considering material and voids (design variables equal to 1 and 0, respectively). The implicit floating projection constraint in the FPTO method numerically simulates 0/1 constraints of the design variables so that even a linear material interpolation scheme can be employed (penalty not required). By gradually tightening 0/1 constraints, more and more design variables are pushed to 0/1 until an optimized element-based design with a clear topology can be accurately represented by a smooth design.
One of the key innovations in this work is the introduction of a novel objective function that focuses exclusively on natural frequencies nearest to the target frequency, independent of their relationship to the fundamental frequency. This approach minimizes computational costs by reducing the range of frequency analysis while improving the robustness of the optimization process, the frequencies adapting to changes in material distribution, ensuring that they cover the target frequency throughout the optimization process.

The algorithm was rigorously tested on lattice structures composed of periodically repeated unit cells in both one-dimensional (1D-CR) and two-dimensional (2D-CR) configurations, incorporating continuity conditions by means of thermal conduction homogenization techniques, thus avoiding the appearance in the unit cell of material geometries surrounded by void (which would not be possible to manufacture, since it loses the continuity of the entire lattice).

F. Gómez-Silva acknowledges support from MCIN/ AEI /10.13039/501100011033 under Grant numbers PID2021-123294OB-100 and TED2021-129709B-I00, from FEDER, UE and from the European Union Next Generation EU/PRTR.

Strain-induced tunability of topological properties in phononic crystals

Perez Compte Eloi (1), Carta Giorgio (2), Brun Michele (2), Bosia Federico (1), Gliozzi Antonio (1)

1 - Department of Applied Science and Technology, Politecnico di Torino, 10129 Torino, Italy (Italy), 2 - University of Cagliari, Department of Mechanical, Chemical and Materials Engineering, Cagliari, 09123, Italy (Italy)

Speaker: Bosia Federico. **Friday**. Start time: **11:40**. Room: Roseraie 2 LVL3. Link to abstract.

The investigation of phononic crystals and their topological properties has opened fascinating avenues for manipulating wave propagation in materials. However, most of the considered systems in the literature are based on static designs, with no possibility of modulating response or of adapting to varying external conditions. In this study, we investigate the possibility of introducing dynamic control of topological properties in phononic crystals by means of varying strain fields. We consider two examples of this concept.

In the first case, we investigate the mechanical modulation of topological modes in a one-dimensional Su–Schrieffer–Heeger (SSH) chain with a central defect, in which an edge mode emerges due to topological protection. By introducing lateral compression, we exploit the stress state of the chain under buckling to tune the edge mode frequency and modify the protected state(s). This setup can be viewed as analogous to a quantum system, where an external field couples to the degrees of freedom of the system, realized here mechanically as strain-induced coupling between the masses in the chain.

The second example extends the approach to a 2D system, i.e. an auxetic mass-spring lattice consisting of hinged masses connected by multiple springs, focusing on its dynamic elastic properties and topological wave aspects as a function of the overall stress state of the lattice. Here, we establish an analytical formulation of the linearized incremental problem, enabling the construction of band diagrams for variable geometric parameters and external load, and highlighting the occurrence of Dirac cones and band gap opening by removing symmetry. The predictions are compared to FEM simulations of the corresponding continuous model consisting in a thin slab with oriented cuts, revealing a relation between auxeticity and topologically protected modes which can be potentially exploited for tunable waveguide applications.

MS6.3 - Dynamic and transient phenomena, phase transitions, nonlinear waves

Organisers: Michael Nieves (Keele University) and Vincent Tournat (Le Mans Université)

Acoustic lattice resonances and generalised Rayleigh–Bloch waves

Peter Malte A. (1), Bennetts Luke G. (2), Chaplain Gregory J. (3), Hawkins Stuart C. (4), Matsushima Kei (5), Starkey Tim A. (3)

1 - Universität Augsburg (Germany), 2 - University of Adelaide (Australia), 3 - University of Exeter (United Kingdom), 4 - Macquarie University (Australia), 5 - University of Tokyo (Japan)

Speaker: Peter Malte A.. Keynote. **Monday**. Start time: **10:10**. Room: Roseraie 2 LVL3. Link to abstract.

Rayleigh–Bloch waves are modes localized to periodic arrays of scatterers with unbounded unit cells. Here, Rayleigh–Bloch waves are studied for line arrays of sound-hard circular scatterers embedded in a two-dimensional acoustic medium, for which it has recently been shown that Rayleigh–Bloch waves exist for higher frequencies than previously thought. Moreover, it was shown that Rayleigh–Bloch waves can cut off (disappear) and cut on (reappear), and additional Rayleigh–Bloch waves can cut on and interact with the existing ones. These complicated behaviours are reconsidered using a family of quasi-periodic Green's functions that allow particular plane-wave components to become unbounded away from the array so as to trace the trajectories of the Rayleigh–Bloch wavenumbers as they swap between Riemann sheets that are categorized according to the unbounded plane wave(s) and provide new understanding of Rayleigh–Bloch waves around the critical frequency intervals where they cut on/cut off/interact.
These theoretical investigations are complemented by experimental results in airborne acoustics, in which we experimentally observe the first generalised Rayleigh–Bloch waves above the first cut-off, i.e., in the radiative regime. We consider radiative acoustic lattice resonances along a diffraction grating and connect them to generalised Rayleigh–Bloch waves by considering both short and long arrays of non-resonant 2D cylindrical Neumann scatterers embedded in air. On short arrays, we observe finite lattice resonances under continuous wave excitation, and on long arrays, we observe propagating Rayleigh–Bloch waves under pulsed excitation.

Achieving negative reflection

Brun Michele (1), Meirbekova Bibinur (2), Carta Giorgio (1), Morini Lorenzo (1)

1 - Department of Mechanical, Chemical and Materials Engineering, University of Cagliari (Italy), 2 - Institute of Mathematics and Mathematical Modelling MES RK (Kazakhstan)

Speaker: Brun Michele. Invited. **Monday**. Start time: **10:50**. Room: Roseraie 2 LVL3. Link to abstract.

The possibility to govern mechanical wave propagation opens the possibility to build devices that can protect region from dangerous excitations or harvest the energy in particular regions.
Here, we give demonstration of negative reflection in a simple mechanical system. The transmission problem in a linear elastic homogeneous medium with a grating interface composed of a regular square distribution of circular pinned inclusions is studied.
The conditions for which an oblique incident anitplane shear wave impinging the interface with an angle θ_I is quasi totally reflected with a negative reflection angle $\theta_R < 0$ are derived and discussed. They are deduced from the combined analysis of dispersion properties of the interface grating and the homogeneous matrix; while the amount of reflection is obtained in term of relative power flux, computed from a numerical analysis with an imposed incident gaussian beam.

Surface waves in 2D bistable lattices

Shuminov Maor (1), Givli Sefi (1)

1 - Technion - Israel Institute of Technology [Haifa] (Israel)

Speaker: Shuminov Maor. Invited. **Monday**. Start time: **11:10**. Room: Roseraie 2 LVL3. Link to abstract.

In this work, we study a relatively new class of metamaterials, namely architected materials with bistable building blocks. These multi-stable architected materials offer a unique set of mechanical properties and extraordinary behaviors, such as the ability to undergo large reversible deformations, the ability to provide mechanical protection and efficient shock absorption, and the ability to retain variety of geometrical configurations after loads have been removed. In addition to its relevance to metamaterials, the study of lattice-based multi-stable structures is of relevance to a range of engineering and physical phenomena, such as atomic models of shape memory materials, mechanics of protein networks, foldable structures for engineering applications, and more. Recently, the quasi-static behavior of bistable lattices has been studied for unidirectional tension and also shear. Importantly, the dynamic response of 1-D bistable lattices (chains) has been studied in a recent series of papers. Still, understanding the dynamic response of 2-D bistable lattices is still in its infancy, particularly the response to impacts. In this work, we make a step towards bridging this gap. We study, theoretically and numerically, the dynamic response to impacts of 2-D multi-stable lattices. Special emphasis is placed on energy landscape, non-linear wave phenomena like solitary waves or impact mitigation as well as the evolution of phase-transition patterns and surface waves. In addition, the influence of the lattice geometry and the properties of the bistable springs on the abovementioned features is investigated. Furthermore, we explored heterogeneous lattices involving bistable springs with different properties within the same lattice. In particular, the surface wave involves a combination of a solitary wave that propagates at the top row (surface) and a kink (transition) wave that follows the solitary wave right below the surface. We show that by clever design of the lattice properties, the propagation of the surface wave can be made stable for arbitrary long distances and that propagation is robust even in the presence of dissipation.

Edge resonance in micro-structured waveguides and convergence to the corresponding continuum case

Carta Giorgio (1), Nieves Michael (2), Brun Michele (1), Pagneux Vincent (3)

1 - University of Cagliari (Italy), 2 - Keele University (United Kingdom), 3 - Université du Maine - CNRS (France)

Speaker: Carta Giorgio. Invited. **Monday**. Start time: **11:30**. Room: Roseraie 2 LVL3. Link to abstract.

We study the scattering problem of Lamb waves at the edge of a semi-infinite triangular lattice strip. To this aim, we employ two approaches: the first one is based on mode matching, while the second one makes use of the Z-transform. With both methods, in the low-frequency range we derive the complex edge resonance frequency, at which localization of waves and trapped modes are observed in proximity of the strip's edge. By increasing the number of lattice's rows while keeping the width of the strip constant, we show that the complex edge resonance frequency of the discrete structure converges to the analogous quantity in the corresponding effective continuum, with the imaginary part being characterized by a non-monotonic trend. In addition, we demonstrate the orthogonality between the total displacement at the edge of the lattice strip and the stress produced by the incident wave, analogously to the continuum problem. Finally, we point out that the analytical results are confirmed by independent finite element simulations.

Acoustic wave diffraction by a quadrant of sound-soft scatterers

Nethercote Matthew (1), Kisil Anastasia (2), Assier Raphaël (2)

1 - University of Cambridge [UK] (United Kingdom), 2 - University of Manchester [Manchester] (United Kingdom)

Speaker: Nethercote Matthew. Invited. **Monday**. Start time: **11:50**. Room: Roseraie 2 LVL3. Link to abstract.

Motivated by research in metamaterials, we consider the challenging problem of acoustic wave scattering by a doubly periodic quadrant of sound-soft scatterers arranged in a square formation, which we have dubbed the quarter lattice. This leads to a Wiener–Hopf equation in two complex variables with three unknown functions for which we can reduce and solve exactly using a new analytic method. After some suitable truncations, the resulting linear system is inverted using elementary matrix arithmetic and the solution can be numerically computed. This solution is also critically compared to a numerical least squares collocation approach and to our previous method where we decomposed the lattice into semi-infinite rows or columns.

Conformal Elastodynamics in 2D Dilational Metamaterials

Watkins Audrey (1), Singh Neel (2), Bordiga Giovanni (1), Tournat Vincent (1) (3), Bertoldi Katia (1), Rocklin D. Zeb (4)

1 - Harvard John A. Paulson School of Engineering and Applied Sciences (United States), 2 - Georgia Institute of Technology [Atlanta] School of Physics (United States), 3 - Laboratoire d'Acoustique de l'Université du Mans LAUM - UMR CNRS 6613 (France), 4 - Georgia Institute of Technology School of Physics [Atlanta] (United States)

Speaker: Watkins Audrey. Invited. **Monday**. Start time: **13:40**. Room: Roseraie 2 LVL3. Link to abstract.

Flexible mechanical metamaterials capable of undergoing large deformations while supporting the propagation of nonlinear waves offer interesting observable phenomena. The rotating square structure is a canonical example of a flexible mechanical metamaterial platform that, when designed strategically, can support various nonlinear dynamic phenomena such as transition waves and solitons while undergoing extremely large deformations. In this work, we consider a harmonically-driven rotating square structure consisting of rigid bodies capable of rotating at their shared corners via flexible hinges. With a Poisson ratio of nearly -1, the rotating square structure can undergo deformations based on a uniform dilation mechanism. This dilational mode introduces a conformal symmetry, in which the dynamics are approximately invariant in an infinitely periodic structure under various physical transformations. At low frequencies, we experimentally and numerically observe that the dynamic response of a finite sized sample is dominated by conformal deformations, which consist of spatially varying dilations that are largest at the edges of the sample. Furthermore, we numerically explore the effect of modifying the experimental parameters, such as hinge stiffness, sample geometry, and number of unit cells, on the dynamic response of the structure. These results offer a promising new framework to observe and study novel wave phenomena in dilational mechanical metamaterials.

A novel theory of elastic wave propagation in a multi-porous medium with multi-permeability

Manna Santanu (1), Pramanik Dipendu

1 - Indian Institute of Technology Indore (India)

Speaker: Manna Santanu or Pramanik Dipendu. Invited. **Monday**. Start time: **14:00**. Room: Roseraie 2 LVL3. Link to abstract.

The work presents a theoretical development of elastic wave propagation in multi-porosity with multi-permeability porous media. We have developed a novel theory for elastic waves after single and double porosities. The theory features n distinct pore fluid phases and considers solid-fluid interactions as well as fluid-fluid interactions. The governing equation of motion for elastic wave propagation in complex multi-porous systems has been formulated using Lagrangian mechanics. The derivation of mass and dissipation coefficients in terms of known measurable parameters is a notable contribution of this research. In order to determine dissipation coefficients, Darcy's law of multi-phase systems was applied. The constitutive equation of an isotropic linear elastic multi-porous medium was also determined through the Gedanken experiments. In a subsequent step, equations of motion and dispersion for compressional and rotational waves within a multi-porous medium are developed. The dispersion equations for these waves in a specific case, like a triple porosity medium, are graphically represented and numerically explained. The validity of the theory is demonstrated by comparison with the existing theory of single porosity and double porosity. It is observed that the solid phase is associated with (n+1) compressional waves, whereas a fluid phase is associated with only one rotational wave. The Love wave and torsional wave, examples of surface waves have been studied in this medium. The concept of multi-porosity theory can contribute to a deeper understanding of wave behaviour in a porous medium.

Low-frequency propagating and evanescent waves in high-contrast sandwich structures

Prikazchikova Ludmila (1), Rege Ameya (2), Prikazchikov Danila (1), Erbas Baris (1)

1 - School of Computer Science and Mathematics, Keele University (United Kingdom), 2 - Faculty of Engineering Technology (ET), University of Twente (Netherlands)

Speaker: Prikazchikova Ludmila. Invited. **Monday**. Start time: **14:20**. Room: Roseraie 2 LVL3. Link to abstract.

The presentation is concerned with elastic waves propagation in aerogel-based sandwich plates, characterised by a high contrast in geometric and mechanical parameters of the layers. A multiparametric approach is developed. It is demonstrated that due to a high contrast an additional low-frequency propagating wave and a slowly decaying evanescent one emerges. The link between them is investigated. Two-mode long-wave low-frequency asymptotic expansions of the full dispersion relation are derived. Comparison of the asymptotic results with the numerical solution of the full dispersion relation is presented.

A high-order implicit time integration method for linear and nonlinear dynamics with efficient computation of accelerations

Daniel O'shea Daniel (1)

1 - University of New South Wales ([Kensington] Australia)

Speaker: Daniel O'shea Daniel. Invited. **Monday**. Start time: **14:40**. Room: Roseraie 2 LVL3. Link to abstract.

An algorithm for a family of self-starting high-order implicit time integration schemes with controllable numerical dissipation is proposed for both linear and nonlinear transient problems. This work builds on the previous works of the authors on elastodynamics by presenting a new algorithm that eliminates the need for factorization of the mass matrix providing benefit for the solution of nonlinear problems. The improved algorithm directly obtains the acceleration at the same order of accuracy of the displacement and velocity using vector operations (without additional equation solutions). The nonlinearity is handled by numerical integration within a time step to achieve the desired order of accuracy. The new algorithm fully retains the desirable features of the previous works: 1. The order of accuracy is not affected by the presence of external forces and physical damping; 2. The amount of numerical dissipation in the algorithm is controlled by a user-specified parameter $\rho_\{\infty\}$, leading to schemes ranging from perfectly nondissipative A-stable to L-stable; 3. The effective stiffness matrix is a linear combination of the mass, damping, and stiffness matrices as in the trapezoidal rule, leading to high efficiency for large-scale problems. The proposed algorithm, with its elegance and computational advantages, is shown to replicate the numerical results demonstrated on linear problems in previous works. Additional numerical examples of linear and nonlinear vibration and wave propagation are presented herein. Notably, the proposed algorithms show the same convergence rates for nonlinear problems as linear problems, and very high accuracy. It was found that second-order time integration methods commonly used in commercial software produce significantly polluted acceleration responses for a common class of wave propagation problems. The high-order time integration schemes presented here perform noticably better at suppressing spurious high-frequency oscillations and producing reliable and useable acceleration responses.

Non-linear waves in an array of bistable flexible cells

Faulconnier Antoine (1), Paliovaios Apostolos (2), Theocharis Georgios (2), Achilleos Vassos (2), Job Stéphane (1), Tournat Vincent (2)

1 - Laboratoire QUARTZ (France), 2 - Laboratoire d'Acoustique de l'Université du Mans (France)

Speaker: Faulconnier Antoine. Invited. **Monday**. Start time: **15:00**. Room: Roseraie 2 LVL3. Link to abstract.

Multistable systems, such as buckled beams, are attracting growing interest in the field of elastic metamaterials. At the scale of a bistable unit cell, we generally observe a double-well potential characterized by an unstable state between two stable regions. This intrinsically non-linear potential induces amplitude-dependent stiffness, which can be negative. Assembled in a network, these cells form a medium favorable to the propagation of nonlinear waves, such as solitons or transition waves. While the propagation of transition waves has been successfully studied, the response of these flexible metamaterials to periodic or sustained excitations remains less explored. In the context of the ANR project ExFLEM (Exploiting Extreme Wave Events in Nonlinear Flexible Elastic Metamaterials), we are studying the mechanical behavior of an array of bistable cells to analyze and exploit wave phenomena localized in time and space. Initially, we focus on the study and characterization of a single cell under quasi-static and dynamic loading. The quasi-static response is measured by tensile-compression tests coupled with displacement field analysis, in relation with the Euler-von Kármán beam model. The dynamic response, marked by Duffing-type softening in a weakly non-linear regime, is analyzed via a frequency response function using a shaker together with accelerometers. In a second step, we extend the analysis to a network of bistable cells connected by linear springs, subjected to harmonic excitation. We first present a model/test comparison of the mechanical response of a system coupling two elementary cells, before showing some preliminary observations concerning the propagation of weakly non-linear waves in a periodic network containing a finite number of elements.

Controlled distributed damage phenomenon in architectured lattice materials.

Ryvkin Michael (1)

1 - School of Mechanical Engineering, Tel Aviv University (Israel)

Speaker: Ryvkin Michael. Invited. **Monday**. Start time: **15:20**. Room: Roseraie 2 LVL3. Link to abstract.

An effective strategy observed in nature for resisting external destructive forces is to avoid localized catastrophic failure by damage of distributed sacrificial elements. This phenomenon significantly contributes to the remarkable mechanical properties of many biological materials. By absorbing energy under extreme loading conditions, these materials can undergo substantial deformations while remaining intact. A specific composite material microstructure can achieve this effect by incorporating distributed weak bonds that fail first. They are found, for example, in the organic adhesive holding together nacre tablets and in bone collagen tissue. Beyond bimaterial composites, the sought microstructure can also be generated by the specific shape voids in solid parent material. The periodic two-dimensional architected lattice cellular materials that realize this opportunity are the subject of the present communication. Their controlled quasi-static brittle failure behavior is considered by modeling the microstructure as a network of Euler-Bernoulli beam elements (links) rigidly connected at the nodal points (1-3).
For the study of the damage propagation dynamics, the model with massless links and point masses at the nodal points is applied. The problems of impulse and step-function loadings applied to the straight linear lattice boundary are considered. As a result of the failure of periodically located separated sacrificial links, the initial lattice material tranforms to a new one with reduced stiffness, and the phase transition takes place. Two waves types are observed: sacrificial elements failure wave and leading elastic wave propagating in front of it in the undamaged lattice. Consequently, the elastic wave velocity exceeds that of the damage front. Due to the breakage of sacrificial elements, the internal force's amplitude in the leading wave is significantly lower than the applied force's magnitude. The high frequency vibrations caused by the breakage of sacrificial elements are localized within the damaged layer and do not affect the leading wave. In practice, the vibration energy finally goes to heat due to the non-linearity of a natural parent material. It is found that the increase of the applied force raises both the damage wave velocity and the leading wave amplitude. However, the amplitude variation is notable only for small applied force values near the fracture initiation limit. The thickness of the partly damaged material layer can far exceed that of the fully damaged layer in lattice materials of the same relative density, which lack a specific architecture with sacrificial bonds. Therefore, for the optimal parameters combination, the sacrificial bonds layout can not only preserve the specimen shape after unloading but also provide outstanding energy absorption properties.

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A quantum graph approach to metamaterial design

Lawrie Tristan (1), Tanner Gregor (1), Chaplain Gregory (2)

1 - University of Nottingham (United Kingdom), 2 - University of Exeter (United Kingdom)

Speaker: Tanner Gregor. Keynote. **Monday**. Start time: **16:00**. Room: Roseraie 2 LVL3. Link to abstract.

We consider a quantum graph approach for designing metamaterials. An infinite square periodic quantum graph, constructed from vertices and edges, acts as a paradigm for a 2D metamaterial. Wave transport occurs along the edges with vertices acting as scatterers modelling sub-wavelength resonant elements. These resonant elements are constructed with the help of finite quantum graphs attached to each vertex of the lattice with customisable properties controlled by a unitary scattering matrix. The metamaterial properties are understood and engineered by manipulating the band diagram of the periodic structure. The engineered properties are then demonstrated in terms of the reflection and transmission behaviour of Gaussian beam solutions at interfaces between different metamaterials. We demonstrate negative refraction, beam steering and wave vector filtering among other effects both within our model and in experiments based on interconnected acoustic tubes.

Lattice systems with frontiers possessing contrasting periodicity: wave scattering and transmission

Aktunc Ege, Nieves Michael(1), Mishuris G. S.,

1 - Keele University

Speaker: Aktunc Ege. **Monday**. Start time: **16:40**. Room: Roseraie 2 LVL3. Link to abstract.

We consider wave scattering in discrete systems by boundaries and interfaces whose periodicity, elastic and inertial properties differ from those used in composing the interior of the system. We focus on the anti-plane motion of a discrete system represented by a square cell lattice formed from periodically placed masses interconnected by elastic rods.
In particular, we derive the Green's function for a lattice half-plane and dissimilar lattice with an N-periodic boundary and interface, though the application of the Fourier transform.
Special attention is given to the case of lattices with diatomic boundaries and interfaces in numerical simulations. These demonstrate the effectiveness of our approach and illustrate how different dynamic regimes that can be realised through tuning contrast in the inertial and elastic properties of the system.

Cochlea-inspired sensor for speech recognition

Beoletto Paolo Han (1), Gliozzi Antonio S. (1), Milano Gianluca (2), Ricciardi Carlo (1), Bosia Federico (1)

1 - Department of Applied Science and Technology [Politecnico di Torino] (Italy), 2 - Istituto Nazionale di Ricerca Metrologica (Italy)

Speaker: Beoletto Paolo Han. Invited. **Monday**. Start time: **17:00**. Room: Roseraie 2 LVL3. Link to abstract.

The digital transition is creating an increasing demand for speech recognition to be integrated into everyday devices. The human-machine interface is becoming increasingly reliant on the device's capability to interact with the user and the accurate detection of spoken words plays a central role in achieving this. Traditional deep learning methods are powerful but consume significant energy and computational resources. They are based on computing architectures where sensing, memory, and processing are separated: this approach increases latency and power consumption, especially when dealing with large networks of sensors. To address these challenges, in-sensor computing and near sensor computing are interesting paradigms, integrating computational tasks directly within the sensor material itself. This not only reduces energy consumption and data transfer times but also opens new doors for intelligent devices that can perform low-level computations internally. This work investigates how mechanical metamaterials can offer energy-efficient solutions for processing wave-based information in applications like IoT, artificial intelligence, and beyond. The device presented in this talk integrates a neuromorphic (mimicking brain's neural processing) auditory sensor inspired by the human cochlea with a physical reservoir based on a memristive architecture. The reduced power consumption and training cost, together with the fast encoding of spatio-temporal inputs, make it an interesting option for speech recognition tasks in the field of Internet of Things. The sensor is based on a spiral structure that exhibits tonotopy, i.e., the spatial discrimination of elastic waves depending on their frequency content. Thanks to an optimization routine the parameters that define the geometry of the spiral are selected to maximize the tonotopic effect in the desired frequency range.This sensor aims to be used as an artificial cochlea: with piezoelectric read-out in different locations of the device, we obtain a spatio-temporal map that is called "cochleagram", whose components are equivalent to the signals measured at different locations of the spiral. The parallel reading of the vibration signal in different locations of the device allows the direct separation of its frequency components, converting the auditory signal into recognizable patterns, thus enhancing the overall performance of speech recognition systems that benefit from frequency-related data. This measurement is run on an entire dataset of spoken digits, with 10 classes corresponding to the digits ranging from 0 to 9, for a total of 3000 samples. A linear classifier is trained with the dataset of measured cochleagrams in order to discriminate between the 10 classes, reaching an overall accuracy of 97.66%. Compared to the classification accuracy achieved by state-of-the-art software on the same dataset, the hardware implementation proposed here delivers superior performance while offering the significant advantage of eliminating the need for additional digital processing units. To further reduce the energy consumption of the system, it is possible to simplify the classifier by reducing the number of features required for the classification. This can be achieved through the integration of a reservoir, which is a network of coupled nonlinear elements capable of capturing time dependencies in the data. By creating a high-dimensional representation of the input, the reservoir significantly reduces the complexity of the neural network processing. The reservoir in this system is implemented in materia, leveraging memristive connections between silver nanowires. Cochleagrams, representing the spatio-temporal output of the spiral sensor, are fed into the reservoir as time-varying inputs. The reservoir condensates the information contained in the original maps in fewer features, allowing the classifier to operate with fewer timesteps of the cochleagram while maintaining high accuracy. Experimental results show that the inclusion of the reservoir preserves the system's ability to discriminate spoken digits, allowing to train the classifieron lower-dimensional data without losing its classification accuracy. This system is an insteresting low-power, efficient alternative to traditional methods for speech recognition, particularly in resource-constrained IoT applications.

Propagation of elastic waves in a soft strip: effect of a static pre-stretch

Delory Alexandre Lanoy Maxime (1), Kiefer Daniel Eddi Antonin Prada Claire Lemoult Fabrice

1 - Laboratoire d'Acoustique de l'Université du Mans (France)

Speaker: Lanoy Maxime. Keynote. **Tuesday**. Start time: **10:00**. Room: Roseraie 2 LVL3. Link to abstract.

Due to their remarkable deformability, soft structures play an essential role in many functionalities of living organisms. Processes such as locomotion, perception, and communication often rely on their particular mechanical properties-for instance, the vibration of vocal cords during speech. In this presentation, I will discuss the experimental investigation of a model system consisting of a simple soft elastomeric strip. I will show how one can capture the full in-plane dynamics using a single camera and highlight the emergence of atypical propagation phenomena, such as conical dispersion. In addition I will examine the effect of the application of an external static pre-stretch on the wave dispersion, thus rationalizing how tension can serve as an external control parameter to tune the propagation; an effect we use one a daily basis as we communicate.

Dual subharmonic instability in a soft strip submitted to a parametric forcing

Duval Eléonore (1) (2) (3), Tournat Vincent (1), Petrelis François (2), Lanoy Maxime (1)

1 - Laboratoire d'Acoustique de l'Université du Mans LAUM - UMR CNRS 6613 (France), 2 - Laboratoire de physique de l'ENS - ENS Paris (France), 3 - Matière et Systèmes Complexes (France)

Speaker: Duval Eléonore. Invited. **Tuesday**. Start time: **10:40**. Room: Roseraie 2 LVL3. Link to abstract.

When a system undergoes parametric forcing, it typically responds at half the excitation frequency. This phenomenon known as parametric resonance, was first observed by Faraday in vertically vibrating liquids and then by Melde in his studies of string resonances. In this presentation, we introduce an experiment akin to Melde's but with a significant twist: we use a strip made of a soft material, i.e. with a low Young's modulus. Under longitudinal vibration, this allows spatial modulation alongside temporal modulation, leading to an atypical response distinct from the classic Faraday-type sub-harmonic instability. We observe the creation of pairs of sub-harmonic frequencies (e.g., f/3 and 2f/3, or f/4 and 3f/4, where f is the forcing frequency). By varying f, the unstable pairs are modified. A theoretical model based on multi-scale analysis is used to predict and describe the dynamics of these observations.

Elastic wavepackets crossing a space-time interface

Delory Alexandre Prada Claire Lanoy Maxime Eddi Antonin Fink Mathias Lemoult Fabrice (1)

1 - Institut Langevin (France)

Speaker: Lemoult Fabrice. Invited. **Tuesday**. Start time: **11:00**. Room: Roseraie 2 LVL3. Link to abstract.

Time-varying media play a prominent role in current wave physics research, offering rich opportunities for wave manipulation, particularly in the realm of metamaterials. The integration of time as a modulation variable significantly expands the scope of potential applications. The space-time interface serves as an elementary building block for such manipulations, and a comprehensive understanding of wave interactions with such an interface is critical. This work presents experimental observations on guided elastic waves in soft strips. The velocities of flexural modes are directly linked to initial prestress, and we introduce an experimental setup capable of modulating these velocities through sudden uniaxial stress application. Our findings reveal that induced deformations propagate within the strip as step functions, causing not only deformation but also consistent translational motion at a constant speed. The potential of this deformation front as a space-time interface is revealed through its characterization. The interaction of flexural waves with this interface are then studied and significant changes in frequency and wavenumber are measured. Notably, we investigate the case of a supersonic interface, which offer interesting observations regarding wave control. In the future, the manipulation of waves through one or more space-time interfaces shows potential for inducing effects such as freezing, significant frequency conversions, and nonlinear modulations. This study is a crucial step in understanding space-time soft metamaterials and offers insights into diverse phenomena, drawing analogies with astrophysical phenomena and metric signature changes.

Dynamics of multistable mechanical metamaterials: recent results on nonlinear waves, transition fronts and their interactions

Tournat Vincent (1) (2)

1 - CNRS, LAUM UMR-CNRS 6613, Institut d'Acoustique - Graduate School, Le Mans Université (France), 2 - John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA (United States)

Speaker: Tournat Vincent. Invited. **Tuesday**. Start time: **11:20**. Room: Roseraie 2 LVL3. Link to abstract.

Multistable metamaterials, composed for example of bistable mechanical units elastically coupled to their nearest neighbors, have recently been conceived in diverse ways, particularly within the family of flexible mechanical metamaterial architectures. Such multistable metamaterials can support progressive fronts, also called transition waves, switching sequentially its multistable units front one equilibrium to another, and resulting in the local or global reconfiguration of the medium. In addition, these nonlinear metamaterials are also known to support a rich variety of nonlinear waves, as vector solitons, breathers, cnoidal waves, among others. In this presentation, I will highlight the fundamentals and a selection of recent results on transition waves: how they can be triggered, what can be their propagation properties, and how they interact with other nonlinear waves. In general, these reconfiguration fronts obey nonlinear reaction-diffusion equations and show specific properties not necessarily found in other waves supported by periodic and/or nonlinear media, e.g., strong nonreciprocity, robustness, extreme amplitude dependent behavior... They can consequently be implemented for applications involving local or global reconfiguration of a medium, manipulating mechanical memory, controlling waves in space and time, mechanical computing or be the vector for material embedded intelligence.

A reduced-order model formulation for dispersion curve computation in nonlinear metamaterial beams

Quqa Said (1), Marzani Alessandro (1), Palermo Antonio (1)

1 - University of Bologna (Italy)

Speaker: Quqa Said. Invited. **Tuesday**. Start time: **14:15**. Room: Roseraie 2 LVL3. Link to abstract.

Elastic metamaterials have garnered significant attention in recent years for their ability to manipulate wave propagation and mitigate vibrations. These properties are typically achieved by engineering frequency band gaps through the integration of resonant structures with subwavelength dimensions into the waveguide. The design of these structures is normally ruled by dispersion laws where linear models of the resonant structures are coupled to the elastic waveguide. Although nonlinear resonators are gaining interest, they are often modeled with simplistic approaches based on single-degree-of-freedom (DOF) models. For multi-DOF nonlinear systems, capturing mode interactions is essential for accurate dispersion analysis, which significantly increases formulation complexity.

This contribution introduces a method to address this complexity by using a reduced-order model (ROM) for nonlinear multi-DOF resonators, which effectively captures mode interactions and enables efficient calculation of dispersion curves for the metamaterial. Specifically, a ROM is derived for each mode (referred to as the "master" mode) of the resonator, incorporating the effects of nonlinear restoring forces from other modes ("slave" modes). In turn, these contributions are expressed as functions of the master mode displacement and velocity using the invariant manifold approach. This allows the calculation of the ROM transfer function and coupling with a substrate to predict dispersion relations near the resonance frequency of the master mode.

The findings reveal that simplifying the original nonlinear system to a single-DOF model without accounting for interactions from other modes introduces substantial errors in the resonator response and, in turn, in the waveguide dispersion prediction, potentially leading to inaccurate metamaterial design. Conversely, the proposed ROM-based approach efficiently predicts resonator responses comparable to those of the full nonlinear model thus leading to accurate determination of dispersion curves.

Acoustoelasticity in Materials: The Influence of Plastic Deformation on Wave Propagation

Ruetz Marcel (1), Antretter Thomas (2), Gänser Hans-peter (1)

1 - Materials Center Leoben Forschung GmbH (Austria), 2 - Institute of Mechanics, Montanuniversität Leoben, Franz Josef-Straße 18, 8700 Leoben, Austria. (Austria)

Speaker: Ruetz Marcel. Invited. **Tuesday**. Start time: **14:35**. Room: Roseraie 2 LVL3. Link to abstract.

Ultrasonic waves are widely used in non-destructive material testing, from defect detection to residual stress analysis. A critical factor influencing wave propagation is the material's microstructure, especially dislocation density changes resulting from plastic deformation. This study extends the acoustoelastic theory by Hughes and Kelly to formulate a model that connects plastic strain with changes in acoustoelastic constants based on metal physics. The theoretical model describes the relationship between dislocation density and propagation velocity, predicting that plastic deformation decreases velocity quadratically. By integrating established theories such as the generalised Taylor rule and the Kocks-Mecking model, a connection is established between dislocation density or the plastic strain and acoustoelastic constants. The theoretical model describes the relationship between dislocation density or plastic strain and propagation velocity. To validate these predictions, experimental measurements from literature are compared, with the theoretical predictions demonstrating a strong alignment. These findings provide a reliable quantitative tool for assessing plastic strain and offer valuable insights to advance ultrasonic testing with respect to residual stresses and plastic strain in plastically deformed materials.

Dynamics and Elasticity of Origami-based Beams

Berinskii Igor (1), Eremeyev Victor (2)

1 - School of Mechanical Engineering, Tel Aviv University (Israel), 2 - Department of Civil and Environmental Engineering and Architecture, University of Cagliari (Italy)

Speaker: Berinskii Igor. Invited. **Tuesday**. Start time: **14:55**. Room: Roseraie 2 LVL3. Link to abstract.

We consider origami-inspired deployable beams consisting of rigid and extensible links connected by torsional springs. First, we study a discrete model and develop the system of ordinary differential equations of motion for multiple degrees of freedom, describing the complete dynamics of the system. Then, we create a homogenized model that allows us to substitute an extensive system of discrete equations with several coupled partial differential equations for continuum functions. The equations of generalized elasticity, such as micropolar and microstretch continua, are expected to represent the continuum media. For both models, dispersion relations are derived and compared. It is shown that the discrete linear model for the rigid links beam introduces severe constraints and limits the possible wave propagation. At the same time, continuum linear models for both extensible and rigid link beams lose the lowest (acoustic) mode compared to their discrete counterparts. Possible solutions for these paradoxes are discussed.
The dynamics of the origami-based beam are simulated using the particle-based method to solve constrained equations of motion explicitly. The resulting continuum model is assumed to be easier to deal with and more suitable for large-scale simulations. Possible applications include the use of shape-morphing materials as advanced sensors and actuators for soft robotics, space solar batteries and antenna deployment, medical stents, and other applications.

Multimode approximations for thin elastic coatings and interfaces

Erbas Baris (1), Kaplunov Julius (1)

1 - School of Computer Science and Mathematics, Keele University (United Kingdom)

Speaker: Erbas Baris. Invited. **Tuesday**. Start time: **15:15**. Room: Roseraie 2 LVL3. Link to abstract.

Thin elastic coatings and interfaces arise in numerical engineering applications, including high contrast laminates involving soft layers. Forced time-harmonic motions are considered not making any restriction on the vibration frequency. Long wave, multimode approximations are derived from the original 3D setup. It is governed by 2D equations with coefficients depending on trigonometric functions of the frequency parameter. The related explicit dispersion relations appear to be of general interest as well. Although formulations are oriented to the analysis of the effect of prescribed stresses slowly varying along the faces, they are also useful of various resonance responses due to concentrated loading. Numerical comparisons between exact results and asymptotic predictions are demonstrated.

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Origami for Robotics and Active Mechanical Haptics

Jiang Hanqing (1)

1 - Westlake University [Zhejiang] (China)

Speaker: Jiang Hanqing. Invited. **Tuesday**. Start time: **15:35**. Room: Roseraie 2 LVL3. Link to abstract.

The capability of stiffness manipulation for materials and structures is essential for tuning motion, saving energy, and delivering high power. However, high-efficiency in situ stiffness manipulation has not yet been successfully achieved despite many studies from different perspectives. In the first half of this talk, we will present curved origami patterns to accomplish in situ stiffness manipulation covering positive, zero, and negative stiffness by activating predefined creases on one curved origami pattern. This elegant design enables in situ stiffness switching in lightweight and space-saving applications, as demonstrated through three robotic-related components. Then in the second half of this talk, we will present a first-person, human-triggered haptic device enabled by curved origami that allows humans to actively experience touching of objects with various stiffness perceptions from soft to hard and from positive to negative ranges. This new device represents a significant shift away from third-person, machine-triggered, and passive haptics currently in practice. The device is synchronized with the virtual environment by changing its configuration to adapt various interactions by emulating body-centered physical perceptions, including hardness, softness, and sensations of crushing and weightlessness. The high-fidelity stiffness perceptions achieve an unprecedented experience of "what a user sees or is immersed in, is what the user feels or steps on".

Modelling the elastodynamics of a thin flexible aerogel layer

Xiong Weibo (1), Prikazchikov Danila (2), Abdusalamov Rasul (1), Itskov Mikhail (1)

1 - Department of Continuum Mechanics, RWTH Aachen University (Germany), 2 - School of Computer Science and Mathematics, Keele University [Keele] (United Kingdom)

Speaker: Prikazchikov Danila. Invited. **Tuesday**. Start time: **16:35**. Room: Roseraie 2 LVL3. Link to abstract.

Aerogels are extremely lightweight materials known for their multifunctional properties, having wide engineering applications (1). Their mechanical properties have been mostly studied within the context of elastostatics. In this contribution, we study dynamics of a thin super-flexible hybrid silica aerogel layer modelled as elastic with density-dependent Young's modulus, relying on the recently developed model (2). The presence of the variable Young's modulus accounts for the effect of porosity at the macro-scale, further developing the results in (3), and, at the same time being significantly less computationally expensive than the approach relying on the microstructure (4). The layer is assumed to have one fixed face, with the other one subject to prescribed vertical displacement, in absence of shear stress. An asymptotic weakly nonlinear procedure is constructed, leading to a two-term expansion, which is then compared to numerical solution.

Acknowledgement
This research was supported by the DFG grant № 520432297 "Multiscale Dynamics of Aerogel and Aerogel Composite Matching Layers".

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Enhancing thermal negative expansion with hierarchical beam structures

Ioannou Sougleridis Ioannis (1) (2) (3), Brun Michele (3), Carta Giorgio (3), Baldi Antonio (3)

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Speaker: Ioannou Sougleridis Ioannis. Invited. **Tuesday**. Start time: **16:55**. Room: Roseraie 2 LVL3. Link to abstract.

Thermal expansion in solids has long been a focus in materials science, with growing attention to mechanical metamaterials that feature tunable coefficients of thermal expansion. The goal of most of these studies is to design structures exhibiting coefficients of thermal expansion that can reach extreme positive values compared to those of the composite materials, and most importantly zero and negative values. This study introduces a novel mechanical lattice composed of a periodic arrangement of structural frames made of beams. The latter presents a highly tunable effective coefficient of thermal expansion, varying from positive to negative values. Our analytical approach demonstrates that the effective coefficient of thermal expansion depends on the geometric characteristics of the frame, the elastic constants and the coefficients of thermal expansion of the constituent elastic elements. Employing a hierarchical approach, based on substituting each elastic beam with a frame, enables the effective coefficient of thermal expansion to reach values far exceeding those of the base materials. Furthermore, the results of the numerical simulations are verified with experimental tests. The proposed tunable model opens up potential applications in energy storage and the control of elastic instabilities in mechanical systems.

Forcing the Silence of the Lamb waves: Uni-directional propagation in structured gyro-elastic strips and networks

Nieves Michael (1), Carta Giorgio (2), Brun Michele (2)

1 - Keele University (United Kingdom), 2 - University of Cagliari (Italy)

Speaker: Nieves Michael. Invited. **Tuesday**. Start time: **17:15**. Room: Roseraie 2 LVL3. Link to abstract.

We consider a gyro-elastic structured strip, formed from rods interconnecting periodically placed masses that are attached to gyroscopes. The presence of the gyroscopes makes the system non-reciprocal. Near bulk resonances of the strip, the medium is capable of supporting uni-directional Lamb waves when subjected to forcing (1). We discuss the solution to this problem and demonstrate how these near-resonance effects can lead to designs of novel waveguides. Namely, we illustrate how we can create a network of structured strips that is capable of channelling the energy supplied by an external source towards any of its endpoints, which can be chosen arbitrarily and in advance.

(1) G. Carta, M.J., Nieves, M. Brun, (2023): Forcing the Silence of the Lamb waves: Uni-directional propagation in structured gyro-elastic strips and networks, Eur. J. Mec. A-Solid 101, 105070

TOPIC: Structural Mechanics

MS7.0 - General session, Structural Mechanics

Organisers: Elodie Prud'Homme (INSA Lyon) and Sabine Rolland Du Roscoat (Grenoble INP)

A Comparative Study on Model Order Reduction Techniques for Structural Health Monitoring and Prediction of Ship and Marine Structures with Detachable Mooring System

Sim Kichan (1), Lee Kangsu (1) (2), Park Byoungjae (2), Kim Byoung Wan (1) (2), Ki Minsuk (2)

1 - Korea Research Institute of Ships & Ocean Engineering School, National University of Science & Technology(UST) (South Korea), 2 - Eco-friendly Ocean Development Research Division, Korea Research Institute of Ships and Ocean Engineering (South Korea)

Speaker: Sim Kichan. **Tuesday**. Start time: **14:15**. Room: Saint Clair 5 LVL2. Link to abstract.

Structural integrity evaluation of ships and offshore structures has seen increasing interest in digital twin applications. Historically, structural safety was maintained through conservative design practices involving large safety factors and scheduled inspections. However, real-time assessment of structural performance is now achievable with digital twin technology. With the increasing demand for eco-friendly energy generation as well as general ships and marine structures, research on implementing digital twins for real-time structural health monitoring in floating offshore wind turbine is being actively conducted. This research explores the application of model order reduction(MOR) methodologies to develop digital twins for structural health monitoring (SHM) of ship and marine structures exposed to irregular wave loads in realistic ocean environments. Specifically, the floating offshore wind turbines in this study utilize a detachable mooring system, enabling efficient maintenance (e.g., damage prevention and repairs) by facilitating detachable mooring system without underwater intervention, thereby significantly reducing offshore operational time. Consequently, a digital twin is crucial for rapid structural damage detection and health assessment, enabling more effective structural maintenance. Model order reduction method offers the advantage of significantly reducing computational cost when analyzing large and complex structures, allowing for quicker estimation of structural responses. Moreover, reduced order model(ROM) facilitates the prediction of structural behavior based on available sensor measurements. In this study, both the Krylov Subspace method and the Proper Orthogonal Decomposition (POD) technique were applyed to generate reduced-order models of representative ship and marine structures. A comparative study was then performed, focusing on the accuracy of structural response predictions, computational time required by each method, and a detailed discussion of the strengths and weaknesses associated with each algorithm. Validation of the proposed techniques was achieved through comparison with experimental data obtained from model tests conducted at the Korea Research Institute of Ships & Ocean Engineering(KRISO). Furthermore, the structural response prediction performance of the reduced-order model (ROM) was analyzed with respect to the number of reduced orders. Compared to the full order model (FOM) with tens of thousands of degrees of freedom, the ROM achieved over 99% accuracy with as few as 20 reduced orders. Consequently, applying model order reduction to ship and marine structure simulations resulted in structural response predictions with an error of less than 1.19% compared to simulations of full order model, achieving over 99% reduction in simulation time. Acknowledgements: This research was supported by a grant from the Endowment Project of "Study on Concept Design of Small Modular Reactor(SMR) powered Ships and Offshore Platforms(2520000281)" funded by the Korea Research Institute of Ships and Ocean Engineering; and the Korea Institute of Energy Technology Evaluation & Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20223030020240).

Improving the Resilience of Structures through Active Curvature Modulation

Varkonyi Peter (1), Guerra Riano Andres F.

1 - Budapest University of Technology and Economics (H-1111 Budapest, Muegyetem rkp. 3. Hungary)

Speaker: Varkonyi Peter. **Tuesday**. Start time: **14:35**. Room: Saint Clair 5 LVL2. Link to abstract.

Plant shoots and roots optimize their access to resources like water, light, and nutrients through tropic movement-by turning toward preferred directions via variations in intrinsic curvature. We explore the enhanced efficiency of structures imitating plant tropism with the aid of rotary actuators driven by standard PID (proportional-integral-derivative) controllers. The study of actuated chains, fixed at one or both endpoints, reveals fundamental differences between under-actuated, fully actuated, and "over-actuated" systems, and also sheds light on the role of controller parameters in optimizing stability and responsiveness. In addition to turning toward prescribed directions, we also investigate how decentralized curvature modulation along a chain can eliminate bending by converging to a funicular shape without explicit knowledge of external loads or the target shape. These findings open the possibility of designing adaptive structures responding to time-dependent loads by active shape control.

Analytic and numerical models for digital twins in sheet metal bending: A computational study

Reisinger Christian (1), Zehetner Christian (1), Mayr Simon (1)

1 - University of Applied Sciences Upper Austria (Austria)

Speaker: Zehetner Christian. **Tuesday**. Start time: **14:55**. Room: Saint Clair 5 LVL2. Link to abstract.

The demands on quality of industrial metal forming processes are constantly rising. To meet all requirements, reliable computational models are needed that can be integrated in digital twins of production lines. In the following we look at the example of sheet metal bending where the workpiece is thin compared to the lateral dimensions. The process is highly nonlinear because of material behavior, contact, and large deformation.
So far, numerical models are based on the Finite Element Method (FEM). There is no doubt that the results are reliable, as is often proved by experimental validation. However, if numerical models are to be used in a digital twin, two main problems arise: First, the license costs of commercial Finite Element software are very high. In our group Abaqus has been successfully used for a long time in research and development. One aim of the present work is to find out whether the open-source software Code_Aster is a suitable alternative to model and simulate metal bending. Secondly, if a digital twin has to be real-time capable, a Finite Element Analysis (FEA) usually requires too much computing time. Therefore, the second aim of this work is to find out whether an analytic model based on Euler's Elastica would be representative of this industrial process.

For our analytical model, we consider a cantilever beam subjected to a transverse follower force on the free end, which is a good approximation of the load case in the industrial process. Using the theory of Euler's Elastica, we consider large flexural deformations but assume inextensibility in longitudinal direction. An analytical solution is presented. The results are then verified by FEA for the special case of a linear elastic material with large deformation. Models based on 3D continuum elements are implemented in Abaqus and Code_Aster. The simulations are performed for different parameter combinations in order to compare analytic and numeric results, the computation times, and to determine the validity limits.
The results show good agreement between the two Finite Element solutions. Parameter studies confirm that the analytic results are representative of the industrial process over a wide range, and clearly show the limitations, especially for the profile angles and the length-to-thickness ratio of the workpiece. Finally, future extensions of the proposed theory are discussed and the next steps to integrate the analytical and the Code_Aster Finite Element model into a digital twin of sheet metal bending production lines are outlined.

Performance of a Guided-Wave SHM System for Launcher Structure Revalidation

El Guerjouma Lina (1) (2) (3), Eiras Jesus (1), Mechbal Nazih (2), Irisarri François-xavier (1), Gaverina Ludovic (1), Hascoët Nicolas (2), Garcia Martinez Adrian (3)

1 - DMAS, ONERA, Université Paris-Saclay, 92320, Châtillon, France (France), 2 - PIMM, Arts et Métiers ParisTech, CNRS, CNAM, 151 Boulevard de l'Hôpital, Paris, 75013, France (France), 3 - CNES DTN/STS, 52 rue Jacques Hillairet, 75012 Paris (FR) (France)

Speaker: El Guerjouma Lina. **Tuesday**. Start time: **15:15**. Room: Saint Clair 5 LVL2. Link to abstract.

The reuse of space launchers is increasingly considered a key strategy to reduce costs and enhance the competitiveness of the space industry. However, this approach requires an efficient and reliable revalidation step before each flight to ensure the mechanical integrity of the structures. Structural Health Monitoring (SHM) offers a promising solution to address this challenge by enabling real-time assessment of structural health through the integration of sensors networks embedded within launcher structures. In this work, we propose the use piezoelectric transducers. With these elements, two SHM strategies can be investigated: active and passive. On the ground, the active-mode SHM system uses guided waves in emission/reception to inspect the structure. During flight, the passive-mode system records acoustic events, such as the emergence of defects, thereby contributing to improved diagnostics.
One of the main challenges facing SHM systems, especially in space applications, is ensuring that they do not introduce damage and assessing their reliability under extreme environmental conditions. The proposed SHM system is bonded to the launcher and experiences the same extreme conditions as the structure itself, resulting in thermomechanical aging of both the launcher being inspected and the monitoring system (1). This aging reduces the SHM system's ability to detect and localize defects on the structure (2), representing a critical challenge for its implementation on reusable launch vehicles (RLVs).

This work focuses on a network of active-mode guided wave piezoelectric wafers bonded to a complex composite structure representative of a launcher vehicle. The objective is to study wave propagation in a complex spatial composite structure and evaluate the ability of the SHM system to detect and localize damage at different aging states. A numerical model is first developed using the finite element method to describe both the SHM system and the structure at a reference state. The numerical model is then validated by comparison with experimental data obtained from wave propagation measurements (using a laser Doppler vibrometer) and electromechanical impedance measurements (using an impedance analyzer). Finally, experimental tests are conducted to subject the SHM system to representative thermomechanical loads. The observed aging trends are injected into the numerical model to evaluate the effects of aging on defect detection and localization.

In conclusion, the aging of the SHM system has been demonstrated to significantly impact its ability to detect and localize defects, highlighting the importance of assessing SHM system performance over time when applied to reusable launch vehicles.

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Free-form Design of Funicular Arches Coupled by Straight Bars in Two and Three Dimensions

Szesztay Ágoston Péter (1), Várkonyi Péter L. (1)

1 - Budapest University of Technology and Economics (Hungary)

Speaker: Szesztay Ágoston Péter. **Tuesday**. Start time: **16:35**. Room: Saint Clair 5 LVL2. Link to abstract.

Funicularity is a central concept in the design of slender, lightweight structures. Slender funicular structures balance external loads through axial forces. For a given load distribution, only a limited set of shapes can bear loads in a funicular manner. This constraint poses a challenge for the widespread application of funicular structures and necessitates form-finding during the conceptual design phase.
In this work, we focus on the form-finding of *coupled pairs*-structures composed of two coplanar or spatial curvilinear arches, connected by a set of densely distributed elements (representing hangers or spandrel columns). Existing form-finding methods for coupled curves allow freedom in shaping one arch, while the shape of the second is dictated by the requirement of funicularity. We introduce new methods that enable designers to prescribe the shapes of both arches in the planar case by appropriately distributing the connecting elements between them. These methods are then extended to pairs of spatially curved arches, where the projected shapes of the curves in a plane can be prescribed by the designer, with the spatial form determined by equilibrium equations. This extension can be seen as a special case of form-finding using Thrust Network Analysis.
The results presented here are relevant to the conceptual design of spatial arch and suspension bridges, cable trusses, beams with external post-tensioning, and the retrofitting of existing beams or vaults.

Screen Printed Piezoelectric Transducers for Structural Health Monitoring of Curved Thick Composite Panels

Rebillat Marc (1), Paunikar Shweta (1), Galanopoulos George (2), Margerit Pierre (1), Wirth Ingo (3), Monteiro Eric (1), Zarouchas Dimitrios (2) (4), Mechbal Nazih (1)

1 - Arts et Métiers Institute of Technology, CNRS, CNAM, PIMM, HESAM Université, Paris, France (France), 2 - Structural Integrity and Composites Group, Aerospace Engineering Faculty, Delft University of Technology, Delft, The Netherlands (Netherlands), 3 - Fraunhofer Institute for Manufacturing Technology and Advanced Materials (Germany), 4 - Center of Excellence in Artificial Intelligence for Structures, Prognostics and Health Management, Aerospace Engineering Faculty, Delft University of Technology, Delft, The Netherlands (Netherlands)

Speaker: Rebillat Marc. **Tuesday**. Start time: **16:55**. Room: Saint Clair 5 LVL2. Link to abstract.

This research focuses on the development and experimental validation of a novel printed piezoelectric transducers network employed on a foreign object damage panel substructure of an aircraft engine fan blade. The main goal of the work is to leverage the screen printing technology to fabricate arrays of piezoelectric transducers and ultimately employ these transducers for operations, enabling the development of structural health monitoring methods for the panel. The printed transducer is made up of a piezoelectric layer sandwiched between two silver electrodes, each printed in a controlled manner. Upon printing and drying of the layers, the transducers undergo polarization. The electromechanical behaviour of the printed transducers, characterized using impedance measurements, exhibits high repeatability, thus indicating its potential for large scale industrial deployment. Following this, it is demonstrated that the transducers are capable of accurately sensing impact, which is one the most common yet critical sources of damage to an engine fan blade. It is also shown that the printed transducers are able to detect acoustic emission events. The ability of the printed transducers to actuate and sense guided wave signals over a range of ultrasonic frequencies is also demonstrated. Furthermore, apart from the noticeable advantages of the non-intrusive nature, and negligible weight as compared to their traditional ceramic counterparts, the printed piezoelectric transducers can potentially be integrated into the manufacturing process in the future, and the presence of transducer arrays ensures the availability of other transducers in case of an individual failure during service. This innovative printing technology for PZT transducer networks thus holds significant promise in bridging the gap between research advancements and the industrial implementation of SHM technology.

Geometry and control of scissor mechanism

A Mohanraj (1), Prasath S Ganga (1)

1 - Indian Institute of Technology Madras (India)

Speaker: A Mohanraj. **Tuesday**. Start time: **17:15**. Room: Saint Clair 5 LVL2. Link to abstract.

Scissor mechanisms are versatile in their utility and have been used in various engineering applications for scalable and extendable planar motion. A scissor mechanism comprises several connected scissor-units, each of which is made up of a pair of rigid linkages fastened by a pin joint. When the mechanism is actuated at one of its ends, this results in displacement across the entire mechanism, making it amenable to non-local control. The geometry of such a mechanism is closely related to discrete curves in 2D and we find that each configuration of the mechanism is completely described by the aspect ratio of the individual units and the angle of actuation. Leveraging the underlying geometry of the scissor-units, we estimate the aspect ratio and the actuation angle required to morph the mechanism to desired shapes. To exhibit the precise controllability of this mechanism, we identify the aspect ratio of each scissor-unit needed to make the distal end traverse a particular trajectory upon actuation, effectively demonstrating its ability to 'write'. Through experiments using precision 3D-printed models, we compare our results with theoretical predictions and demonstrate the viability of our approach for robotic applications. Our approach provides a general framework for designing mechanical structures by embedding functions into their form while accounting for intrinsic geometric non-linearities.

Potential of friction to damp vibrations in the use case of a car tailgate

Kugler Marion (1) (2) (3), Koschnik Frank (4), Marx David Sebastian Dienwiebel Martin (1) (2) (3)

1 - Fraunhofer Institute for Mechanics of Materials (Germany), 2 - Institute for Applied Materials - [Karlsruhe] (Germany), 3 - MicroTribology Centrum µTC (Germany), 4 - Bertrandt Simulations GmbH (Germany)

Speaker: Kugler Marion. **Tuesday**. Start time: **17:35**. Room: Saint Clair 5 LVL2. Link to abstract.

In modern cars, background noise is a common issue, and it is expected to become more pronounced as vehicles, particularly those with electric powertrains, become quieter, making it easier for passengers to detect disturbing sounds. This phenomenon, known as NVH (noise, vibration, and harshness), is often addressed by introducing additional mass into the structure, which reduces vibrations or shifts them to other frequencies. However, this method may not be sustainable in the long term.

In this study, we explore the possibility of damping vibrations through energy dissipation based on friction. We test the concept of damping through friction in the tailgate of a commercially available car, where a mass-based vibration damper is currently installed. We aim to replace the mass damper with small friction elements that can be distributed throughout the structure of the tailgate. This study investigates whether damping can be achieved through dissipated energy based on friction, which could provide a more sustainable solution to the NVH problem in cars.

However, the ideal contact conditions of the friction elements must be found for the application. For example, little energy is dissipated at low relative displacements or high contact pressures. The contact is in the so-called stick. However, if it is possible to adjust the contact so that a certain threshold value for the relative displacement is exceeded or a certain contact pressure is undershot, the contact can start to slide. In sliding the dissipated energy due to friction is significantly higher.

A design with screws was developed as friction elements. With the screws, a contact pressure can be specifically set by means of different tightening torques. As the relative displacement cannot be actively influenced, the contact pressure, i.e. the tightening torque, must be used to ensure that the contact can start to slide and thus dissipate energy. In order to test the concept, experiments were carried out on a geometrically simplified model of the tailgate.

For this purpose, a friction element in the form of a plate with screws was inserted into the model of the tailgate. The screws were mounted with four different tightening torques and the entire tailgate model was excited on a shaker. Acceleration sensors were used to measure the reaction of the tailgate model to this excitation of the shaker. Under a certain tightening torque, there is a reduction in the acceleration amplitude at the frequency relevant for the interference noise. It was also assessed whether an increase in the number of friction elements leads to a further reduction in the acceleration amplitude. For this purpose, three friction elements were used instead of just one.

In order to be able to better estimate the damping potential, tests were also carried out with similar materials on a Fretting tester. Here, the frequency responsible for the interference noise can be specifically stimulated. In addition, measuring the relative displacement in the contact and the frictional force in the experiment allows the energy dissipated by friction to be calculated. An energetic comparison between a contact in sticking and sliding is possible.

Cyclic elastoplastic shakedown behavior of an auxetic metamaterial

Wang Shen (1), Peigney Michael (2), Vermaak Natasha (1)

1 - Lehigh University [Bethlehem] (United States), 2 - Université Gustave Eiffel (France)

Speaker: Wang Shen. **Tuesday**. Start time: **17:55**. Room: Saint Clair 5 LVL2. Link to abstract.

Auxetic structures exhibiting effective negative Poisson's ratio behavior have shown promising energy absorption capabilities in applications subject to cyclic loadings in the elastic domain. However their cyclic elastoplastic behaviors, and shakedown response in particular, have not been fully understood. Wang et al. (1) predicted the maximum loading capacity of a variety of auxetic tubular lattice structures using the proposed direct numerical shakedown method. The study was entirely computational and did not discussed the relationship between the structure auxeticity and their shakedown behaviors. The present work (2) focuses on auxetic metamaterial structures achieved by regular perforations in Aluminum sheets (3). These auxetic sheets are subjected to asymmetric cyclic uniaxial tensile loads at room temperature to elicit elastic and resilient elastoplastic behaviors without compressive buckling. The study aims to determine the safe elastoplastic shakedown limit of the perforated auxetic aluminum sheet structures (AA5083-TO) with fixed void fraction (16.4%). The motivation is that shakedown-based designs can be used to expand the feasible design space under cyclic loading conditions compared to conventional yield-limited designs. Experimental, numerical, and theoretical results are used to elucidates interactions between auxeticity and maximum shakedown loading capacity. In particular, a non-monotonic relationship between the shakedown multiplier and auxeticity was identified. Furthermore, it was found that shakedown occurs at stress levels 2-4 times the elastic limit of the structure for a fixed allowable equivalent strain level (at approximately 3%). The analytical model is used to explore the underlying mechanisms and to propose a simple structural index to aide in optimal design.
KEYWORDS: Shakedown; Auxetic metamaterials; Cyclic plasticity

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Perturbed holes in two-dimensional anisotropic elastic solids

Hsieh Meng-ling Hwu Chyanbin (1)

1 - National Cheng Kung University (Taiwan)

Speaker: Hwu Chyanbin. **Wednesday**. Start time: **10:00**. Room: Saint Clair 5 LVL2. Link to abstract.

This study explores perturbed holes in finite and infinite two-dimensional anisotropic elastic solids, which is a challenging problem for analytical methods owing to the mathematical complexity involved. The perturbed hole contours, defined as small variations from an ellipse, include a variety of shapes, such as polygons with rounded corners. The hole boundary is assumed to be traction-free. We formulate the problem with the Stroh formalism, which is a complex-variable formalism for anisotropic elasticity, and then use the method of analytical continuation to derive the solution. The solutions are addressed through two distinct approaches: the nonconformal mapping technique and the perturbation method. The nonconformal mapping approach, which directly transforms the solution domain onto the exterior of a unit circle, is recommended for cases where critical points (where the derivative of the mapping function equals zero) lie far from the hole. On the other hand, the perturbation approach, which expands the solution into a series form, is employed for cases where the nonconformal mapping approach falls short. For finite domains containing perturbed holes, a novel set of boundary elements is developed using Green's functions presented in this study. These boundary elements eliminate the need for meshing along the hole boundary, thereby enabling more efficient and accurate analysis of finite problems. Numerical examples validate the proposed solutions through comparisons with results of the finite element method.

Projective Geometric Elasticity

Baranyai Tamás (1)

1 - Budapest University of Technology and Economics (Hungary)

Speaker: Baranyai Tamás. **Wednesday**. Start time: **10:20**. Room: Saint Clair 5 LVL2. Link to abstract.

The coordinate description of lines of 3 dimensional projective space developed by Julius Plücker in the 1860's originates from the description of spatial force and inifinitesimal displacement systems. This was later extended with elastic beam theory and the description is actively used today, for instance in the deisgn of kinematic chains. The subject of the talk is the next step in the projective treatment of mechanics: describing how to treat continuum problems in the projective setting. We show how to embed the stress and infinitesimal strain tensor in projective line geometry and identify stress and strain states with generalized conics and quadrics. This opens up the possibility to take projective collineations (transformations that preserve point-line incidence but not parallelism) of elasticity problems advancing beyond the previously explored affine transformations. We show that many boundary conditions of elasticity problems are incidence conditions and thus are projective invariants. We show that material properties like isotropy or global orthotropy are not projective invariants. As such the talk concludes with the projective transfromations of membrane shells such that the correspondence of the shape and stress functions as established by Pucher's equation is preserved.

The Impact of Pitch Angle and Porosity on the Tensile Properties Porous Bouligand Structured Polymer.

Patil Praveenkumar (1), Alam Parvez (2), Mccarthy Edward D (1)

1 - School of Engineering, The University of Edinburgh, UK (United Kingdom), 2 - School of Engineering, The University of Edinburgh, UK (United Kingdom)

Speaker: Patil Praveenkumar. **Wednesday**. Start time: **10:40**. Room: Saint Clair 5 LVL2. Link to abstract.

The study examines the effects of pitch angle and porosity on the tensile properties of bio-inspired porous Bouligand structured polymer. Bouligand structured polymers are energy-absorbent, damage-tolerant, and thermally tough materials with potential use in high-performance engineering applications. Here, we examine the impact of varying the pitch angle of the structure, using specifically 10○, 20○, 30○, 45○, and 90○ angles. We combine these pitch angles with an additional independent variable, that of fibre gap distance. The fibre gap distances we use are 0.5, 0.75, 1, and 1.25 mm, and we manufacture the materials by stereolithography (SLA) 3D printing. The 3D-printed porous Bouligand-structured polymers were subjected to tensile testing, and their properties and behaviours were corroborated by finite element analysis (FEA). We demonstrate that tailoring the pitch angle and porosity can substantially influence the mechanical performance of Bouligand structured polymers. A pitch angle of 30○ resulted in the highest tensile strength, and we consider that this is because the fibres were oriented optimally for stress transfer and crack deflection. Smaller fibre spacings, particularly at 0.5 mm, were consistently superior gap distances for mechanical performance, and this is at least partly because there is more material available to redistribute stress. Comparison of the strength and density of the 3D-printed porous Bouligand-structured polymer to other structural materials suggests that these designed polymers achieve strength-to-density values comparable with natural, polymer and elastomeric materials, whilst showing superior over other porous materials such as foams. Our work demonstrates how complex helicoidal structures with varied porosities and pitch angles, can be designed to create light and efficient mechanical materials.

A coupled FEM-BEM formulation to solve electroelastic problems including free space effects

Shikhar Manoj (1), Kumar Ajeet (1)

1 - Indian Institute of Technology Delhi (India)

Speaker: Shikhar Manoj. **Wednesday**. Start time: **11:00**. Room: Saint Clair 5 LVL2. Link to abstract.

In this work, we have developed a coupled FEM-BEM computational framework for arbitrary 3D solids as well as slender rod-like bodies to obtain the nonlinear behavior of an electro-elastic body incorporating also the impact of free space surrounding it. As the body deforms, the boundary of the free space changes too. Therefore, it is a two-way coupled problem which requires simultaneous solution of electromechanical problem of the body as well as free space electric problem outside the body. The free space problem can be neglected if the electric field remains contained in the body or outside electric field is strong enough to be modulated by body's deformation. Otherwise, one needs to also solve a Laplace equation for electric free space (1). The high computational expense to solve the Laplace equation in 3D free space domain has motivated us to work with the boundary integral equation(BIE) which simply sits on the boundary of the body (1). However, the BIE has singular integrand terms and this study also proposes a mixed analytical-numerical approach to evaluate these integrations. In addition to usual electromechanical variables for the body such as displacements and electric potential, an electric flux-like variable acting on the boundary of the body accounts for the influence of free space. A comparison of 3D FEM-BEM with axisymmetric formulation and the formulation by Barreto et.al.(2) for slender structures of different slenderness ratios verifies each of these theories. A 3D non-isotropic electroelastic stored energy density suitable for piezoelectric and dielectric material is taken for both 3D FEM-BEM and slender bodies. The numerical results show that free space has a substantial influence on the electric and mechanical response of the body. Moreover, both analytical and numerical results suggest that the free space effect is dominant when the electric field is applied across the length of rod-like slender structures. This analysis also demonstrates a fascinating change in stiffness, moments and forces due to interaction between mechanical and electrical variables. The proposed study will help in enhancing the design of soft electroelastic robots, actuators and sensors.

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Detaching a sphere from an elastic nanofilm: Experiments and multiscale theories

Dai Zhaohe (1)

1 - Peking University (China)

Speaker: Dai Zhaohe. **Wednesday**. Start time: **11:20**. Room: Saint Clair 5 LVL2. Link to abstract.

In the presence of adhesion, separating two objects in contact requires overcoming a finite detachment force. In this talk, I will discuss experiments and theory for the detachment force between a rigid sphere and a tensioned elastic sheet from polymeric to graphene sheets. I will show that the detachment force can increase with the tension applied to the sheet, which cannot be explained by existing adhesion theories. This increase manifests itself when the deformation of the sheet during detachment is constrained to the atomic level by the applied tension. We then develop a multiscale adhesion theory by considering intermolecular forces that are often overlooked at the macroscopic level, elucidating our findings consistently. This work points to a generic strategy to understand the adhesion of slender structures across various length scales and also provides important implications for cell mechanics and micro/nano-electromechanical systems (M/NEMS).

Surface morphing in 3D-printed magneto-active elastomers.

Selvam Vignesh (1), Bodelot Laurence (1), Danas Kostas (1)

1 - Laboratoire de Mécanique des Solides (LMS) (France)

Speaker: Selvam Vignesh. **Wednesday**. Start time: **11:40**. Room: Saint Clair 5 LVL2. Link to abstract.

This study investigates the controlled morphing of surfaces through the harnessing of magnetically-induced instabilities in heterogeneous magneto-rheological elastomer (MRE) layers bonded to non-magnetic soft substrates. The interplay between magnetic fields and elastic deformations is indeed utilized to actively control surface morphologies, where shape transformations are influenced by the material properties and the geometrical design of the active layer.
Herein, the Direct Ink Writing (DIW) printing technique is employed to print heterogeneously-structured MRE films bonded to a non-magnetic soft substrate. A rheologically-optimized MRE ink is developed, exhibiting the shear-thinning and yield-stress behaviors crucial for effective extrusion and deposition. Magneto-mechanical experiments then demonstrate how the geometrical design of the heterogeneous MRE layer influences surface morphing.
In parallel, a full-field 3D finite element numerical code capable of performing under large strains and magnetic fields is introduced and validated by experiments. It permits investigating a much wider breadth of material properties and geometrical designs, thereby opening up the path towards efficient programming of magnetically induced surface morphing.

MS7.1 - Nonconservative stability problems of structural mechanics and fluid structure interactions

Organisers: Oleg Kirillov (Northumbria University) and Olivier Doare (ENSTA Paristech)

The instability of a membrane enclosed by two viscous fluids with a free surface

Labarbe Joris (1)

1 - Université Côte dÁzur (France)

Speaker: Labarbe Joris. Keynote. **Thursday**. Start time: **10:00**. Room: Bureau Forum 2 LVL-2. Link to abstract.

This study examines the stability of a flexible material interface between two fluids of the same viscosity in interaction with a free surface. When the layers are motionless, we provide evidence for the onset of a novel instability by means of analytical and numerical solution of the associated boundary value problem in the region stable against Rayleigh–Taylor instability, i.e. when the acceleration due to gravity acts from the lighter to the heavier fluid. This destabilisation phenomenon is attributed to the non-conservative tangential forces acting at the interface and the fluid-structure interaction. Furthermore, we examine the scenario in which an external forcing mechanism induces a monotonic parallel shear flow within the upper layer. In addition to the long-established inflectional instability predicted in the inviscid limit, we demonstrate the existence of membrane flutter in the absence of density stratification. The latter is either due to an over-reflection process of surface gravity waves or to the growth of Tollmien–Schlichting waves, as outlined in the context of boundary-layer theory. This fluid-structure configuration represents a paradigmatic model for investigating the interplay between inflectional, radiation-induced and shear-induced instabilities. It also serves as a viscous counterpart to the classical Kelvin–Helmholtz instability when layers with distinct densities are assumed.

Numerical Simulation of Fluid-Structure Interaction in Soft Cylindrical Actuators

Siddiqui Aquib (1), Santapuri Sushma (1), Nair Prapanch (1)

1 - Indian Institute of Technology Delhi (India)

Speaker: Siddiqui Aquib. **Thursday**. Start time: **10:40**. Room: Bureau Forum 2 LVL-2. Link to abstract.

This study presents a computational analysis of fluid-structure interactions involving a soft membrane in an 2D axisymmetric settings, using the continuous forcing Immersed Boundary Method (IBM). The flexible membrane undergoes significant deformations and is modeled using both linear and nonlinear constitutive relationships. The governing equations for the homogeneous isotropic axisymmetric membrane are derived using the variational asymptotic method, as prior implemented by Steigmann (1) and Ali et al. (2).
The fluid is treated as a Newtonian fluid under laminar flow conditions, governed by the 2D axisymmetric Navier-Stokes equations. The incompressible Navier-Stokes equations are solved numerically using Chorin's Projection method. The IBM employs continuous forcing to handle the interaction between the fluid and the membrane, enabling the structural geometry to remain independent of the fluid's Cartesian grid. Two-way coupling is achieved between the Eulerian grid and the Lagrangian nodes through a smoothing function. The membrane exerts forces on the fluid, while the fluid's velocity is interpolated onto the membrane nodes at the interface. Various smoothing functions (3, 4) can be used depending on the application.

The stability of the IBM algorithm is significantly influenced by factors such as geometry, discretization, material properties, flow conditions, and smoothing kernel parameters. A Python-based solver has been developed to simulate several cases like transverse fluid impact on the membrane, deformation of a perturbed membrane in a static fluid and axisymmetric actuator (where the fluid flows inside a cylindrical tube). The resulting solutions effectively capture velocity profiles, pressure distributions, and boundary layer dynamics at the interface. The framework can be used to simulate various biomechanics and soft robotics simulations.

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Dynamic analysis of a thin blade moving inside a narrow fully lubricated kerf

Scheidl Jakob (1), Scheidl Rudolf (2)

1 - Institute of Mechanics and Mechatronics, TU Wien (Austria), 2 - Institute of Machine Design and Fluid Power, Johannes Kepler University Linz (Austria)

Speaker: Scheidl Jakob. Invited. **Thursday**. Start time: **11:00**. Room: Bureau Forum 2 LVL-2. Link to abstract.

The primary objective of using lubrication in machining is to prevent wear and overheating of the tools. Although the necessity of lubrication is well recognised, the corresponding mechanical interactions of the lubricant with the working tools are rarely taken into account in studies concerned with the dynamics of such systems. An exceptional machining operation with regard to this kind of fluid structure interaction is band sawing of thick slabs. In particular, metal band sawing serves as the motivational use-case behind the mechanical model considered here. This intriguing process is known to exhibit complicated dynamic phenomena such as torsional flexural buckling under excessive cutting forces, parametric oscillations or self excited vibrations, with regenerative chatter being the most prominent example of the latter. Band sawing features a thin structure (the blade) moving in a narrow kerf, which distinguishes it from other standard machining operations such as milling or turning.

The considered mechanical system resembles fully immersed cutting: A thin blade with constant rectangular cross section is moving through a fully lubricated narrow kerf. For simplicity sake, only transverse deflections of the blade in the kerf, i.e.: orthogonal to the vertical direction of the cut, are considered. The moving blade is modelled as an axially pre-tensioned Euler-Bernoulli beam. It exhibits transverse vibrations that dynamically alter the sizes of the lubrication gaps. These gaps' widths are the distances of the beam central axis to the left and right boundaries of the kerf; the geometry of the kerf is assumed to be ideally straight. Reynolds hydrodynamic lubrication theory is assumed to govern the fluid part of the problem, which rests on the usual prerequisites: fluid inertia and pressure variation accross the gap are negligible, fluid flow is parallel to the gap, the fluid is Newtonian and the gap is small with respect to the length of the kerf but large in comparison to the roughness of the kerf surface; cavitation is disregarded, but may be detected by the absolute pressure falling below vapor pressure of the fluid. The beam transverse deflection and the fluid pressure are the primary fields of this fluid-structure interaction problem. It is addressed numerically with an isoparametric finite element method that utilizes cubic Hermitian polynomials for interpolation purposes. The finite element implementation is facilitated by the variational form of the Reynolds equation, which induces a nonlinear coupling of fluid pressure and transverse deflections. Transient simulations are conducted for selected cases of forced or free vibrations to estimate the impact of these nonlinear effects. A dynamic stability analysis is performed for the linearised system with respect to the straight reference motion. The corresponding set of linear equations further allows to quantify viscous damping and circulatoric effects induced by the hydrodynamic lubrication films.

The present study provides insight into the potential load bearing and damping capabilities of a properly formed lubrication film in band sawing. This may present novel opportunities to counteract detrimental dynamic phenomena or to even guide the blade in transverse direction to straighten the cut. The simplified planar problem provides a solid foundation for more intricate investigations that aim to capture some of the dynamic phenomena mentioned above. In this respect, a true 3D model of the beam with the inclusion of constrained torsion already necessitates a two-dimensional treatment of the Reynolds equation owing to the variability of the lubrication gaps in two directions.

Non-Hamiltonian symmetry for coupled Ziegler pendulums

Disca Stefano (1), Coscia Vincenzo (1)

1 - Università degli Studi di Ferrara = University of Ferrara (Italy)

Speaker: Disca Stefano. Keynote. **Thursday**. Start time: **14:15**. Room: Bureau Forum 2 LVL-2. Link to abstract.

The Ziegler pendulum is a classical dynamical system introduced by Ziegler (1), that has been subject to deep studies by mathematicians, physicists and engineers in the last decades. The system is well-known for the paradoxical destabilization of the system when subject to damping (2-6), while in general a non-conservative system gains stability in presence of a dissipative force; furthermore, such as the classical double pendulum (7-9), the system shows itself to be chaotic. Recently, it has been proved in (10) that also a simpler version of the system exhibits chaotic motion for a general choice of initial conditions and parameters, while regular periodic solutions are found in presence of Hamiltonian and non-Hamiltonian symmetries. The authors presented in (11) analytical and numerical results concerning several variants of the Ziegler pendulum, including the presence of gravity, linear elastic potentials and friction in two possible formulations, in order to analyze the surviving or breaking of the integrable cases found in (10). Furthermore, a study of a discrete version has been performed through explicit calculations on the sets of periodic points, suggesting that the discrete map associated to the Ziegler pendulum does not satisfy the definition of chaotic map in the sense of Devaney (12) for a choice of the parameters that corresponds to a general case of chaotic motion for the original system. This last result is not totally unexpected, as one can see for example in the recent work (13).
Our aim is now to present further results on the regular and chaotic dynamics of the Ziegler pendulum as defined in (10-11). In detail, we provide a proof of the non-density of the sets of periodic points in presence of the non-Hamiltonian symmetry that was conjectured in (11). Moreover, we analyze the coupling of two or more Ziegler pendulums in order to highlight the persistence of regular and chaotic dynamics in terms of mutual interactions. In particular, we look for a new control parameter for the non-Hamiltonian symmetry that generalize the qualitative and quantitative results presented in (11).

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Mechanical characterization and sensitivity of critical parameters in inflatable soft elliptical snap-through

Piri Barnabas (1), Berezvai Szabolcs (1)

1 - Department of Applied Mechanics, Faculty of Mechanical Engineering, Budapest University of Technology and Economics (Hungary)

Speaker: Piri Barnabas. **Thursday**. Start time: **14:55**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Soft materials have many engineering applications due to their favourable mechanical properties like flexibility, energy absorption, and storage, not to mention that they are easy to manufacture and have a low cost of prototyping. These characteristics make such materials the perfect basis for designing complex mechanical systems, addressed as soft robotics (1,2).
However, describing the exact behaviour of these materials is a complex task, as they exhibit nonlinear stress-strain characteristics, which are often paired with nonlinear geometric- and loading conditions. By exploiting unstable configurations of these hyperelastic materials, we can enhance the response of the fluidic actuators, which are widely used in soft robots.

In this contribution, the snap-through instability of soft elliptical shells due to inflation is investigated using numerical, analytical and experimental approaches. The goal of this contribution is to analyse the critical (loading- and geometric) parameters and their sensitivity, which determines the main characteristics of the snap-through.
The applied soft materials (soft elastomers, silicones) in soft robotics applications show highly nonlinear elastic behaviour that can be accurately modelled by hyperelastic constitutive models. However, analytical solutions for the thick-wall shell buckling problem can only be derived for specific, simpler hyperelastic models (e.g. Neo-Hookean or Varga models), which can only characterize the material nonlinearity in a limited way (4,5). For highly nonlinear hyperelastic materials, the Ogden hyperelastic model can be adopted (6), which defines the strain energy density function as a series of principal stretches with positive and negative powers. By utilizing this property and reformulating the model in a mathematically favourable way, a consistent hyperelastic model is provided, which is then used to solve the snap-through problem of thick-walled hyperelastic shells.
Secondly, a general finite element approach is proposed by combining the RIKS method and the fluid cavity contact formulation for the fluid-structure interaction in Abaqus to investigate the behaviour of a wide variety of loading- and geometric conditions, and the sensitivity of both the geometric and loading parameters for the snap-though. Finally, the numerical simulations and the analytical predictions are compared with experimental investigations using a self-developed fluidic control board, which provides the possibility to apply different loading- and control approaches.

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Advanced Numerical Modeling of Buckling in Thin-Walled Structures Under Nonconservative Dynamic Loads

Bogey Maxence (1) (2), Cadou Jean-marc (1), Combescure Christelle (1) (3), Girault Gregory (1), Leble Bruno (2)

1 - Institut de Recherche Dupuy de Lôme (France), 2 - Naval Group (France), 3 - Centre de Recherche des Ecoles de St-Cyr Coëtquidan (France)

Speaker: Bogey Maxence. Invited. **Thursday**. Start time: **15:15**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Dynamical buckling of immersed thin-walled structures subjected to complex loadings coupling surface follower pressure and shock waves is one of the most delicate instability problems in solids mechanics. The intricate fluid-structure interaction, the non-linear response of the thin-walled structure in the post-buckling regime and the accurate modeling of the loading are three scientific bottlenecks that need to be addressed to be able to uncover the behavior of the structure under such circumstances.
This study represents a significant advancement in the numerical modeling of structural instabilities by proposing an innovative method to simulate the buckling of thin elastic structures subjected to nonconservative dynamic loads. A particular focus is placed on structures immersed in a fluid, subjected to surface pressure of a nonconservative nature coupled with shock waves, which notably influence their structural inertia.

The approach is based on the Asymptotic Numerical Method (ANM), a high-order perturbation technique enabling the explicit integration of motion equations, using time as the perturbation parameter. Unlike conventional methods, which compute solutions at discrete points, ANM provides a continuous approximation of solutions through high-order polynomials. This feature enhances the robustness of computations, even in the presence of geometric nonlinearities and nonconservative loading conditions.

Spatial discretization employs shell elements, maintaining the three-dimensional formulation of constitutive laws. Numerical locking phenomena, frequently encountered in such discretizations, are avoided through the Enhanced Assumed Strain (EAS) concept, introduced by (Simo and Rifai, 1990).

Encouraging findings from previous research (Claude et al., 2023) have motivated this study. Earlier work focused on the buckling of a cylindrical panel subjected to a time-dependent localized load and demonstrated that ANM predicted earlier buckling onset compared to reference results (Kuhl and Ramm, 1999; Baguet and Cochelin, 2011). Validation through Abaqus simulations with increasingly refined meshes confirmed convergence toward ANM results, albeit at a significantly higher computational cost (506 elements for Abaqus versus only 16 for ANM).

The primary goal of this research is to extend the developed method in the case of nonconservative, time-dependent pressure loads. This development process, with validation at each step, aims to deepen the understanding of mechanisms influencing structural stability. In quasi-static analyses, ANM already identifies bifurcation points and stability limits. It is desired to extend its capabilities to dynamic analyses, exploring nonlinear stability under complex loading scenarios.

At the conference, results will be presented comparing our developments against benchmark cases and other numerical approaches. These findings highlight the strengths of ANM, particularly its precision and computational efficiency for thin-walled elastic shells subjected to nonconservative dynamic and quasi-static loads.

Keywords: Asymptotic Numerical Method (ANM), explicit time integration method, dynamic buckling.

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Explicit analysis of a planar Timoshenko beam : Pure shear follower load example

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Speaker: Hariz Marwan. Invited. **Thursday**. Start time: **15:35**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Analytical solutions of a plane, quasi-static but large transformation of a Timoshenko beam are exposed. The problem is first reformulated as a Cauchy initial value problem, where the load (force and moment) is prescribed at one end, and the kinematics (translation and rotation) at the other.
Within this framework, explicit solutions are derived for arbitrary loads. The existence, uniqueness, and regularity of the solutions are rigorously proven.
Analytical post-buckling solutions are obtained, characterized by different regimes explicitly governed by two invariants of the problem. A case of pure shear follower load is studied, with explicit solutions expressed in terms of kinematical and dynamical variables. Both qualitative and quantitative analyses are provided.
Perturbation of the problem is presented in a general way, enabling the computation of perturbed solutions under various boundary conditions.

The strongest stable massless column with a follower load and relocatable masses

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Speaker: Kirillov Oleg. Invited. **Thursday**. Start time: **15:55**. Room: Bureau Forum 2 LVL-2. Link to abstract.

We consider the problem of optimal placement of concentrated masses along a massless elastic column that is clamped at one end and loaded by a nonconservative follower force at the free end. The goal is to find the largest possible interval such that the variation in the loading parameter within this interval preserves stability of the structure. The stability constraint is nonconvex and nonsmooth, making the optimization problem quite challenging. We give a detailed analytical treatment for the case of two masses, arguing that the optimal parameter configuration approaches the flutter and divergence boundaries of the stability region simultaneously. Furthermore, we conjecture that this property holds for any number of masses, which in turn suggests a simple formula for the maximal load interval for n masses. This conjecture is strongly supported by extensive computational results, obtained using the recently developed open-source software package GRANSO (GRadient-based Algorithm for Non-Smooth Optimization) to maximize the load interval subject to an appropriate formulation of the nonsmooth stability constraint. Our work provides a foundation for new approaches to classical long-standing problems of stability optimization for nonconservative elastic systems arising in civil and mechanical engineering.

MS7.2 - Structural analysis of historical buildings

Organisers: M.Angelillo (Univ.Salerno), S. Huerta (UP Madrid)

Computerized Upper Bound Limit Analysis CUBLA for complex historical masonry structures

Milani Gabriele (1), Gandolfi Alessandro Buzzetti Martina Hua Yiwei Pingaro Natalia Wang Peixuan

1 - Politecnico di Milano, Department of Architecture, Built environment and Construction engineering (Italy)

Speaker: Milani Gabriele. Keynote. **Monday**. Start time: **13:40**. Room: Saint Clair 5 LVL3. Link to abstract.

The paper discusses the main features of a novel limit analysis software called CUBLA (Computerized Upper Bound Limit Analysis) aimed at the accurate prediction of the ultimate behavior of historical masonry structures exhbiting high geometric complexity. Particular attention is given to the estimation of the seismic vulnerability.
The approach bases on a full 3D discretization of the masonry structure, which allows plastic dissipation exclusively at the interface between contiguous elements. After the derivation of a standard linear programming problem to predict collapse multiplier, active failure mechanism and -from the dual problem- internal stress distribution at failure, an efficient iterative procedure is discussed to simulate the problem in case of interfaces purely frictional.
A series of paradigmatic case studies is reviewed, focusing in particular on building aggregates and churches. A final extension of the approach presented is proposed, which relies in a fast algorithm equipped with a surrogate optimization kernel, to automatically provide that disposition of tie rods that maximizes the load carrying capacity.

On the integrated use of continuous FE-based computational approaches for the structural analysis of 2D compression-only structures

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Speaker: Iannuzzo Antonino. Invited. **Monday**. Start time: **14:20**. Room: Saint Clair 5 LVL3. Link to abstract.

The assessment of masonry structures and, more generally, compression-only systems requires accurate modelling of stress distributions and fracture patterns induced by external loads and boundary displacements. However, in engineering scenarios where time constraints are critical, stereotomy is difficult to obtain, or during the early stages of the design process, discontinuous approaches are often unsuitable, as they fail to explore broad solution spaces from both static and kinematic perspectives. For this reason, continuous approaches offer significant advantages in terms of computational efficiency and modelling options.
To this aim, this research explores, compares, and discusses the integrated use of two continuous methods, namely the CASS (1) and CDF (2) methods, highlighting their respective advantages and limitations. Both computational strategies model the material as Normal No-Tension (NNT) (3) and solve the corresponding boundary value problem using two dual-energy approaches based on minimising total potential and complementary energy, respectively. The domain is discretised using finite element meshes, and the numerical problems are formulated and solved as second-order cone programming (SOCP) problems.
Various applications are presented and discussed, ranging from simple yet meaningful engineering examples to more complex real-case studies. Internal stress conditions and fracture patterns induced by combined loadings and boundary settlements are examined, and their evolution is tracked up to structural failure.

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Airy-based form-finding process for purely compressed masonry cross vaults under combined vertical and horizontal loading

Cocking Sam (1), Sibille Luigi (2), Adriaenssens Sigrid (3), Fabbrocino Francesco (4), Olivieri Carlo (4)

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Speaker: Cocking Sam. Invited. **Monday**. Start time: **14:40**. Room: Saint Clair 5 LVL3. Link to abstract.

Unreinforced masonry structures throughout the world are often condemned or subjected to inappropriate and potentially damaging 'strengthening' interventions in the aftermath of seismic events. This is due to an inability to readily estimate their horizontal force capacity – a knowledge gap which can also be a barrier to new masonry construction, particularly of structurally efficient shells and vaults. After a certain load capacity threshold, hinge formation leads to the activation of rocking-like mechanisms in these structures, requiring a dynamic analysis dependent on characteristics of the earthquake. However, this activation threshold and the structural behaviour before it is reached are primarily dictated by geometry. This paper presents a strategy for calculating this horizontal load threshold for compression-only shells, with applications in the assessment of historic constructions and form finding of new designs. The method utilises Membrane Equilibrium Analysis (MEA), based on the Safe Theorem of Limit Analysis and Heyman's assumptions for masonry-like, no-tension materials. By formulating horizontal equilibrium as a set of parametric equations and constraining the solution for the stress potential to be concave, this method obtains the maximum value of the horizontal load multiplier for which equilibrium remains satisfied by a given shell geometry. Challenges of discontinuity in the structural form are then tackled, through application of the method to the analysis of cross vaults.

FEMANOLA: A finite element nonlinear software for masonry structures

Pingaro Natalia (1), Milani Gabriele (1)

1 - Politecnico di Milano, Department of Architecture, Built environment and Construction engineering (Italy)

Speaker: Pingaro Natalia. Invited. **Monday**. Start time: **15:00**. Room: Saint Clair 5 LVL3. Link to abstract.

In the present paper, a novel nonlinear finite element model to analyze masonry structures in plane-loaded is proposed. The software works within a heterogenous discretization of masonry walls in-plane loaded where bricks are assumed elastic and joints are reduced to interfaces with a cohesive frictional behavior with mode 1 and 2 failures truly coupled. In particular, for bricks four noded elastic elements in plane stress are used, whereas for interfaces a modification of the standard four noded element is proposed. The joint nonlinear behavior is thus obtained by enforcing the normal stress along the joint direction to vanish, with normal and tangential stresses acting along the interface coupled by means of a constitutive model ruled by two distinct fracture energies in modes 1 and 2, a compressive behavior defined by a multilinear hardening/softening monoaxial relationship, and a dependence of the tangential post-peak behavior which obeys a parabolic nondimensional law. The procedure is benchmarked on a single mortar joint subjected contemporarily to bending, normal compression and shear, and then tested to reproduce some experimental data available from the literature for triplets subjected to standard shear and normal precompression. A final structural analysis is carried out for a windowed panel tested at TU Delft, for which several previously presented numerical models are available. Excellent agreement with both experimental data and outcomes from numerical literature is found, at a very reduced computational time, promoted by a fully explicit sawtooth elastic algorithm used to deal with nonlinearity and softening of the interfaces.

Advanced numerical model for historical masonry structures subjected to seismic sequences

Buzzetti Martina (1), Milani Gabriele (1)

1 - Politecnico di Milano, Department of Architecture, Built environment and Construction engineering (Italy)

Speaker: Buzzetti Martina. Invited. **Monday**. Start time: **15:20**. Room: Saint Clair 5 LVL3. Link to abstract.

The seismic assessment of historical masonry structures presents substantial challenges due to the non-linear behaviour of materials and the geometric intricacies involved. Predicting their seismic response becomes even more complex under the influence of seismic sequences. To address this, an integrated methodology is proposed, combining Limit Analysis (LA) with pushover analysis performed on Finite Element (FE) models to account for cumulative damage. The integration of LA with FE modelling significantly reduces computational demands for pushover analyses. Specifically, the LA approach identifies the collapse load, active failure mechanisms, internal force distribution, and energy dissipation at interfaces, enabling the detection of structural portions experiencing significant inelastic deformation. The LA model employs infinitely resistant hexahedral elements, with plastic deformations lumped at elements interfaces. Two horizontal loading patterns-uniform and inverse linear-are applied at varying entry angles relative to the geometric axes. In the FE model, material non-linearities are limited to the interfaces within the failure mechanism, where the majority of energy dissipation occurs, while the rest of the structure remains linear elastic. This approach facilitates the evaluation of structural capacity and damage progression with reduced computational effort. For a given seismic sequence, the damage induced by each event is analysed using the N2-method, and a new active failure mechanism is identified through LA, incorporating cumulative damage by adjusting the properties of affected interfaces. Consequently, an updated FE model is developed to account for damage from prior seismic events and the revised failure mechanism. The proposed methodology is validated using two well-known mock-ups in literature, namely the U-shaped masonry walls tested in the LNEC laboratory in Lisbon.

Investigating the mechanics of masonry structures with the help of virtual experiments

Bagi Katalin (1)

1 - Budapest University of Technology and Economics (Hungary)

Speaker: Bagi Katalin. Invited. **Monday**. Start time: **16:00**. Room: Saint Clair 5 LVL3. Link to abstract.

The main focus of the efforts of our team is on discovering how the different types of masonry arches and vaults carry their loads, and how they respond to their typical external quasi-static mechanical effects. Masonry structures are, by their deepest nature, discrete systems that consist of separate solid bodies, and this discrete nature fundamentally determines their behaviour. This is why continuum methods (like membrane theory or FEM) can only be rough approximations in many situations. In addition, as Heyman often stated, small perturbations of the structural geometry (e.g. slight support displacements) can significantly modify the system of internal forces, hence a range of slightly differing geometrical positions of the structure should be considered and compared before drawing conclusions.

To validate such conclusions, physical experiments are indispensable; however, physical experiments are expensive, troublesome, and not always feasible. In order to partially replace them, our team uses "virtual reality", i.e. numerical models that are calibrated according to the results of a low number of physical experiments. Our main tool for this is the Discrete Element Method (DEM). The presentation will shortly summarize what is DEM, and then give an overview how our team suggests to calibrate the material parameters of a discrete element model according to a real physical experiment so that the model could then be applied for simulating several similar tests based on the same physical experiment. Then, the presentation will show recent results of our team that were reached using virtual experiments.

Three-dimensional limit analysis through the Thrust Surface Method to investigate the structural behaviour of Apulian star vaults

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Speaker: Scarcelli Ilaria. Invited. **Monday**. Start time: **16:20**. Room: Saint Clair 5 LVL3. Link to abstract.

The investigation of the structural behaviour of masonry vaults remains a subject of ongoing research. Indeed, conventional structural analysis approaches reveal to be inadequate for understanding the complex mechanical behaviour of these constructions, governed by anisotropy, material non-linearity, damage, plasticity and fracture. The employ of advanced computational models is obstructed by masonry's intrinsic irregularity and heterogeneity, which clash with the in-depth mechanical characterization and accurate definition of boundary conditions required.
These difficulties suggest to shift away from searching for the full characterization of the masonry structural response, and instead focus on estimating collapse loads following the path traced by Heyman's studies (1), which reread ancient geometrical theories into the modern framework of Limit Analysis, highlighting that the safety of a masonry structure depends substantially on its geometry.

For a fully three-dimensional Limit Analysis masonry vaults and domes, several approaches have been recently proposed. In particular, some of the Authors have recently developed the Thrust Surface Method (TSM) (2), a new computational method framing the equilibrium problem into a constrained optimization problem. This way, "extremal" or "optimal" statically admissible solutions are obtained, capable of fully exploring the entire load-bearing capacity spectrum of a vault or a dome having an arbitrary geometry, also considering horizontal loads such as those representing maximum inertia effects from seismic actions. Through a convenient numerical formulation, no a priori assumptions are required, making it possible to simultaneously determine the two unknown functions of the problem: the Airy stress function $\mathbf{F}$ and the membrane shape function f. TSM could be a valuable tool for visualizing and understanding the complex three-dimensional behaviour of masonry vaults, highlighting the intricate relationship between form and structure.

Here we apply TSM for deepening the structural behaviour of star vaults, a typical vaulting system that characterizes mainly the historical Apulian architecture (southern Italy). The complex shape of the star vault originates from the intersection of a cross vault with an ellipsoidal dome: this makes the structural analysis quite challenging. Indeed, despite their widespread, star vaults have been insufficiently investigated and their mechanical behaviour is not completely understood yet.
With the use of TSM, the capability of analysing optimal solutions provides a comprehensive assessment of the load-bearing capacity spectrum of the star vault. Indeed, the investigation of the vault's complex three-dimensional behaviour reveals a strong spatial distribution of stresses on the central dome area, which cannot be accurately represented by flat patterns, highlighting how traditional approaches may be overly conservative.
Furthermore, evaluations of critical stress states near the folding lines characterizing the vault's geometry are made.
Finally, the substantial differences with the well-known cross vault are studied, and the corresponding load-bearing capacity is also compared.
This yields critical insights into the relative safety levels of the two vault typologies for the same covered span.

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Structures, 2020, 202: 109846.

Condition Assessment and Enhancing Seismic Resilience of an Existing Masonry Building in a Bradyseismic Region

Katouli Habibollah (1) (2), Martuscelli Giampiero (2), Serino Giorgio (1)

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Speaker: Katouli Habibollah. Invited. **Monday**. Start time: **16:40**. Room: Saint Clair 5 LVL3. Link to abstract.

Masonry structures differ significantly from modern constructions that utilise contemporary materials such as steel and reinforced concrete as their main bearing elements. Unlike these newer structures, masonry relies predominantly on compressive forces for stability, with limited tensile capacity. Over time, these buildings have demonstrated the ability to adapt to changing environmental conditions through the formation of cracks, which allow for minor displacements and the re-establishment of equilibrium. However, with modern expectations for buildings to not only withstand seismic events but also ensure occupants' comfort and serviceability, traditional masonry structures often don't meet current seismic performance requirements. As a result, retrofitting is essential to enhance their resilience and meet the demands of larger, more frequent seismic events.

This study focuses on the seismic performance assessment of a three-storey masonry building constructed in the 1920s, located in Pozzuoli, Italy-a region highly susceptible to the bradyseism activity. Given the building's significance and the seismic risks, a thorough structural investigation and visual inspection are conducted to document structural details, identify existing damage, and evaluate its current condition. Additionally, an extensive experimental campaign is carried out, comprising both in-situ non-destructive testing and laboratory-based sample tests, to gain a deeper understanding of the building's structural integrity and mechanical properties. Furthermore, the seismic vulnerability assessment is performed with nonlinear static analysis to evaluate the building's global performance. The analysis reveals the building's current capacity to withstand seismic demands.

Based on these findings, a tailored intervention plan is developed to seismically upgrade the building while preserving its origin. The proposed retrofitting measures aim to enhance the structure's resistance to both vertical and horizontal loads, ensuring its safety for future use under a new functional purpose. This research contributes to the growing field of seismic assessment and conservation of historic masonry buildings, offering insights into effective methodologies for balancing structural safety with heritage preservation.

The late gothic ribbed vaults of San Miguel church in Segovia: from geometric and proportional analysis to structural assessment

Cirabisi Chiara (1), Parente Maria (2) (3), Calderini Chiara (1), Ottoni Federica (3), Borin Paolo (4), Bortot Alessio (5), Angelillo Maurizio (6)

1 - Università degli Studi di Genova (Italy), 2 - Sapienza, Università di Roma (Italy), 3 - Università degli studi di Parma (Italy), 4 - Università degli Studi di Brescia (Italy), 5 - Università degli Studi di Trieste (Italy), 6 - Universita degli studi di Salerno (Italy)

Speaker: Cirabisi Chiara or Parente Maria. Invited. **Monday**. Start time: **17:00**. Room: Saint Clair 5 LVL3. Link to abstract.

Introduction and description of case study

The present work aims to study the Church of San Miguel in Segovia (Spain), focusing on the late-Gothic ribbed vault, from a geometric and a structural point of view.

The construction of the current church began in 1532, after the demolition of a previous Romanesque church located in Plaça Mayor. The project for the reconstruction was assigned to Rodrigo Gil de Hontañón (1500-1577), one of the most prominent Spanish architects of 16th century. However, at his death the church was not completed and its construction was continued by Diego Matienzo.

The layout of the church features a central nave - composed of five bays - a transept and lateral chapels. Each bay is covered by a domical ribbed vault, the design of which is described in detail in the treatise. The ribs are of four types: cross arches *(cruceros)*, located along the diagonals; formerets (*formeros*), that are the longitudinal ones; transverse arches (*perpianos*), that are the transversal ones, that divide one bay from another; tercelets (*tiercerons*), located between the formerets or the transverse arches and the cross arches. Finally, the shape of the vault is characterized by the *ligadura*, which are ribbed elements that connect the *tiercerons* to the cross ribs, the formerets or the transverse arches, creating a floral pattern.

Identification of the ideal geometry of the vaults and comparison with the real one and with Rodrigo Gil's rules

Rodrigo Gil, who designed the church, was also the author of a Treatise of Architecture (1544-1554) which provides rules for the different aspects of the design of a late gothic church. Therefore the first aim of this study is to compare the real vault's geometry with the prescriptions of the treatise. The real geometry, has been obtained from the point cloud of the church which resulted from a previous laser scanner and photogrammetric survey.

The analysis started considering the central vault, at the intersection between the nave and the transept, which has an almost squared plan. From a first analysis of the plan and of some significant sections made in correspondence of the cross ribs and longitudinally in the main nave, it appears evident that the main vault of San Miguel church belongs to the type of the late gothic "*bóvedas baídas*", which are typical of the 16th century churches built in Spain. These vaults are dome-shaped. According to the ideal shape, the central part of the vault (bounded by the so called *tiercerons*) corresponds to a sphere, the cross ribs are perfect semicircles (at least in the ideal geometry), and each *tierceron* is a circular segment (since they result from the cutting of a sphere). The peripheric parts, which are the lunettes situated between the *tiercerons* and the transversal ribs, are instead formed by ruled surfaces, which serve to connect two pointed arches: one is formed by the two *tiercerons* and the other by the transversal arches or by the tercelets, whose crowns are lower than that of the *tiercerons*. Since it is not possible to find information on the shape of transverse and longitudinal arches (formerets), their geometry was evaluated starting from the point cloud and considering the radius of the two symmetric segments of the pointed arch as a fraction of the span.

These ideal shapes have been compared with the real ones of San Miguel's central vault, obtained from sections of the point cloud. The real cross ribs of this vault with squared plan are perfectly semicircular, although one is slightly deformed because of a settlement of one of the pillars that is clearly detectable and measurable from the point cloud. From the comparison between the spherical ideal surface and the real sections of the vault, it emerges that, differently from the cross ribs, the real profile of the web is a bit lowered, with a maximum error of around 10 cm. However, this is more probably due to the adjustment of the vault during construction or to later deformation than to a different design shape.

After having identified the geometric shapes forming the vault, the focus has been on the analysis of the geometric proportions of the structure. This analysis started considering the plan, since gothic master builders used the plan as reference, and compares the proportional system of San Miguel's vaults with the rules contained in the treatise by Rodrigo Gil de Hontañón. Of course, all proportions are referred to a module, a unit of measurement. According to the prescription of the treatise, the width of a nave bay is 40 units. Starting from the reference measure that sets the width (and also the length for the squared vault) to 40 units, the position of the keystones has been determined using multiples of the reference unit. For example, the keystones that form the edge of the central square are 8 units away from the perimeter of the vault. The direction in plan of the *tiercerons* was derived accordingly. Following this method, all the proportions needed to define the ideal plan were derived. By superimposing the ideal geometry thus obtained on the real plan, an almost perfect overlap can be observed.
Then the proportions of the rib sections has been analysed. Rodrigo Gil's treatise provides the rule to determine the height of the different types of ribs as a fraction of the nave's span. He also sets an analogy with the human body: each type of rib corresponds to a finger. Again, the height of the different ribs has been calculated according to Rodrigo's rule (transverse rib are 1/20 of the span, cross ribs 1/24, *tiercerons* 1/28) and then compared with sections of the real ribs obtained from the point cloud: the difference is no more than 3 cm. The treatise also provides rules to determine the height of the so called *tas-de-charge* (that is where the ashlars of the ribs start to have no more horizontal but radial joints) and of the infill at the extrados; the measure obtained according to the rules have been compared with the real one showing again no significant differences.
Subsequently, the analysis focused on the other vaults of the church, which are of rectangular plan. For these vaults, in the real geometry, the surface of the web, also in the central part, is more distant to the ideal sphere. Indeed, the parts between the ribs are closer to ruled surfaces with just a small curvature. However, the cross ribs are almost semicircular also in vaults with rectangular plan.

The geometric model
On the basis of the results of the previously described study on the proportion of the elements that are part of the vault system, a geometric model was built. The starting point was the plan, from which the diameter of the star-shaped spherical surface contained within the *tiercerons* could be determined. Then, the lunetted parts between the *tiercerons* and the transversal arches were modelled with ruled surfaces, extruded in the direction of the joints between the voussoirs. All ribs were modelled as extrusions of the previously discussed sections on the profiles.
To complete the geometric model, it was relevant to divide the ribs in a finite number of voussoirs. This procedure was applied only for the ribs, without discretizing the web, by tracing the end surfaces of each voussoir using the photogrammetric survey of the plan. The procedure consisted in creating a sheaf of planes originating from the centre of the vault and ending in the boundaries of each voussoir, used to trim the rib in a finite number of blocks.
The final geometric model thus consists of the spherical star-shaped web and the four lunettes, both 12 cm thick, and a set of discretized ribs. A verification of the accuracy of the three-dimensional model was then conducted, comparing the intrados of the spherical surface and the lunettes with the point cloud of the survey.

Structural analysis of the main vault
The geometric model was firstly employed to assess the equilibrium and the safety of the vaulted system, by using the Membrane Equilibrium Analysis, developed under the Heyman's theory of Limit Analysis. Within this theory, it is possible to find one surface within the web of the vault, being in equilibrium under dead loads in a compressive state. Through analytical solution it is possible to find parallel and meridian stresses in each point of the surface and, therefore, the dead load on each voussoir of the ribs. In the case of the *tierceron* both stresses transmitted from the spherical surface and the lunette ruled surface have been considered and summed, to find the vertical components. Then, equilibrium assessment is done by computing the thrust line of the ribs.
After this analysis, a Finite Element Model (FEM) is used to analyse the effects of the movements of the supports. The blocks are modelled considering a sufficiently stiff materials, while interfaces are modelled considering no-tension contact, in accordance with Heyman's theory. The results in terms of crack openings are then compared to the real crack pattern, in order to verify the possible developed mechanism.

Stop Motion Computation for Masonry Arches according to Limit Analysis Theorem

Cennamo Claudia (1), Di Gennaro Luciana (1), Massaro Luigi (1), Frunzio Giorgio (1)

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Speaker: Cennamo Claudia. Invited. **Monday**. Start time: **17:20**. Room: Saint Clair 5 LVL3. Link to abstract.

Around the mid-19th century, Jean Claude De Saint-Venant developed the theory of elasticity, which remained essentially a theoretical study until, at the end of the same century, François Hennebique presented the scientific community with a new challenge: reinforced concrete, a new material to which De Saint-Venant's theories were well suited.
Following the enthusiasm generated by the discovery and subsequent use of reinforced concrete in construction, the elastic theory served as the foundation for any computational calculations for over a century.
At the end of the 20th century, thanks to some brilliant Italian professors such as Edoardo Benvenuto (1), Salvatore Di Pasquale (2), Antonino Giuffrè (3), et al., as well as international scholars like Jacques Heyman (4), who embarked on a research path that moved beyond the now-classic approach embodied in elasticity theory, the scientific community came to the realisation that the built heritage, the historical patrimony of which all of Europe is still rich, could not be computed using the same theoretical models applied to reinforced concrete or steel.
The scholars, therefore, resumed reading ancient treatises and began to question how historical monuments managed to maintain such good health after millennia, having been built in an era when modern scientific theories were unknown.
Thus, the scientific community (5 - 10) began to seek alternatives to the classic duality between force-displacement and stress-strain systems, which were not always effective, especially when dealing with materials that had characteristics such as lack of tensile strength, sudden and brittle failure, and absolute incompressibility.
Masonry, which constitutes the entire architectural heritage, generally exhibits all these characteristics, but it also has multiple typological aspects, making it an oxymoron, indefinable by definition, which scholars can only manage by grouping its most salient and common features, with the understanding that each structural component must be considered individually.
In line with the above, the present work, based on Heyman's hypothesis of a rigid block, in the sense of a material that does not respond to tension, has infinite friction, and infinite compressive strength, proposes a model of a rigid-labile arch structure that is not subject to problems of strength but only of geometry.
The opening of four unilateral hinges is in predetermined positions to enable the activation of a kinematic mechanism. The position of the hinges is obtained by identifying the smallest collapse multiplier that is kinematically admissible (11).
It is possible to apply the Principle of Virtual Work to calculate displacements at a given time t_i, being the kinematic chain determined. The superposition of the time steps for i=1 to n determines the static collapse of the structure resulting from the alignment of the hinges.
The model provides a simple approach derived from traditional frame-by-frame cinematic animation. Allowing each successive configuration to be identified by iterating the previous one enables the frames in succession to create movement, with the advantage of obtaining a dynamic overview and an easier computation that does not rely on step-by-step analysis.

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Seismic fragility of historical masonry constructions: A variational-based non-smooth contact dynamics formulation

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Speaker: Nodargi Nicola A.. Invited. **Tuesday**. Start time: **10:00**. Room: Saint Clair 5 LVL3. Link to abstract.

Historical masonry constructions represent a valuable part of the architectural heritage, whose structural safety in seismic regions could be endangered by earthquakes. Ensuring their preservation thus requires a reliable assessment of their seismic vulnerability, which depends on accurately predicting their dynamic response under ground acceleration.
Due to the occurrence of impacts, i.e., of events producing velocity discontinuities, the rocking motion of block masonry structures represents a non-smooth dynamic problem. Following Housner's pioneering work on the rocking motion of a single rigid block (1), the dynamics of masonry structures has been extensively investigated using event-driven numerical schemes. However, these schemes are challenged by numerical issues arising from the need of precisely detecting the events in time by some root-finding procedures, such as a sub-stepping.
As an alternative, the attention is focused here on the Non-Smooth Contact Dynamics (NSCD) method (2), originally proposed as a time-stepping scheme to investigate the dynamic behavior of collections of rigid bodies. The fundamental idea of the method is to address a discrete version of the time-integrated version of the equations of motion. The resulting impulse-theorem format has the crucial advantage that, by interpreting the hard-contact laws between the bodies in a time-averaged sense and by introducing suitable contact gaps in the contact relationships, the need for a precise identification of the event times is circumvented and the solution can advance in time with a fixed time step.
Several applications of the NSCD method have proven its merit when considering historical masonry block structures modeled as systems of rigid blocks in unilateral and dry-frictional contact with each other (3–5). In (6), a variational-based NSCD approach has been proposed to investigate the dynamic behavior of 3D masonry block structures subject to seismic excitation. As a merit of the formulation, large-scale problems can be robustly and efficiently addressed thanks to the convex framework of the time-step optimization problem, specifically formulated as a second-order conic programming problem. By leveraging those computational potentialities and considering a broad database of natural earthquake records, a systematic and critical investigation of the seismic fragility of historical masonry constructions is presented, providing valuable engineering insights for their seismic preservation.

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Dome of Nuestra Señora de los Ángeles, case study and assessment

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Speaker: Orozco Barrera Fabian Bernal. Invited. **Tuesday**. Start time: **10:20**. Room: Saint Clair 5 LVL3. Link to abstract.

Preserving Masonry structures represents a considerable challenge due to the loss of knowledge in their construction and materials, creating a need for appropriate tools and methods to understand their structural behavior accurately, especially when a hazard occurs that gravely affects the integrity and safety of the structure.
Different calculation methods have been implemented to explain the behavior of masonry; a particularly useful model for masonry is based on the limit analysis implemented by Jaques Heyman, considering a unilateral compression-only material in which the geometry of the structure is essential to assess its level of stability and in which equilibrium analysis is essential. The basis of this method is to find a thrust line within the structure's thickness. One of the benefits of this approach is the correlation of the tangent positions of the thrust line with the structure's contour, allowing the interpretation of the visible crack pattern present in the real structure.
In Mexico City in 2017, the Dome of the Church of Nuestra Señora de los Ángeles partially collapsed after an earthquake. This dome was the only one to collapse in Mexico City in 2017th earthquakes; this paper aims to explain the partial collapse of the dome and its geometric safety by assessing the collapse load using different equilibrium approaches, like the slicing technique that fits the segmented nature of masonry, comparing its results with discrete element modeling. Since the dome has a three-dimensional behavior, the analysis can consider the influence of hoop forces and ties and the particular soil conditions and their effect as differential settlements in the dome's behavior can be addressed as the boundary conditions change throughout its history. The above can be managed using laser scanning and photogrammetric surveys that correctly register the geometry and help identify cracking patterns.

The dome of the Royal Museum for Central Africa: Construction of a tile dome and its graphical static analysis

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Speaker: Santiago Huerta. Invited. **Tuesday**. Start time: **10:40**. Room: Saint Clair 5 LVL3. Link to abstract.

The central dome of the Royal Museum for Central Africa in Tervuren (Belgium), was completed in 1906. The architect of the building, Charles Girault, designed a double brick dome with a pointed profile and a span of approximately 20 m. It features an oculus at its center. Documentation held in the Museum's archives provides detailed information about its construction. The first layer of both shells consists of hollow bricks laid flat, working as a centering for several layers of solid bricks. The shells of the dome have varying thickness, and twelve ribs connect both shells at the lower part of the dome, where several mild steel ties absorb tensile stresses. Among the construction drawings, a graphic static analysis, signed by the architect in 1905, is preserved. This article examines the graphic method used to analyze the dome and explains the state of the art at the time of this analysis, when several publications were addressing similar problems. The matter has not only historic interest. The equilibrium analysis is completely correct within the frame of modern limit analysis of masonry and the paper shows that it is possible to analyze complex domes with this approach.

An improved interface material model for the in-plane cyclic response of masonry

Cera Giovanna (1), Rots Jan (1), Slobbe Arthur (2), Messali Francesco (1), Geurts Chris (2)

1 - Delft University of Technology (Netherlands), 2 - The Netherlands Organisation for Applied Scientific Research (TNO) (Netherlands)

Speaker: Cera Giovanna. Invited. **Tuesday**. Start time: **11:00**. Room: Saint Clair 5 LVL3. Link to abstract.

A large portion of old European buildings and historical structures are made of unreinforced masonry. Although it is one of the oldest construction materials, the assessment and prediction of the highly non-linear mechanical response of masonry structures is still a challenge. Masonry consists of units and dry or mortar joints. The properties of each constituent and their arrangement within the structure can result in a different mechanical response of the material. Among various modelling approaches for studying masonry structures, micromodels describe this material at the level of its constituents. These micromodels provide satisfactory results, but are computationally expensive. However, simplified micromodels, that describe masonry as elastic expanded bricks and lump the non-linearities in zero-thickness interfaces located in between the bricks, can represent a good compromise between accuracy and computational cost (1). In this work, an interface material model, originally presented in the context of the Discrete Element Method (2), has been implemented, improved and tested in an implicit Finite Element Code. The original interface accounts for mode-mixity in tension-shearing and combines cohesive and frictional behaviour in compression-shearing. In order to increase the robustness of the model, a smoothening of the function defining the frictional contribution is proposed. Furthermore, the consistent tangent stiffness has been derived to achieve fast convergence in full-scale analyses. Finally, the model has been enhanced with a compressive plastic-damage cap, to include crushing as a failure process in the interface material model. The improved interface material model has been used to simulate full-scale laboratory tests of a wall and a spandrel subjected to cyclic loading. The numerical outcomes are in good agreement with experimental tests: the capacity of the systems is successfully captured and energy dissipation adequately described. Satisfactory results in simulating different local failure mechanisms and reproducing the complex in-plane response of masonry are demonstrated. Finally, a critical comparison with other existing material models is carried out, highlighting capabilities and limitations of the proposed model in simulating the evolution of the damage in masonry structures.

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MS7.4 - Mechanics and physics of structures

Organisers: Sebastien Neukirch (Sorbonne Universit), Benoit Roman (ESPCI), F. Dal Corso (Univ. Trento) and M.Diaz (University of Edinburgh)

Apparent and real Gaussian curvature in axisymmetric kirigami

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Speaker: Vella Dominic. **Monday**. Start time: **10:10**. Room: Amphi lumière LVL-1. Link to abstract.

Cutting material from planar sheets has recently emerged as a strategy for generating three-dimensional shapes, particularly in flexible electronics. One particular form creates a planar structure that resembles a bicycle wheel with a central hub connecting multiple spokes. When this structure is compressed, it buckles out of the plane creating a structure that appears approximately axisymmetric and hence the structure appears to have Gaussian curvature, even though it was fabricated from a flat sheet. We begin by discussing how this strategy can work, showing that the cut pattern can be chosen to create either a tesselated 3D structure or an arbitrary axisymmetric shape with at most one inflection point. We emphasize that the 'spokes' of the structure deform cylindrically and so the Gaussian curvature of the axisymmetric structure that is generated is only 'apparent'. However, the hub region, which is approximately circular, deforms with real Gaussian curvature. We discuss the origin of this Gaussian curvature, showing that it is localized to the edge of the hub and give scalings for its size.

Bending properties of kirigami sheets

Domino Lucie (1) (2), Marthelot Joel (3)

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Speaker: Domino Lucie. **Monday**. Start time: **10:25**. Room: Amphi lumière LVL-1. Link to abstract.

'Kirigami' is a Japanese art form that comes from the words 'kiri' (to cut) and 'kami' (paper). While in the traditional art the goal is to obtain very intricate objects that can pop out beautifully, in the scientific literature it usually designates thin sheets that are pre-cut using a staggered pattern of slits. These kirigamis have been widely studied because of their very rich mechanical response when stretched as well as their numerous applications in adaptable solar panels (1) or shape morphing structures (2, 3) for instance.
Despite this extensive scrutiny, the bending properties of kirigami sheets have so far been overlooked. Here, we study thin sheets pre-cut with a staggered pattern of slits and measure their deflection due to gravity. We model their shape using a heavy elastica equation, and from this, extract the effective bending modulus of the kirigami sheets. We then study how the bending modulus depends on the geometric properties of the kirigami (size of the slits and spacing of the pattern).
Our work provides new insights into the mechanical behavior of kirigami structures, and opens up possibilities for their application in areas where controlling the bending properties is critical.

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Inverse Design of Conformal Kirigami Structures

Ying Xiaoyuan (1), Fernando Dilum Dias Marcelo

1 - University of Edinburgh (United Kingdom)

Speaker: Ying Xiaoyuan. **Monday**. Start time: **10:40**. Room: Amphi lumière LVL-1. Link to abstract.

Shape-morphing structures can transform from one state to another, making them highly valuable in engineering applications. In our study, we are interested to design kirigami structures that can morph into prescribed configurations. During the first phase of this study, we propose a two-stage shape-morphing framework, inspired by 2D kirigami, to design structures that can deploy from a compacted configuration to a prescribed state, under certain mechanical stimuli. The proposed framework establishes a connection between some known aspects of the geometry and previously missing elements in the mechanics of kirigami structures. This approach combines finite element analysis, genetic algorithm, and an analytical energy-based model to obtain kirigami designs with robustness and computational efficiency. In the second phase of our study, we leverage our framework to 3D scenarios. By combining conformal mapping and optimised bistable kirigami units, we can design a cut pattern that can morph from 2D kirigami sheets into 3D configurations that can be stable without external constraints.

Plastically controlled deployable kirigami structures

Hong Joo-won (1), Bico José (1), Reyssat Etienne (1), Ibarra Alejandro (2), Roman Benoît (1)

1 - Laboratoire PMMH (CNRS - UMR 7636) (France), 2 - Experimental soft matter physics, University of Luxembourg (Luxembourg)

Speaker: Hong Joo-Won. **Monday**. Start time: **10:55**. Room: Amphi lumière LVL-1. Link to abstract.

Kirigami structures are very popular in a wide range of engineering applications such as stretchable electronics, bioengineering or architectural components. Their overall deployment under load relies on the local bending of beam elements defined by alternate cuts in a plate. Here, we are interested in 3D structures obtained with an azimuthal pattern of cuts actuated by a point force normal to the plate. In a previous study, we described how to program the cutting pattern to reach a target shape under load. A perfectly elastic structure recovers its initial flat state as the force is released. In contrast, using a plastic material (thermoplastic, metal) leads to a permanent 3D shape as local deformations exceed plastic strains. Knowing the plastic mechanical response of a given material, can we program the cuts to obtain the desired shape ?

Stress Distribution and Buckling prediction in Kirigami sheets: an analytical approach

Du Yuwen (1), Groh Rainer (1)

1 - University of Bristol (United Kingdom)

Speaker: Du Yuwen. **Monday**. Start time: **11:10**. Room: Amphi lumière LVL-1. Link to abstract.

Kirigami, the Japanese art of creating intricate patterns by cutting and folding a thin sheet, offers exciting possibilities for engineers. For example, a kirigami sheet with a linear matrix of cuts perpendicular to an applied tensile load produces intricate out-of-plane buckling patterns. Depending on the ratios of cut length to longitudinal (parallel to applied load) and transverse (perpendicular to applied load) cut spacing, both symmetric and anti-symmetric buckling patterns can form. In addition, some sheets show a planar combination of or multi-stability between these two states. Prior research has employed analytical methods, finite element (FE) simulation, and experiments to uncover a phase diagram of these behaviours. While FE modelling of whole sheets and unit cells is effective for predicting buckling modes and loads, it provides less physical insight into the pre-buckling stress distribution and the transition between different buckling regimes. To fill this gap, we present a 2D analytical model for the pre-buckling stress distribution, the critical buckling force and the corresponding buckling modes. FE models in the commercial FE package ABAQUS are used as a benchmark, demonstrating good correlation in the critical buckling force prediction at low computational cost. In addition, the interaction zone and transition behaviour between two buckling modes is also explained by the model. In addition to providing physical insight, our method enables rapid design and parameter sensitivity studies of this particular kirigami sheet.

Keywords: Pattern formation, Tensile buckling, Finite element analysis, Multi-stability

Geometry of multi-state pop-up materials.

Chavda Jay (1), Prasath S Ganga (1)

1 - Indian Institute of Technology Madras (India)

Speaker: Chavda Jay. **Monday**. Start time: **11:25**. Room: Amphi lumière LVL-1. Link to abstract.

Keywords: Kirigami, Pop-up mechanism, Shape-morphing material, Mechanics of thin sheets

Kirigami & Origami, the Japanese art of paper cutting & folding, offer a powerful approach to fabricating complex geometric patterns from a single sheet of paper without adding or removing material. We integrate these two techniques by using both cuts & folds to create a pop-up material that provides the freedom to localize deformations at desired locations. By identifying the right cut and fold patterns, we can transform a flat sheet into three-dimensional shapes with few actuation degrees of freedom. To achieve this, we construct a pop-up unit with two straight cuts and three parallel folds orthogonal to the cuts on a flat sheet. This unit is then deployed by folding the sheet along its centerline, bringing the edges of the sheet together. By patterning a sheet with several pop-up cuts and folds at precisely computed locations, we demonstrate the transformation to a tessellated 3D shape upon deployment. We also show that one pattern of cuts & folds can be programmed to take multiple shapes at different deployment angles by employing the geometry underlying deployment. Using precision cuts on a sheet of paper we experimentally realize these materials and highlight their applicability in soft-robotics, architecture and biomedical engineering.

Origami tubular structures with degree-n vertices for anisotropic stiffness properties

Zhang Mingkai (1), Farhadi Davood (1)

1 - Delft University of Technology (Netherlands)

Speaker: Zhang Mingkai. **Monday**. Start time: **11:40**. Room: Amphi lumière LVL-1. Link to abstract.

Thin sheets can be assembled into tubular origami structures, forming mechanically unique three-dimensional structures with broad engineering applications ranging from robotics to deployable structures. These tubular structures are dynamic by design, ideally allowing deployment along one axis while maintaining structural rigidity along the others. Most existing origami tubular designs rely on patterns incorporating degree-four origami vertices, as these single degree-of-freedom (DOF) vertices are well understood and relatively straightforward to design.
However, the design of tubular origami structures based on higher-degree origami vertices remains unexplored. The challenge lies in simultaneously managing deployability and stiffness properties, which makes achieving the desired anisotropic stiffness properties difficult. This paper addresses this gap by introducing a general design strategy for constructing tubular origami structures based on degree-n vertices. Through a combination of numerical simulations and experiments, we first characterize the stiffness properties of these structures. We then define a set of objective functions to evaluate their stiffness properties under large deformations and develop a numerical framework to study the impact of higher-degree vertices on stiffness characteristics.
Our findings, validated by experimental results, reveal two key outcomes. First, careful selection and optimization of degree-four vertices can yield a 20% improvement in anisotropic stiffness properties compared to state-of-the-art designs (1). Second, transitioning to higher-degree vertices as unit cells enables the design of tubular structures with significantly enhanced anisotropic stiffness (with a 17% improvement over degree-four designs). These results demonstrate the potential of multi-degree origami vertices in advancing the mechanical performance of tubular origami structures, providing a foundation for future applications requiring tunable stiffness properties.

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Mechanics of Metallic Kirigami-based Energy-Dissipating Devices

Walker Martin (1), Khalilzadehtabrizi Sahand (2), Mohagheghian Iman (2), Singh Amanpreet (1)

1 - Durham University (United Kingdom), 2 - University of Surrey (United Kingdom)

Speaker: Walker Martin. **Monday**. Start time: **11:55**. Room: Amphi lumière LVL-1. Link to abstract.

Kirigami, the Japanese art of paper cutting, can be used to generate complex 3D shapes from 2D sheets. Kirigami structures can also be highly stretchable and accommodate extremely large strains when made from common materials, such as aluminium alloys, which allow relatively small strains at failure. The high stretchability of Kirigami makes it an ideal basis for energy dissipation applications. We will present an investigation into the mechanics of Kirigami sheets made from metallic materials. We derive a reduced-order model, using a simple yield-line mechanism analysis, which shows the behaviour is governed by a single dimensionless parameter related to the geometry of a unit cell. This is confirmed by a combination of finite element analysis and laboratory experiments. Furthermore, we present early results describing the strain-rate sensitivity of these metallic kirigami structures. The results of this study will enable the efficient design of novel energy-dissipating devices acting in tension.

Plasticity can yield doubly-negative post-buckling behaviour in hard metastructures

Box Finn (1), Jain Shresht (1), Johnson Chris (1), Pihler-puzović Draga (1)

1 - University of Manchester (United Kingdom)

Speaker: Box Finn. **Monday**. Start time: **13:40**. Room: Amphi lumière LVL-1. Link to abstract.

Perforating a structure with a series of holes can render it auxetic. The negative Poisson's ratio that emerges beyond the buckling threshold is a consequence of geometric nonlinearities introduced by the holey topology. Here, we explore the buckling behaviour of hard, holey structures which exhibit distinct post-buckling behaviour to their elastic counterparts. In particular, we observe both negative Poisson's ratio and a negative stiffness in hard materials that deform plastically as they buckle. We demonstrate that the post-buckling softening behaviour is a consequence of material constitutive nonlinearities in the rotation and shear response of the structural microarchitecture.

Mechanics of ribbon gridshells

Hong Joo-won (1), Castro Daniel Bico José (2), Reyssat Etienne Aharoni Hillel Roman Benoît

1 - Laboratoire PMMH (CNRS - UMR 7636) (France), 2 - pmmh (France)

Speaker: Bico José. **Monday**. Start time: **13:55**. Room: Amphi lumière LVL-1. Link to abstract.

Bending a sheet of paper into a doubly curved surface such as a dome or a saddle is a challenging operation generally leading to crumples or tears. More generally, changing the local Gaussian curvature of surfaces – the product of the main curvatures – imposes in-plane distortions. Geometrical strategies such as folding (origami) or cutting (kirigami) can be deployed to transform a poorly stretchable sheet into a complex 3D shape. Sheets obtained by weaving inextensible rods bring another degree of freedom as they are free to shear. Such gridshells structures can adopt doubly curved shapes that have been widely studied since the seminal works from Chebyshev and Shukhov motivated by applications ranging from clothing to architecture. We are interested in gridshells formed by crossed ribbons. We first present structures where the ribbons are originally assembled into a regular array with their normal direction perpendicular to the array. We will illustrate how the bending rigidity of the individual ribbons combined with the finite stiffness on their cross-sections dictate in-plane mechanical properties of such arrays. As the deformations of the ribbons are limited to bending in a single direction and twisting, the out-of-plane deflections of the array are geometrically constrained to shapes of negative Gaussian curvature. Can other type of shapes be programmed by adjusting the initial direction of the ribbons at each cross-section?

Programmable anisotropy with pressure: nonlinear effects in homogenization of cellular solids

Lacorre Paul (1), Fiore Louison (1), Linares Jean-marc (1), Tadrist Loïc (1)

1 - Institut des Sciences du Mouvement Etienne Jules Marey (France)

Speaker: Lacorre Paul. **Monday**. Start time: **14:10**. Room: Amphi lumière LVL-1. Link to abstract.

When flowers or other plants with soft stems lack water, they lose the rigidity that allowed them to stand upright. These important changes in stiffness are mainly caused by variations in osmotic pressure within the intracellular liquid. Through a bio-inspired approach, we designed a large artificial plant tissue and assessed its capabilities as a resilient actuator.
In our prototype, plant cells are represented by cubic or spherical cavities within a massive polymer block. The air pressure in each cell is controlled individually through small tubes connected to an air tank.

The effective mechanical properties of the medium are obtained by periodic homogenization of a representative volume element (RVE). Our finite element simulations take into account geometric and material nonlinearities. Custom boundary conditions are implemented to allow "periodic expansion" of the RVE. The elasticity tensor is reconstructed to track the evolution of material coefficients as a function of pressure and wall properties. The anisotropy of the tissue can be controlled by changing the distribution of pressure. Counter-intuitively, the apparent Young's modulus decreases with increasing pressure. A linear analytical model shows this is mostly due to volume changes upon inflation while the "actual" stiffness remains constant.

Due to the large number of individual cells, the actuator retains its stiffness even if one or more cells are damaged (i.e. punctured). We study the impact of spatial distribution of defects on mobility reduction. This artificial tissue is a programmable metamaterial that can serve as a resilient actuator for robotics. Moreover, it provides insights into how plants are able to move without muscles.

A generalized beam model for the analysis of the mechanical behavior of beam-like metamaterials

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Speaker: Pancella Chiara. **Monday**. Start time: **14:25**. Room: Amphi lumière LVL-1. Link to abstract.

Metamaterials are widely studied as they combine the practical needs for optimization and innovation with the desire to explore new frontiers in the mechanics of materials and structures. In fact, thanks to a proper design, metamaterials can exhibit exceptional characteristics overcoming those of traditional materials (1), such as low stiffness-to-weight ratio, ductile failure and exotic behaviors. Since metamaterials are often periodic structures, they can be treated as equivalent continua through the homogenization technique, which offers great advantages, including reduced computational effort and the possibility to find closed-form solutions.
Among metamaterials, there is the so-called grid beam (2), which is composed of a cellular microstructure made up of two orders of orthogonal micro-beams. For such microstructured beam, warping can be categorized into two types: micro-warping, which involves the bending of the microstructure around a plane to which the joints are constrained, and macro-warping, where the joints are free to move out of the plane. This behavior challenges traditional beam theories and has not been accurately described yet. In fact, de Saint Venant highlights its importance but neglects volume-applied loads, while Timoshenko's beam model approximately accounts it by introducing a shear factor but still assumes the hypothesis of rigid cross-sections out-of-plane. Moreover, the homogenized model for the grid beam, already existing in the literature, approximately accounts for micro-warping (2) by adopting an approach similar to that of Timoshenko but neglecting macro-warping.

To overcome these limitations, this study proposes a homogenized generalized beam model that extends classical frameworks by introducing additional strain measures to capture distortional and bidistortional effects accurately. The model is derived within the framework of the direct one-dimensional approach, while the constitutive law is determined through a homogenization procedure, i.e. the mixed homogenization approach (3), which enforces an energy equivalence between the cell, the smallest unit of the microstructured beam, and its one-dimensional counterpart of same length. The inertial properties for dynamic purposes are evaluated under the assumption of lumped masses at the cell joints. Linear static and free dynamic analysis of some grid beams, taken as case studies, are analyzed.

To highlight the effectiveness of the equivalent beam model, results obtained by the latter are compared with those derived from finite element (FE) analysis of refined models.

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Mechanics of woven tensile fibrous networks

Papin Thibault (1), Bico José (2), Cohen Caroline Bourrianne Philippe (3), Roman Benoît (4)

1 - PMMH/LadHyX (France), 2 - Laboratoire PMMH (CNRS - UMR 7636) (France), 3 - Physique et mécanique des milieux hétérogenes (France), 4 - Laboratoire PMMH (France)

Speaker: Papin Thibault. **Monday**. Start time: **14:40**. Room: Amphi lumière LVL-1. Link to abstract.

Woven fibers are ubiquitous in a wide range of applications ranging from clothing to composites for aerospace industry or artificial biological tissues. They generally resist tension along weft and warp directions stretch along the bias direction and bend under compression. We are interested in the mechanical properties of tennis racket heads. Professional tennis players learn by experience the major role of tensions along the strings, friction between strings or with the ball or viscoelastic properties of the strings. What is the relative impact of these different parameters? We propose to analyze individual ingredients through model experiments from the scale of a string to model rackets where tension and frictional properties to the strings can be quantitatively monitored. In particular we show the strong interplay between string mechanics and geometry on the deformation of a racket head subjected to a load. Our final goal would be to provide quantitative tools to obtain the "perfect" stringing suited for individual player style.

Homogenization of an inflatable architectured material for free-form surface design

He Siyuan (1), Skouras Mélina (2), Lebée Arthur (1)

1 - Navier (France), 2 - Inria (France)

Speaker: He Siyuan. **Monday**. Start time: **14:55**. Room: Amphi lumière LVL-1. Link to abstract.

There has been growing interest in inflatable structures across fields such as civil engineering, soft robotics, and aerospace due to their lightweight nature and ease of deployment. In the present work, we propose an inflatable made of two identical quasi-inextensible layers welded flatwise with spatially varying regular patterns. The inflation of air chambers induces nonuniform auto-contraction in the plane (or metric change) which from the Gauss theorem makes the inflatable become a 3D shell. In order to reach a given target surface, we rely on quasi-conformal transformation of a non-structured coarse triangular mesh filled with specific welding patterns. The main challenge for designing such free-form inflatable shells comes from the programming of the metric change. By means of non-linear periodic homogenization, we are able to compute the isotropic metric change of a single triangular welding pattern after inflation. This allows us to build a mapping of achievable contraction ratio as a function of geometric parameters of the welding pattern. Then we solve the inverse fitting problem as follows. First, we built a 3D coarse mesh on the target surface which is flattened as a 2D mesh with a quasi-conformal transformation. Then, we compute the area shrinkage per triangle and find the welding pattern according to the mapping of achievable contraction ratios. This approach already allows us to fit a rather wide spectrum of doubly curved surfaces. Nevertheless, as our mesh is non-structured, we are able to introduce cone singularities in the flat mesh. This opens an even wider design space. Our methodology is validated against full-scale simulations and fabricated models, demonstrating the strong applicability of our inflatable architectured material.

Influence of elasto-plastic behavior of thin films on buckling delamination of circular blisters

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1 - Science et Ingénierie des Matériaux et Procédés (France), 2 - Institut Pprime (France)

Speaker: Parry Guillaume. **Monday**. Start time: **15:10**. Room: Amphi lumière LVL-1. Link to abstract.

Thin films and coatings are now currently used in a very large number of technological applications such as for instance micro-electronics devices, protective layers or thermal barriers for turbine engines. Some deposition techniques now widely used in industrial processes, such as physical vapor deposition, are known to induce high internal stresses, sometimes about few GPa in compression.
This may lead to some mechanical damages with adverse consequences for the functional properties of these film/substrate systems. One of them, the buckling delamination of thin films has been widely studied by the past, analytically in the framework of the Föppl-von Kármán equations describing the equilibrium states of thin plates or numerically by finite element method (FEM) simulations. Three main elementary buckling structures have been evidenced and experimentally observed: the straight-sided buckles (SSB), the telephone cords (TC) and the circular blisters.
The circular blisters are the most frequently observed since they form spontaneously, sometimes just after the deposition process, but usually quickly evolve into TC, or SSB, because of a delamination front instability bove a critical diameter (at a given stress). Whatever the buckles morphology, their study was confined to the framework of elasticity. Only a few works were focused on the effect of plasticity, confirming the unstability of the circular shape.
However, in ductile films like Au, two **paradoxal** observations are made: 1) the dimensions of the circular blisters (especially the heigth) fail to be predicted by linear-elastic buckling models and 2) the circular shape seems to be able to propagate in a stable way, which is known to be impossible in a purely elastic framework.
In this presentation, we focus our attention on circular blisters forming on gold ductile thin films. Spontaneous circular blisters on Au 500 nm thick films on Si wafers observed by optical and atomic force microscopies are presented. Their maximum deflections are compared to what would be expected from a purely elastic plate theory. The Au film elasto-plastic behavior is determined by finite elements simulations based on nanoindentation experiments. The impact of plasticity on the buckled circular morphology is then finally studied using numerical simulations, and compared to our experimental observations. Additionaly it is shown by numerical calculations that plastic deformations in the film during blister delamination help stabilizing the circular shape of the delamination front (see Fig 1.).

Dynamic performance of architected beam structures

Ul Hassan Irfan (1), Singh Agyapal (2), Bergamini Andrea (3), Karathanasopoulos Nikolaos (4)

1 - NYU (United States), 2 - NYUAD (United Arab Emirates), 3 - Empa (Switzerland), 4 - New York University (United States)

Speaker: Karathanasopoulos Nikolaos. **Monday**. Start time: **16:00**. Room: Amphi lumière LVL-1. Link to abstract.

The contribution investigates the dynamic vibration performance of architected beam structures, engineered with different triply periodic minimal surface topologies, both experimentally and numerically. Their eigenfrequency response as a function of the inner topological designs is analyzed, providing insights into the effect of topology and relative density on the recorded mechanical performance (Figure 1). Topology-dependent modifications of the dynamic response are identified that are not feasible for solid and non-architected structures. Moreover, their dynamic damping performance is assessed, quantifying topological effects along with the role of inner material grading. Furthermore, machine learning models are developed, capable of predicting the dynamic performance and employed, not only as universal predictors, but also as surrogates for the inverse estimation of the feature importance of the underlying design parameters. Overall, the work provides benchmark results and insights into the dynamic performance of architected beam structures.

Impacting metamaterials : the threshold for wave propagation in holey columns

Monnery Sophie Jain Shresht Box Finn (1), Pihler-puzovic Draga (1), Johnson Chris

1 - University of Manchester (United Kingdom)

Speaker: Monnery Sophie. **Monday**. Start time: **16:15**. Room: Amphi lumière LVL-1. Link to abstract.

We report on the mechanical response of columns containing a periodic array of holes subject to impact loading. These holey columns are prototypical examples of mechanical metamaterials which have applications in sports engineering and as crumple zones ; here, the presence of holes render auxetic properties to the structure. When compressed slowly holey columns buckle locally beyond a compressive strain, and pattern switching (from circular holes to orthogonal ellipses) occurs everywhere at the same time. However, many applications involve dynamic loading. We observe that impact induces a compressive wave that buckles the ligaments surrounding a hole, nucleating a sequential pattern switching process, which ultimately leads to sequential self-contact of holes. Our focus is the threshold that separates a quasi-static and dynamic response to loading. We identify the critical impact velocity above which the compression can no longer be considered quasistatic and show that it depends on system size. Finally, we investigate the speed of buckling and self-contact waves, and their dependence on the impact velocity.

3D straw-based metamaterials: modeling, experimental characterization, and tunable mechanical properties

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Speaker: Chen Junyu. **Monday**. Start time: **16:30**. Room: Amphi lumière LVL-1. Link to abstract.

Straw-based truss metamaterials are composed of multistable, straw-like elements interconnected by rigid links, creating highly reconfigurable structures with multiple stable states. Their mechanical properties, such as Poisson's ratio, Young's modulus, and shear modulus, are adaptable based on their configuration, making them promising for applications in energy absorption, deployable structures, and soft robotics. To leverage these characteristics for engineering applications, we present a quasi-static computational framework in 3D space to model those metamaterials. Starting with a single straw element, we introduce nodal and internal degrees of freedom (DOFs) alongside holonomic constraints. The straw element exhibits infinite anti-symmetrical stable states in 3D without theoretical energy barriers, yet experiments reveal a damping force during transitions. We characterize this force and amend the model with an artificial friction term. Subsequently, the model is extended to represent complex 3D structures with multiple unit cells and rigid links. After characterizing the model coefficients, experiments are carried out for model validation with the help of force sensors and computer vision techniques. Finally, we demonstrate the model's configuration-dependent properties, including tunable Poisson's ratio, energy absorption, and adjustable stiffness, highlighting its potential for a wide range of engineering applications.

Architected Piezoelectric Metamaterials with Electric Auxetic Effect and Multi-deformation Modes

Zewei Hou (1), Bo Yu

1 - Beijing Institute of Technology (China)

Speaker: Zewei Hou. **Monday**. Start time: **16:45**. Room: Amphi lumière LVL-1. Link to abstract.

The Poisson effect of conventional materials refers to that when stretched longitudinally, they contract transversely. The same effect exists in the conventional piezoelectrics for electric-deformation modes. Considerable efforts have been devoted to the design of force-induced auxetic metamaterials, providing remarkable potential applications. However, research on piezoelectric metamaterials with electric auxetic effect remains scarce. in this work, the design mechanisms are fully investigated for architected piezoelectric metamaterials with electric auxetic effect. Inspired from the typical re-entrant structures with auxeticity, the geometric parameters design and polarization are investigated to realize the piezoelectric metamaterials with electric auxetic effect. The electric auxetic effect is tunable based on the mechanoelectric coupling effect. Interestingly, the results reveal that the auxetic effects are opposite for the architected piezoelectric metamaterials and mechanics metamaterials. Furthermore, we propose a strategy for heterogeneous piezoelectric metamaterials based on the electric auxetic effect. Multi-deformation modes are realized, such as flexure, twist, and standing wave modes. The novel standing wave mode is capable of achieving bidirectional robotic movement, thus remedying the drawback of conventional standing wave robots, which can only move in one direction. Our work paves the way for the research on electric auxetic metamaterials and facilitates the emergence of more intelligent devices and robots.

Cellular solids under geometric frustration: Animal architecture and bio-inspired designs

Lopez Jimenez Francisco (1), Gharooni Fard Golnar (1), Peleg Orit (1)

1 - University of Colorado [Boulder] (United States)

Speaker: Lopez Jimenez Francisco. **Monday**. Start time: **17:00**. Room: Amphi lumière LVL-1. Link to abstract.

We explore how bees collectively adapt their environment to build their honeycomb structure in the presence of various types of geometric frustrations preventing the use of a regular hexagonal lattice. In order to create well controlled and repeatable experiments, we 3D-print starter frames with imprinted foundations, imposing a variety of constraints. These range from misalignment between regular hexagonal regions, to imposing hexagonal lattices of different size from that naturally used by the bees. The resulting constructed combs show clear evidence of reoccurring, self-organized patterns built by the bees in response to specific geometric frustrations in the starter frames.
In the case of misalignment, we observe grain boundaries similar to those observed in other 2D crystal systems, such as graphene or colloidal crystals. We also show that the patterns can be replicated using a simulated annealing process, in which the minimized potential is a variation of the Lennard-Jones potential that only takes into account first-neighbor interactions according to a Delaunay triangulation.

We have also explored the case in which the 3D-printed panels have a regular hexagonal lattice, but with size different from the natural worker cells. Our findings suggest three distinct construction modes when faced with foundations of varying cell sizes. For smaller cell sizes, bees occasionally merge adjacent cells to compensate for the reduced space. However, for larger cell sizes, the hive uses adaptive strategies like tilting for cells up to twice the reference size, and layering for cells that are three times larger than the reference cell. We use X-ray microscopy to characterize these complex three-dimensional structures. Inspired by our results, we leverage simulated annealing as a design tool, in which the cellular solid is defined as the Voronoi/Delaunay tessellation of the particles used in the minimization process. We explore potentials that, while not directly based in physics, have use in a design process, particularly for problems in which a cellular solid conforms to irregular geometries. We also explore the effect of isolated topological defects (e.g., a disclination) on the mechanical properties of an otherwise topologically regular lattice.

Design of optimal architectures for ultra-light isotropic microtruss-based metamaterials

Derieux Thibaud (1), Bonamy Daniel (1), Guenoun Patrick (2)

1 - Service de physique de l'état condensé (France), 2 - Laboratoire Interdisciplinaire sur l'Organisation Nanométrique et Supramoléculaire (France)

Speaker: Derieux Thibaud. **Monday**. Start time: **17:15**. Room: Amphi lumière LVL-1. Link to abstract.

Microtruss-based architectured materials offer unique opportunities for tailoring mechanical properties, enabling novel combinations of stiffness, strength, and density. Their exceptional stiffness-to-weight ratios have spurred interest, particularly in transportation applications. However, the inherent anisotropy of most proposed architectures poses challenges in characterizing their fracture behavior on macroscopic scales (1).
In this work, we introduce a novel class of microtruss-based metamaterials designed to exhibit isotropy at small scales. These isotropic architectures were developed using an advanced computational framework, enabling precise structural generation and the creation of digital twins to predict mechanical properties comprehensively (2). The resulting materials demonstrate exceptional stiffness-to-density ratios that approach the theoretical upper limits established by the Hashin–Shtrikman bounds for isotropic porous solids (3).

While these materials exhibit exceptional stiffness, their compressive strength and fracture resistance remain areas of improvement. To address these challenges, we propose two complementary approaches. The first involves a statistical spatial modulation of local microbeam properties-such as diameter, shape, and material composition. This method leverages scale-invariant parameters to preserve overall isotropy while enabling fine-tuning of local autocorrelation properties with minimal control variables. The second approach draws inspiration from nacre, employing a monomaterial composite architecture that combines soft and hard microstructural elements (4). By interleaving these contrasting architectures, we achieve tunable elastic modulus and significantly enhanced fracture resistance. Together, these strategies enable the optimization of mechanical properties for a broader range of applications, balancing stiffness, strength, and toughness as needed.

This talk will present the design methodology, numerical tools, and mechanical performance of these isotropic architectured materials, along with ongoing efforts to enhance their compressive strength. These advances open new avenues for the application of microtruss-based metamaterials in engineering and material science.

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Domain wall propagation in assembled structures of rotating squares

Kopecz-muller Caroline (1), Liu Wenfeng (1), Acuña Ramirez Daniel (1), Coulais Corentin (1)

1 - Universiteit van Amsterdam (Netherlands)

Speaker: Kopecz-Muller Caroline. **Monday**. Start time: **17:30**. Room: Amphi lumière LVL-1. Link to abstract.

Metamaterials have been of increasing interest in various application fields, such as absorbing shocks or vibrations, ensuring a deformation regime that preserves the indenting object and prevents damages. Until now, investigations have focused mainly on varying the geometry of structures rather than considering the mechanical properties of the material itself. More precisely, plasticity has been carefully avoided while it may constitute a key point in designing new metamaterials, that could be produced industrially. In this work, we treat plasticity as a new design tool for metamaterials. Indeed, we observe that plasticity triggers the emergence of a transition wave in buckling, that propagates through the whole structure. Moreover, we observe that the transition wave may emerge at different places of the structure, depending on the loading history. Here, we exploit first a 2d-structure made of a chain of rotating squares and second a 3d-structure made of rotating octahedrons, to show regimes of inhomogeneous rotation upon compression, defining domains in the structure and propagating through it. We exhibit compression tests performed on 3d-printed structures that are compared to Finite Element Method (FEM) simulation results, based on an elasto-plastic description of the hinges. Additionally, we propose modelling ingredients describing the domain wall propagation in 2d structures, in accordance with observations made in FEM simulations. Finally, such concepts of system show resistance to a mechanical load while dissipating energy, which constitutes a key point to design efficient load absorbers.

Discontinuous mechanical metamaterials with controllable Poisson's ratios

Lee Hyeon (1), Syed Amer (1), Alam Parvez (1)

1 - University of Edinburgh (United Kingdom)

Speaker: Lee Hyeon. **Monday**. Start time: **17:45**. Room: Amphi lumière LVL-1. Link to abstract.

Mechanical metamaterials were designed with internal discontinuities to enable the judicious control of Poisson's ratio as a function of compressive loading. Two different unit cells, inspired by face-centred crystalline and re-entrant honeycomb structures, were parametrically designed, optimising the internal geometries to maximise the difference between lateral and longitudinal deformation when compressed.The discontinuities utilise a combination of free movement of internal structures and geometrical interlocking to enable control over deformational behaviours and consequently their Poisson's ratios. Various interfacial geometries were investigated to couple mass reduction to the ease of manufacture. The local Poisson's ratios of individual unit cells and their corresponding arrays were analysed through static compression testing and FEA. We report the deformational behaviours and Poisson's ratio outputs to validate our design objectives. The arrays were homogenised with micropolar assumptions, and bulk properties determined to map their mechanical properties. Elastic instabilities alongside strain-dependent interlocking are found to affect the local trajectories of deformation, which in turn influence the Poisson's ratios of the metamaterials.

Compaction and Buckling of a Sheet Confined by Rigid Walls

Deboeuf Stephanie (1), Dupont Audren (1), De Brion Matthieu (1), Abramian Anaïs (1), Katzav Eytan (2)

1 - Institut Jean Le Rond d'Alembert (France), 2 - Racah Institute of Physics (Israel)

Speaker: Deboeuf Stephanie. **Tuesday**. Start time: **10:00**. Room: Amphi lumière LVL-1. Link to abstract.

DNA in viral capsids, plant leaves in buds, and geological folds are natural examples of tightly packed low-dimensional structures. Modeling the deformations and stresses in such confined systems remains a significant challenge. We report experimental and theoretical studies of an elastic sheet compressed within rigid walls -a model system conceptualized as a one-dimensional line confined in a two-dimensional rectangular box. In this setup, the ends of a planar sheet are brought closer together while its sides are constrained by walls separated by a fixed gap. Previous studies have demonstrated that the sheet undergoes successive buckling events, resulting in uniformly distributed quasi-periodic patterns. Beyond this initial regime, we observe a spontaneous instability leading to the localization of the sheet into a single Yin-Yang pattern. By applying the linearized Euler's Elastica theory for rods (equivalent to the von Kármán approximation for plates) and global energy considerations, we predict certain scaling laws. However, to capture the symmetry breaking and to explore regimes of larger compression, the non-linear Euler's Elastica theory is required.

Dominantly Funicular Arches via Active Supports

Sipos Andras A. (1) (2), Várkonyi Péter L. (1)

1 - Budapest University of Technology and Economics [Budapest] (Hungary), 2 - HUN-REN-BME Morphodynamics Research Group [Budapest] (Hungary)

Speaker: Sipos Andras A.. **Tuesday**. Start time: **10:15**. Room: Amphi lumière LVL-1. Link to abstract.

Funicular structures are highly efficient by proper choice of form but sensitive to variations of load distributions, i.e., their performance depends strongly on their shape. We aim to explore the quasi-static shape adaptation of elastic arches by active supports. We investigate an incompressible, unshearable, 2D, prismatic elastica using a geometrically exact rod theory. Curved shapes are enforced by non-conform, statically indeterminate boundary conditions: the two endpoints are fixed at points A and B with a distance smaller than the length of the rod. The tangent angles alpha and beta at the two endpoints are set by actuators. The external load is a quasi-static vertical, distributed force.
Using a variational formulation, we show that the equilibrium paths of the problem can be related to the classical bifurcation diagram of Euler buckling, and specifically, the stability of an equilibrium solution is determined by the magnitude of the axial load, a Lagrange multiplier in the variational setting.

We study several optimization goals to be achieved via slowly varied tangent angles alpha and beta:
(i) maximize the critical load intensity associated with the planar stability failure of the structure. Nonetheless, maximization of the load intensity leads to shapes where the internal axial force is dominant, and internal bending plays a secondary role, i.e., we expect close-to-funicular shapes corresponding to the load. Perfect funicularity is, however, unlikely as the system is underactuated, i.e., only a limited set of shapes can be enforced by the two control parameters alpha, and beta.
(ii) minimize the deviation from perfect funicularity (i.e., vanishing internal bending) for a given load distribution.
(iii) generate paths of quasi-static transformation from an initial to a target shape without dynamic instability (e.g. snapping).

Elastica Constrained Between Walls

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Speaker: Wang Jiayu. **Tuesday**. Start time: **10:30**. Room: Amphi lumière LVL-1. Link to abstract.

In this study, we investigate the deformation of an Euler elastica confined between two walls under varying wall heights and end compression. We analyze the behavior of the elastica, focusing on the formation and structure of folds, the number of folds, and the forces involved, using multiple analytical and numerical methods. By comparing numerical simulations of the complete system with a simplified analytical model, we demonstrate that the simplified approach provides good predictions of the system's behavior.

dynamical snap-through of a buckled beam

Bense Hadrien (1), Domino Lucie (2), Kozyreff Gregogry (3), Radisson Basile (4)

1 - Laboratoire d'Acoustique de l'Université du Mans (France), 2 - Institut universitaire des systèmes thermiques industriels (France), 3 - Université libre de Bruxelles (Belgium), 4 - Institut Jean Le Rond d'Alembert (France)

Speaker: Bense Hadrien. **Tuesday**. Start time: **10:45**. Room: Amphi lumière LVL-1. Link to abstract.

Slender structures can undergo different forms of mechanical instabilities. For a long time they have been regarded as detrimental–one would rather not use a bridge that buckles! (1)–, but over the last 20 years this opinion have shifted. These events can indeed create large and rapid deformation which can be harnessed in numerous systems. Snap-through buckling is a particular form of mechanical instability in which a multistable system brutally goes from one stable state to another one. Venus flytraps are known to utilise this instability to swiftly close their leaves and capture their prey (2). Snap-through of buckled beams are also more and more used in flexible mechanical metamaterials to generate various forms of nonlinear waves (3). While the features of this instability are fairly well understood when the control parameter is varied in a quasistatic manner (4,5), the picture becomes less clear when its variation is dynamic. Yet, not only is this dynamical approach more relevant to real case scenarios, it might also provide additional levers to control the instability.
In this talk, I will discuss the effect of dynamical actuation on the snap-through instability of a buckled beam. We studied a model experiment in which the clamp angle of one end is swiftly varied below the static critical angle. While conceptually simple, this experiment allows us to see a strong effect of the dynamics on the deformation of the beam and on the snap-through threshold.

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Bending and Torsion of Composite Cable Structures

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Speaker: Doerlich Vanessa. **Tuesday**. Start time: **11:00**. Room: Amphi lumière LVL-1. Link to abstract.

Electric cables and cable bundles are highly flexible slender objects consisting of multiple components. The high variety of cable and bundle structures from single conductors and twisted cable pairs to wiring harnesses consisting of up to 100 different cable types leads to various deformation characteristics. However, these structures can be modelled efficiently using geometrically exact rod models formulating the constitutive behaviour in terms of the sectional quantities (i.e. forces and moments) and objective deformation measures (strains and curvatures) of the rod. In accordance with this modelling approach, classical experiments for clamped rods can be utilized in adapted setups to investigate the deformation behaviour of cable structures, derive fitting constitutive models and the corresponding model parameters. Typically, bending, torsion and their combination define the three-dimensional shape of a cable-like structure in applications. In this contribution, we will show real and virtual experiments to investigate cable behaviour under bending-torsion coupling and the derivation of suitable constitutive laws.

A Model for the Dynamic Snap-Through of an Elastica

Rangarajan Ramsharan (1), Bhattacharyya Chiraprabha

1 - Indian Institute of Science, Bangalore (India)

Speaker: Rangarajan Ramsharan. **Tuesday**. Start time: **11:15**. Room: Amphi lumière LVL-1. Link to abstract.

We study the problem of dynamic snap-through of a pre-buckled arch. Predicting the occurrence of the instability is straightforward, as is identifying the equilibrium configuration to which the arch jumps from a limit point. However, less is understood about the dynamic nature of the transition itself. We propose a new model to describe the dynamics of the arch during the snap-through. The model is validated with fully dynamic simulations and experimental measurements and provides insights that are immediately useful in designing robotic devices that function by exploiting snap-through instabilities for locomotion.
Specifically, we study the symmetric snap-through of a pre-buckled arch with clamped ends. The elastic response of the arch is characterized by the ratio d/L, with d denoting the distance between the clamps and L, the length of the arch. When the clamps are rotated to a critical angle that depends on d/L, the arch snaps spontaneously and dynamically to a new equilibrium configuration. The instability is displacement/angle controlled, and in particular, not load-controlled. The snap is typically visualized on a plot of equilibrium solutions. Such a depiction is convenient but misleading since the arch is never at equilibrium during the transition. In reality, the arch snaps past the stable equilibrium and vibrates about this configuration. Recent studies have focused on the arch's dynamic behavior near the unstable equilibrium point (critical slowing down). Instead, our work identifies an approximate, albeit useful, description of the dynamic evolution of the arch during the snap-through event.

To study the instability, we devise benchtop experiments to initiate it, record forces and moments, and image its configurations while ensuring that the arch profile remains symmetric. For a spring-steel arch with L_~25 cm and d/L_~0.95, the arch snaps within about 80 ms, and its midpoint reaches a peak velocity of about 6m/s. These observations reinforce the snap-through's dynamic nature and inertia's significance. This stands in contrast to the quasi-static nature of buckling instabilities. Over an extensive range of d/L ratios, examining the sequences of profiles of the arch during its snap-through reveals that its midpoint's displacement dictates the arch's configurations. Specifically, we find that the arch profiles during its dynamic transition are indistinguishable from strain energy-minimizing configurations with identical boundary conditions at the clamps and with coincident midpoint displacements.
Based on this observation, we propose a model that identifies the sequence of arch configurations during its dynamic transition as a 1-parameter family of strain energy-minimizing configurations, with the parameter being the midpoint displacement. Then, imposing conservation of energy yields a time-dependent sequence of configurations. From a computational perspective, the model only requires the resolution of ODEs. We validate the model's efficacy through comparisons with fully dynamic simulations and experiments over a wide range of d/L ratios that far exceed the expected range of use in robotic applications. The model's reliance on strain energy minimization, and consequently on quasistatic solutions to determine dynamic configurations, may appear paradoxical. However, this is not the case. In fact, the model can be interpreted as identifying the "most dynamic" transition between the unstable and stable equilibria or as one that minimizes the midpoint's time of travel rather than the Hamiltonian. In the presentation, we will discuss these aspects of the model and its application to designing underwater robots that locomote by harnessing the energy released during the snap-through.

Tencers: Tension-Constrained Elastic Rods

Dandy Liliane-joy (1), Vidulis Michele (1), Ren Yingying (2), Pauly Mark (1)

1 - EPFL (Switzerland), 2 - ISTA (Austria)

Speaker: Pauly Mark. **Tuesday**. Start time: **11:30**. Room: Amphi lumière LVL-1. Link to abstract.

In this talk I will discuss a class of lightweight structures that we coin tencers, short for tension-constrained elastic rods. Tencers consist of initially straight, flexible rods that are shaped through inextensible cables connected to the rods or external anchor points. Such a bending-active structure is in static equilibrium when the tension forces in the cables exactly cancel the bending, stretching, and twisting forces in the rods. The resulting 3D shapes of the rods then emerge as a consequence of all the forces acting on them. Our formulation supports arbitrary rod cross-sections and material properties. Rods can be open or closed, knotted, and arranged in arbitrary topologies.
We specifically focus on equilibrium states with no contacts among rods, i.e. each rod is only constrained by cables but no self-contacts or contacts with other rods. These configurations can be considered as a generalization of tensegrities, which are commonly composed of rigid rods in compression and flexible cables in tension. We show how this generalization to flexible rods leads to a rich design space, where complex target shapes can be achieved even with a small set of rods and cables.

However, allowing the rods to deform fundamentally changes the underlying kinematics and thus warrants a different computational approach than those commonly used for tensegrities. To explore the space of tencers, we present an inverse design optimization algorithm that solves for the length and placement of cables such that the equilibrium state of the rod network best approximates a given set of input curves. This algorithm continuously tracks the equilibrium state of the tencer while the geometric and physical parameters of the structure are optimized. For this purpose, we employ an efficient simulation method based on the discrete elastic rods formulation in the inner loop of the optimization.

We introduce appropriate sparsity terms to minimize the number of required cables, which significantly simplifies fabrication. Using our algorithm, we explore new classes of bending-active 3D structures, including elastic tensegrity knots that only require a few internal cables. We design and fabricate several physical models from basic materials that attain complex 3D shapes with unique structural properties.

Tencers are intriguing mechanical structures that find applications across scales, from lightweight structures in architecture to building blocks of mechanical metamaterials. Tencers commonly exhibit complex buckling and multistability. Even in the simplest examples, we observe interesting geometric and mechanical behavior. For example, an elastic ring buckles into 3D as the length of a cable spanning its diameter is reduced. As this length approaches zero, the rod flattens into a self-intersecting eight-shaped configuration.

Beyond their practical relevance, tencers are also interesting objects of theoretical study. We mention a few open questions: For an elastic knot of a specific knot type, what is the minimal number of cables needed to separate all self-contacts? When does a tencer have multiple stable equilibrium states? Can a transition between such states be achieved without inter-penetrations of rods or cables?

This is joint work with Liliane-Joy Dandy, Michele Vidulis, Yingying Ren, based on the paper Tencers: Tension-Constrained Elastic Rods, ACM TOG, 2024

Optimal Targeted Reconfiguration of Straw-Inspired Elements

Ilssar Dotan (1), Kochmann Dennis (1)

1 - ETH Zurich (Switzerland)

Speaker: Ilssar Dotan. **Tuesday**. Start time: **11:45**. Room: Amphi lumière LVL-1. Link to abstract.

Reconfigurable structures having several carefully designed stable configurations have a great potential for diverse applications such as deployable and shape morphing structures, as well as architected materials with configuration dependent mechanical properties. Multistability, allowing to stabilize a structure in different configurations can be achieved by embedding it with elements which have instability regions, such as precompressed elastic beams. A promising multistable elastic element discussed here is inspired by the 'bendy straw'. Under the assumption of planar deformations, such straw-inspired elements are modelled as arrays of unit-cells having up to four stable equilibria, allowing them to be stabilized in a large number of multiaxial configurations. These elements can be further used to form networks of customized geometries and operative stable configurations, to create complex structures and metamaterials with different configuration-dependent forms and functionalities. For applicability, the transition between different stable configurations of such structures should be done efficiently and with a minimal number of actuators, which raises a challenge of path finding in a highly nonconvex energy landscape. Here we focus on targeted reconfiguration of a single straw-inspired element. For this we begin by setting up the theoretical foundations and introduce a numerical scheme used to describe its mechanical behavior under prescribed relative translational and rotational displacements between its ends. This theoretical model is then validated utilizing an experimental demonstrator consisting of a cantilevered straw, multiaxially actuated by a single XY-Theta stage. Finally, we present an algorithm based on the Nudged elastic band (NEB) method, which is utilized to find the boundary conditions needed to be applied to the straw, for optimal targeted reconfiguration.

Modal self-tuning and mode-jumping of an oscillating variable-length rod

Dal Corso Francesco (1), Koutsogiannakis Panagiotis (2) (3), Misseroni Diego (2), Bigoni Davide (1)

1 - University of Trento [Trento] (Italy), 2 - Università di Trento (Italy), 3 - University of Colorado [Boulder] (United States)

Speaker: Dal Corso Francesco. **Tuesday**. Start time: **14:15**. Room: Amphi lumière LVL-1. Link to abstract.

An elastic rod, straight in its undeformed state, has a variable length because it is constrained at one end by a frictionless sliding sleeve. The constraint is arranged with the sliding direction parallel to a gravitational field, so that the rod can slide freely inside the sleeve when the latter is not moving. When the sliding sleeve is subjected to a harmonic transverse vibration, it is shown that the rod can oscillate around a finite height, appearing to be 'suspended', due to the configurational force developing at the sliding sleeve and acting in opposition to gravity. It is shown (experimentally, analytically and numerically) that by varying the oscillation amplitude and frequency of the sliding sleeve within certain ranges of values, the rod can oscillate under one or more modes of vibration and spontaneously adjust the sustained motion by self-tuning of the rod's external length. In addition, it is observed that the nth mode may become unstable as the frequency decreases, reaching a critical frequency at which the system may switch to the (n-1)th mode depending on the amount of system dissipation.

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Dynamic instability of nonlinear mechanical systems subject to non-holonomic constraints

Migliaccio Giovanni (1), D'annibale Francesco (1), Bigoni Davide (2), Dal Corso Francesco (2)

1 - University of L'Aquila (Italy), 2 - University of Trento (Italy)

Speaker: Migliaccio Giovanni. **Tuesday**. Start time: **14:30**. Room: Amphi lumière LVL-1. Link to abstract.

The complex interplay between nonlinear dynamics, stability, and non-holonomic constraints in elastic systems is explored through the paradigmatic model of a double pendulum. This system is subject to a conservative force at one end and a non-sliding wheel constraint at the other. Interestingly, and in contrast to the well-known Ziegler's double pendulum with a non-conservative follower force, the studied system can exhibit dynamic instabilities such as flutter and divergence even under purely conservative loading conditions. Dynamic instabilities in elastic systems are traditionally linked to non-conservative follower loads, which also introduce counterintuitive phenomena. One such phenomenon is the well-known "Ziegler's paradox", or damping destabilization paradox, where the critical load of the system decreases when small damping is present, compared to the undamped case. Typically, instabilities like flutter and divergence, as well as paradoxical effects such as damping-induced destabilization, are regarded as exclusive to systems under non-conservative loading conditions. However, recent investigations suggest that similar behaviors can also arise under conservative loading conditions when non-holonomic constraints are introduced (1). This highlights the crucial role of non-holonomic constraints in influencing the nonlinear dynamic behavior and stability of elastic systems.
This study analytically examines the nonlinear dynamics of a double pendulum with a non-holonomic constraint at one end and a conservative loading device at the other. Using the Method of Multiple Scales as in (2), the analytical determination of the limit cycles of the system near Hopf's bifurcation points is achieved, offering new insights into the nonlinear dynamics induced by this configuration. The findings reveal that Hopf's bifurcations can emerge in elastic systems under purely conservative loading conditions when non-holonomic constraints are present. Interestingly, the perturbation equations at different orders of the Multiple Scales Method exhibit the same non-symmetric structure as those governing the Ziegler's double pendulum, except for the force term, which restores the conservative nature of the system under study. The amplitude of the resulting limit cycles is derived analytically and corroborated through comparisons with benchmark numerical solutions. This analytical framework opens avenues for designing advanced mechanical systems with potential applications in areas such as limbless locomotion, where non-holonomic constraints and dynamic stability play crucial roles.

Acknowledgements:
All the authors acknowledge funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme, Grant agreement No. ERC-ADG-2021-101052956-BEYOND.

References:
(1) Cazzolli A., Dal Corso F., Bigoni D., Non-holonomic constraints inducing flutter instability in structures under conservative loadings, Journal of the Mechanics and Physics of Solids, 138:103919 (2020).
(2) Migliaccio G., D'Annibale F., On the role of different nonlinear damping forms in the dynamic behavior of the generalized Beck's column, Nonlinear Dynamics, 112, 13733-13750 (2024).

Nonreciprocal dynamics of active structures

Boiardi Ariel Surya (1), Noselli Giovanni (1), Santucci Pietro Maria (1)

1 - SISSA - International School for Advanced Studies (Italy)

Speaker: Boiardi Ariel Surya. **Tuesday**. Start time: **14:45**. Room: Amphi lumière LVL-1. Link to abstract.

Reciprocity is a property of linear physical systems that manifests through relations of symmetry (e.g. Betti's theorem). This remarkable and fruitful property also imposes strict constraints, escaping which is of interest in science and engineering (1). Working with polyelectrolyte (PE) hydrogels as a prototypical example of artificial active materials, we investigate the complex nonreciprocal behaviours arising from their response to electric stimuli by theoretical, numerical and experimental methods.
The movements of aquatic micro-organisms need to break time-reversal symmetry in order to produce fluid flows and achieve locomotion, as dictated by the constraints of low Reynolds number hydrodynamics. We found that flutter instability can be harnessed to produce self-sustained nonreciprocal oscillations in a PE hydrogel-based soft robot, leading to undulatory swimming under minimal actuation from a steady electric field (2).

The susceptibility of PE hydrogels to environmental stimuli can also be exploited to break spatial symmetry and thus investigate nonreciprocal transmission phenomena both in the static and dynamic regime. In particular, we focus on a periodic structure of PE hydrogel rods, exhibiting nonreciprocal behaviours, that can be predicted with a simple mathematical model. Moreover, the ability of PE hydrogel to harvest energy from the external stimulus allows to overcome viscous damping from the surrounding fluid and eliminate attenuation, leading to unidirectional wave amplification.

While notable examples of these behaviours have been presented in recent literature, our research proposes a different approach where the material itself acts both as actuator and control system. By exploiting the intrinsic response of PE hydrogels to the electrical stimulus, low level control tasks are offloaded to the interaction of the structure with the environment.

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2. A. S. Boiardi, G. Noselli, Minimal actuation and control of a soft hydrogel swimmer from flutter instability. *J. Mech. Phys. Solids* 191, 105753 (2024).

How Curvature Governs the Snap-Through Dynamics of a Bi-Stable Arch

Simpkins William (1), Hennessy Matthew (1), Taffetani Matteo (2)

1 - University of Bristol [Bristol] (United Kingdom), 2 - University of Edinburgh (United Kingdom)

Speaker: Simpkins William. **Tuesday**. Start time: **15:00**. Room: Amphi lumière LVL-1. Link to abstract.

Recent research on the snap-through buckling of elastic structures has undergone a paradigm shift, transitioning from the classic "buckliphobic" approach of determining buckling loads to avoid catastrophic failure to a "buckliphilic" approach of using shape transitions to enable novel modes of functionality. While static buckling loads and linearly stable configurations are well-documented for the former, the dynamic behaviour critical to the latter remains underexplored. In this work, we consider a compressible bi-stable circular arch under a central load, which acts as the controlling parameter to trigger snap-through. Using a combination of finite-element analysis and multiple-scales asymptotic methods, we characterise the dynamic behaviour of this system during snap-through transitions. Our findings reveal how the nature of the snap-through bifurcation, the total time of snapping, and the evolution of the snap-through event can be tuned via changing the curvature of the arch. Specifically, we show how increases in the curvature of the system can dramatically prolong the time taken for the structure to snap through. These results provide new insights into the dynamic nature of snap-through instabilities and highlight potential engineering applications for thin curved structures.

Dynamical elastic boundary layer in a snapping problem

Kozyreff Gregory (1), Bense Hadrien (2), Domino Lucie (3) (4), Radisson Basile (5)

1 - Université libre de Bruxelles (Belgium), 2 - Laboratoire d'Acoustique de l'Université du Mans (France), 3 - Institut universitaire des systèmes thermiques industriels (France), 4 - laboratoire IUSTI (France), 5 - Institut Jean Le Rond d'Alembert (France)

Speaker: Kozyreff Gregory. **Tuesday**. Start time: **15:15**. Room: Amphi lumière LVL-1. Link to abstract.

We study the snap-through of a buckled beam triggered by the rotation of one of its end. A quasistatic actuation leads to a saddle-node bifurcation at a known critical angle which depends only on the compression. Dynamics, however, changes this picture. Experiments indicate that the more rapidly one actuates the end of an elastic beam, the lower the critical angle at which it can snap from a high-order stable buckling mode to the fundamental one. We consider here actuation times that are much smaller than the fundamental natural oscillation period of the beam and present an asymptotic analysis of the transient leading to snapping in that limit. We find that the perturbation induced at one end of the beam invades the rest of the body through an expanding boundary layer. This boundary layer is inherently dynamical and not due to the smallness of the bending stiffness of the beam. During the transient, highly dispersive self-similar waves are identified in the boundary layer. As these waves escape the boundary layer and enter the core of the beam, their oscillations progressively match the natural frequencies of the beam.

Parametric excitation of rotating modes

Koutsogiannakis Panagiotis (1), Ruzzene Massimo (1)

1 - University of Colorado [Boulder] (United States)

Speaker: Koutsogiannakis Panagiotis. **Tuesday**. Start time: **15:30**. Room: Amphi lumière LVL-1. Link to abstract.

In the present study, we explore the existence and the characteristics of a rotating mode for elastic systems with an axially symmetric potential exhibiting a zero energy mode. For such systems the equilibrium configuration can rotate continuously around the axis of symmetry of the underlying potential field at no energy expense. The simplest system showing this behavior is an underdetermined mass-spring system with one end of the spring pinned and allowed to rotate freely. Elastic systems of this class, show an induced near-zero energy rotating mode for the case that the oscillator is driven by a harmonic force in the radial direction. The rotational oscillations can be excited when introducing a perturbation in the underlying potential field such that the axial symmetry is broken. A theoretical study of the induced rotation shows that the behavior of this system is governed by the physics of a parametric oscillator that leads to parametric instability. Indeed two nondimensional parameters dictate the stability of the trivial limit cycle for which there is no rotation. More complex systems, as is a network of masses connected with springs can also exhibit rotating modes when excited by a force perpendicular to the plane. In the case of continuous systems, zero energy modes can appear when certain conditions are met. As an example, an elastic circular disk with imposed internal stresses can buckle and the resultant deformation field can freely rotate around the axis of symmetry of the internal stresses. The rotation of this mode can be controlled by an imposed vibration in the direction perpendicular to the flat disk without inducing any angular momentum. Elastic systems with a rotating vibration mode can be used in applications such as actuation and transmission of rotary motion and more. Acknowledgments. PK and MR gratefully acknowledge funding from the National Science Foundation (NSF) under the grant "Collaborative Research: Design and Reconfiguration of Curved Surfaces for Targeted Wave Propagation" with award number 224709.

Random-access mechanical memory with a spin: path-dependent control of independent bistable beams in a rotating frame

Reis Pedro (1), Gutierrez-prieto Eduardo (1), Meulblok Colin (2) (3), Van Hecke Martin (2) (3)

1 - Ecole Polytechnique Fédérale de Lausanne (Switzerland), 2 - FOM Institute for Atomic and Molecular Physics (Netherlands), 3 - Universiteit Leiden = Leiden University (Netherlands)

Speaker: Reis Pedro. **Tuesday**. Start time: **15:45**. Room: Amphi lumière LVL-1. Link to abstract.

Controlling transition sequences in multistable mechanical systems traditionally relies on complex interactions between elements, making the design of specific sequences challenging. Here, we present a novel strategy that achieves path-dependent switching in a system of non-interacting bistable (clamped-clamped) beams, which encode memory through their stable states, using a single control functional parameter in a rotating frame of reference. By controlling the time series of angular position as an input function, we leverage the two fictitious forces that emerge in the rotating frame: the Centrifugal and Euler forces. The Centrifugal force scales as the square of angular velocity and pointing radially outward. The Euler force is proportional to the angular acceleration (the derivative of the angular velocity and points perpendicular to the radius, with a direction that can be switched by decelerating vs. accelerating the angular dynamics. These coupled forcing terms create distinct stability domains that enable deterministic but path-dependent transitions.

Through precision experiments and theoretical modeling using a von Mises truss system as a base framework, we demonstrate that the transition boundaries between stable states can be precisely tuned through geometric parameters, including the end-to-end shortening of the beams, their tilt orientation relative to the radial direction, and a heterogeneous and asymmetric bending stiffness of the beams. When multiple beams are positioned within the rotating frame, their transition boundaries can be accurately designed to intersect, leading to multiple possible transition sequences depending on the path taken in the space of angular velocity and acceleration input signals. We show that non-elliptical orbits in this (angular) velocity-acceleration space can enable the access of states that are otherwise unreachable by simple harmonic driving, thereby providing complete control over the individual beam states.

For a three-beam system, we achieve fully connected transition sequences with minimal Hamming distance between their binary states, demonstrating the potential for random-access mechanical memory. Our approach enables the design of programmable multistable systems without requiring complex coupling between elements. This strategy significantly simplifies the implementation of mechanical computing and memory systems, with potential applications in soft robotics, rewritable mechanical memory, and microfluidic devices.

Continuous and soft robot modeling based on Cosserat rod theory

Boyer Frédéric (1), Lebastard Vincent Briot Sébastien

1 - Frédéric BOYER (France)

Speaker: Boyer Frédéric. **Tuesday**. Start time: **16:35**. Room: Amphi lumière LVL-1. Link to abstract.

Robotics is today experiencing a paradigmatic revolution. The "stiffer is better" of our rigid robots is challenged by a new generation of robots with controlled deformations of finite amplitudes. This is the case of silicon-made soft robots, continuum robots in medical robotics or hyper-redundant eel/snake-robots in bio-inspired robotics. While rigid robotics has been establishing its models and methods since the 80s, this new robotics has long suffered from a lack of a generic modeling framework adapted to its problems. In the case of slender structures, this problem is now being solved thanks to a nonlinear theory of rods now known as Cosserat rod theory.

At the crossroad of rigid body mechanics and continuum mechanics, the Cosserat rod model is an ideal tool for the study of slender bodies undergoing large deformations. Initially presented as an abstract object by the Cosserat brothers, it has been applied over time to many problems in engineering sciences such as structural mechanics, where it gave birth to the geometrically exact finite element method (GE-FEM), in ocean engineering for the simulation of submarine cables, or in computer graphics, for the needs of interactive simulation. In robotics, whether for the study of hyper-redundant bioinspired locomotion, the simulation and control of non-invasive continuous medical robots, or for the design of new concepts of soft arms, it is gradually becoming a standard, comparable to the multi-body models of rigid robotics in the 80's.

In this talk, we will present a modeling framework based on Cosserat rod theory, developed in recent years with the aim of modeling, simulating, analyzing and controlling continuous and soft robots. The approach is based on a new parameterization of the configuration space of Cosserat rods, called "strain-based parameterization". Specifically adapted to the needs and uses of roboticists, we will show how it can be applied to many recently proposed robotic designs.

Stability and Singularities of Continuum Robots

Briot Sebastien (1), Boyer Frédéric Lebastard Vincent

1 - CNRS (France)

Speaker: Briot Sebastien. **Tuesday**. Start time: **16:50**. Room: Amphi lumière LVL-1. Link to abstract.

Compared to traditional rigid robots, currently used in many manufactories, continuum robots (CRs) are not more composed of an assembly of rigid components connected by lower mobility joints, but are made of flexible bodies encountering large deformations. The motions of their end-effector, the organ where the tool is placed, are carried out by the controlled deformations of the different flexible links composing them.
Their intrinsic flexibility allows their use in many fields where soft interaction with the external environment is required, such as minimally invasive surgery, collaborative tasks or even inspection of confined environments. Various CRs designs exist. Initially, serial-like designs have been proposed, among which we may note tendon-actuated or concentric tube robots. Later, in order to increase the payload capacity of such types of systems, or to obtain higher positioning accuracy, parallel designs were proposed. These CRs, also called continuum parallel robots, are made by the parallel assembly of several passive flexible link together.

All such robots are interesting for their safe-interaction properties, however, they may meet certain configurations where their physical is degraded: unstable areas or singular configurations. Singularities may lead to controller instability, and instability areas to unstable-stable transitions motions dangerous for the external environment.
In this presentation, we will present our most recent work in the analysis of the singular and/or unstable configurations, both from a statics and a dynamics mechanical point-of-view.

Non-material finite element model for the contact problem of sliding extensible rods

Ramsauer Stefan (1), Vetyukov Yury (1)

1 - Institute of Mechanics and Mechatronics, TU Wien (Austria)

Speaker: Ramsauer Stefan. **Tuesday**. Start time: **17:05**. Room: Amphi lumière LVL-1. Link to abstract.

We present a numerical investigation into the statics of two flexible rods, one partially inserted into the other, thus considered as a flexible sleeve. Both rods are subjected to external moments at their simply supported ends. The insertion naturally divides the system into three segments with the overlap as the central one. Here, the centerlines of the rods coincide while allowing for frictionless sliding. The variability of the overlap's length leads to configurational forces being exchanged between the rods in addition to concentrated moments and a distributed force.
Although recent theoretical analysis has provided foundational insights towards finding the specific values of the configurational forces, computational validation of these results remains absent. Besides, previous numerical studies focused on the case of inextensible centerlines, precluding the determination of the normal force distribution among the rods within the overlap. This work advances the field by incorporating an elastic constitutive relation that links the normal force to the axial strain, resolving the static indeterminacy and enabling the computation of these quantities throughout the entire system.

However, extensibility introduces significant complexity to the problem, particularly as the material lengths of the rods within the overlap generally differ. Consequently, the system requires two configurational parameters instead of one to describe the segment partitioning uniquely. Moreover, finite element modeling is challenging in this context. A purely Lagrangian formulation is cumbersome due to non-coincident nodes of the two rods in the overlapping region, and a purely Eulerian approach is unsuitable due to the spatial mobility of the transition points between segments.

To address these challenges, we propose an approach characterized by the following properties: The approximated quantities are the transverse deflection y and the material coordinate s, represented as piecewise functions of an auxiliary parameter σ, which ranges from 0 to 1 in each segment. The mapping between σ and the spatial axial coordinate x is chosen in a piecewise linear fashion. Within each segment the nodes σ=const are distributed equidistantly with respect to σ and hence also x. Cubic Hermite polynomials are employed to interpolate y and s, ensuring C1-continuity within segments, while additional procedures establish the necessary degree of continuity at transition points. Providing all the boundary, transition and overlap conditions, we apply the principle of virtual work for the conservative system at hand and finally solve for equilibrium at static or kinematic loading.

The computational results are compared with theoretical predictions. From one side, we can evaluate the curvature and thus the bending moment in the transition points. Similarly, the axial forces at the rods' central ends can be obtained via the longitudinal strain. As a simple consequence of the boundary conditions for the individual rods, these forces are exactly equal to the configurational ones. Conducting these calculations, it is possible to exemplary verify the general relation between bending moment and configurational force obtained from previous analytic investigations.

Again, using the constitutive law for extensibility, the axial force distribution within the overlapping region can be computed. Not only does this provide a novel insight, but it also allows for further comparisons with analytic results. In case of inextensibility, the rods are known to each have an invariant – the Hamiltonian, which is conserved even transitioning from one segment to another. For extensible rods with finite yet high tension stiffness relative to bending stiffness, we hypothesize that the Hamiltonian retains its role as a quasi-invariant. Indeed, numerics reveal no significant change in this quantity, especially when passing the segments' boarders.
In conclusion, this study provides a computational validation of recent theoretical findings, including the relationship between bending moment and configurational force for a flexible rod, sliding in a flexible sleeve. It also sheds light on axial force distribution within the overlap and demonstrates the quasi-invariant behavior of the Hamiltonian under high tension stiffness. These contributions not only confirm

analytic results and deepen our understanding of mechanical systems featuring sliding contact of elastic structures, but also provide a further example of mixed Eulerian-Lagrangian kinematic description for contact problems.

On the use of the Hamiltonian invariant of elastic rods

Neukirch Sebastien (1), Bertails-descoubes Florence (2)

1 - Institut Jean Le Rond d'Alembert (IJLRA), CNRS : UMR7190, Université Pierre et Marie Curie (UPMC) - Paris VI (France), (2) - Laboratoire Jean Kuntzmann (LJK), Institut National de Recherche en Informatique et en Automatique, Centre National de la Recherche Scientifique, Université Grenoble Alpes, Institut Polytechnique de Grenoble - Grenoble Institute of Technology Centre INRIA (France)

Speaker: Neukirch Sebastien. **Tuesday**. Start time: **17:20**. Room: Amphi lumière LVL-1. Link to abstract.

The static-dynamic analogy discovered by G. Kirchhoff shows that the statics of an elastic beam are equivalent to the dynamics of a spinning top. In this analogy, time and angular velocity are, for example, equivalent to arc length and curvatures. This static-dynamic analogy allows us to find a quantity that is invariant along the elastic rod at equilibrium: A spinning top will have its mechanical energy constant in time and, in the same manner, an elastic rod will have the sum of its curvature energy and its axial force uniform along the structure. The invariant property is known in simple cases, but the present approach generalises it to more complex cases where extensibility, shear, gravity, and contact are involved. Finally, we will show how to compute this invariant and illustrate its usefulness in three examples: the capstan, the elastic arm scale, and plectonemes.

Kirchhoff Knots: a new analytical model for loose and semi-tight regimes

Bertails-descoubes Florence (1), Metivet Thibaut (1), Neukirch Sebastien (2), Romero Victor (1)

1 - INRIA-ELAN (France), 2 - Institut Jean Le Rond d'Alembert (France)

Speaker: Bertails-Descoubes Florence or Neukirch Sebastien. **Tuesday**. Start time: **17:35**. Room: Amphi lumière LVL-1. Link to abstract.

We revisit existing models of elastic trefoil knots based on the Kirchhoff theory for thin elastic rods. We substantially improve the accuracy of previous analytical models by accounting for higher order terms. In addition, we analyse the transition from loose to semi-tight knots, which reveals a dependency upon the thickness of the rod, and show that this transition to a semi-tight knot can be properly covered by simply consideringextensibility in the tails of the open trefoil knot. By comparing our results to fully 3D simulations, we show that our improved analytical model for Kirchhoff knots remains valid for a large range of parameters, from extremely loose to moderately tight knots. Finally, we carefully confront various 1D rod simulators of the literature (based on the Reissner, or extensible/inextensible Kirchhoff models) against our theory, and provide key invariant quantities to refine the analysis. Overall, our model can serve to verify accurately experimental and numerical results of knots produced in a wide tying range.

Effects of Bending Stiffness on the Pull-Out of Model Roots

Yamaguchi Tetsuo (1)

1 - The University of Tokyo (Japan)

Speaker: Yamaguchi Tetsuo. **Tuesday**. Start time: **17:50**. Room: Amphi lumière LVL-1. Link to abstract.

Roots anchorage onto soil is one of the most essential functions of plant roots. Although there have been many reports on root-soil interactions and root anchorage for individual plants, few studies have focused on the effects of mechanical or geometrical parameters. In this study, we performed pull-out experiments using 3D-printed branched roots with various stiffness and diameters out of the soil at a constant velocity. Consequently, we found that the geometry and the bending stiffness of the root significantly affected the pull-out performance. We developed a theoretical model describing the pull-out behavior and successfully calculated maximum pull-out forces in reasonable agreement with experiments. Our results suggest that the bending deformation of the roots and friction or fracture of the soil determine the pull-out behavior and that the pull-out forces can be estimated using a simple theoretical model.

Perversions in Helical Rods and a Plant-Inspired Phase Transition

Dilly Emilien (1), Derr Julien (2), Neukirch Sebastien (3), Zanchi Dražen (4)

1 - Reproduction et développement des plantes (France), 2 - Reproduction et développement des plantes (France), 3 - Institut Jean Le Rond d'Alembert (Boite 162 4 place Jussieu 75005 Paris France), 4 - Laboratoire Matière et Systèmes complexes (France)

Speaker: Dilly Emilien. **Tuesday**. Start time: **18:05**. Room: Amphi lumière LVL-1. Link to abstract.

Helical rods (elastic springs) provide a simple system that highlights complex non-linear phenomena occurring right at our fingertips. The unwinding of helical rods leads to the formation of a *perversion*. This topological defect connects a helix of positive chirality to one of negative chirality, as seen in the tendrils of climbing plants such as cucumbers or vines. Upon rotation, the perversion can migrate along the rod, enabling a complete reversal of helix chirality. Mechanical measurements conducted during chirality reversal revealed that the perversion migration occurs at a pseudo-constant axial torque, drawing an analogy to fluid phase transitions, where the two phases-helices with opposite chiralities-are connected by a perversion acting as the interface, resulting in the emergence of an analogous Maxwell plateau. Within the framework of this biphasic expansion, the overall mechanical behavior, including a phase diagram detailing the existence of the conformations with helices of opposite chiralities, was reproduced. The stability of the perversion solution was also studied as a function of the imposed axial load. Experimental observations revealed that the perversion solution destabilizes at low axial loads, leading to self-touching conformations. This destabilization was also captured numerically using shooting methods and continuation techniques. The shooting method also enabled the recovery of configurations featuring multiple perversions, consistent with experimental observations. Examples include configurations with two perversions and periodic perversion patterns, also known as godet solutions.

Hydraulically-Actuated Asymmetric Flexible Hinge: A Bio-Inspired Design Principle

Starostin Eugene (1) (2), Goss Geoff (1)

1 - London South Bank University (United Kingdom), 2 - University College, London (United Kingdom)

Speaker: Starostin Eugene. **Tuesday**. Start time: **18:20**. Room: Amphi lumière LVL-1. Link to abstract.

Insect wings are composed of thin, highly flexible, double-layered elastic membranes. Veins form where these layers separate, often creating campanulate cross-sections. The vein walls are also elastic structures, making the entire wing an interconnected elastic continuum. One can think of a wing membrane as a set of flexible 'panels' connected by flexible struts (veins). Many species of insect can fold, unfurl, and adjust the shape of their wings during flight. Although such shape control is primarily exerted by basal wing muscles, changes in wing shape are observed throughout the wing. However, unlike those of birds and bats, insect wings lack internal musculature.

While the potential for hydraulic contributions to this control has been long hypothesised, it remains largely unexplored. Insect veins contain hemolymph, a fluid circulated by thoracic 'wing hearts.' Hydraulic pressure has been implicated in the folding/unfolding of hindwings in beetles and other insects. It is plausible that vein rigidity could be actively controlled through pressure variations, either synchronised with wingstrokes or maintained over multiple wingbeats.

We propose a novel mechanism for active wing shape control: hydraulic distortion of vein cross-sections, which exert leverage on adjacent cross-veins and membrane. Insect veins exhibit a wide range of cross-sectional shapes and wall thicknesses. Some sections, particularly in dragonflies, appear visually capable of deformation in response to lateral pressure. Hydraulic distortion of such vein cross sections can induce wing shape changes by varying relative orientation of adjacent membrane panels. This mechanism holds significant technical potential, with applications in deployable structures and micro aerial vehicle wing design.
An assumption of translational invariance along the vein's length allows us to simplify the analysis and consider the deformation of the vein's cross section. We model the vein cross-section as a cavity bounded by two elastic curves (elasticae) of different lengths, this difference captures the asymmetry of the cross-section shape. Hemolymph pressure is approximated as a differential normal pressure acting on the boundary of the cross-section.

Our model may be considered as a generalisation of the 'elastica hypoarealis' – a classical problem involving the deformation under a uniform distributed normal force of a single elastica bent into a smoothly closed loop. It has attracted occasional interest since the end of 19th century, yet remains the subject of active research. Our model differs from that because the boundary is now not differentiable in two points, where the two membrane layers separate.

The force and moment balance equations, expressed as a system of nonlinear ordinary differential equations, describe how the vein cross-section quasi-statically deforms under differential pressure and forces caused by wing membrane panels. A boundary value problem is formulated to obtain the equilibrium configurations of the two elasticae under pressure. The pressure, force, and moment acting on the end points influence the deformation of the vein cross-section and the subsequent deflection of adjacent wing panels. This deflection is characterised by a relative orientation angle and relative displacement. Numerical methods are employed to solve the boundary value problem.

This model accounts for large deformations and sudden shape changes, such as the snap-buckling observed during wing folding and unfolding. Asymmetry, a key factor in snap-buckling, is inherent in the non-circular cross-sections of many insect veins. We explore the relationships between haemolymph pressure, vein cross-sectional geometry, wall stiffness, and resulting deformations. Design criteria for triggering wing folding/unfolding are formulated. Graphical representations of key parameter relationships provide a benchmark for experimental studies and biomimetic design.

Thin-walled rods with open sections: asymptotic dimensional reduction of shell equations from 2D to 1D

Vetyukov Yury (1)

1 - Institute of Mechanics and Mechatronics, TU Wien (Austria)

Speaker: Vetyukov Yury. **Wednesday**. Start time: **10:00**. Room: Amphi lumière LVL-1. Link to abstract.

The elastic response of a thin-walled rod with the cross-section in the form of a thin curved strip is governed by generally known equations. Low torsional stiffness, importance of bi-moments and capability to carry torsional loads by means means of axial stresses caused by warping (deplanation) of cross-sections, as well as the location of the flexural center at a significant distance from the center of mass in a cross-section are the effects that essentially differentiate the thin-walled rods with thin open cross-sections from the common solid ones. As it is often the case with structural mechanics theories, the equations are usually derived using some technical approach involving hypotheses about the kinematics of deformation as well as the orders of smallness of different components of mechanical stresses. The most straightforward approach to the equations of the theory is the variational one, based on an approximation of the displacement field in a cross-section in terms of the deformation of the centerline of the rod, rotation of the cross-section due to bending and torsion as well as out-of-plane warping proportional to the rate of twisting. Expressing the strain energy per unit length in terms of the introduced functions of the axial coordinate and minimizing the total mechanical energy, one arrives at the differential equations of the dimensionally reduced theory. After solving the 1D equations it is possible to recover the 3D distribution of the stress components in the body of the rod, which usually results in a good correspondence with the reference results of full 3D numerical analysis.
Although the theory of thin-walled rods with open sections belongs to the core arsenal of methods of engineering analysis, it still lacks a theoretical justification in the sense of a rigorous mathematical derivation from the general equations of elasticity theory. It is known, that the theories of bending of plates and plane rods follow with the asymptotic analysis of the 3D problem: the leading order terms in the asymptotic expansion of the exact solution with respect to a small parameter are governed by the dimensionally reduced equations of the structural mechanics theory. However, existing attempts to perform a similar asymptotic procedure for thin-walled rods are highly complicated due to the curved geometry of the cross-section and the necessity to match asymptotic expansions.

This paper presents an alternative approach with the dimensional reduction of the 2D elasticity problem for a curved prismatic shell to the 1D problem for a rod. The asymptotic ratio of the thickness of the shell to the size of the cross-section is equal to the ratio of the size of the cross-section to the length of the rod and determines the formal small parameter λ. The starting point of the procedure are the equilibrium equations of the shell theory with the tensors of the membrane forces
tau and the bending moments μ, the respective boundary conditions at the side edges of the prismatic shell as well as the compatibility condition for small deformations of a material surface. Introducing asymptotic expansions of the components of
tau and μ, matching the coefficients at different powers of λ and performing three steps of the asymptotic procedure, we determine the leading order terms from the conditions of solvability of the minor ones. The analysis is concluded with the kinematic relations for the deformation of the shell surface, leading to the known 1D equations.

The main outcome of the present research is that the theory of thin-walled rods with open sections no longer needs to be considered as a "technical" formulation, but rather as an asymptotically exact consequence of the respective problem for an elastic shell. The asymptotic orders of the different components of the membrane force and bending moment tensors are established, thus enabling the stress recovery on a sound mathematical basis.
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Buckling and post-buckling of twisted strips: experimental and numerical analyses

Niiranen Jarkko (1), Khakalo Sergei (1)

1 - Department of Civil Engineering, Aalto University (Finland)

Speaker: Niiranen Jarkko. **Wednesday**. Start time: **10:15**. Room: Amphi lumière LVL-1. Link to abstract.

This study is about the buckling and post-buckling responses of columns formed by twisting a flat, straight and narrow material strip having a rectangular cross section. In essence, the analysis and results are of experimental and numerical nature: from real laboratory and virtual simulation environments. The problem set-up has its roots in the design of a wooden pavilion relying on finding structurally more efficient geometrical configurations for originally straight and flat birch plywood strips: twisting leads to structural members stiffer in both bending and compression. In the problem set-up, a straight and narrow material strip is first twisted and then compressed. For a flexible material strip, twisting can evidently be seen as a natural shaping process: forces or kinematical constraints are applied only at the ends of the strip, whereas the strip span takes its form according to the laws of the mechanics and physics of solids and structures. The reported experimental results cover flexible birch plywood strips twisted up to 90 degrees and compressed subsequently. The corresponding finite element analyses cover both the twisting phase up to 400 degress and the subsequent compression phase, including a study on the influence of the twisting-induced stresses on the buckling response. Numerical analysis extends to the post-buckling regime as well. The experimental and numerical results are in a good agreement and reveal somewhat surprising behaviour concerning the correspondence between the critical buckling load and the twisting angle.

Twist-controlled force amplification and spinning tension transition in yarn

Crassous Jérôme (1), Seguin Antoine

1 - Institut de Physique de Rennes (France)

Speaker: Crassous Jérôme. **Wednesday**. Start time: **10:30**. Room: Amphi lumière LVL-1. Link to abstract.

Combining experiments and numerical simulations with a mechanical-statistical model of twisted yarns, we discuss the spinning transition between a cohesionless assembly of fibers into a yarn. We show that this transition is continuous but very sharp due to a giant amplification of frictional forces which scales as exp(theta^2), where theta is the twist angle. We demonstrate that this transition is controlled solely by a nondimensional number H involving twist, friction coefficient, and geometric lengths. A critical value of this number Hc approx. 30 can be linked to a locking of the fibers together as the tensile strength is reached. This critical value imposes that yarns must be very slender structures with a given pitch. It also induces the existence of an optimal yarn radius. Predictions of our theory are successfully compared to yarns made from natural cotton fibers.

A ribbon model for nematic polymer networks

Singh Harmeet (1), Suryanarayanan Krishnan Virga Epifanio

1 - Indian Institute of Technology [Gandhinagar] (India)

Speaker: Singh Harmeet. **Wednesday**. Start time: **10:45**. Room: Amphi lumière LVL-1. Link to abstract.

Nematic polymer networks (NPNs) are rubber-like materials with nematogenic molecules embedded in the constituent polymer chains of the material. These materials can be deformed reversibly by the action of heat/light on the material from a distance, without any material contact with the source of heat/light. This key property of NPNs can be exploited for a wide variety of applications in industry, such as soft actuators, strain sensors, etc. In this talk, I will discuss a theory of deformation of ribbons cut out from a thin NPN sheet. The theory describes the natural and deformed configurations of an NPN ribbon as ruled surfaces, connected by a deformation map that allows for stretching that involves the imprinted nematic director field (an idealisation of the average orientation of the nematogenic molecules embedded in the polymer matrix). The main result of the theory is an energy density for NPN ribbons, obtained by a dimension reduction of a surface energy density of a thin NPN sheet. Thereafter, I will discuss planar as well as three dimensional numerical solutions of the developed theory, and present computations that provide us with an estimate of the efficiency with which NPN ribbons convert heat into mechanical work.

Torsional buckling in tape-springs: wavelength considerations

Clarkson Jamie (1), Seffen Keith (1)

1 - Department of Engineering, University of Cambridge (United Kingdom)

Speaker: Clarkson Jamie. **Wednesday**. Start time: **11:00**. Room: Amphi lumière LVL-1. Link to abstract.

Tape-springs are long, thin, strips with transverse curvature: they are highly deformable and hence widely used in deployable structures applications. Upon bending, longitudinal curvature precipitates in a "fold" region characterised by high curvature and flattened cross-section; a prime example of elastic localisation, where uniform deformation gives way to deformation divided into two distinct regions of differing strain (1). The properties of the fold are uniform throughout, with the exception of a small boundary layer at the edge of the tape, and further bending is accommodated by a lengthening, or "growth" of the fold at a constant moment.
Doubly-curved tape-springs, which were originally proposed for use in a deployable satellite reflector (2), feature a longitudinal curvature in addition to the transverse curvature, thus forming either a mudguard-like surface, with positive Gaussian curvature, or a saddle-surface, with negative Gaussian curvature. Upon bending, they form folds which at first glance appear identical to those in straight tape-springs. Finite element analysis, however, reveals a fundamentally different nature: longitudinal and transverse curvature are no longer uniform within the fold, instead varying in both the transverse and longitudinal direction. In particular, there is a pronounced dip in the longitudinal curvature at the centre of the fold.

There is a further paradox that the folds in doubly-curved tape-springs appear broadly developable. We expect developable folds in straight tape-springs, which have zero initial Gaussian curvature, but why should doubly-curved tapes, with non-zero Gaussian curvature, behave in a similar manner?

We seek simple explanations for the non-uniform folds by consideration of the Gaussian curvature and the geometry of generator lines lying on the surface of the shell.

(1) JA Clarkson & KA Seffen, Elastic localisation with particular reference to tape springs, (2024) *Journal of Applied Mechanics*
(2) KA Seffen & Z You & S Pellegrino, Folding and deployment of curved tape springs, (2000) *International Journal of Mechanical Sciences*

A 1D Kinematically Enriched Ribbon Model for Simulation of Winding of Superconducting Tapes for CORC-like Cables

Saadat Mohammad Ali (1), Torre Alexandre (2), Durville Damien (1)

1 - LMPS (France), 2 - CEA (France)

Speaker: Saadat Mohammad Ali. **Wednesday**. Start time: **11:15**. Room: Amphi lumière LVL-1. Link to abstract.

CORC® (Conductor on Round Core) superconducting cables are an innovative technology designed to enable high-current, high-field applications in compact and flexible configurations. These cables consist of multiple high-temperature superconducting (HTS) tapes wound around a cylindrical core, forming a structure capable of carrying significant electrical current with minimal loss. Understanding the mechanical behavior of the tapes in such cables during the winding process is crucial to improving their design and performance.
In this work, a novel one-dimensional (1D) ribbon model was developed to study the deformation mechanics of tapes used in CORC-like cables. The model incorporates enriched kinematics in the ribbon's cross-section, based on polynomial expansions with respect to transverse coordinates, to account for the complex deformation patterns that arise during wrapping. This representation enables the accurate prediction of in-plane and out-of-plane deformations, including warping, twisting, and bending of the ribbon, which are commonly observed in practice.

The ribbon model was applied to simulate the wrapping of a superconducting tape around a cylindrical core. The simulation results provided detailed insights into the mechanical response of the tape during the process, including stress and strain distributions across its cross-section. These results are critical for optimizing the ribbon's material properties and geometric parameters, ensuring minimal damage to the superconducting layer and enhancing the overall performance of the cable.
The proposed ribbon model offers a computationally efficient approach to addressing the complex deformation behavior of ribbons in CORC-like cable manufacturing. By improving the understanding of tape mechanics, this work contributes to the advancement of superconducting cable technology, supporting its application in fusion, energy transmission, particle accelerators, and other high-field systems.

Local Impenetrability in Slender Bodies of Finite Thickness

Suryanarayanan Krishnan (1), Singh Harmeet (1)

1 - Indian Institute of Technology [Gandhinagar] (India)

Speaker: Suryanarayanan Krishnan. **Wednesday**. Start time: **11:30**. Room: Amphi lumière LVL-1. Link to abstract.

A slender body is a solid whose one dimension is much larger than the other two. Theoretical modelling of a slender body generally entails reducing it to a centerline curve, and augmenting it with a frame of directors that track the flexure of the body in space.
The lateral dimensions, i.e. the cross-sectional thicknesses, of the slender body do not explicitly feature in such theories, except by way of a bending modulus, that penalises flexural deformations of the curve. In this talk, we will discuss the effect of the thickness of a slender body via the local impenetrability of the material surrounding the centerline curve.

By local impenetrability of the surrounding material, we mean that the determinant of the deformation map, connecting the tangent spaces of the reference and deformed configurations, must remain positive-definite. We compute the consequences of this constraint on the kinematics of a slender body of circular cross-section, and derive an inequality constraint connecting the Frenet-curvature, the centreline stretch, and the thickness of the body. For inextensible deformations, the relation reduces to an upper-bound on the Frenet-curvature of the centerline.
We incorporate this inequality constraint within the theory of Kirchhoff elastic rods using a variational principle. We derive the corresponding Euler-Lagrange equations for our system, and note that local impenetrability modifies the constitutive relation between the internal moment and the curvatures of the centerline. As an illustrative example, we use our theory to compute the shape of a fully flexible string hanging under gravity, and show that below a critical horizontal distance between the two ends of the string, our solutions deviate from the well-known classical catenary solution. Finally, we validate our results with some table-top experiments, and discuss the implications of our theory on the computations of ideal shapes of clasps and knots.

The problem of shear in finite elasticity: An alternative formulation to simple shear and pure shear

Falope Federico Oyedeji (1), Lanzoni Luca (1), Tarantino Angelo Marcello (1)

1 - DIEF, Università di Modena e Reggio Emilia (Italy)

Speaker: Lanzoni Luca. **Wednesday**. Start time: **11:45**. Room: Amphi lumière LVL-1. Link to abstract.

The problem of shear at large strains deserved a lot of interest because of its relevant applications in engineering. The most popular formulations adopted to analyse finite shear are known as "simple shear" and "pure shear". Both these layouts have been widely investigated due to their (apparent) simplicity (1). However, the abovementioned schemes lead to some inconsistencies as the corresponding Green-St.Venant strain tensor contains components related to extensional deformations also, thus violating the pure shear strain condition. Likewise, the related Cauchy stress tensor does correspond to a pure shear stress state as it involves normal stress components. As a consequence, both "pure shear" and "simple shear" schemes lead to ambiguities, and they provide different results in matching experimental data (2). In the present work, we proposed an alternative kinematical model to study finite homogeneous shear deformations. The proposed formulation, called herein "angular shear", involves only shear strains due to pure angular variations of fibers. An extension to 3D (3D angular shear deformation) has been also formulated. The absence of Poynting effect (3) in the proposed layout is also proven.

As shown through experimental investigations performed on rubber-like prismatic samples, the proposed shear model allows understanding better the main aspects related to the nonlinear response of hyperelastic bodies under shearing forces and, in turn, it permits more reliable material characterization of the elastic parameters than the previous formulations would do.

References

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(2) Moreira, D.C., Nunes, L.C.S., "Comparison of simple and pure shear for an incompressible isotropic hyperelastic material under large deformation", Polym. Test. 32 (2013) 240-248.
(3) Gurtin, M.E., Fried, E., Anand, L. The Mechanics and Thermodynamics of Continua. Cambridge University Press (2010).

Simulating plane deformations of elastoplastic Cosserat rods using a variational approach

Linn Joachim (1), Schneider-jung Fabio Manfredo Davide Dörlich Vanessa Arnold Martin

1 - Fraunhofer Institut für Techno- und Wirtschaftsmathematik (ITWM) (Germany)

Speaker: Linn Joachim. **Wednesday**. Start time: **14:30**. Room: Amphi lumière LVL-1. Link to abstract.

In our contribution, we outline a variational procedure that provides stable solutions of quasistatic sequential plane deformations of Cosserat rods possessing elastoplastic constitutive properties. The variational procedure can be interpreted as an algorithmic generalization of the computation of stable equilibira of elastic Cosserat rods by energy minimization. We demonstrate our approach with an elastoplastic Cosserat rod model, where the constitutive law yields the bending moment as a rate independent functional of the current bending curvature, combining nonlinear elastic bending stiffness characteristics with plastic curvature evolution modeled via an inverse Prandtl-Ishlinskii (PI) hysteresis operator. We show some illustrative numerical examples of plane bending with the resulting hysteretic effects. Wealso indicate how the model parameters can be identified from results of cyclic plane bending experiments, with composite cables as a concrete application example.

The Design Space of Kirchhoff Rods

Hafner Christian (1), Bickel Bernd

1 - Institute of Science and Technology Austria (ISTA) (Austria)

Speaker: Hafner Christian. **Wednesday**. Start time: **14:45**. Room: Amphi lumière LVL-1. Link to abstract.

The Kirchhoff rod model describes the bending and twisting of slender elastic rods in three dimensions and has been widely studied to enable the prediction of how a rod will deform, given its geometry and boundary conditions. In this work, we study a number of inverse problems with the goal of computing the geometry of a straight rod that will automatically deform to match a curved target shape after attaching its endpoints to a support structure. Our solution lets us finely control the static equilibrium state of a rod by varying the cross-sectional profiles along its length. We also show that the set of physically realizable equilibrium states admits a concise geometric description in terms of linear line complexes, which leads to very efficient computational design algorithms. Implemented in an interactive software tool, they allow us to convert three-dimensional hand-drawn spline curves to elastic rods and give feedback about the feasibility and practicality of a design in real time. We demonstrate the efficacy of our method by designing and manufacturing several physical prototypes with applications to interior design and soft robotics.

Asymmetric Bending Boundary Layer

Vani Nathan (1), Ibarra Alejandro (2), Bico José (3), Reyssat Etienne (3), Roman Benoit (4)

1 - Physique et mécanique des milieux hétérogenes (UMR 7636) (ESPCI, 7 Quai Saint Bernard 75005 Paris France), 2 - Experimental soft matter physics, University of Luxembourg (Luxembourg), 3 - Laboratoire PMMH (CNRS - UMR 7636) (France), 4 - PMMH (France)

Speaker: Vani Nathan. **Wednesday**. Start time: **15:00**. Room: Amphi lumière LVL-1. Link to abstract.

We investigate the mechanics of two ribbons bound at one end and pulled apart at the other ends. We provide a thorough experimental and analytical characterization of the elastic junction and conceptualize it as a 'bending boundary layer'. The rotational stiffness of the structure exhibits a non-linear but universal behavior. The ratio of the bending stiffnesses fully prescribes its shape independently of the pulling force.
Remarkably, the angle of the bound end with the pulling force acts as a scale-free geometric marker of the bending stiffness. Our results thus challenge the standard assumption of neglecting bending stiffness of thin shells at large tensile loading. We furthermore highlight how this specific boundary layer appears in various areas of active research (*kirigamis*, inflatables, architected metamaterials) as well as in everyday objects (food packaging, double-sided tape, magazines).
Finally by exploiting the self-similar shape of the junction, we introduce the λ-test, a novel method for characterizing the bending stiffness of thin membranes. The procedure allows for a robust, visual measurement of an otherwise difficult-to-quantify material property.

The deterministic role of edge states in slender structures buckling, and how edge states depend on geometric defects

Yang Tian (1), Schneider Tobias (1)

1 - EPFL (Switzerland)

Speaker: Yang Tian. **Wednesday**. Start time: **15:15**. Room: Amphi lumière LVL-1. Link to abstract.

The buckling of slender elastic structures, particularly the buckling of spherical and cylindrical shells, is highly sensitive to imperfections and external perturbations. This often leads to buckling at loading conditions well below the threshold for linear instability. One approach to rationalize this phenomenon is to consider the nonlinear finite-amplitude instability of the linearly stable system. Within such a dynamical systems description and for subcritical values of the control parameter (typically the applied load or end-shortening), the unbuckled state is surrounded by its basin of attraction. Initial perturbations within the basin decay to the unbuckled state, while perturbations outside trigger buckling. The basin boundary is formed, at least locally, by the stable manifold of special unstable equilibria, termed *edge states*. Consequently, these edge states control the critical size of deformation perturbations triggering buckling.
Edge states and their dependence on loading conditions have been numerically analyzed for axially compressed cylinder shells in the absence of geometric defects, where their role in guiding buckling has been demonstrated (1, 2). For imperfect cylinder shells with geometric imperfections, edge state equilibria have so far not been studied numerically in detail. However, experiments on the buckling of commercial aluminum shells strongly suggest that (a) edge states remain relevant for the buckling of imperfect shell structures and (b) edge states may encode the affects of specific realizations of geometric defects so that tracking edge states can provide information on the spontaneous buckling load of an individual defected shell (3). Here, we consequently study the role of edge states in the buckling of both geometrically perfect and imperfect slender structures.

For a perfect axially loaded cylinder shell, we demonstrate the existence of a full snakes-and-ladders bifurcation structure. Two branches of unstable equilibria containing either an even or odd number of localized dimples undergo sequences of saddle-node bifurcations under parametric continuation in the imposed end-shortening. These branches of reflection-symmetric solutions are connected by asymmetric 'rung' branches. Those rungs bifurcate off the snaking branches in pitchfork bifurcations that break the discrete reflection symmetry. Together snaking and rung branches form the well-known snakes-and-ladders bifurcation structure, previously studied within the Swift-Hohenberg model PDE with 2-3 nonlinearity.

Geometric imperfections, small modifications of the unloaded reference configuration, may break continuous and discrete symmetries and are thus expected to modify the edge state equilibria as well as their bifurcation structure. We thus develop numerical tools for the parametric continuation of equilibria in the amplitude of geometric imperfections. These methods are developed in the context of a circular arc subject to a central point load. We show that even for a large class of imperfections, there is a unique edge state that captures critical deformations to trigger buckling and that this edge state can be identified using probing techniques such as those developed in the context of shell buckling studies. Transferring the parametric continuation scheme, termed *Continuation in Geometry (CIG)*, to the axially loaded cylinder shell problem, we study the imperfection-dependence of edge state equilibria. We specifically discuss the breakdown of regular snaking, the emergence of additional solution branches with complex spatial structure, and the modification of the critical load value, at which edge-state branches bifurcate off the trivial unbuckled equilibrium. The significance of characterizing the imperfection dependence of edge states lies in the potential to better understand and predict when a real defected slender structure buckles and collapses.

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Static friction models for a rod deforming on a cylinder

Shah Rehan (1)

1 - Queen Mary University of London (United Kingdom)

Speaker: Shah Rehan. **Wednesday**. Start time: **15:30**. Room: Amphi lumière LVL-1. Link to abstract.

We develop a comprehensive geometrically-exact theory for an end-loaded elastic rod constrained to deform on a cylindrical surface. By viewing the rod-cylinder system as a special case of an elastic braid, we are able to obtain all forces and moments imparted by the deforming rod to the cylinder as well as all contact reactions. This framework allows us to give a complete treatment of static friction consistent with force and moment balance. In addition to the commonly considered model of hard frictionless contact we analyse in detail two friction models in which the rod, possibly with intrinsic curvature, experiences either lateral or tangential friction. As applications of the theory we study buckling of the constrained rod under compressive and torsional loads, finding critical loads to depend on Coulomb-like friction parameters, as well as the tendency of the rod to lift off the cylinder under further loading. Our results are relevant for many engineering and medical applications in which a slender structure winds inside or outside a cylindrical boundary.

Modeling ribbons/ strips as a Cosserat rod

Kumar Roushan (1), Kumar Ajeet (1)

1 - Indian Institute of Technology Delhi (India)

Speaker: Kumar Roushan. **Wednesday**. Start time: **15:45**. Room: Amphi lumière LVL-1. Link to abstract.

Strip (or Ribbon)-like structures refer to elongated objects that are flat and have a narrow width compared to their length. Such structures are used in a wide range of fields encompassing various applications such as in building blocks for fabricating nanodevices, nanoelectronics and nanostructured materials, sensors and actuators, photonic waveguides, light-emitting devices, etc. For an effective modeling of strips/ ribbons as a Cosserat rod, an accurate knowledge of the strip's constitutive relations in terms of the rod's strain is essential. This study presents a computational approach to obtain nonlinearly elastic constitutive relations of strip/ribbon-like structures modeled as a special Cosserat rod. Starting with the description of strips as a general Cosserat plate, the strip is first subjected to a strain field which is uniform along its length. The Helical Cauchy-Born rule is used to impose this uniform strain field which deforms the strip into a six-parameter family of helical configurations-the six parameters here correspond to the six strain measures of rod theory. Two vector variables are introduced to model the position of the deformed centerline of the strip's cross-section and to model orientation of thickness lines along the strip's width. The minimization of the strip's plate energy together with the aforementioned uniformity in strain field reduces the partial differential equations of plate theory from the entire midplane of the strip to just a system of nonlinear ordinary differential equations along the strip's width line for the above mentioned two vector variables. A nonlinear finite element formulation is further presented to solve the above mentioned set of ordinary differential equations. This, in turn, yields the strip's stored energy per unit length as well as the induced internal force, moment and stiffnesses of the strip for every prescribed set of six strain measures of rod theory. The developed model is used to study the uniform bending, twisting, and shearing of a strip. For the case of uniform twisting and shearing, the strip is also seen to buckle along its width into a more complex configuration, which are accurately captured by the developed model. This model involves the system of non-linear ordinary differential equation and therefore found to be computationally efficient and accurate when compared with the model of Arora et al.(2), as their scheme requires solving the partial differential equation. Further, the result from developed computational scheme is compared with the analytical scheme of Audoly and Neukirch (3) wherein they made several assumptions to come up with their analytical results. Finally, the developed model accurately obtained non-linear constitutive relation of strip when modeled as rod.

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Knot Strength – A Mechanics-Based Investigation

Sabater Gazulla Javier (1), Reis Pedro M. (2), Crassous Jérôme (3)

1 - Flexible Structures Laboratory, École Polytechnique Fédérale de Lausanne (Switzerland), 2 - Flexible Structures Laboratory, École Polytechnique Fédérale de Lausanne (Switzerland), 3 - Institut de Physique de Rennes (France)

Speaker: Sabater Gazulla Javier. **Wednesday**. Start time: **16:00**. Room: Amphi lumière LVL-1. Link to abstract.

Knots play a crucial role in diverse applications, ranging from securing surgical wound closures to facilitating complex biological processes such as DNA tangling. Despite their routine use in fields such as sailing, climbing, and surgery, current knowledge about knot mechanics is largely based on empirical data and practical experience rather than a mechanics-based understanding. In surgery, this gap has led to significant variability in knot-tying techniques among physicians and inconsistencies in defining what constitutes a secure knot (1). Knots are inherently complex mechanical systems due to the interplay of topology, geometry, self-contact interactions, and elasto-plastic material behavior. Existing analytical models based on Kirchhoff's theory for elastic rods are unable to fully capture the functional behavior of physical knots (2). Moreover, until recent years, the computational expense of finite element method (FEM) simulations for rods has further limited advances in knot mechanics. Recent work by Johanns *et al.* (3) identified the key factors influencing the mechanical strength of surgical sliding knots, offering a crucial foundation for developing safer knot-tying techniques. Their experimental and numerical findings showed a consistent power-law relationship between the knot strength and the applied pre-tension across various elastoplastic filaments, with an exponent of 1.6. However, the underlying mechanics driving this non-linear behavior remain unclear.

In this talk, we present the latest advancements in our study of the mechanics of knots, building on the findings of Johanns et al. (3). We have analyzed the strength of multiple knot configurations, exploring a variety of materials and topologies through precision experiments and systematic FEM simulations. Specifically, we have investigated multiple topologies, including a single loop tied around a straight rod, two consecutive loops, and the clove hitch knot. These configurations were examined both when tied around another rod of the same diameter and around a thicker rigid cylinder. Our results evidence three distinct regimes for the behavior of the knot strength as a function of the applied tension: (i) loose knots, when there is no continuous contact between both rods (ii) a nonlinear (power-law) regime, with an exponent 1.6 and (iii) a linear regime observed in (3). This mechanical behavior has been consistently observed across all materials tested, including elastomeric rods (vinyl polysiloxane, VPS), ropes, and Nitinol wires underscoring that the mechanisms governing knot strength extend beyond pure elasticity. In parallel to the experiments, we conduct FEM simulations, which provide additional physical insight; the contact pressure field data reveals the same scaling as the knot strength for the tested knots. To probe further into the underlying mechanics, we extend our study to even simpler contact configurations, such as the Capstan problem, toward isolating the physical ingredients underlying knot strength.

By bridging the gap between empirical practice and mechanics-based modeling of knots, we anticipate that this research will offer a robust foundation for optimizing and rationalizing knot designs, enhancing safety and efficiency in both traditional and emerging applications, including the development of protocols for tying safer knots in critical fields such as surgery and climbing.

When does matter matter with slender matter?

Croll Andrew (1)

1 - North Dakota State University (United States)

Speaker: Croll Andrew. **Wednesday**. Start time: **16:15**. Room: Amphi lumière LVL-1. Link to abstract.

There has been considerable progress in understanding and modelling the many interesting behaviours of slender continua. Effects like buckling and localization are now routinely used in higher-order structures like metamaterials or crumpled matter. Much of this success has been predicated on linear-elastic (or slightly non-linear) theories roughly under the assumption that, to first order, geometry is dominant. On the other hand, because localized structures do form, material properties such as plasticity and viscoelastic loss must appear – particularly in higher order structures where many structures are in play. In this work, we experimentally examine the response of a large number of different materials, ranging from elastic to fragile in several different idealized localized structures. As an example higher-order structure, we focus on crumpled structures where the interplay between point localizations and sharp folds is known to dominate the large scale mechanical behaviour.

Active twisting for adaptive droplet collection

Yang Yifan (1), Dai Zhijun (1), Chen Yuzhen (1), Xu Fan (1)

1 - Fudan university (China)

Speaker: Xu Fan. **Wednesday**. Start time: **16:45**. Room: Amphi lumière LVL-1. Link to abstract.

Many xeric plant leaves exhibit bending and twisting morphology, which may contribute to their important biological and physical functions adapted to drought and desert conditions. Revealing the relationships between various morphologies and functionalities can inspire device designs for meeting increasingly stringent environmental requirements. Here, demonstrated on the biomimetic bilayer ribbons made of liquid crystal elastomers (LCE), we reveal that the stimuli-induced morphological evolution of bending, spiraling, twisting as well as various coupling states among them can be selectively achieved and precisely tuned by designing the orientations of director in LCE bilayers. The mathematical models and analytical solutions are developed to quantify the morphology selection and phase transition of these liquid crystal elastomer ribbons for material design, as confirmed by experiments. Moreover, we show that under activation and control of external stimuli, twisting configuration can be harnessed to effectively collect and guide transportation of droplets, and enhance structural stiffness for resisting wind blow and rain falling to realize optimal configuration for water collection. Our results uncover the interesting functions correlated with bending, spiralling and twisting morphologies widely existed in natural world, with providing fundamental insights into their shape transformation and controlling factors, and also demonstrate potential application with integrating morphogenesis - environment interactions into devices or equipments.

Soft textured sheets mimic the hummingbird's tongue for efficient fluid capture

Siéfert Emmanuel (1), Cappello Jean Scheid Benoit Brau Fabian

1 - LIPhy, CNRS , Université Grenoble Alpes (France)

Speaker: Siéfert Emmanuel. **Wednesday**. Start time: **17:00**. Room: Amphi lumière LVL-1. Link to abstract.

Passive and effective fluid capture and transport at small scale is crucial for industrial and medical applications, but also for the feeding of small nectarivores. Among them, hummingbirds have developed a highly specialised tongue made of two soft open grooves that efficiently trap nectar by elastocapillary effects. Inspired by this observation, we design a fast and efficient fluid capture device at the capillary scale. The device consisting in soft grooves stacked together on a flat sheet exhibits a sequential capillary rise when dipped in a liquid bath. Combining elasticity, capillarity and viscous flow, we rationalize the speed of the liquid fronts as well as the deformation of the structure. This device captures more liquid that its rigid flat counterpart and captures a given amount of liquid much faster than its rigid closed counterpart. Such structures may open the way for the design of optimal devices for fluid capture, aliquoting and transport in microfluidics.

Periodic bulging in the elastic Rayleigh-Plateau instability

Magni Francesco (1), Riccobelli Davide (2)

1 - Scuola Internazionale Superiore di Studi Avanzati / International School for Advanced Studies (Italy), 2 - MOX - Dipartimento di Matematica, Politecnico di Milano (Italy)

Speaker: Magni Francesco. **Wednesday**. Start time: **17:15**. Room: Amphi lumière LVL-1. Link to abstract.

Experiments reveal that surface tension can destabilize soft elastic cylinders, resulting in a periodic series of bulges along their length. This instability represents the elastic analog of the Rayleigh-Plateau instability in fluids. Traditional elastocapillary models typically assume a constant surface tension, predicting a single isolated bulge. However, this prediction contrasts with experimental observations, which show multiple periodic bulging. An important distinction in elastic materials is that surface tension is strain-dependent, a phenomenon known as the Shuttleworth effect. In this talk, we demonstrate that the use of a strain-dependent surface tension accurately predicts a buckled morphology with a finite critical wavelength. Our approach models surface tension as the behavior of a pre-stretched elastic surface, following the framework proposed by Gurtin and Murdoch. When linearized for small strains, this model reduces to Shuttleworth's equation. We complement our theoretical analysis with numerical simulations, which provide insight into how mechanical properties and an applied axial stretch influence the wavelength and shape of the resulting periodic structure.

Coalescence of slender structures removed from a liquid bath

Bense Hadrien (1), Siéfert Emmanuel (2), Hua Hoa-ai Béatrice (3), Brau Fabian (3)

1 - Le Mans Université (France), 2 - Université Grenoble Alpes (France), 3 - Université libre de Bruxelles (Belgium)

Speaker: Brau Fabian. **Wednesday**. Start time: **17:30**. Room: Amphi lumière LVL-1. Link to abstract.

We study the coalescence between two slender structures withdrawn quasi-statically or at finite velocity from a liquid bath. When partially immersed, the structures interact with each other through the capillary force induced by their menisci whose shape changes with the retraction speed. As the structures are removed from the bath, their dry length increases, and they become easier to bend until the capillary force is strong enough to trigger contact. Surprisingly, the structures snap to contact from a finite distance at a critical dry length. The transition to coalescence is thus subcritical and exhibits a large hysteresis loop between two stable states.
An analytical coalescence criterion is derived when the structures are withdrawn quasi-statically from the bath with a good agreement with experimental data for rods and lamellae (1).

In the case of two rods removed at finite velocity, the size of the menisci around them grows with the retraction speed and the capillary interaction increases. The rods coalesce then at a shorter dry length. We characterize the menisci growth as a function of the capillary number and show that the interaction between the structures is given by the static interaction with an effective surface tension increasing with the capillary number (2).

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Optimum control strategies for maximum thrust production in underwater undulatory swimming

Fu Li (1), Israilov Sardor (2) (3), Sánchez-rodríguez Jesús Brouzet Christophe Allibert Guillaume (4), Raufaste Christophe (5) (6), Argentina Médéric (5)

1 - Laboratoire de Tribologie et Dynamique des Systèmes (France), 2 - Institut de Physique de Nice (France), 3 - Signal, Images et Systèmes (France), 4 - I3S (France), 5 - Université Côte d'Azur, CNRS, Institut de Physique de Nice (France), 6 - Institut universitaire de France (France)

Speaker: Fu Li. **Wednesday**. Start time: **17:45**. Room: Amphi lumière LVL-1. Link to abstract.

Fishes, cetaceans, and many other aquatic vertebrates undulate their bodies to propel themselves through water. Swimming requires an intricate interplay between sensing the environment, making decisions, controlling internal dynamics, and moving the body in interaction with the external medium. Within this sequence of actions initiating locomotion, biological and physical laws manifest complex and nonlinear effects, which does not prevent natural swimmers to demonstrate efficient movement. This raises two complementary questions: how to model this intricacy and how to abstract it for practical swimming. In the context of robotics, the second question is of paramount importance to build efficient artificial swimmers driven by digital signals and mechanics. In this study, we tackle these two questions by leveraging a biomimetic robotic swimmer as a platform for investigating optimal control strategies for thrust generation.

Our primary objective was to determine the actuation that yields the highest thrust, and thus the highest swimming speed, for underwater swimmers. Considering the complex fluid-structure interaction at relatively high Reynolds numbers, we employed various approaches and methods to shed light on this topic. Notably, reinforcement learning techniques played a crucial role in revealing that the most effective method to achieve high thrust in experiments involves employing a bang-bang controller. This type of actuation oscillates abruptly and periodically between the two extreme command values. To rationalize and validate these experimental results, we studied a simple model using reinforcement learning. The results from this model closely aligned with those obtained through the experimental approach, further reinforcing the effectiveness of the bang-bang controller. Additionally, full 2D numerical simulations of autonomous swimmers confirmed the validity of our findings.

We have successfully illuminated the strategy to attain the highest thrust for underwater swimmers, comprising three key messages. Firstly, the command should resemble a periodic square function, exploiting the natural oscillation of the tail-fin system. Secondly, the frequency of actuation needs to be close to that which maximizes tail speed. If damping vanishes, this frequency will approach the body's natural undulation frequency. Lastly, an efficient approach to selecting a nearly optimal swimming gait is to switch the actuation sign as the fin speed becomes too small.

Optimal brush for fluid capture

Radisson Basile (1), Bense Hadrien Siéfert Emmanuel Domino Lucie (2), Hua Hoa-ai Béatrice Brau Fabian

1 - D'alembert (France), 2 - Institut universitaire des systèmes thermiques industriels (France)

Speaker: Radisson Basile. **Wednesday**. Start time: **18:00**. Room: Amphi lumière LVL-1. Link to abstract.

Parallel assemblies of slender structures forming brushes are common in our daily life from sweepers to pastry brushes and paintbrushes. These porous objects can easily trap liquid between their filaments when removed from a liquid bath. This property is exploited to transport liquids in many applications ranging from painting, dip-coating, brush-coating to the capture of nectar by bees, bats and honeyeaters. Rationalizing the viscous entrainment flow beyond simple scaling laws is complex due to its multiscale structure and the multidirectional flow. Here, we provide an analytical model, together with precision experiments with ideal rigid brushes, to fully characterize the flow through this anisotropic porous medium as it is withdrawn from a liquid bath. We show that the amount of liquid entrained by a brush varies non-monotonically during the withdrawal at low speed, is highly sensitive to the different parameters at play and is very well described by the model without any fitting parameter. Finally, an optimal brush geometry maximizing the amount of liquid captured at a given retraction speed is derived from the model and experimentally validated. These optimal designs open routes towards efficient liquid manipulating devices

Snap-induced flow in a closed channel

Oshri Oz (1), Goncharuk Kirill (1), Feldman Yuri (1)

1 - Ben-Gurion University of the Negev (Israel)

Speaker: Oshri Oz. **Wednesday**. Start time: **18:15**. Room: Amphi lumière LVL-1. Link to abstract.

Snap-through is a buckling instability that allows slender objects, including those in plants and biological systems, to generate rapid motion that would be impossible if they were to use their internal forces exclusively. In microfluidic devices, such as micro-mechanical switches and pumps, this phenomenon has practical applications for manipulating fluids at small scales. The onset of this elastic instability often drives the surrounding fluid into motion – a process known as snap-induced flow. To analyze the complex dynamics resulting from the interaction between the sheet and the fluid, we develop a prototypical model of a thin sheet that is compressed between the two sides of a closed channel filled with an inviscid fluid. At first, the sheet bends towards the upstream direction and the system is at rest. However, once the pressure difference in the channel exceeds a critical value, the sheet snaps to the opposite side and drives the fluid dynamics. We formulate an analytical model that combines the elasticity of thin sheets with the hydrodynamics of inviscid fluids to explore how external pressure differences, material properties, and geometric factors influence the system's behavior. To analyze the early stages of the evolution, we perform a linear stability analysis and obtain the growth rate and the critical pressure difference for the onset of the instability. A weakly nonlinear analysis suggests that the system can exhibit a pressure spike in the vicinity of the inverted configuration.

Bioinspired shape shifting of liquid-infused ribbed sheets

Cappello Jean (1), Scheid Benoit (1), Brau Fabian (2), Siéfert Emmanuel (3)

1 - Transfers, Interfaces and Processes (TIPs), Université libre de Bruxelles, 1050 Brussels, Belgium (Belgium), 2 - Université libre de Bruxelles (Belgium), 3 - Laboratoire Interdisciplinaire de Physique (France)

Speaker: Cappello Jean. **Wednesday**. Start time: **18:30**. Room: Amphi lumière LVL-1. Link to abstract.

At small scales, capillary forces can deform flexible structures. A common everyday example of this phenomenon is the aggregation of wet hair into bundles. With the miniaturization of technologies, these capillary forces have become at the core of numerous strategy owning to avoid them as they can lead to the catastrophic collapse of slender structures obtained by lithography. But, changing of perspective, it can also appear as an ingenious self-assembly solution to achieve targeted shapes or movements at scales where conventional techniques fail.
Until now, studies have mainly focused on elastocapillary deformation of either thin free membranes in contact with a drop (capillary origami, Py *et al*, PRL 2007) or networks of slender structures fixed on a rigid substrate (Pokroy *et al.* Science 2009). Here, taking inspiration from the fern sporangium that uses the capillary pressure at the scale of the cells to unbend its whole structure and release spores as it dries (see Fig.1(a)), we focus on the case of initially liquid imbibed flexible textured sheets, consisting in an array of grooves and ribs attached to a thin membrane that deforms as the structure dries (see Fig.1(b)).

Combining an analytical model together with precision experiments, we find the combination of physical parameters – geometry and elasticity of the sheet, surface tension of the liquid – for which the whole structure deforms. In this regime, the sheet curls until neighbouringribs enter in contact. The final curvature of the curled structure may thus be accurately predicted as a function of the local geometry of the ribs. Harnessing this simple geometric control over the final curvature, we then derive an inverse design model to accurately program complex self-shaping structures by spatially varying the geometry (see Fig.1(c)) and orientation of the ribs.
This novel approach opens a new avenue within the field of elastocapillary self-assembly: as opposed to the self-assembly of textures on rigid substrates, here, the capillary forces lead to a global shape transformation (from 2D to 3D) and in contrast to capillary origami, the deformation process takes place locally, at the scale of the textures, allowing for a fine control over the local deformation. Moreover, using a photosensitive solution as the evaporating liquid, we show that the obtained 3D structures can be additionally cured and "frozen" into their deformed shape. The physics underlying this phenomenon is mostly independent of the liquid and the material properties and this strategy is particularly adapted to down-scaling. We thus expect our findings to have a strong application potential in the micro- and nano-fabrication of detailed 3D structures.

Soda forming: sequential ring buckling of uniaxially compressed beverage cans

Jain Shresht (1), Pihler-puzovic Draga (1), Box Finn (1), Johnson Chris (1)

1 - University of Manchester (United Kingdom)

Speaker: Jain Shresht. **Thursday**. Start time: **10:00**. Room: Amphi lumière LVL-1. Link to abstract.

When uniaxially compressed empty cylinders buckle, they typically form periodic structures that break both axial and radial symmetry. By contrast, thin membranes develop undulations that break the symmetry along the axis of compression. We make a surprising observation that when a beverage can, mostly filled with a liquid, is compressed under uniaxial loading, the system buckles axisymmetrically. The resulting ring buckles are localised and appear sequentially, eventually filling the entire can surface. The final periodic pattern has a predictable wavelength that scales with the shell thickness and radius. We characterise the material properties of the cans experimentally in order to model their post-buckling behaviour. The results of our model, which is similar to the 1-D nonlinear Swift-Hohenberg equation, suggest that the sequential appearance of ring buckles occurs via homoclinic snaking. Our system provides a novel experimental demonstration of this mechanism, thereby linking nonlinear dynamics of localised patterns and mechanics of shell buckling

Simple stimuli drive complex responses in non-Euclidean active shells

Marchello Roberto (1), Santucci Pietro Maria (1), Noselli Giovanni (1)

1 - Scuola Internazionale Superiore di Studi Avanzati / International School for Advanced Studies (Italy)

Speaker: Marchello Roberto. **Thursday**. Start time: **10:15**. Room: Amphi lumière LVL-1. Link to abstract.

Active materials have recently drawn the attention of the mechanical community since their response to external stimuli can be harnessed to reproduce natural phenomena. In this regard, active slender structures may display complex behaviors through mechanical instabilities. As an example, recent works have shown that polyelectrolyte hydrogel filaments actuated by a constant and uniform electric field exhibit nonreciprocal self-sustained oscillations as a consequence of flutter instability, generating a net thrust in the surrounding viscous fluid (1, 2, 3). We explore whether such nontrivial responses to simple stimuli can be achieved also in non-Euclidean active shells, i.e. shells that lack a stress-free rest state due to a geometric incompatibility caused by internal activity (4, 5). Compared to rod-like structures, active shells are found to exhibit a richer behavior at large deformations ensuing from the competition between stretching and bending energies. To capture this complexity, we adapt a nonlinear shell model of Koiter type in the context of morphoelasticity, encoding the activity by a time-evolving spontaneous spherical curvature. The mathematical model is specialized to morphoelastic elliptic plates and cylindrical shells free to move in a viscous environment, taking into account the fluid-structure interaction. We demonstrate the emergence of flutter through a linear stability analysis and predict its dependence upon the model parameters.Our analysis is confirmed by numerical simulations of the nonlinear model and by physical experiments on polyelectrolyte hydrogel shells under the action of a constant and uniform electric field. Both simulations and experiments agree in showing the achievement of oscillatory nonreciprocal motions of large amplitude. Our findings may be exploited in soft-robotics and micro-fluidics. The results we have found at the level of a single structural element open new perspectives on the possible applications of complex structures based on active materials.

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Nontrivial and Nonlinear Behavior of Negative Gauss Curvature Shells

Ubamanyu Uba K. (1), Reis Pedro M. (1)

1 - Flexible Structures Laboratory, École Polytechnique Fédérale de Lausanne (Switzerland)

Speaker: Ubamanyu Uba K.. **Thursday**. Start time: **10:30**. Room: Amphi lumière LVL-1. Link to abstract.

Thin elastic shells, defined by their inherent curvature, are commonly found in nature and engineering due to their remarkable structural efficiency. While the mechanics of shells with zero (e.g., cylindrical and conical) and positive (e.g., spherical and ellipsoidal) Gaussian curvature has been widely studied (1), the nonlinear response of shells with negative Gaussian curvature has been far less explored. Among these thin elastic shells, the positively curved shells, such as pressurized spheres and ellipsoids, are particularly known for their "geometry-induced rigidity," where local curvature significantly enhances resistance to deformation (2). In contrast, negatively curved shells, including saddle-shaped surfaces, are expected to display markedly different nonlinear responses.
In this talk, we will report results from a combined experimental and numerical investigation of shell structures constructed from triply periodic minimal surfaces (TPMS), such as the Gyroid discovered by Alan Schoen in 1968 (3). These surfaces, characterized by zero mean curvature and non-positive Gaussian curvature, can serve as models for more complex, interconnected geometries found in natural and engineered systems, from cellular structures to metamaterials (4). We will present experimental results from mechanical tests of representative examples of these negative curvature shell structures. We seek to characterize and rationalize the nonlinear mechanical response of TPMS and other intricate shell-like geometries. Experimentally, we employ rapid prototyping techniques, focusing on 3D printing, to fabricate thin elastic shells with controlled geometric and material properties. We then perform mechanical tests on these samples, subject to various loading conditions, including indentation and pressurization, to assess their stiffness, buckling thresholds, and post-buckling behavior. Moreover, the sensitivity of negatively curved shells to imperfections is explored systematically by numerical simulations using the finite element method.

The findings of this research yield fundamental insight into the underlying deformation mechanisms and the role of geometric nonlinearities in the mechanical properties of TPMS and other complex geometries. Our work on the mechanics of negatively curved shells provides a predictive understanding of the rational design of lightweight, shape-morphing, and energy-absorbent structures and metamaterials.

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Modelling a feather as a strongly anisotropic elastic shell

Romero Victor (1), Jouve Jean Bertails-descoubes Florence (2), Narain Rahul (3), Kim Theodore (4), Boissieux Laurence (5)

1 - Inria Grenoble - Rhône-Alpes (France), 2 - Laboratoire Jean Kuntzmann (Centre INRIA, Inovallée F-38334 Montbonnot France), 3 - Indian Institute of Technology Delhi (Hauz Khas, New Delhi - 110 016. India India), 4 - Yale University [New Haven] (157 Church Street, New Haven, CT 06510-2100 United States), 5 - INRIA Grenoble Rhône-Alpes (France)

Speaker: Romero Victor. **Thursday**. Start time: **10:45**. Room: Amphi lumière LVL-1. Link to abstract.

Feathers exhibit a highly anisotropic behaviour, governed by their complex hierarchical microstructure composed of individual hairs (barbs) clamped onto a spine (rachis) and attached to each other through tiny hooks (barbules). To investigate the anisotropic properties of a feather vane, we design precise measurement protocols on real feather samples. Our experimental results suggest a linear strain-stress relationship of the feather membrane with orientation-dependent coefficients, as well as an extreme ratio of stiffnesses in the barb and barbule direction, of the order of 10000. From these findings we build a simple continuum model for the feather vane, where the vane is represented as a three-parameter anisotropic elastic shell. However, implementing the model numerically reveals severe locking and ill-conditioning issues, due to the extreme stiffness ratio between the barb and the barbule directions. To resolve these issues, we align the mesh along the barb directions. We extensively validate our membrane model against real-world laboratory measurements, by using an intermediary microscale model that allows us to limit the number of required lab experiments. Finally, we enrich our membrane model with anisotropic bending.

Geometrically Frustrated Rose Petals

Zhang Yafei (1), Sharon Eran (1), Moshe Michael (1), Cohen Omri (1)

1 - Hebrew University (Israel)

Speaker: Zhang Yafei. **Thursday**. Start time: **11:00**. Room: Amphi lumière LVL-1. Link to abstract.

Roses, known worldwide for their beauty and symbolic significance, have long captivated artists and poets alike. Yet, the underlying mechanism shaping the distinctive form of rose petals and its implications for petal development remain elusive. Here, we unveil the mechanical instability that governs the unique evolution of rose petals geometry. We show that it emerges from simple growth that induces uniaxial reference curvature perpendicularly to the petal's edge. Though simple and highly symmetric, this curvature field violates the Mainardi-Codazzi-Peterson (MCP) compatibility equations. As a result, a sequence of cusps gradually appears along the growing petal's edge. Using analytical, numerical and experimental work, we study the problem of a circular disc with radial reference curvature and determine the phase space of the problem, including the formation of the first, as well as subsequent cusps along the initially axisymmetric edge. We go further and study the characteristic shape of a cusp, which partially regularizes the curvature singularity of an idealized cusp. Finally, we find evidences for the effect of the stress focusing generated by the cusps, on the local petal tissue morphology and its further growth. To our best knowledge, this is the first report on MCP geometric frustration, the following stress-focusing and its effect on growth in natural systems. This study not only advances our understanding of fundamental principles governing shape formation and growth regulation in nature, but also opens avenues for developing innovative functionalities in engineered materials and structures.

The many shapes of a knitted fabric at rest

Poincloux Samuel (1), Crassous Jérôme Steinberger Audrey

1 - Department of Physical Sciences, Aoyama Gakuin University (Japan)

Speaker: Poincloux Samuel. **Thursday**. Start time: **11:15**. Room: Amphi lumière LVL-1. Link to abstract.

Textiles consist not only of our daily clothes, but also act as reinforcement for composite materials, or soil consolidators, and found a renewed interest in emerging fields such as soft robotics. For all these applications, their mechanical properties are crucial aspects, but predictive models of textiles remain incredibly challenging to construct owing to their complex intertwined thread structures.
Knitted fabrics are textiles composed of a periodic array of looped and intertwined threads. A knit can then be viewed as a structure made of multiple slender elements interacting via frictional contacts. For such structures, even basic mechanical properties such as the rest state of the object, or its natural shape without external forces, are not obvious nor unique.

We used a combination of experiments, numerical simulation, and analytical calculations to predict and understand the natural shapes of knitted fabrics from three basic ingredients: yarn elasticity, loop geometry, and frictional contacts between the yarns. From laboratory experiments and numerical simulations, we determined that the possible natural shapes of a model Jersey knit span a continuous set of possible aspect ratios bounded by a maximum height. From a theoretical description inspired by knot mechanics, we find that geometrical constraints and yarn elasticity control the set of accessible aspect ratios, while inter-yarn friction sets the maximum height.

Reference:
Crassous, J., Poincloux, S., & Steinberger, A. (2024). Metastability of a periodic network of threads: what are the shapes of a knitted fabric?. *arXiv preprint arXiv:2404.07811*. Accepted in *Physical Review Letters*.

Laddering in a knitted fabric

Steinberger Audrey (1), Crassous Jérôme (2)

1 - Laboratoire de Physique (France), 2 - Institut de Physique de Rennes (France)

Speaker: Steinberger Audrey. **Thursday**. Start time: **11:30**. Room: Amphi lumière LVL-1. Link to abstract.

A knitted fabric is a meta-material composed of a series of loops, called stitches, which are intertwined from a single thread. This network of loops is stabilized by its topology. Knits are all at once highly flexible, stretchable, lightweight, and strong. These remarkable mechanical properties emerge from their architecture, controlled by the deformation of the loops on one hand and solid friction at the thread crossings on the other.
Following a localized break in the thread that makes up the fabric, the network of loops develops a topological defect that can propagate along the column of stitches where the break occurs, a process known as "laddering". This is the primary cause of failure in stockings and tights. In practice, however, some ladder defects propagate through the entire length of the knit, others stop after a finite distance, and some do not propagate at all. Why does this happen? What governs the propagation speed of these defects? We have conducted experiments and numerical simulations to address these questions.
In this talk, after shedding light on this damage phenomenon, I will present our research and the key results we have obtained, offering insights into the mechanisms behind ladder propagation in knitted fabrics.

Vibration Analysis of Curved Lattice Metamaterial Structures by Using Higher-Order Shear Deformation and Modified Strain Gradient Theories

Soleimani Javid Zeinab (1), Niiranen Jarkko (2), Arshid Ehsan

1 - Zeinab Soleimani Javid (Finland), 2 - Department of Civil Engineering, Aalto University (Finland)

Speaker: Soleimani Javid Zeinab. **Thursday**. Start time: **11:45**. Room: Amphi lumière LVL-1. Link to abstract.

This study investigates vibrational behavior of curved structures based on triangular lattice metamaterials. Curved beam and shell structures couple the bending and extension states, making their behavior more complex compared to straight structures and requiring more advanced modeling theories. To address this, higher-order theory is utilized, along with modified strain gradient theory, to account for size effects in lattice structures. Strain gradient theory enables modeling structures as equivalent homogenized models with effective material properties. Governing motion equations for are formulated using Hamilton's principle, and numerical solution is implemented via the differential quadrature method (DQM) under clamped boundary conditions. Numerical experiments for lattice metamaterial structures conducted with elements of commercial finite element software Abaqus demonstrate a good agreement with effective beam and shell models and detailed finite element modeling, validating the reliability of the results. This paper examines the effects of various parameters, such as the central opening angle of shells and beams, thickness of structure and lattice cells, strain gradient length-scale parameters on the natural frequencies. The findings highlight the significant influence of length-scale parameters on structural behavior. The strain gradient model shows excellent agreement with numerical simulations, particularly for thin structures. In other words, the inclusion of strain gradient effects plays a crucial role in enhancing the accuracy of analytical models. One key result reveals that, for a constant thickness, by reducing lattice cells' scale and increasing the number of cells, the structure's stiffness decreases. These results provide valuable insights for structural engineering applications, for the development of efficient, lightweight, and high-performance lattice-based curved beam and shell structure.

Computational Homogenization for Inverse Design of Surface-based Inflatables

Ren Yingying (1)

1 - ISTA (Austria)

Speaker: Ren Yingying. **Thursday**. Start time: **14:15**. Room: Amphi lumière LVL-1. Link to abstract.

We present a computational design framework for surface-based inflatables, which are composed of two thin sheets joined along a sparse set of fusing curves. During inflation, the unfused areas separate to maximize enclosed volume, while the fusing curves control both out-of-plane expansion and in-plane contraction. By spatially varying the fusing pattern, we can create structures with incompatible contraction ratios, resulting in metric frustrations and buckling into doubly-curved equilibrium states that balance the inflation pressure forces and elastic forces stored in the sheets. To design these structures, we develop a numerical homogenization method with a novel deformation parametrization, enabling efficient evaluation of bending and stretching stiffness for inflated unit cells with arbitrary fusing patterns. By applying the homogenization algorithm, we create a database of fusing patterns with a wide range of material properties. Finally, we incorporate this database into an inverse design optimization framework to create lightweight yet structurally sound inflatable structures that closely approximate freeform target shapes.

Shape and mechanics of asymmetric inflatables

Vani Nathan (1), Ibarra Alejandro (1) (2), Reyssat Etienne (1), Bico Jose (1), Roman Benoît (1)

1 - Laboratoire PMMH (France), 2 - Faculty of Science, Technology and Medicine, Université du Luxembourg (Luxembourg)

Speaker: Reyssat Etienne. **Thursday**. Start time: **14:30**. Room: Amphi lumière LVL-1. Link to abstract.

Inflatables are particularly popular shape-morphing materials. Their simple, purely mechanical actuation allows for fast deployment and reusability. Moreover, just as the overall shape and stiffness of a party balloon are directly linked to its internal pressure, inflatable objects offer an elegant example of the coupling of elasticity and geometry.
We study networks of parallel inflatable tubes obtained by welding two elastic sheets. Composite tubes presenting two sides of distinct stiffness are made by using two sheets of different thicknesses. Upon inflation of such tubes, the torque balance at the junction of two asymmetric sheets results in the rotation of the seam line connecting two neighbor tubes. This local misalignment allows for enormous displacements when integrated across large networks. We present experimental results on the mechanics of inflation of one or several connected tubes.

The shape of one tube throughout inflation is determined using a minimal Kirchhoff beam model, for which analytical solutions are given in the asymptotic limits of low and high pressures. In the latter case, a boundary layer at the edge of the seam line fully determines the rotation between two connected tubes. We highlight as well how contact between neighboring tubes limits in practice the overall curvature of our inflatables.
We then formulate and solve an inverse problem to design a wide variety of objects that can be described as a two-dimensional curve normal to the direction of the tubes. The stiffness of such structures is discussed as well. We finally present several applications of asymmetric tubular inflatables to more complex geometries: axisymmetric surfaces, *kirigami*, and curved folding.

Creating patterned microchannels by swelling

Pihler-puzovic Draga (1), Retallick Aidan (1), Li Haolin (2), Heil Matthias (1), Juel Anne (1)

1 - University of Manchester (United Kingdom), 2 - Nanyang Technological University (Singapore)

Speaker: Pihler-Puzovic Draga. **Thursday**. Start time: **14:45**. Room: Amphi lumière LVL-1. Link to abstract.

We study the effect of inflation on the swelling-induced wrinkling of thin elastic membranes in a set-up that is commonly used to create microchannels in lab-on-chip applications. Using a combination of experiments, mathematical analysis and associated numerical simulations, we demonstrate that the out-of-plane deformation of the inflated membrane and the resulting anisotropic stress lead to two distinct instabilities as the swelling progresses.
The membrane first develops small-amplitude wrinkles that retain the cross-channel symmetry. Their wavelength depends on the pressure and is set in a process similar to the axisymmetric buckling of pressurised, uni-axially compressed cylindrical shells. As swelling increases, the membrane undergoes a secondary instability during which the wrinkles coarsen into large-amplitude folds whose morphology can be controlled by the degree of pre-inflation.
At modest levels of inflation, a secondary (symmetry-breaking, wavelength-doubling) bifurcation results in the formation of worm-like patterns, reminiscent of those occurring in blister delamination processes. At even greater levels of inflation, the symmetric initial wrinkling pattern undergoes a different secondary bifurcation that no longer breaks the cross-channel symmetry but leads to the formation of symmetric large-amplitude folds that are separated by random (but integer) multiples of the initial wrinkling wavelength. We elucidate the fundamental mechanisms responsible for this behaviour to explain how inflation can be used as a control mechanism in the manufacture of microchannels.

D-cone : influence of gravity and dynamics

Nouvel Berenice (1), Boedec Gwenn (1), Deschamps Julien (1)

1 - Institut de Recherche sur les Phénomènes Hors Equilibre (France)

Speaker: Boedec Gwenn or Deschamps Julien. **Thursday**. Start time: **15:00**. Room: Amphi lumière LVL-1. Link to abstract.

When a thin elastic disk is pushed into a hollow cylinder by an indenter, the so-called d-cone (1) is observed. It has been shown that close to threshold, the d-cone solution coexist with regular buckling of the disk (2). Using a similar experimental set-up, we extend this static study to take into account the influence of gravity on the state diagram of the system, and show that new branches of solution appears. We also look at the dynamics of (dis)appearance of the d-cone from the buckling branch.

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Evaluating the efficacy of using drop-film interaction to estimate the film's tension and surface energy.

Nair Vineet (1), Sharma Ishan (2)

1 - Mechanics and Computing Group, Amrita School of Artificial Intelligence, Amrita Vishwa Vidyapeetham, Bengaluru 560035, India (India), 2 - Mechanics and Applied Mathematics Group, Department of Mechanical Engineering, Department of Space, Planetary and Astronomical Sciences and Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India (India)

Speaker: Nair Vineet. **Thursday**. Start time: **15:15**. Room: Amphi lumière LVL-1. Link to abstract.

We investigate the equilibrium solutions of axisymmetric systems consisting of sessile drops on free-standing, pre-stretched, elastic membranes. The capillary forces acting on the membrane deform it appreciably, and so we incorporate both geometric and material nonlinearities in the model. The surface energies at the membrane-liquid and membrane-air interfaces are not assumed to be constants, and they vary with stretches within the membrane. We minimize the free energy of the system to obtain the governing equations. Assuming that the surface energies are strain-independent, we solve these coupled nonlinear equations and obtain the global equilibria of the drop–membrane system. We then study the effects of drop's volume and membrane's pre-tension on the system's geometry and tension/stretch distribution in the membrane, thereby providing an insight into the role of geometric and material nonlinearities of the membrane. For a given liquid drop, its volume, and membrane's solid material, we calculate the pre-tension and surface energies of the membrane and compare our results with experiments. This allows us to compare and contrast our more exact model with that of Davidovitch and Vella (1). They found that the drop considerably alters the stress state within the sheet, and thus, the current state of stress cannot be employed to measure the pre-tension within the sheet prior to wetting, disputing the understanding obtained from previous experiments (2,3). However, the analysis of (1) made several approximations, and we revisit this issue utilising our more exact description.

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(3) Schulman, R. D., & Dalnoki-Veress, K. (2015). Liquid droplets on a highly deformable membrane. *Physical Review Letters, 115*(20), 206101.

Wrinkling of thin sheets on a rotating cylinder

Ebine Yuna (1), Sano Tomohiko (1), Dal Corso Francesco (2)

1 - Department of Mechanical Engineering, Keio University (Japan), 2 - Department of Solid and Structural Mechanics, University of Trento (Italy)

Speaker: Ebine Yuna. **Thursday**. Start time: **15:30**. Room: Amphi lumière LVL-1. Link to abstract.

Wrinkles are around us, not only on the skin of humans and animals but also in industrial applications, such as wearable devices and stretchable electronics. The mechanism of wrinkling instability has been extensively studied in several boundary conditions: swelling, elastic foundations, or curved substrate. Still, the wrinkling of stretched sheets on a rigid cylinder has not been less investigated so far. We perform systematic experiments for the stretched sheet on a rotating cylinder. The elastomeric sheet suspended and stretched by weight is attached to the cylinder which rotates at a constant speed. We find that the wrinkles appear and propagate along the cylinder, depending on the sheet aspect ratio and loading conditions. In parallel with the rotating experiments, we consider the shape of the suspended sheet under the same loading condition, combining experiments and finite element simulations, which will help the understanding the wrinkling on the rotating cylinder. Our findings will be applied to predict and control wrinkling, which appears as an obstacle in wearable devices.

Tension-induced giant actuation in unstructured elastic sheets

Suñé Marc (1), Guo Kexin (2), Liu Mingchao (2) (3), Hsia K Jimmy (2), Vella Dominic (4)

1 - Mathematical Institute, University of Oxford (United Kingdom), 2 - Nanyang Technological University [Singapour] (Singapore), 3 - University of Birmingham [Birmingham] (United Kingdom), 4 - Mathematical Institute [Oxford] (Mathematical Institute University of Oxford 24-29 St Giles' Oxford, OX1 3LB UK United Kingdom)

Speaker: Suñé Marc. **Thursday**. Start time: **15:45**. Room: Amphi lumière LVL-1. Link to abstract.

Buckling in compression is the archetype of elastic instability: when compressed along its longest dimension, a thin structure such as a playing card will buckle out-of-plane accommodating the imposed compression without a significant change of length. However, recent studies have demonstrated that tension applied to sheets with microscopic structure leads to out-of-plane deformation in applications from 'groovy metasheets' for multi-stable morphing to kirigami grippers and edge-clamped graphene sheets. In this talk, I will explain how this counter-intuitive behaviour - a large transverse motion actuated by a relatively small imposed longitudinal tension - occurs also in unstructured sheets of isotropic material. Reflecting both the mode of actuation and its surprising effectiveness, we refer to this as 'Tension indUced Giant' (TUG) actuation. Our work shows that TUG actuation occurs because of an efficient transfer of applied tensile load into compression - a geometric consequence of a localized applied tension. We determine scaling results for the actuation angle as a function of applied strain in agreement with both experiments and simulations. The generic nature of TUG actuation suggests that it might be utilized in a broader range of materials and structure than previously realized.

Buckling of a hanging elastic sheet

Borum Andy (1), Ma Leixin (2), Mukkamala Sruthi (3), Jawed M. Khalid (4)

1 - Mathematics and Statistics Dept., Vassar College, NY, USA (United States), 2 - School for Engineering of Matter, Transport & Energy, Arizona State University, AZ, USA (United States), 3 - Robotics Institute, Carnegie Mellon University, PA, USA (United States), 4 - Dept. of Mechanical and Aerospace Engineering, University of California, Los Angeles, CA, USA (United States)

Speaker: Borum Andy. **Thursday**. Start time: **16:00**. Room: Amphi lumière LVL-1. Link to abstract.

This talk will explore the buckling behavior of a square, intrinsically flat sheet suspended from one of its corners. If the sheet is sufficiently stiff, it will resist deformation due to gravity and remain flat. On the other hand, if the sheet is sufficiently compliant, it will buckle under its own weight into a wrinkled configuration, with each successive buckling mode introducing an additional wrinkle-similar to the buckling modes of an elastic column. However, unlike a column, we show that higher-order buckling modes can become stable for sheets that are sufficiently large, heavy, or compliant. We approximate the sheet's deformation by first assuming that the sheet is developable and then that every generator spanning the developable surface intersects the corner from which the sheet is suspended. Under these assumptions, the problem of finding stable equilibrium configurations of the two-dimensional sheet can be reduced to a one-dimensional calculus of variations problem. We then show via an application of Noether's theorem that the Euler-Lagrange equations for this problem can be integrated to find a closed-form expression for the sheet's curvature. These results are used to compute the critical combinations of geometry, weight, and stiffness at which the flat sheet buckles into a wrinkled configuration. Finally, we apply numerical continuation methods to compute the sheet's post-buckled configurations and determine their stability. We find that some higher-order solution branches undergo pitchfork bifurcations, through which wrinkled configurations become stable.

MS7.6 - Shape and topology optimization

Organisers: Francois Jouve (Université Paris Cité), Alex Ferrer (CIMNE, Spain)

Shape derivative : A mortar formulation

Pantz Olivier (1)

1 - Université Côte d'Azur (France)

Speaker: Pantz Olivier. Invited. **Monday**. Start time: **10:10**. Room: Rhône 5 LVL1. Link to abstract.

In shape optimization, a widely used method pioneered by Hadamard involves applying the classical gradient descent approach to identify a (possibly local) optimum. At each iteration, the shape is updated via a small perturbation of the identity. A key challenge lies in computing the shape gradient, particularly when the cost function depends on the solution of a partial differential equation (PDE). This computation is inherently approximate, with two main approaches: "discretize-then-optimize" and "optimize-then-discretize".
The "discretize-then-optimize" approach applies the gradient method to the discretized cost function but may result in degenerate discretizations, artificially lowering the cost function or producing solutions dependent on the discretization refinement. Conversely, the "optimize-then-discretize" approach discretizes the gradient method itself, but it may lead to non-converging algorithms, particularly if stopping criteria are set too strictly. This talk focuses on the "optimize-then-discretize" framework, with an emphasis on cost functions dependent on solutions to the Laplace equation.

The "optimize-then-discretize" approach is not unique due to multiple equivalent expressions for the continuous shape gradient. According to the Hadamard structure theorem, the shape gradient can be expressed as a boundary integral depending only on the normal velocity of the convection field. This boundary-based expression is commonly used in academia. Alternatively, the distributed shape gradient-highlighted in Hiptmair et al. (2015)-offers improved precision in some cases, albeit at the expense of violating the Hadamard structure theorem, raising challenges such as the choice of convection field extension. Recent work by Gong et al. (2021) demonstrates that boundary-based gradients can achieve similar precision by reconstructing the flux on the boundary.

In this talk, we propose a novel discretized shape gradient formulation based on the mortar method. Like the boundary-based or flux-reconstructed approched, it satisfies the Hadamard structural Theorem. We also compare the precision of the different approach for cost functions potentially depending on the gradient of the primal solution. Several numerical example and optimization problem will be presented.

This work is a collaboration with Timothée Devictor and Marc Josien.

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- Hiptmair, R.; Paganini, A. & Sargheini, S. Comparison of approximate shape gradients BIT Numerical Mathematics, Springer, 2015, 55, 459-485
- Gong, W. & Zhu, S. On discrete shape gradients of boundary type for PDE-constrained shape optimization SIAM Journal on Numerical Analysis, SIAM, 2021, 59, 1510-1541

An incompatibility-based model of small-strain elastoplasticity

Le Thien-nga (1), Amstutz Samuel (2), Van Goethem Nicolas (3)

1 - Laboratoire de Mécanique des Solides (France), 2 - CER Mathématiques (France), 3 - Departamento de Matematica, Universidad de Lisboa (Portugal)

Speaker: Le Thien-Nga or Amstutz Samuel. Invited. **Monday**. Start time: **10:30**. Room: Rhône 5 LVL1. Link to abstract.

In this contribution we present an iterative model of small-strain elastoplasticity. A novel deformation field E is defined, our first kinematic variable, the second kinematic variable being inc E= curl(curltE), which, as we shall prove, is directly related to Kröner's incompatibility η. Our method consists in computing E at each time step by solving the virtual work principle and a flow rule, with two variable tangent effective moduli. The model departs from the traditional small-strain decomposition of the strain field ϵ= ϵe+ ϵp, which raises known intermediate configuration issues.
Despite the eventual macroscopic perspective of the model, we believe it is first illuminating to show the mesoscopic interpretation of the various quantities involved, as they differ from the classical ones. The reworking of the usual quantities is explained in the case of a single crystal containing one single dislocation. The aim is to treat in a mathematically clean manner an elementary dislocation case. The subsequent construction of our new field E will be shown.

Whereas the mesoscopic interpretation enriches it, the model's initial purpose is to deliver macroscopic elastoplasticity results. Through the Clausius Duhem inequality, we define the parameter θ, which will be the sole parameter used to describe the variations of the two tangent moduli. Combining the virtual work principle and a principle of maximal dissipation parametrized by this " incompatibility parameter " θ, we derive a double minimization equation in the variables (E,θ,) which can be solved by alternate minimizations
The model is therefore an iterative one. We validated it on different numerical benchmarks. First, a simple loading-unloading cycle has been performed in the case of perfect plasticity. The theory is appropriate for an incremental setting, so that incremental calculations have also been achieved, by adding hardening in the model.

Optimal perforation of bending-active sheets

Fehér Eszter (1) (2)

1 - Department of Morphology and Geometric Modeling, Budapest University of Technology and Economics (Hungary), 2 - HUN-REN-BME Morphodynamics Research Group (Hungary)

Speaker: Fehér Eszter. **Monday**. Start time: **10:50**. Room: Rhône 5 LVL1. Link to abstract.

Perforated thin sheets morphing into three-dimensional structures are inspired by the kirigami paper technique that allows the placement of cuts and holes on the initially flat surface to create a wide range of possible deformations of the paper. This method has many applications, such as wind-steering devices (1) and space-structures (2). Typically, curved shapes are created by parallel cuts, resulting in strips that move out of the plane by buckling. By determining the location of the cuts and holes using inverse design, it is possible to deform the surface into prescribed shapes (3-4).

Here, we investigate one rectangular, bending-active sheet perforated by rectangular holes as the simplest example of the phenomenon. The sheet is supported at two ends and loaded by the self-weight, and a concentrated vertical force acts in the middle. On the one hand, the perforation weakens the cross-section of the sheet, and it can reduce the rigidity of the structure. On the other hand, higher curvatures can develop at weakened cross-sections, which can result in a structurally preferable overall shape. It was shown that the global porosity, that is proportional to the area of the holes, and the local porosity, describing the distribution of the holes, affect the structural rigidity in the same order of magnitude (5).

It follows from the previous findings that for a given level of global porosity, it is possible to improve the structural rigidity by changing the local porosity. Holes located closer to the center increase both the height and the rigidity of the structure. However, the structures do not allow for an arbitrary weakening of the cross-section without failure. In this work, we seek for the optimal perforation pattern, and for a given level of global porosity, we determine the maximum achievable structural rigidity. The structure is modeled using a nonlinear beam model that we solve using numerical continuation. The results are validated using laser-cut PET sheets with a thickness of 0.5 mm.

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(4) Ye, F., Chang, J., & Fan, Z. (2024). Kirigami-based inverse design for 3D surfaces formed by mechanically guided method. Thin-Walled Structures, 196, 111462.
(5) Fehér, E., Gyetvai, Zs. (2024), Tailoring rigidity of bending-active perforated sheets. In: Proceedings of the IASS 2024 Symposium Redefining the Art of Structural Design. August 26-30, 2024, Zurich, Switzerland Philippe Block, Giulia Boller, Catherine DeWolf, Jacqueline Pauli, Walter Kaufmann (eds.)

Topology Optimization Based on an Approximate Model of a 2D Link Mechanism Derived from Generalized Continuum Mechanics

Sayo Yurika Yamada Takayuki (1)

1 - The University of Tokyo (Japan)

Speaker: Yamada Takayuki. **Monday**. Start time: **11:10**. Room: Rhône 5 LVL1. Link to abstract.

This study presents a topology optimization method for synthesizing multi-input and multi-output link mechanisms. Traditional approaches rely on intuition, limiting complexity. Using micropolar elasticity, which independently defines bending and tensile stiffness, we model links and joints with distinct elastic properties. This allows accurate approximation of link mechanisms within a multi-material topology optimization framework. The optimization minimizes displacement errors and strain energy, ensuring desired motion with appropriate degrees of freedom. Numerical examples demonstrate successful designs of multi-output and multi-input slider-crank mechanisms, showcasing the method's potential for lightweight, robust solutions. This work enables advanced mechanism synthesis and offers avenues for experimental validation.

Design of compliant mechanisms using topology optimization involving design-dependent effects

Shuya Onodera (1), Takayuki Yamada (1)

1 - The University of Tokyo (Japan)

Speaker: Shuya Onodera. **Monday**. Start time: **11:30**. Room: Rhône 5 LVL1. Link to abstract.

This study presents a topology optimization method for compliant mechanisms that accounts for boundary conditions influenced by variables such as thermal convection and pressure load. The objective is to design shapes that balance flexibility and stiffness in environments involving high-temperature fluids. Stress constraints are incorporated to mitigate issues such as stress concentration resulting from excessive flexibility. The method employs a novel approach to setting boundary conditions by integrating fictitious physical problems with level-set functions, allowing for the precise specification of various boundary types across different domains. Initially, a weighted-sum method is used to define the objective function and incorporate key evaluation functions to assess the performance of the thermal actuators. The method is demonstrated through numerical examples that address minimum mean compliance problems under conditions of thermal convection and pressure load, aiming to improve structural deformability while controlling deformation at the target surface plane. The effectiveness of the proposed method is verified through numerical examples under various conditions.

A multimaterial topology optimisation approach to Dirichlet control with piecewise constant functions

Sturm Kevin (1)

1 - TU Wien (Austria)

Speaker: Sturm Kevin. Invited. **Monday**. Start time: **13:40**. Room: Rhône 5 LVL1. Link to abstract.

In this talk we study a Dirichlet control problem for the Poisson equation, where the control is assumed to be piecewise constant function which is allowed to take $M \geq 2$ different values. The space of admissible Dirichlet controls is non-convex and therefore standard derivatives in Banach spaces are not applicable. Furthermore piecewise constant functions do not belong to $H^{1/2}$ standard extension techniques to consider the weak solution of the Dirichlet problem do not apply. Therefore we resort to the notion of very weak solutions of the state equation in L^p spaces. We then study the differentiability of the shape-to-state operator of this problem and derive the first order necessary optimality conditions using the topological state derivative. In fact we prove the existence of the weak topological state derivative for a multimaterial shape functional which is then expressed via an adjoint variable. The topological derivative resembles formulas found for derivative in the more standard Dirichlet control problems. In the final part of the paper we show how to apply a multimaterial levelset algorithm within the finite element software NGSolve and present several numerical examples in dimension three.

A variational method for the topology optimisation problem

Portillo David (1), Bell-navas Edmund (1), Romero Ignacio (1)

1 - Technical University of Madrid (Spain)

Speaker: Portillo David. Invited. **Monday**. Start time: **14:00**. Room: Rhône 5 LVL1. Link to abstract.

The numerical solution of topology optimization problems is plagued with difficulties that result from the ill-posedness of the continuous problem. Many of the strategies leading to the most common and successful numerical methods for topology optimization are essentially regularization techniques that yield robust numerical approximations to a solution of the continuous boundary value problem.
In this talk, we will describe a new numerical technique that approximates the solution to the topology optimization problem of small-strain mechanics by transforming it into a well-posed evolution problem and later approximating its solution with a time integration scheme based on an incremental variational principle. With this procedure, the topology optimization solution will be obtained through a sequence of discrete optimization problems, each of them well-posed. Once the variational principle is posed, no other regularization or filter will need to be employed, as customary in other approximations.

The numerical discretization that we propose pivots on identifying a unique incremental functional whose stationarity conditions determine the evolution of the optimal density field. This approach has several advantages as compared with other numerical solutions of topology optimization: first, the incremental functional simplifies the mathematical analysis of the problem; second, its numerical solution by means of Newton-Raphson type methods invariably gives rise to symmetric tangents, which can be exploited for efficient numerical methods.
The numerical performance of the proposed framework will be illustrated by optimising a series of structures of minimum compliance and fixed mass. Its solutions will be compared against those obtained with standard numerical methods such as SIMP and Allen-Cahn phase-field-type methods.

Macroscopic optimization of porosity distribution using Thermodynamic Topology Optimization

Pravda Ján (1), Jantos Dustin R. (1), Junker Philipp (1)

1 - Institute of Continuum Mechanics, Leibniz University Hannover (Germany)

Speaker: Pravda Ján. **Monday**. Start time: **14:20**. Room: Rhône 5 LVL1. Link to abstract.

Functionally graded materials may vary in their local physical properties (structural, mechanical, thermal, electrical...) and thus open up new challenges for the optimization of technical components.
This gradation is usually achieved by manipulating the microstructure to achieve the desired properties. One of the possible ways is by varying the porosity distribution in the material. Thus, we can achieve similar structure as in bones, with a solid hard outer surface and a spongiform structure inside. Porous materials can be very light with relatively low moment of inertia and exhibit good resistance to dynamic stresses and advantageous damping properties.
Determining the optimal porosity distribution is often not trivial, meaning a dedicated optimization method needs to be developed. It seems sensible to extend the existing topology optimization algorithms and optimize both the geometry and the porosity simultaneously.
As a basis we are using the Thermodynamic Topology Optimization (TTO), derived from the Hamilton principle, which in its most basic form maximizes the stiffness under a maximal volume constraint, evolving the density variable towards a (local) optimum.
Introducing a new design variable and extending the TTO, we're able to optimize the porosity distribution within a given range in non-void regions of the topology optimization depending on local strains. Modifying the material model, based on the standard SIMP (Solid Isotropic Material with Penalization) approach, we define a metamaterial, whose stiffness changes depending on the local porosity. The density and porosity variables are coupled through the maximal volume or cost constraint, and new evolution equations for both design variables are derived. In the search for ideal numerical parameters, a parameter study has been performed, identifying the best values for a stable convergence. To obtain reasonable results, further adjustments to the optimization have been made, delaying the density evolution after a first graded porosity distribution has formed.
Obtained results show an optimized bone-like structure with low (or no) porosity in areas where forces are applied and on the outer surface of the component, with continuously increasing porosity towards the inner areas of the component.

On third medium regularization in thermodynamic topology optimization

Von Zabiensky Max (1), Jantos Dustin R. (1), Junker Philipp (1)

1 - Institute of Continuum Mechanics, Leibniz University Hannover (Germany)

Speaker: Von Zabiensky Max. **Monday**. Start time: **14:40**. Room: Rhône 5 LVL1. Link to abstract.

Topology optimization of hyperelastic structures is an ongoing challenge in which the numerical stability depends in particular on the regularization of the deformation of low-density elements. Void elements must not significantly influence the deformation of the entire structure due to their residual stiffness and should not tend to penetrate themselves in case of large distortions. Previous studies have repeatedly emphasized this aspect and have suggested various solutions. One of the latest approaches uses the stiffness of highly compressed void elements to implement a third-medium approach. Beside stability, this enables smooth contact within the formed structure. In the present work, a new third-medium approach based on linear shape functions is implemented in the thermodynamic topology optimization. The additional field variables, used for the regularization of the rotation of elements, are treated as additional degrees of freedom in Hamilton's principle. These variables are solved in their strong formulation of the related stationarity condition, using the Neighbored Element Method. The effect of the implemented third-medium approach will be present in various numerical results.

On the solution of stochastic topology optimization problems via OCM and MMA

Stingl Michael (1), Uihlein Andrian (1), Pflug Lukas (1)

1 - Friedrich-Alexander Universität Erlangen-Nürnberg = University of Erlangen-Nuremberg (Germany)

Speaker: Stingl Michael. Invited. **Monday**. Start time: **16:00**. Room: Rhône 5 LVL1. Link to abstract.

With the so called continuous stochastic gradient (CSG) method, recently a tool has been developed, which allows to efficiently solve density based topology optimization problems which are subject to random data.
In this talk it is demonstrated how the CSG idea to can be incorporated into classical solution methods for density based topology optimization problems such as the well known optimality criteria method (OCM) or the method of moving asymptotes (MMA).
The ease of use as well as the practical efficiency of the resulting methods will be demonstrated by a couple of examples from structural optimization covering, among others, stochastic loads and stochastic damage.

A Reinforcement Learning-Based Cellular Automaton Method for Structural Topology Optimization

Si Yuanhang (1), Benabou Lahouari (1), Chalvet Vincent (1)

1 - Université Paris-Saclay (France)

Speaker: Si Yuanhang. **Monday**. Start time: **16:20**. Room: Rhône 5 LVL1. Link to abstract.

Conventional topology optimization methods, such as the Solid Isotropic Material with Penalization (SIMP) and Bi-directional Evolutionary Structural Optimization (BESO) approaches, rely on sensitivity analysis, which requires repeated mathematical derivations for different structures and constraints. This reliance not only limits generalization but also results in slow convergence and high computational costs. To overcome these limitations, this study develops a Reinforcement Learning Cellular Automaton (RLCA) framework that combines reinforcement learning with cellular automaton principles. By treating finite elements as cells and aggregating their behavior into a unified learning agent, efficient optimization can be achieved without explicit sensitivity calculations. The proposed method explores innovative designs for state representation, action spaces, and adaptive reward functions to better balance structural stiffness and material usage. Unlike traditional algorithms, the RLCA framework learns through interaction with the environment, enabling it to adapt and improve across diverse problems. This research highlights the potential of reinforcement learning in structural optimization, demonstrating the RLCA method's model-free learning capability, efficient convergence, and adaptability.

Modular-Topology Optimization: Towards Performant and Reusable Designs

Doškář Martin (1), Tyburec Marek (2), Somr Michael (2), Kruzik Martin (3), Zeman Jan (1)

1 - Czech Technical University in Prague (Zikova 1903/4, 166 36 Prague 6 Czech Republic), 2 - Czech Technical University in Prague (Czech Republic), 3 - Institute of Information Theory and Automation of the Czech Academy of Sciences (Czech Republic)

Speaker: Doškář Martin. **Monday**. Start time: **16:40**. Room: Rhône 5 LVL1. Link to abstract.

Modularity has long been a fundamental design paradigm in civil and mechanical engineering. However, optimization algorithms for modular structures have only recently begun to emerge. This lag is partly due to the fact that single-scale optimisation of both modules and their layouts requires addressing two main questions simultaneously: (1) what should the topology of individual modules look like, and (2) how should these modules be arranged in the final design? Especially the second question poses a challenge due to its combinatorial nature.
We address these challenges with a modular-topology optimization framework designed to produce structures and mechanisms that balance high performance with sustainability and reusability. In prior work on truss-like modular structures (1), we utilized the convex formulation of truss topology optimization for module design and meta-heuristics for module arrangement, resulting in a bi-level staggered scheme. However, extending this approach to continuum-like modules presents two key obstacles: (i) the lack of an efficient convex formulation, making module arrangement comparison non-deterministic, and (ii) the high computational cost of fine continuum finite-element representations.

To overcome these limitations, we propose a sequential optimization strategy (2). Our method begins with free material optimization, which determines the optimal distribution of material stiffness across the design domain while suppressing numerical artifacts like checkerboarding. The optimized stiffness tensors pertinent to positions of future modules are then segmented into distinct regions using a deterministic clustering algorithm, which defines the layout of modular components. Finally, the topology of each module is optimized using a standard density-based topology optimization strategy with variable linking scheme employed to achieve desired mechanical properties while using the initial free material optimization results as a starting point.

To ensure the modules can be manufactured and assembled effectively as a single piece, we incorporate additional constraints to (i) maintain connectivity and (ii) account for potential fabrication inaccuracies using a three-field projection technique (3). We showcase the full design process of modules capable of being assembled into two distinct compliant mechanisms: an inverter and a gripper, including an experimental validation. Our results represent the beginning of a broader exploration into modular-topology optimization, with significant opportunities for further refinement and application in complex engineering systems.

Acknowledgement
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Spin-It Faster: Quadrics Solve All Topology Optimization Problems That Depend Only On Mass Moments

Hafner Christian (1), Ly Mickael (1), Wojtan Chris (1)

1 - Institute of Science and Technology [Klosterneuburg, Austria] (Austria)

Speaker: Ly Mickael. **Monday**. Start time: **17:00**. Room: Rhône 5 LVL1. Link to abstract.

The behavior of a rigid body primarily depends on its mass moments, which consist of the mass, center of mass, and moments of inertia. It is possible to manipulate these quantities without altering the geometric appearance of an object by introducing cavities in its interior. Algorithms that find cavities of suitable shapes and sizes have enabled the computational design of spinning tops, yo-yos, wheels, buoys, and statically balanced objects. Previous work is based, for example, on topology optimization on voxel grids, which introduces a large number of optimization variables and box constraints, or offset surface computation, which cannot guarantee that solutions to a feasible problem will always be found.
In this work, we provide a mathematical analysis of constrained topology optimization problems that depend only on mass moments. This class of problems covers, among others, all applications mentioned above. Our main result is to show that no matter the outer shape of the rigid body to be optimized or the optimization objective and constraints considered, the optimal solution always features a quadric-shaped interface between material and cavities. This proves that optimal interfaces are always ellipsoids, hyperboloids, paraboloids, or one of a few degenerate cases, such as planes.
This insight lets us replace a difficult topology optimization problem with a provably equivalent non-linear equation system in a small number (< 10) of variables, which represent the coefficients of the quadric. This system can be solved in a few seconds for most examples, provides insights into the geometric structure of many specific applications, and lets us describe their solution properties. Finally, our method integrates seamlessly into modern fabrication workflows because our solutions are analytical surfaces that are native to the CAD domain.

Liquid Crystal Elastomer Kirigami

Strugaru Irina Malina (1), Martinet Quentin (1), Ly Mickael (1), Bickel Bernd (2), Palacci Jérémie (1)

1 - Institute of Science and Technology [Klosterneuburg, Austria] (Austria), 2 - ETH Zurich (Switzerland)

Speaker: Strugaru Irina Malina. **Monday**. Start time: **17:20**. Room: Rhône 5 LVL1. Link to abstract.

Liquid crystal elastomers (LCEs) are soft responsive materials where orientable liquid crystal units (mesogens) are components of a polymer structure. They present exciting opportunities for soft robotics and environmentally-adaptive systems owing to their heat-responsive deformation capabilities: more than 25% uniaxial contraction when heated uniformly from 25C to 80C. The programmability of LCEs is however challenging, as their material properties and heat-induced deformation are prescribed by chemical synthesis and by alignment of the mesogens. In effect, LCE structures are typically programmed by microscopic patterning. Here we use macroscopic topology alterations, namely (kirigami) cuts to control the heat-deformation and mechanical properties of uniaxially-aligned LCEs. The cuts are oriented orthogonal to the alignment of the LCE sheets. We characterize the mechanical response of tethered LCE kirigami under heating and show that it maps to the uniaxial extension of an LCE kirigami at constant high temperature. This allows us to model and quantify the deformation and tensile response of the LCE kirigami with mechanical FEM simulations. We prove that cuts made into LCEs enable us to program their elastic properties and their heat-actuation force. Further we are able to design heat-deployable structures with multiple deformation modes. Finally, we use kirigami patterns to tap into the viscoelastic behavior of the LCE sheets and showcase structures with tunable recoil dynamics. Altogether, we demonstrate that LCE kirigami offer opportunities beyond conventional soft robots or kirigami.

TOPIC: Tribology

MS8.1 - Contact Mechanics

Organisers: Lars Pastewka (University of Freiburg), Nicola Menga (Politecnico Bari), and Thibaut Chaise (LAMCOS)

Rounded conforming Contacts in Partial Slip

Hills David (1) (2), Eames Beth (3)

1 - Department of Engineering Science (United Kingdom), 2 - University of Oxford (United Kingdom), 3 - Department of Engineering Science, University of Oxford (United Kingdom)

Speaker: Hills David. **Monday**. Start time: **10:10**. Room: Saint Clair 4 LVL2. Link to abstract.

One of the most commonly found static contacts is that formed between a flat faced component with rounded corners and a flat counterface -for example in gas turbine root fanblades and in the locking segments used to fasten risers onto sea-floor 'Christmas Tree' assemblies. Most analyses use a solution based on half-plane theory but this inaccurately represents the domain shape of both of these applications, because the free surfaces are too nearby for the half-plane representation to be applicable.
In this paper we show a combination of three solutions – first, an overall view of the contact pair, (fused together but without the radius present, and whose function is to include the free surfaces), secondly a wedge-based solution which fits into the contact corner, incorporating a crack to calibrate the third element of the solution. This is. a semi-infinite flat-faced but rounded-edge contact solution, derived from half-plane theory, because in this neighbourhood – at the contact edge - half-plane theory applies.

The three phases of the solution are linked by rigorous calibrations, and mean that we are able, also, to take into account a wide range of loads sequences relatively easily, and also to incorporate much more complex domain shapes than is possible using a standard based wholly on half-plane theory.

An explicit solution for the elastic quarter-space and general wedge problem in matrix formulation

Guo Liang (1)

1 - SKF Research and Technology Development (Netherlands)

Speaker: Guo Liang. **Monday**. Start time: **10:30**. Room: Saint Clair 4 LVL2. Link to abstract.

Obtaining analytical solutions for quarter-space and general three-dimensional wedge problems is challenging. Consequently, alternative methods like the finite element method are often employed. This paper introduces an explicit matrix algorithm for solving quarter-space and general 3D wedge problems under surface loads. The methodology involves overlapping two half-spaces formed by the surfaces of a wedge, with all calculations based on half-space equivalent loads. The generated matrices depend solely on the mesh structure and Poisson's ratio, making them applicable to various loading scenarios. This approach significantly enhances the efficiency of numerical iterative analyses, such as elastohydrodynamic lubrication (EHL) of contacts in an elastic quarter-space or truncation. Some truncated EHL solutions using the current matrix solution will be presented.

Towards robust calculations in axial blade/disk attachments

Kabondo Kashala Ben (1) (2), Platzer Auriane (1), Duval Arnaud (1), Chaise Thibaut (1), Nelias Daniel (1)

1 - Laboratoire de Mécanique des Contacts et des Structures [Villeurbanne] (France), 2 - Safran Aircraft Engines (France)

Speaker: Kabondo Kashala Ben. **Monday**. Start time: **10:50**. Room: Saint Clair 4 LVL2. Link to abstract.

The aim of this work is to extend the calculations used for power transmissions to the technology and design of high-pressure turbine blade-disk attachments. In this context, the use of a mixed method combining semi-analytical formulations with a limited number of finite element computations has significantly reduced computation times compared to conventional methods relying on full finite element modelling. However, the current modelling approach is based on simplifying assumptions aimed at testing the feasibility of the method and estimating the reduction in computation time.
Given the geometry of the parts under study, several surfaces of the blade will be simultaneously in contact with other surfaces of a sector of the disk. So, one of the first challenges of this work will be to be able to solve several contacts at the same time by starting from a model that solves one contact at a time between two surfaces.

To answer this question, we have chosen an approach that decouples the effect of the global structural deformation due to the flexion of the part from the effect of the local deformation on the pressure distribution due to local contact. This type of approach is often used to calculate load sharing on gears and splines (1).

To compute the local deformation due to contact, we use a scale separation approach between the global scale associated with the attachment and the local scales related to the contact areas. An initial equilibrium is established between the local variables used to control the various contacts calculated upstream and the contact pressures obtained at the output of the semi-analytical (SA) model. This SA model has already been employed in several previous studies, such as the prediction of fretting and wear in blade-disk attachments (2). Then, a second equilibrium is achieved between the contact pressures and the applied load in the global frame using an iterative numerical method until full load equilibrium is reached.

The numerical method is then tested under loading conditions representing the various types of forces that can be applied to the attachment during operation. Finally, the results obtained from the local contact resolution are compared to those from an existing code that also isolates the structural deformations.

To account for the effects of structural deformation, the SA model will later be coupled with a finite element model isolating only the effects of global structural deformation. This will provide a structural displacement that will be added to the local displacement to obtain a complete model as in (3).

Further work is planned to take account friction in the contact using Coulomb's law, plasticity, inertial effects due to rotation and thermal effects, in order to make the modelling more robust and realistic.

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Keywords:

Contact, modelling, semi-analytical method

Primal-Dual Non-Smooth Friction for Rigid Body Animation

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1 - Institute of Science and Technology [Klosterneuburg, Austria] (Austria)

Speaker: Chen Yi-Lu. **Monday**. Start time: **11:10**. Room: Saint Clair 4 LVL2. Link to abstract.

Current numerical algorithms for simulating Coulomb friction fall in one of two camps: smooth solvers sacrifice the stable treatment of static friction in exchange for fast convergence, and non-smooth solvers accurately compute friction at convergence rates that are often prohibitive for large scenes with densely packed objects. We introduce a novel bridge between these two ideas that computes static and dynamic friction stably and efficiently. Our key idea is to convert the highly constrained non-smooth problem into an unconstrained smooth problem using logarithmic barriers that converges to the exact solution as accuracy increases. We phrase the problem as an interior point primal-dual problem that can be solved efficiently with Newton iteration. We observe quadratic convergence despite the non-smooth nature of the original problem, and our method is well-suited for large systems of tightly packed objects with many contact points.

We demonstrate the efficacy of our method with stable piles of grains and stacks of objects, complex granular flows, and robust interlocking assemblies of rigid bodies.

Impact of friction on adhesion of elastomeric contacts

Dalmas Davy (1), Oliver Cristobal (1), Scheibert Julien (1)

1 - Laboratoire de Tribologie et Dynamique des Systèmes (France)

Speaker: Dalmas Davy. Keynote. **Monday**. Start time: **13:40**. Room: Saint Clair 4 LVL2. Link to abstract.

From industry to biomechanics and basic sciences, adhesion forces have been an object of study for the last decades. These forces are present in most contact interactions and depend strongly on the microscopic properties of the surfaces in contact. A conventional method to measure the energy of adhesion between two surfaces is to measure simultaneously the force and the real contact area during the charge or discharge of a sphere/plane contact and then to evaluate the adhesion energy by applying a relevant adhesive model, for instance the JKR model (1). Here, using smooth contacts between elastomer spheres and rigid plates, we study the evolution of this the pull-off force (adhesion) when the contact is sheared prior to separation.

In our experiments, we have first generated a contact between a semi-sphere of elastomer (PDMS) and a glass plate at a constant normal force. Once the surfaces are in contact, a preliminary shear is performed (with different amplitudes) generating tangential forces smaller than those necessary to trigger the full sliding. Finally, the normal load is reduced until the full separation of the contact. During the process, high precision measurements of the forces (6-axes) and detailed images of the contact area are obtained thanks to the multi-axes opto-mechanical apparatus recently designed in our laboratory (2). In practice, we study the pull-off force, ie the force necessary to fully separate the solids in contact, as a function of the amplitude of the initial shear force.

Our experiments for different normal forces and maximal preliminary tangential forces show that the pull-off force steadily decreases as the preliminary shear increases, as long as the initial shear is lower than about 50 microns (3). For larger shear, we find that the contact reaches full sliding during unloading and thus the pull-off force remains constant, at a residual value 10%–15% of its initial value.

Based on those observations, a first modeling attempt of the critical shear displacement is proposed, involving a competition between jump instability and transition to sliding. Overall, those results offer new insights into the interplay between adhesion and friction, provide new constraints on adhesion measurements and challenge existing adhesive models (4).

Finally, this drastic decrease in pull-off forces could be used as a method to separate surfaces in a possibly more efficient way that simple normal pulling and may be useful wherever soft contacts undergo both normal and shear stresses, including tire grip, soft robotics, haptics and animal locomotion (5).

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Frictional Contact in an Eulerian Phase-Field Framework

Lorez Flavio (1), Pundir Mohit (1)

1 - Institute for Building Materials, ETH Zurich (Switzerland)

Speaker: Lorez Flavio. **Monday**. Start time: **14:20**. Room: Saint Clair 4 LVL2. Link to abstract.

Traditional approaches to contact modeling – and solid mechanics in general – primarily rely on Lagrangian frameworks. While effective for systems with fixed domains, these methods encounter significant challenges when addressing dynamic or evolving surfaces, such as growing biofilms, emerging crystal precipitates, or other multiphysical problems where changes in geometry induce contact and mechanical loading. Eulerian frameworks have re-emerged as a promising alternative, offering a unified description of interface dynamics and the mechanical problem.

In this work, we incorporate friction in an Eulerian framework. We use a diffuse phase-field representation of solids, the reference-map technique for modeling elasticity, and apply penalty-based body forces for both normal and tangential traction components. Each solid is represented by its own set of field variables, enabling straightforward detection of overlapping regions. Frictional interactions are captured through the local slip rate, derived from velocity differences between the two solids, and used to implement a frictional contact law. Besides the known advantages of a Eulerian description, this framework avoids the need for explicit contact tracking, making it particularly well-suited for problems involving complex and evolving geometries.

We demonstrate the implementation using a simple Coulomb friction law and validate it by a comparison with the analytical Cattaneo-Mindlin solution. The results show the framework's ability to accurately capture the tangential traction profile, distinguish between stick and slip regions, and reproduce history-dependent energy dissipation via hysteresis loops. We include additional examples involving large sliding scenarios and frictional interactions under significant deformations, highlighting the robustness and versatility of the method.

In conclusion, this Eulerian phase-field framework provides a streamlined, adaptable solution for modeling interfacial interactions that are coupled with multiphysical phenomena such as growth. By leveraging the inherent strengths of the Eulerian description – including simplified contact detection and compatibility with evolving interfaces – we broaden the applicability of computational contact mechanics to holistically model an array of new systems. This work lays a foundation for further exploration of frictional contact phenomena in multiphysical settings, with potential applications in the study of biological growth patterns or corrosive damage in concrete.

Modeling of the elastic tractive rolling contact for the prediction of pavement damage

Chaise Thibaut (1), Duval Arnaud (1), Wallace Efoé (1), Nelias Daniel (1)

1 - Laboratoire de Mécanique des Contacts et des Structures [Villeurbanne] (France)

Speaker: Chaise Thibaut. **Monday**. Start time: **14:40**. Room: Saint Clair 4 LVL2. Link to abstract.

Pavements are complex, multi-layered materials subjected to intricate loading conditions that lead to damage (1). As traffic moves over the road, various forms of degradation occur, and the renewal of pavements represents a significant global cost. Understanding the causes and evolution of this degradation is challenging, as both the road's behavior and the loads it experiences are difficult to model and predict. A pavement consists of multiple layers with varying thicknesses and widely different elastic moduli. The magnitude of these layers is comparable to the contact size, making their influence crucial in determining the contact behavior. Additionally, temperature gradients throughout the day and across different seasons can cause the pavement's response to change. The velocity of passing loads introduces time-dependent behavior, a viscoelastic model may be necessary to account for. Lastly, while pavements are not homogeneous materials, this study assumes a continuous media.

On the loading side, several factors must be considered. First, the tire-pavement contact results in contact sizes similar to the thickness of the pavement layers. Moreover, the material properties of the contacting bodies are dissimilar, leading to complex interactions between normal and tangential behaviors. Furthermore, during acceleration, braking, or turning, a vehicle generates tangential forces or moments that are transmitted through the contact area. This tractive rolling situation results in complex contact conditions (2).

To address these challenges, a semi-analytical model for tractive rolling contact between dissimilar, multi-layered elastic materials is proposed. The model accounts for the behavior of the layered bodies by deriving influence coefficients for perfectly bounded layers of uniform thickness (3). The formulation is extended to include viscoelastic behavior, allowing the layers to have different properties and relaxation times. The normal and tangential problems are coupled and solved sequentially, enabling the consideration of transient contact behavior under transverse loads (4). This semi-analytical approach ensures a fast and robust solution, enabling the prediction of contact pressures, shear fields, and stresses within the body.

The model is applied to simulate a pavement subjected to a standard truck tire under various loading conditions, including pure rolling, acceleration, turnaround, and drift. The results highlight the significant impact of friction in the contact zone and show how different loading conditions lead to varied damage behaviors depending on the road configuration. These findings are crucial for road design, where only simple normal contact conditions are typically considered.

Finally, the results are compared to experiments from a full-scale traffic simulator on a real road, where deformations in the pavement's subsurface layers were measured. A very good agreement between the model and the experimental data was observed.

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CONTACT MECHANICS OF HYDROGELS

Hu Yuhang (1)

1 - Georgia Institute of Technology (United States)

Speaker: Hu Yuhang. **Monday**. Start time: **16:00**. Room: Saint Clair 4 LVL2. Link to abstract.

Gel is composed of cross-linked polymer network and solvent molecules. Gels have broad application in many engineering fields such as drug delivery, tissue scaffold, soft robots among others. Mechanical characterization of soft gels has been challenging because of the extreme softness and its complex time-dependent behavior. Comparing with other mechanical testing techniques, indentation method provides many practical advantages, which requires minimum sample preparation and can be easily applied across a wide range of length scales, but the difficulty for using indentation is mostly in the theoretical aspect. It is a complex boundary value problem and the gels have convoluted time-and-length dependent behaviors. To interpret data, one must carry out finite element simulation for each geometry and do curve fitting often with multiple parameters to be fitted at the same time. There is a lack of a physical basis to justify whether the fitted values are intrinsic to the materials' properties. In this work, we focus on identifying the underlying physics that governs the time-dependent behavior of gels and find clear scaling relations that allow for a unified solution and master curve independent of geometry to be obtained. The parameters can be extracted definitively without curve fitting and have clear physical meanings. The ease of use of the method makes it possible for people without mechanics background to easily extract the properties of their challenging materials. Beyond the time-dependent bulk properties, we also use indentation to study the adhesion hysteresis (or aging) of hydrogels. Combining a unique multi-time and multi-length scale indentation technique and rigorous theoretical analysis, we can decouple the time-dependent adhesion from the time-dependent bulk behaviors of the gels and extract the intrinsic interfacial properties including adhesion energy, separation distance, and cohesive strength. We also, for the first time, show the transition of mechanism from uniform bond breaking to Griffith type of fracture as the contact size goes across a big range of length scales. It is also the first time that adhesion hysteresis is discovered in hydrogels.

Influence of surface roughness on the mechanics of nano-objects

Iteney Hugo Cornelius Thomas Thomas Olivier Amodeo Jonathan (1)

1 - Aix Marseille Univ, Univ Toulon, CNRS, IM2NP UMR 7334, 13397 Marseille, France (France)

Speaker: Amodeo Jonathan. **Monday**. Start time: **16:20**. Room: Saint Clair 4 LVL2. Link to abstract.

Material surface state is a key parameter in several fields such as friction or machining. At small scales, surface alteration is also at the roots of major physical phenomena as in catalysis or nanomechanical engineering.
In this study, we investigate the influence of surface roughness on the mechanical response of metallic nanocrystals (1). After a brief introduction to *Pyrough* (2), the tool we recently developed to design virtual samples with rough surfaces, we present atomistic simulations of Au nanoparticles with rough surfaces under compression. Results demonstrate that surface roughness has a major impact on the mechanical response of Au nanoparticles, with critical strength variations reaching up to 90% compared to the strength computed for flat-surface samples. Additionally, the evolution of the dislocation microstructure during plastic deformation reveals new and intriguing features, as confirmed by statistical analysis performed on hundreds of atomistic simulations. These findings provide valuable insights into the mechanics of nanomaterials and help explain the measurement discrepancies often observed in nanomechanical experimental tests.

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Physico-chemical characterization of a third body adherent deposit on highly loaded greased oscillating ball bearings

Gilleron Louis (1), Philippon David (1), Ferrieux Amandine (1), Galipaud Jules (2) (3), Bouscharain Nathalie (1), Saulot Aurélien (1), Descartes Sylvie (1), Lengagne Thomas (4)

1 - LaMCoS (France), 2 - Laboratoire de Tribologie et Dynamique des Systèmes (France), 3 - Matériaux, ingénierie et science (France), 4 - SKF - Aerospace [Valence] (France)

Speaker: Gilleron Louis. **Monday**. Start time: **16:40**. Room: Saint Clair 4 LVL2. Link to abstract.

Oscillating bearings have a wide range of industrial applications in robotics, wind energy, aeronautics, amongst others. In aeronautics, they are crucial component of aircraft flight control surfaces such as ailerons or flaps. In those applications, bearings are greased and submitted to very high loads (resulting in several GPa between the ball contact and the raceways) and almost zero speeds. In such conditions, the bearing is operating in mixed or even boundary lubrication regimes. In previous studies, numerous repeatable tests (1, 2) were carried out to understand the effect of grease lubrication on bearings lifetime and observed failure. It was demonstrated that the lifetime was related, among other things, to the formation of a protective nanometric layer at the contact interface, resulting from interactions between the grease and its environment (1). In addition, a more detailed analysis of the bearing life showed a long period of steady state without major disturbance in friction and of the bearing surface. Thanks to previous work, this modified layer has been highlighted, but only after the bearing has failed.
This communication will focus on the formation and behaviour of this layer over the life of the bearing. For the purpose, interrupted tests are carried out. The experimental approach allows to understand the mechanisms of formation of this protective layer, its adaptation with its environment, its evolution (physical, chemical and mechanical properties) throughout the bearing life cycle, as well as the triggering of its failure. The samples used for this analysis are tested on a dedicated test bench that reproduces an oscillation motion on bearings inner ring of 20◦ amplitude, at a frequency of 5Hz with a radial force equivalent to a stress of 5GPa between the most loaded ball and the inner ring. Deep groove ball bearings are used which are greased to at least 80% of their free volume.

Simulations (1) show that the most stressed element is the inner ring in the radial force axis. Therefore, the study will focus mainly on this contact. Optical microscopy, scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS) and an interference profilometry were used to analyse the surface to obtain information about its chemical composition, as well as its deformation, wear and failure. Cross sections were made to observe the change in microstructure in the depth of the samples.

The first results show a softening of surfaces observed at the SEM confirm by profilometry. This transformation is not homogeneous over the entire surface of the inner ring, and its morphology can be granular or a result of plastic flow. XPS analyses show that this adhesive deposit is formed from the elements of the grease and of the contacting surfaces, and this deposit is stratified, i.e. its chemical composition is not homogeneous throughout its thickness.

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Multiscale modeling of a sphere-plane contact based on local third-body simulations

Daigne Kévin (1), Mollon Guilhem (1), Chaise Thibaut (1), Duval Arnaud (1), Molnar Gergely (1), Dureisseix David (1), Gravouil Anthony (1)

1 - Laboratoire de Mécanique des Contacts et des Structures [Villeurbanne] (France)

Speaker: Daigne Kévin. **Monday**. Start time: **17:00**. Room: Saint Clair 4 LVL2. Link to abstract.

The friction coefficient is often mandatory for many applications involving the numerical modeling of two bodies in contact. However, particularly for dry contact, this coefficient is often not well understood. Indeed, even for two given materials, the friction coefficient can vary significantly according to several parameters (humidity, temperature, etc.). Moreover, even if the coefficient value is known, the relationship between normal and tangential force sometimes differs from the well-known Coulomb friction law. Finally, this coefficient is usually reduced to an average value for the whole contact, whereas its value can vary locally. In this work, we propose to determine the friction coefficient locally (at the scale of the third body), and to implement a local friction model at the scale of the whole contact.
First, using a multibody meshfree approach (MELODY), dry contact is modeled at the scale of the third body (the contact is not fully considered). This makes it possible to model the third body explicitly and derive a local friction coefficient (which is an output and not an input of the model). A parametric study was carried out and a friction coefficient model was derived. This model especially takes into account three material parameters, which are the Young modulus, a cohesion coefficient describing the strength of the third body, and a damping parameter. Kinematics (which varies from viscous to visco-plastic flow) is described by a scalar, which can also be evaluated from the friction coefficient model.

This local friction model is implemented in a semi-analytical model (ISAAC) to study the whole contact. The use of the previous friction model permits the study of the local friction coefficient, which gives a shear profile that differs from the classical theory (Hertzian profile multiplied by a scalar). The results show that the local friction coefficient decreases with increasing contact pressure. Consequently, it is lower at the center of the contact (where the pressure is higher) and higher at the boundaries. In severe cases, such as when contact pressure is very high, shear can even become constant within the contact, since the local friction coefficient decreases in the same proportion as the pressure increases.
Information on the kinematics of the third body is also kept at the upper scale. Kinematics is highly dependent on maximum contact pressure. For silicon nitride and relatively "low" maximum contact pressure (0.10 times Young modulus), kinematics is uniform within the contact and shows that half the energy is dissipated by material relaxation, the other half by plastic phenomena. As contact pressure increases, energy is increasingly dissipated by plastic phenomena at the center of the contact, and remains unchanged at the contact boundaries.

Enhancing and regulating the adhesive performances of soft viscoelastic contacts with microvibrations: an experimental and numerical study

Tricarico Michele (1), Ciavarella Michele (1), Papangelo Antonio (1)

1 - Polytechnic University of Bari / Politecnico di Bari (Italy)

Speaker: Tricarico Michele. **Tuesday**. Start time: **10:00**. Room: Saint Clair 4 LVL2. Link to abstract.

Surface adhesion is a key material property in several engineering applications. In the past decades, many efforts have been made in mimicking nature to achieve outstanding adhesion performances. A well-known example is given by geckos, which are able to climb walls at a pace of up to 0.8 m/s thanks to the hierarchical structure of their feet, that allows them to quickly (in the order of tens of milliseconds) adjust surface adhesion. Drawing inspiration by geckos, a controlled tuning of interface adhesion could potentially be crucial to a broad range of applications, such as soft robotics, space technology, micro-fabrication, and flexible electronics.
Recently, high-frequency micrometrical vibrations have been proposed as a promising approach for fast adhesion tuning, due to their capability to significantly enhance or diminish the adhesive performance of soft interfaces (1). However a detailed comparison between theoretical predictions and experimental results is still missing.
In this talk, the problem of "vibroadhesion", i.e. the adhesive behaviour of vibrating viscoelastic contacts, will be addressed.
The experimental tests were performed by unloading a spherical indenter from a soft PDMS substrate excited by high-frequency micrometrical vibrations. We show that as soon as the vibration starts, the contact area increases abruptly and then progressively decreases upon unloading, following approximately the JKR classical model, but with a much increased work of adhesion. We observe an enhancement of the pull-off force when the amplitude of vibration is increased, up to a certain saturation level. Under the hypothesis of short range adhesion, a lumped mechanical model was derived, which, starting from an independent characterization of the rate-dependent interfacial adhesion, predicted qualitatively and quantitatively the experimental results (2).

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Construction of Johnson-Kendall-Roberts Relations for Adhesive Contact between an Indenter and an Elastic Layer of Arbitrary Thickness

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Speaker: Perepelkin Nikolay. **Tuesday**. Start time: **10:20**. Room: Saint Clair 4 LVL2. Link to abstract.

The Johnson-Kendall-Roberts (JKR) theory invariably remains popular among researchers due to its simplicity and mathematical elegance. The theory was originally developed for the contact between two elastic spheres. The recent advances in the JKR formalism, however, led to the creation of a set of formulae suitable for explicit transformation of the non-adhesive force-displacement relations of a contact problem into the respective JKR adhesive ones, which brought an opportunity to construct the JKR relations on the basis of computational methods, e.g. the Finite Element Method (FEM).
Here we present an accurate and robust algorithm that allows conversion of a non-adhesive force-displacement relation obtained from an FEM simulation into the respective JKR force-displacement curve. Broadly speaking, the method can be applied without modification to a wide range of contact problems that involve an axisymmetric convex indenter and an elastic medium such as layers, multi-layered structures, finite size models etc. We discuss possible challenges that arise from the discrete approximate nature of FEM and ways to overcome those challenges. We show how a sequence of auxiliary FEM models can be used to improve overall accuracy and robustness of the process.
The robustness of the present method is demonstrated on a problem of contact between a rigid spherical indenter and a layer of finite thickness. The cases of both compressible and incompressible isotropic material are considered for a wide range of the dimensionless indenter radii (i.e. the results cover problems ranging from an asymptotically thick layer, to the layer of finite thickness, and then to an asymptotically thin layer). These results are in excellent agreement with existing analytical and numerical results published in the literature and the theoretical limiting scenarios.

Adhesive contact mechanics of viscoelastic materials

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Speaker: Mandriota Cosimo. **Tuesday**. Start time: **10:40**. Room: Saint Clair 4 LVL2. Link to abstract.

Several experimental investigations performed over the last decades clearly indicate that the contact behavior of rubbery-like materials is highly affected by a complex interplay between adhesion and viscoelasticity. Viscoelasticity is a major source of friction: the hysteretic losses occurring during the cyclic deformations induced by sliding or rolling motion are eventually responsible for a lateral force opposing the relative velocity. In 1963, Grosch's experimental study (1) demonstrated that the overall dependence of the viscoelastic friction on the sliding velocity is highly affected by the presence of interfacial adhesion: the measured friction coefficient is found substantially increased compared to corresponding adhesiveless conditions. This evidence might depend on different mechanisms. First, in the presence of adhesion, the contact area is enlarged, therefore a larger amount of volume undergoes cyclic deformation leading, in turn, to higher dissipation. Additionally, adhesive interactions induce significant amount of energy dissipation close to the contact edges, responsible for adhesion hysteresis. This phenomenon is usually referred to as "small-scale viscoelasticity". Importantly, it is often identified as a primary source of adhesive strength enhancement. Indeed, experiments demonstrate that the maximum tensile load (i.e., the pull-off force) might be significantly increased compared to theoretical predictions of models assuming a purely elastic rheology. Notably, this evidence is observed both in rolling contacts (2) and dynamic normal indentation (e.g., approach-retraction cycles) (3,4). Many of the existing studies in the field rely on scale separation: the material response is assumed to be purely elastic within the bulk, with viscoelastic losses localized close to the contact area's boundary. Viscoelasticity is therefore completely accounted by introducing an effective velocity-dependent energy of adhesion. However, neglecting the bulk viscoelasticity while modelling adhesive contacts might prevent tackling many of the observed phenomena. Moreover, a comprehensive theory of viscoelastic adhesion is currently lacking and the overall effect of the interplay between adhesion and viscoelasticity on the contact behavior is not fully understood yet. Aiming at filling this gap in the literature, we present a novel energy approach for viscoelastic adhesive contact mechanics. The energy formulation relies on the virtual work principle: the variation of adhesive energy due to virtual variations of the contact area must be balanced by the work of internal stresses. The theoretical framework has been developed either for steady state sliding or rolling contacts (5,6) and general unsteady conditions (7). The proposed theory provides results in solid agreement with many of the experimentally observed phenomena. In steady state sliding contacts (5,6), the adhesion-induced increase of viscoelastic friction is predicted, and the overall trend of the friction coefficient vs. the sliding velocity is a similar fashion to Grosch's experimental results (1). In agreement with experimental observations provided by Charmet and Barquins (2) the pull-off force is velocity-dependent and significantly increased compared to static conditions. Adhesion enhancement is correctly predicted in general unsteady conditions (7), in the so-called JKR dynamic contacts. In this case, the effect of viscoelasticity on the effective adhesion is found highly dependent on the specific enforced loading time-history. At relatively low velocity, the adhesive strength enhancement depends on small-scale viscoelastic losses. However, a different fundamental mechanism is also identified, in agreement with experimental observation (3,4): when the retraction of the indenter starts from a fully relaxed state, the pull-off force is highly increased even at very high retraction speed. This result depends on the glassy elastic response of the material, that prevents the contact area from decreasing, eventually resulting in a flat-punch like behavior. Importantly, under these conditions, the contact behavior cannot be predicted by exploiting the JKR elastic adhesive model with increased effective adhesion energy.

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Real-time insight into adhesion of Hertzian indenter unloaded from a broadband viscoelastic substrate through a physic-augmented machine learning model

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Speaker: Maghami Ali. **Tuesday**. Start time: **11:00**. Room: Saint Clair 4 LVL2. Link to abstract.

Real-time insights into the adhesive properties of viscoelastic materials, such as polymers and elastomers, greatly benefit engineering applications in gripping technologies, switchable adhesion, friction, biomechanics, soft robotics, and climbing robotics technology. Predicting the adhesive properties in real time supports secure handling, adaptability to diverse surfaces, and fine control. Heinrich Hertz (1) laid the groundwork for contact mechanics in 1882 with his solution for elastic bodies with curved surfaces, but addressing adhesive forces, such as van der Waals interactions, introduced a nonlinear boundary-value problem solvable only through iterative numerical methods. The foundational Johnson-Kendall-Roberts (JKR) theory (2) and later models, such as Derjaguin-Muller-Toporov (DMT) theory (3), have driven significant advances but exhibit limitations in their generalizability, especially when extending to rate-dependent viscoelastic materials (4). We should consider that the adhesion in viscoelastic solids introduces rate-dependent responses and is irreversible. It is generally a "difficult problem in contact mechanics" as noted by Johnson (4). Energy-based theories, such as the Persson-Brener (PB) theory (5), address adhesive crack propagation under steady-state conditions but require fitting parameters and often fall short when considering broad-band viscoelasticity. To overcome these limitations, recent developments, including the extended PB model (XPB) (6), offer improved analytical descriptions for Hertzian contact but remain constrained to specific regimes, such as high Tabor parameters and saturated indentation conditions. We address the adhesive interaction between a rigid sphere and a broad-band viscoelastic half-space using a combination of numerical simulations, analytical modeling, and machine learning (ML). Numerical simulations, based on the Lennard-Jones separation law within a boundary element method framework coupled with time-marching algorithms, are employed to generate a comprehensive dataset that captures viscoelastic effects under diverse conditions. We develop and evaluate multiple ML models to replicate the adhesive behavior, comparing their predictions with analytical solutions from our extended PB model (XPB). While the XPB model accommodates broad-spectrum viscoelasticity, it remains limited to saturated indentation regimes and higher Tabor parameters. Meanwhile, ML models struggle to deliver accurate predictions in scenarios with insufficient data due to high production costs. To overcome these shortcomings, our physics-augmented ML framework integrates XPB knowledge with data-driven insights. It offers improved predictive accuracy across varying indentation depths and loading rates. Our results demonstrate that ML models achieve computational efficiency suitable for real-time applications. Furthermore, the physics-augmented models extend the applicability of analytical solutions, bridging gaps in accuracy for scenarios where traditional methods fall short.

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Oscillating a JKR adhesive viscoelastic contact

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Speaker: Tricarico Michele replacing Ciavarella Michele. **Tuesday**. Start time: **11:20**. Room: Saint Clair 4 LVL2. Link to abstract.

Shui et al (Nat.Comm.(2020), 11(1), 1583) have recently shown that applying high-frequency vibrations, we can increase the mean adhesion between viscoelastic solids. This is due to the fact that oscillating contact area leads to an effect of increased apparent surface energy during the retraction phase which can be described by the well known empirical Gent and Schultz law (GS). However, Shui et al solution surprisingly appears not to depend on GS constants, which would imply perhaps no amplification. Yi et al (Advanced Intelligent Systems, (2024), 2400394) have made similar experiments, and proposed a simpler fitting model, which seems to work however with widely different GS constant when changing the sphere radius. Here, we solve the JKR dynamic adhesion problem for a sphere oscillating on a substrate by imposing an harmonic oscillation of the contact area, which permits to obtain a very simple solution by simply averaging the resulting cycle of indentation. We find that the solution is close to a JKR form for the mean indentation vs mean force, which we find in a simple approximation. Although there is saturation in the amplification when the contact radius shrinks to zero and the problem becomes that of impacts at large amplitudes of vibrations, experiments show that saturation occurs first, probably due to other mechanisms. We discuss also the influence of resonances. We find reasonable agreement with experiments conducted on PDMS.

Unsteady crack propagation in viscoelastic solids

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Speaker: Carbone Giuseppe. Keynote. **Tuesday**. Start time: **14:15**. Room: Saint Clair 4 LVL2. Link to abstract.

Crack propagation in rubbery-like materials is a fundamental topic in several engineering applications: rubber wear, pressure sensitive adhesives, windscreen wipers, tire friction, peeling of tapes, just to mention some examples. Significant scientific interest in this field is driven by the experimental observation that linear elastic fracture mechanics falls short in tackling the observed phenomena. Indeed, the fracture behavior of rubbery-like materials is governed by their intrinsic viscoelastic response, which entails a certain amount of energy dissipation occurring during crack propagation. As a result, given a remotely enforced loading condition (e.g., a certain applied stress or strain) a certain crack propagation speed is recovered once that the transient effects have faded out and steady-state conditions are reached. The steady crack velocity can be predicted by enforcing the overall energy equilibrium: the energy release rate must equate the variation of surface energy plus the internal dissipation occurring within the bulk per unit free surface created, as shown by de Gennes (1) and Persson (2). Many other existing studies are based on cohesive zone models, exploiting a detailed description of the failure zone, where local force equilibrium is enforced (3). However, most of the existing studies focus on the steady-state regime, and viscoelastic crack propagation in unsteady conditions is still poorly understood. Notably, if the steady-state assumption is relaxed, the calculation of the energy release rate might be much more complex, as recently shown in (4). Nonetheless, experimental observation clearly suggests that the viscoelastic response of rubbery-like materials might result in complex phenomena before steady-state conditions are reached. E.g., when a viscoelastic specimen, initially unloaded, is instantaneously subjected to a constant force, the fracture behavior is governed by the material's creep response involving its entire volume. Indeed, since the amount of elastic energy stored within the solid monotonically increases over time, crack propagation might occur after a certain delay time, once a sufficient amount of elastic energy is available. This phenomenon, usually referred to as delayed fracture, has been experimentally observed in fracture tests performed on viscoelastic materials (5,6). In this study, we perform a comprehensive analysis of crack propagation in linear viscoelastic materials under general unsteady conditions by exploiting a novel energy formulation. The proposed approach relies on the virtual work formalism: the variation of surface energy caused by virtual variations of the crack tip position must be balanced by the virtual work of internal stresses. This allows for correctly tackling the non-conservative nature of viscoelastic materials. Moving from the assumption of infinitely short-range adhesive forces and exploiting the Green's function approach, the overall time-history of crack propagation is predicted under general loading conditions. The proposed approach can predict the delayed fracture of viscoelastic materials and, specifically, provides a closed form relation between the delay time and the applied stress, which clearly indicates that this phenomenon is triggered by the creep response of the material. The overall time-history of the crack propagation is predicted and analyzed in detail, from the transient stage to the steady-state regime. Results are in solid agreement with experimental observations and previous studies.

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Extensions of the Johnson–Kendall–Roberts Theory of Adhesive Contact to Transversally-Isotropic Systems and Structures

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Speaker: Borodich Fedor. **Tuesday**. Start time: **14:55**. Room: Saint Clair 4 LVL2. Link to abstract.

Molecular adhesion is a physical phenomenon that is specific for nanometre scale interactions. The most popular theory of adhesive contact is the Johnson-Kendall-Robert (JKR) theory that has originally developed for isotropic elastic spheres. The theory is based on the use of the JKR formalism that integrates two fundamental concepts: (1) the Derjaguin balance energy approach and (2) the superposition of solutions to two non-adhesive contact problems, namely, the Hertz-type and the Boussinesq-type problems. The effectiveness of the JKR formalism could be further underscored by harnessing the characteristics of slopes in force-displacement diagrams of non-adhesive cases. This enhancement facilitates explicit transformations of force–displacement curves from non-adhesive to corresponding adhesive cases. The resultant condition could be expressed through a set of formulas, which proves to be a valuable extension of the JKR theory. The explicit transformations demonstrate practical applicability across a myriad of adhesive contact problems in diverse elastic structures.
The JKR method is extended to contact problems between an axisymmetric indenter of arbitrary profile and transversely isotopic half-space or layers.
Keywords: Adhesion, JKR theory, Axisymmetric contact, Adhesive layers

Viscoelastic crack propagation: is the fracture process zone contribution to dissipation rate-dependent?

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Speaker: Papangelo Antonio. **Tuesday**. Start time: **15:15**. Room: Saint Clair 4 LVL2. Link to abstract.

Soft viscoelastic materials are attracting increasing attention as they play a crucial role in advanced technologies, including grippers, manipulators, soft robotics, pressure-sensitive adhesives, rubber supports, and dampers. Elastomers, silicones, and rubbers exhibit time-dependent behavior; their response at time "t" depends not only on the current state of stress and strain but also on the contact history. Furthermore, soft contacts are inherently compliant, allowing them to conform easily to the countersurface and exhibit macroscopic adhesion. The key parameter that determines interfacial stickiness is the thermodynamic surface energy, defined as the energy per unit area required to separate two infinite flat surfaces from their equilibrium position to infinity. However, for viscoelastic materials, the "apparent" surface energy of the interface must also account for energy dissipation within the bulk material.
First, we will introduce our current understanding of viscoelastic crack propagation theories, focusing on: (i) an accurate description of the stress and displacement fields at the crack tip through a cohesive zone model (1, 2), and (ii) the energy balance approach proposed by Persson and Brener (PB) (3). We will demonstrate that both approaches (i and ii) yield very similar results. As a paradigmatic test case, we consider the contact between a rigid Hertzian indenter and an adhesive broad-band viscoelastic substrate. A modified power-law constitutive model for the viscoelastic material is assumed, defined by only four parameters: the glassy and rubbery elastic moduli, a characteristic exponent n, and a timescale t0.

The dependence of the maximum adhesive force (the pull-off force) on the unloading rate will be studied numerically using a scheme based on the boundary element method, assuming that unloading begins from a fully relaxed substrate. By comparing predictions made using the PB theory with numerical results, we found excellent agreement, suggesting that PB theory accurately accounts for internal viscoelastic dissipation in the material. Through a comprehensive numerical analysis, we determined the minimum contact radius required to achieve maximum amplification of the pull-off force at a specified unloading rate and for various broadness of the viscoelastic material spectrum.

Additionally, we compared the numerically predicted pull-off force versus unloading rate with experimental results. Tests were conducted using a glass lens indenting a PDMS substrate, showing that numerical and experimental data align up to an unloading rate of approximately 100 um/s. This finding suggests that, contrary to current numerical and theoretical models (1-3), the fracture process zone may contribute to dissipation through a rate-dependent term. In our experiments, we estimated this term to be of the same order of magnitude as the energy dissipated within the bulk material (4). Thus, we discuss the limitations of current numerical and theoretical models for viscoelastic adhesion, considering recent contributions to the literature on this topic.

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A periodic Semi Analytical Method (SAM) for the tire pavement contact

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Speaker: Durand Nicolas. **Tuesday**. Start time: **15:35**. Room: Saint Clair 4 LVL2. Link to abstract.

Since the early 2010s, the weight of individual vehicles is increasing as electric-power technologies are favored of combustion-powered engines; especially due to heavy batteries built to meet large autonomy requirements. This results in higher stress and wear at the tire pavement interface, for instance leading to increased fine particles emissions (1).
From a tire manufacturers perspective, the transition to new materials formulation also influences tire/pavement contact. To predict the tire performances, models and simulation tools of contact mechanics are developed to estimate the interaction between the rubber material and the rough surface.

However, this physics is challenging to model. In fact, its complexity comes from two different aspects of the problem: the viscoelastic behavior of the tire and the multi-scale roughness of the road. On the one hand, a tire is made of a non-linear viscoelastic rubber material filled with aggregates of silica and carbon. The amount and composition of such rigid inclusions in the elastomer matrix drastically change the materials properties and can make it even more non-linear (2). On the other hand, a road is a complex multi-scale rough surface that needs fine discretization to be properly modelled.

In addition, the time-dependency of the material behavior, combined with the different scales of the rough surface to consider constitutes the major numerical challenge. The Finite Element Method (FEM) is disregarded in this context as computation time could quickly skyrocket with the required time and spatial discretizations. Semi-Analytical Method (SAM) however offers significant cost reduction because only the meshing of the surface is needed: the response in the bulk being given by the Boussinesq solutions. Hence considering a complex viscoelastic material and some detailed multi-scale surfaces can be computed at reasonable costs (3).

Existing in-house developed SAM code solves the contact problem as a minimization of the enthalpy of the considered system, which is equivalent to the minimization of the gap between the two surfaces in contact. The contact problem is solved with a Conjugate Gradient Method (CGM), where the displacements are computed thanks to dedicated Fast Fourier Transform (FFT) algorithms.

To apply this method to our study (viscoelastic solid sliding on a multi-scale rough surface), we first implemented a periodic way to solve the contact problem. One of our hypotheses is that the road could be represented as a cyclic load of the same representative portion of the pavement applied to a viscoelastic slab (2,4). This periodic behavior is embedded within the CC-FFT (Continuous Convolution FFT) technique, where the periodicity is computed exclusively in the Fourier space (5). The viscoelasticity of the material is represented with a linear model, using elastic/viscoelastic correspondence of the contact problem with the introduction of the creep function (6). The resulting numerical tool is formulated both in the transient and steady-state regimes as in (7).

Our formulation can therefore predict an apparent friction coefficient of a given linear rubber material sliding on a rough surface, computed from the hysteric-driven asymmetry of the pressure distribution, without considering any Coulomb friction nor adhesion (neglected for now) at the tire/pavement interface. The evolution of this apparent friction coefficient is analyzed with respect to the periodicity and multi-scale characteristics of the rough surface and some relevant regimes are exhibited with analytical surfaces and realistic pavement reproductions.

Research in progress is focused on including non-linear viscoelastic effects in the material's description,

to fit with experimental campaigns run on tire.

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MS8.2 - Lubrication and Interfacial Rheology

Organisers: Juliette Cayer-Barrioz (Ecole Centrale Lyon) and Nicolas Fillot (LAMCOS)

Bridging Theory and Practice in Transient Elastohydrodynamic Lubrication: Implementation and Experimental Insights

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1 - Laboratoire Génie de Production (France), 2 - Laboratoire de Tribologie et Dynamique des Systèmes (France)

Speaker: Yahiaoui Malik. Invited. **Thursday**. Start time: **16:30**. Room: Bureau Forum 2 LVL-2. Link to abstract.

This study offers a fresh perspective on the elastohydrodynamic lubrication (EHL) regime under time-varying conditions, with a focus on applications in fretting-like scenarios. By developing a comprehensive analytical solution to the Reynolds equation for forced oscillations, the work captures the dynamic evolution of film behavior with unprecedented accuracy. Experimental validations confirm the predictive power of the derived equations, which effectively model key phenomena: the transient squeeze effects shaping film thickness over time, asymmetry and hysteresis in film distribution due to directional changes, and transport effects. Furthermore, integrating these analytical equations with a modulation of the inlet flow accurately predicts starvation effects caused by directional reversals, where the former outlet zone transitions to the next inlet zone. The implementation of the analytical solution was facilitated using **IssyOsborne**, our open-source and open-access software, enabling precise modeling and reproducibility of results. The study also examines the critical influence of lubricant viscosity and contact velocity on film behavior, providing a deeper understanding of their roles in EHL dynamics. Finally, compelling results under fretting-like conditions further enhance the relevance of this work, offering valuable insights into oscillatory contact scenarios. This comprehensive approach highlights the robustness and accessibility of the analytical and experimental findings.

Lubrication of a truncated EHL spinning contact

Patrigeon Tristan (1), Philippon David (1), Fillot Nicolas (1)

1 - Institut National des Sciences Appliquées de Lyon (France)

Speaker: Patrigeon Tristan. **Thursday**. Start time: **16:50**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Film thickness predictions in an elastohydrodynamic lubricated (EHL) contact are mainly based on the hypothesis of a semi-infinite equivalent solid to calculate elastic deformations. However, this assumption is not valid in a number of applications where the contact is close to an edge as in the case in roller-end flange contact in roller bearings. Manufacturing tolerances on the roller and the flange, together with the specific operating conditions may lead to the displacement of the contact zone on the flange. In some cases, the contact may operate very closed to the edge or even on the edge of the flange. In the former case, the classical circular (or elliptical) contact will be truncated. The study focuses on the effect of the contact distance from the free edge, on the film thickness of a lubricated circular contact. In particular, the behaviour of contacts close to or on the edge of the solid will be investigated. A dual numerical-experimental approach is performed. To be closer to realistic conditions, the analysis is performed with chamfered edge. An additional spinning component is implemented in the contact in order to reproduce the kinematics that occur in the roller-end on flange contact. The results show a great decrease in the film thickness as the contact approach the edge, especially on minimum film thickness which reaches critical values.

Heat generation in high speed rolling element bearing : the role of the cage-ring contact

Rion Valentin Martinie Laetitia Fillot Nicolas (1)

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Speaker: Rion Valentin. **Thursday**. Start time: **17:10**. Room: Bureau Forum 2 LVL-2. Link to abstract.

To reduce energy consumption in mechanical systems such as flying machines (helicopters, planes), friction and heat dissipation between the rotating parts should be controlled. In the context of high-speed rolling element bearings, the cage (silver coated steel or carbon reinforced PEEK) is a very important element as a cage failure leads to the ruin of the bearing. Simulations at the bearing scale show that most of the heat is due to the contact between the cage and the ring (in the case of inner or outer ring guided cage). This contact (purely sliding contact, with conform surfaces) is yet poorly studied in the literature. We propose here a numerical model of the cage-ring contact involving mass flow rate as well as thermal equilibrium in order to identifiy the amount of heat generated in this contact. This analysis allows to understand how heat is evacuated though the solid surfaces or transported by the lubricant to the sides, depending on the operating conditions.

Hydrodynamic Lubrication Mechanisms under Transient Severe Loading Conditions

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1 - Laboratoire de Tribologie et Dynamique des Systèmes (France)

Speaker: Zwick Cyril. **Thursday**. Start time: **17:30**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Hydrodynamic bearings can be found in all modern cars. Indeed, the camshafts, which are responsible for opening the intake and exhaust valves in both combustion and hybrid engines, are supported by these systems. Moreover, the engines in electric vehicles, which represent one of the most environmentally-friendly form of motorized transportation in the present era, also have rotating shafts supported by bearings operating under hydrodynamic conditions, although at a significantly higher velocity than those seen in combustion engines. In recent years, it has been demonstrated that more than a quarter of the energy consumed in these systems is used only to compensate friction losses. In order to reduce fuel consumption and therefore greenhouse gas emissions in one case, or electricity consumption to extend autonomy in the other, it is necessary to enhance comprehension of the tribological and dynamic phenomena inherent to these mechanical systems for steady-state and transient loading regimes. A novel full-scale measurement bench was developed enabling the experimental simulation of journal bearings with a radial clearance of 20 μm under real-life working thin-film conditions. The fully instrumented measurement system allowed for the acquisition of in situ in operando data series, including the nominal friction torque in the bearing, pressure gradient, temperature and shaft position under controlled contact kinematics and loading kinetics. The dynamic loads can be applied to the bearing in a contactless manner via a dedicated electromagnet, thus preventing any alteration to the low torque measurement. This type of actuator has the potential to induce any type of excitation over time: for instance, it can apply a rapid loading, reaching 2500 N in less than 3 ms. This talk presents the results obtained on smooth surfaces for a low-viscosity lubricant, at speeds up to 2000 RPM, with varying acceleration values, and radial forces ranging from 600 to 1500 N. The relevance of the data collected was analyzed, the dynamics of the shaft was investigated as a function of the velocity and the thin-film hydrodynamic lubrication mechanisms under steady-state and transient loading conditions were discussed.

Transition from boundary to hydrodynamic lubrication

Bertin Vincent (1), Pouliquen Olivier

1 - Institut universitaire des systèmes thermiques industriels (France)

Speaker: Bertin Vincent. **Thursday**. Start time: **17:50**. Room: Bureau Forum 2 LVL-2. Link to abstract.

The addition of a thin lubricant film in between two sliding surfaces is a widely employed strategy to reduce friction. However, at large normal force, the lubricant film is squeezed out and the sliding friction is governed by contact mechanics (boundary lubrication). The transition to the hydrodynamic lubrication is reached when a critical sliding speed is applied to overcome squeezing force. The transition between those frictional states for rough surfaces is still not fully understood, and will be the focus of this work.

We use a mean-field EHD lubrication model, inspired by the work of Persson and Scaraggi (J. Phys.: Condens. Matter 21 (2009) 185002), where the pressure is split into a contact and an hydrodynamic part and we perform both numerical and analytical analysis. Lubricated systems offer a large scale separation between microscopic scales (film thickness and roughness) and the macroscopic scale of contact. We exploit this scale separation and use asymptotic matching technics to characterise the different regimes of friction.

Theoretical and experimental research on the tribological characteristics of reciprocating seals

Peng Chao (1) (2), Chen Haidong (1), Jin Sibo (1), Yuchao Ke (3)

1 - Sun Yat-Sen University [Guangzhou] (China), 2 - RWTH Aachen University = Rheinisch-Westfälische Technische Hochschule Aachen (Germany), 3 - Anhui Province Key Laboratory of High Performance Rubber Materials & Products (China)

Speaker: Peng Chao. **Thursday**. Start time: **18:10**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Reciprocating rod seals are vital in ensuring the safety and efficiency of hydraulic actuators, with their tribological characteristics significantly impacting operational lifespan and reliability. Utilizing mixed-lubrication theory, a fluid-solid-coupled model for these seals was developed. This model evaluates sealing performance across various working conditions, encompassing different system pressures and temperatures. It delves into the film thickness, film pressure, and asperity contact pressure within the sealing zone. Furthermore, the wear profile throughout the reciprocating process was simulated. A comparison between experimental and simulation results was conducted. This research offers a methodology for designing reciprocating seals and contributes to enhancing their sealing performance.

Surface Curvature Enhances the Electrotunability of Ionic Liquid Lubrication

Espinosa-marzal Rosa (1), Gus Greenwood (1)

1 - University of Illinois at Urbana-Champaign (United States)

Speaker: Gus Greenwood. Keynote. **Friday**. Start time: **10:00**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Ionic liquids (ILs) are a promising class of lubricants that allow dynamic control of lubrication at electrified interfaces. In the real world, surfaces inevitably exhibit some degree of roughness, which can influence lubrication. In this work, we deposited single-layer graphene onto 20 nm silica nanoparticle films to investigate the effect of surface curvature and electrostatic potential on both the lubricious behavior and interfacial layering structure of 1-ethyl-3-methyl imidazolium bis(trifluoromethylsulfonyl)imide on graphene. Normal force and friction force measurements were conducted by atomic force microscopy using a sharp silicon tip. Our results reveal that the friction coefficient at the lubricated tip–graphene contacts significantly depends on surface curvature. Two friction coefficients are measured on graphene peaks and valleys with a higher coefficient measured at lower loads (pressures), whereas only one friction coefficient is measured on smooth graphene. Moreover, the electrotunability of the friction coefficient at low loads is observed to be significantly enhanced in peaks and valleys compared with smooth graphene. This is associated with the promoted overscreening of surface charge on convex interfaces and the steric hindrance at concave interfaces, which leads to more layers of ions (electrostatically) bound to the surface, i.e., thicker boundary films (electrical double layers). This work opens new avenues to control IL lubrication on the nanoscale by combining topographic features and an electric field.

Monitoring the in situ formation of slippery tribofilms by ab initio and machine learning molecular dynamics

Righi Maria Clelia (1)

1 - Alma Mater Studiorum Università di Bologna = University of Bologna (Italy)

Speaker: Righi Maria Clelia. Invited. **Friday**. Start time: **10:40**. Room: Bureau Forum 2 LVL-2. Link to abstract.

I will present the results of ab initio and machine learning molecular dynamics simulations that show how slippery layered materials can be synthesized at the tribological interface thanks to tribochemical reactions. In particular, I will show that selenide layers can be formed by sprinkling Se nanopowders onto sliding contacts (1) and graphene can be obtained by the tribologically-induced polymerization of aromatic molecules (2). Finally, I will discuss the potentiality of machine-learning interaction potentials to design self-assembled monolayers as friction modifiers (3).

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These results are part of the "Advancing Solid Interface and Lubricants by First Principles Material Design (SLIDE)" project that has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (Grant agreement No. 865633).

An atomistic study of temperature and surface chemistry effects on the slip constitutive law of polyalfaolefins in contact with amorphous carbon

Peeters Stefan (1), Garcia Edder J. (1) (2), Stief Franziska (1) (3), Falk Kerstin (1), Moras Gianpietro (1), Moseler Michael (1) (2) (3)

1 - Fraunhofer IWM, MicroTribology Center μTC, Freiburg, Germany (Germany), 2 - Freiburg Materials Research Center, University of Freiburg, Germany (Germany), 3 - Institute of Physics, University of Freiburg, Germany (Germany)

Speaker: Peeters Stefan. Invited. **Friday**. Start time: **11:00**. Room: Bureau Forum 2 LVL-2. Link to abstract.

The quantitative description of lubricants in nanoscale channels is complicated by various effects that are often neglected in conventional elastohydrodynamic models. One of those effects is wall slip, a phenomenon that has been extensively studied both theoretically and experimentally. Slip occurs whenever the velocity of a solid wall and the fluid in contact with the wall differ, changing the shear rate of the fluid, thus the shear stress, with respect to the no-slip condition. There is evidence for friction reduction in the elastohydrodynamic regime due to slip (1), which is connected to the limited momentum transfer, i.e., energy dissipation, between the lubricant molecules and the surface of the wall (2). However, some authors suggest that thermal effects, which change the viscosity of the fluid, are responsible for low friction (3). Slip depends on a variety of different properties of the system, ranging from the pressure, temperature and shear stress in the lubricant, to the surface chemistry and the commensurability between lubricant molecules and the surfaces. Due to the relevance of slip especially at the boundary lubrication regime, we performed an extensive molecular dynamics study on the effect of temperature on the slip of a polyalphaolefin base oil in a nanosized amorphous carbon channel. We observed that higher temperatures promote the slip of the lubricant molecules on the surfaces, changing the parameters of the Eyring constitutive law (4), which describes slip as an activated process. The emergence of an interfacial thermal resistance is connected to slip since both effects originate from the incommensurability between lubricant and wall. Nonetheless, we show that temperature effects have a limited impact on the viscosity of this lubricant, and therefore we argue that low friction mainly comes from slip. These results represent a first step towards the definition of a non-isothermal slip law to extend the validity of continuum models for lubrication. We will also discuss our preliminary results regarding the effect of the surface chemistry, particularly the surface termination of amorphous carbon, on the slip properties of the lubricant.

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Squeeze and Nanomechanics of Boundary Layers in a Lubricated Interface

Lai Van-vuong Sidoroff Francois Mazuyer Denis Cayer-barrioz Juliette (1)

1 - Laboratoire de Tribologie et Dynamique des Systèmes (France)

Speaker: Cayer-Barrioz Juliette. **Friday**. Start time: **11:20**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Due to environmental concerns, the use of low-viscosity fluids to reduce viscous losses in lubricated contacts, the use of low-viscosity fluids has increased, resulting in smaller surface separation.
In order to simulate the squeeze of a confined thin film between two adsorbed layers on antagonistic solid surfaces, a numerical model based on continuum mechanics has been developed using the generalized œdometric Reynolds equations extended to the case of heterogeneous films such as two adsorbed layers separated by a fluid film. This model takes into account the film compressibility and the substrate deformation for a sphere/plane configuration in both static and dynamic situations, under small amplitude oscillations as used for example in non-contact dynamic surface force or AFM measurements.

For the static contact resolution, an explicit approach based on small incremental displacements of the sphere with respect to the plane was chosen. For the dynamic situation, the generalized Reynolds model was assumed to be still valid with a harmonic solicitation and a complex solution was obtained. The numerical solution of the governing equations was carried out thanks to the Finite Element-Method in Matlab.

After a short description of the numerical solution method, the validation of the model was confirmed by confronting numerical results with theoretical and experimental ones. Our model was able to predict such parameters as contact stress or complex stiffness as well as to provide physical insights of the squeeze mechanisms. The application of our numerical model to experimental squeeze of low-viscosity fluid between fatty acid monolayers and polymer brush layers allowed to evaluate the mechanical properties of the adsorbed boundary layers and to discuss the molecular organization within the squeezed interface.
This method opens new perspectives for measuring the viscoelastic properties of adsorbed layers and their evolution under confinement and pressure.

Singular viscoelastic perturbation to soft lubrication

Ferreira Quentin (1), Bharti Bharti (2), Jha Aditya (1) (3), Dean David S. (1), Carlson Andrea (4), Chan Tak Shing (4), Amarouchene Yacine (1), Thomas Salez (1)

1 - Laboratoire Ondes et Matière d'Aquitaine (LOMA) (France), 2 - Department of Mathematics, University of Oslo (Norway), 3 - Cavendish Laboratory, University of Cambridge (United Kingdom), 4 - Department of Mathematics, University of Oslo (Norway)

Speaker: Ferreira Quentin. **Friday**. Start time: **11:40**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Soft lubrication governs the behavior of industrial roller bearings, cells in our blood vessels, allows our articulations to work smoothly, and contactless probing of elastic properties. Previous studies showed the drastic impact it has on the motion of an object immersed in a viscous fluid next to a purely elastic wall at low Reynolds numbers. From those theoretical predictions arose a new array of forces, some analogous to high-Reynolds situations and others completely original. However, most of the previous models do not take into account the inherent viscoelasticity of realistic elastic materials such as polymers and biological membranes. Our work consists of combining the Winkler foundation for a thin compressible elastic material with a Kelvin-Voigt model to describe the soft-lubricated motion of a free infinite cylinder. From the numerical integration of its nonlinear, singular, and coupled equations of motion, we reveal the rich and unpredicted effects of viscoelasticity on the cylinder's behavior. Among them, we find a non-trivial increase of some of the previously derived purely elastic effects, the spontaneous apparition of a torque at equilibrium and a regulation to the previous models. These results open the way toward better theoretical and experimental descriptions of the interaction between a moving object and a nearby soft and complex layer, which is a widespread situation encountered in biological and microfluidic systems.

MS8.3 - Wear Mechanisms

Organisers: Martin Dienwiebel (Karlsruhe Institute of Technology), Anna Igual Munoz (EPFL), Aurélien Saulot (LAMCOS)

A combined Cellular Automata/FFT based tool for modelling third body flows

De Sercey Agathe (1) (2), Renouf Mathieu (1), Bouillon Florent (2), Frérot Lucas (3)

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Speaker: De Sercey Agathe. **Wednesday**. Start time: **10:00**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Modelling the third body behaviour in dry contacts remains a significant challenge in tribology. The third body, a layer located at the interface between two bodies in contact, arises from the conceptualization of dry contact proposed by Godet in the 70s (1). His aim was to establish a link between solid and fluid lubrication in the treatment of contact problems. This layer is liquid in fluid lubrication problems, while in dry contact scenarios, it is solid and composed mainly of debris particles. In a closed contact, third body plays a crucial role in friction and wear processes. However, in these conditions, 'in situ' experimental measures are challenging to conduct. Many scientists have turned to numerical approaches to complement the experimental study of third body behaviour.

Still, selecting an appropriate model is complicated by several factors. The significant difference in scales between the third body and the first bodies presents a primary challenge. Indeed, the thickness of the third body is often smaller by four or five orders of magnitude than that of the first bodies. Additionally, the multiphysics nature of the problem, involving mechanical, thermal, and chemical interactions, adds layers of complexity. The continuous reshaping of the bodies due to wear processes further complicates the modelling approach. Consequently, the choice of an appropriate modelling tool is highly dependent on the specific characteristics of the system under study; for instance, its size, its simulation time, or the physics studied. Each of these factors plays a crucial role in determining the most suitable modelling approach for accurately representing the tribological behaviour of the system.

To adress these modelling challenges, researchers have developed and adapted various numerical methods to study tribological phenomena across different scales. Amongst them, two methods are commonly used: the FEM (Finite Element Method), and the DEM (Discrete Element Method). The challenges of FEM lie both in understanding the phenomenology and in improving the convergence and performance of the models. Thus, to obtain relevant results, it is necessary to adjust the mesh refinement as needed. Consequently, when modelling a contact, the mesh must be refined at the interface, which leads to very significant computational costs. Moreover, the third body layer is not always homogeneous or continuous. The FEM being a continuous approach, the modelling of wear and the consideration of the third body layer is thus complicated and computationally expensive. The DEM may seem more relevant to represent a discontinuous media as the third body layer. In addition, the discrete models can represent both the fluid and solid behaviour of the third body, and can take into account the physico-chemical interactions between the particles. Despite these qualities, these models are suitable for a limited number of particles, a short simulation time, generally limited to 2D, and entail a high computational cost.
Even with FEM/DEM dialogues, the computational cost remains unfit for engineering applications.

To account for the different flows present in a contact (2), some questions should be solved:
1) How does the third body move at the contact, depending on the velocity, the roughness on the surfaces, etc.?
2) Why and how is the third body created?
3) How does the third body get out of the contact?
4) How can we efficiently simulate a macroscopic system over a long period with reduced computation time?

While some models found in the literature have provided insights to address our questions individually, none of them offer a comprehensive and precise description of the entire system.

These questions led to the creation of an original approach, based on a dialogue between a Boundary Element Model (BEM) accelerated by Fast Fourier Transform (FFT) (3), and a Cellular Automata (CA) approach (4). The BEM calculates the quasi-static mechanical equilibrium between two rough surfaces. The resulting pressure and displacement fields feed the CA model, which aims to represent the creation and distribution of the third body in the moving system.

Knowing the surface roughness and the local third body thickness, the BEM model calculates the pressure and displacements fields as functions of the applied pressure. These fields are used as input for calculating the third body flows. The CA models a slight movement between the two surfaces, changing the spatial configuration at the contact. Depending on this new configuration, and on CA rules describing the mechanical and physico-chemical behaviour of the third body, the layer redistributes itself. Then, local pressure information is used to calculate the generation of the third body. The resulting spatial configuration is introduced in the BEM algorithm, and the process continues. The low computational time allows the calculation of the system evolution over a long time.

The novelty and originality of this approach lie in the CA model developed, and its dialogue with the BEM. This dialogue between the two models allows for a comprehensive simulation of tribological phenomena across multiple scales. The versatility of the CA rules enables the method to be neither system or material-dependant, making it highly adaptable. Importantly, this approach authorizes multiscale simulations while keeping computational times low. This balance between multi-scale capability and computational efficiency makes our approach a valuable tool for analysing complex contact behaviours. This method will provide information on the coefficient of friction and enable parametric studies on various factors. For instance, on surface roughness, as well as on various conditions of pressure, temperature, speed, and others.

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An analytical wear model for particles generation during dry sliding

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1 - Institut Pprime (11 Boulevard Marie et Pierre Curie, 86360 Chasseneuil du Poitou France), 2 - Institute of Construction Science“Eduardo Torroja"- Spanish National Research Council (Spain)

Speaker: Brunetiere Noël. **Wednesday**. Start time: **10:20**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Recent research has shown that when two solid surfaces slide against each other, debris can form if the junction between two protruding microscopic regions on the mating surfaces exceeds a certain critical size. By combining the concept of critical junction size with the Greenwood-Williamson contact model for rough surfaces, we can analytically express the Archard wear coefficient. This model also allows us to predict the size distribution of the wear particles generated during the sliding process. To validate the proposed model, the predicted particle size distributions were compared with experimental data obtained from alumina/alumina dry abrasion at different normal loads. The aerosol particles generated by abrasion have a multimode distribution with three main modes centred at around 80 nm, 165 nm and 1050 nm. With increasing normal load, the third mode became dominating. We found good agreement between the measured and calculated wear volumes and coefficients. Further insight into the mechanisms of nanometric debris generation was made through structural analysis using TEM, SEM and electron diffraction.

How third body thickness influences sub-surface damage

Bouillanne Olivier (1), Mollon Guilhem (1), Descartes Sylvie (1), Saulot Aurelien (1)

1 - Laboratoire de Mécanique des Contacts et des Structures [Villeurbanne] (France)

Speaker: Saulot Aurelien. **Wednesday**. Start time: **10:40**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Experimental evidence shows that dry sliding contacts are characterized by the presence of a third body, i.e. by a layer of solid matter trapped in the interface. This matter originates from the degradation and wear of surfaces during past sliding, and exert an important control on the interface rheology, on its friction coefficient, and on its wear mechanisms. In most cases, however, the precise functional relation between the third body properties and the contact behaviour is unpredictable, and can only be tested experimentally.

In the past decades, progress has been made in the understanding of third body layers through advances in experimental testing and characterization, and numerical modelling. The latter is often based on discrete (e.g. granular) approaches, which allow to represent the possibly discontinuous nature of the third body and the complexity of its kinematics in the sheared interface. Most promising approaches also include the deformability of each third-body particle in order to widen its applicability to pasty or ductile rheologies. In a recent work, such a synthetic collection of third body particles was sheared between two planar bodies, one of which being a linear elastic half space simulated with a meshfree technique close to the finite-element method. This allowed to observe and characterize the tribological loading applied by the third body flow to the subsurface, under the form of stress concentrations and fluctuations in space and time. These simulations showed that the damaging effect of the third body is strongly related to its flow regime, which is in turn controlled by its grain-scale properties.

In this communication, we present new results obtained with the same class of models, by systematically varying the thickness of the third body layer in the simulations. We show that a smaller third body thickness is prone to increase the magnitude of the stress concentrations and fluctuations, and therefore to increase the wear rate. This trend, however, varies from one accommodation regime to the next, and is more pronounced when the third body tends to form large agglomerates. We provide quantitative rules regarding the expected surface damage as a function of third body thickness, and discuss the implications of this result on contact life.

Quantitative Wear Prediction Based on Persson Contact Mechanics

Xu Ruibin (1) (2), Persson Bo (1) (2)

1 - Forschungszentrum Jülich = Research Center Juelich (Germany), 2 - Lanzhou Institute of Chemical Physics, Chinese academy of science (China)

Speaker: Xu Ruibin. **Wednesday**. Start time: **11:00**. Room: Bureau Forum 2 LVL-2. Link to abstract.

We present a comprehensive experimental and theoretical study on the wear mechanisms of rubber and polymer materials, leveraging the newly developed sliding wear theory (Persson wear theory), which extends Persson contact mechanics to quantitatively predict wear rates and particle size distributions. The study investigates the wear of rubber on surfaces such as concrete and sandpaper, as well as the wear of PMMA on surfaces with varying roughness, including polished steel, sandpaper, and ceramic tiles. Experimental results demonstrate excellent agreement with theoretical predictions, highlighting the versatility and accuracy of the Persson wear theory.

A key finding is the identification of distinct wear mechanisms based on surface roughness. For rough surfaces, wear is driven by shear-stress-induced crack propagation, while for smoother surfaces with roughness below a critical threshold, shear stress is insufficient to drive crack propagation, and wear originates from alternative mechanisms. This provides crucial insights into the origins of wear across materials and conditions.

As the first quantitative theory of wear mechanisms, Persson wear theory is able to predict wear rate and particle size distributions. It offers practical tools for assessing wear-related phenomena, such as the environmental impacts of wear particles, and paves the way for sustainable material design and improved surface engineering strategies.

Evolution of stress/displacement fields and contact area of elastomer spheres during oblique landing

Mille Antoine (1)

1 - Laboratoire de Tribologie et Dynamique des Systèmes (France)

Speaker: Mille Antoine. **Wednesday**. Start time: **11:20**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Under increasing shear, the contact between a rough elastomer and a rigid surface, for example in the case of a contact between a tire and a road surface, may undergo significant changes in terms of morphology of the micro-contacts due to the presence of wear (1). In this context, our research have been motivated by the observation made on these worn contact which are governed by heterogeneous wear traces (2) that may come from heterogeneous stress fields.

To better understand the initiation of wear, in this study, our aim is to analyze the contact stress and displacement state of a sphere made of elastomer during a representative kinematic for a rolling system: the oblique landing. These analyses are performed by measuring not only the classical evolution of macroscopic normal and tangential forces but also that of the true contact area and interfacial stress and displacement fields.

To do so, we perform a single normal loading/unloading cycle during a continuous shearing motion representative of one tire revolution in a new generation opto-mechanical device recently developed in our laboratory (4). The latter enables rich contact loading through five simultaneous and independent degrees of freedom with simultaneous high-resolution monitoring of all three forces and three moments at the contact interface. It also enables high-resolution in-situ visualization of the contact area, giving access to in-operando, measurements in the real contact area of the stress/displacement fields through advanced image analysis techniques (5).

This experimental procedure makes it possible to study the effect of several characteristic parameters, such as the ratio between "landing" and sliding speed or the maximal normal force. At first, we performed preliminary tests on unworn spheres of uncharged elastomer (PDMS) seeded with markers to monitor the evolution of contact area and interfacial stress and displacement field via image analysis. Then, we compare our experimental measurements with the prediction of a new analytical models already existing (3). Subsequent tests on pristine tire-type rubber enabled us to extend our comprehension to more realistic rubber materials and to make the link between wear pattern (2) and interfacial stress/strain fields.

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Coupling tribological and advanced electrical measurements for the monitoring of sliding interfaces

Mekouar Naoufal (1), Bissardon Rémi (1), Fontaine Julien (1), Minfray Clotilde (1), Cobian Manuel (1), Dubreuil Frederic (1), Galipaud Jules (1), Guibert Matthieu (1), Graton Olivier (1), Braccini Muriel (2), Verdier Marc (2), Volpi Fabien (2)

1 - Laboratoire de Tribologie et Dynamique des Systèmes (France), 2 - Science et Ingénierie des Matériaux et Procédés (France)

Speaker: Mekouar Naoufal. **Wednesday**. Start time: **14:30**. Room: Bureau Forum 2 LVL-2. Link to abstract.

In today's society, the rapid growth of electric mobility and power sourcing systems (such as electric vehicles, wind turbines, etc.) presents new challenges for enhancing energy efficiency. In these devices, significant energy losses and durability limitations are often linked to tribological issues at sliding interfaces. At these interfaces, complex interactions between chemical, mechanical, and electrical processes play a crucial role in determining their tribological behavior. In particular, the nucleation and growth of tribofilms result from the synergistic interplay of these processes.
This presentation will introduce an innovative characterization methodology that combines tribological testing with advanced electrical measurements. This approach enables both electrical monitoring and the application of electrical stresses at sliding interfaces. Tribological tests are conducted using a ball-on-flat linear reciprocating tribometer with steel balls and flats. Focus will be made on a ZDDP based lubricant.

- Electrical monitoring: In the present methodology, the standard Electrical Contact Resistance (ECR) method is complemented by the monitoring of the full current-voltage (I-V) characteristics. These characteristics are indicative of fine chemical processes at the interface, such as tribofilm nucleation and growth. Additionally, impedance-based techniques, including capacitance and conductance spectroscopy, provide valuable insights into the thickness and chemical composition of growing tribofilms.

- Electrical stressing: Various considerations can be made to explore the effect of electrical stimuli on lubricated sliding interfaces. Indeed, electrical stimuli can be electric fields (inducing dielectric breakdown), absolute voltages (activating or inhibiting electrochemical processes), current density (linked to Joule heating), or electric charges (associated with redox reactions). The presentation will show an illustrative example of the significant effect of electrical stresses on wear behavior.

Key Words: Tribology, Tribofilm nucleation and growth, Electrical characterization

Insights of material flows under shearing and pressure

Pereira Agudelo Juan Ignacio (1), Lafarge Lionel (1), Lachambre Joël (2) (3), Adrien Jérôme (3), Maire Eric (3), Descartes Sylvie (4)

1 - Laboratoire de Mécanique des Contacts et des Structures [Villeurbanne] (France), 2 - Laboratoire de Mécanique des Contacts et des Structures [Villeurbanne] (France), 3 - Matériaux, ingénierie et science [Villeurbanne] (France), 4 - Laboratoire de Mécanique des Contacts et des Structures [Villeurbanne] (France)

Speaker: Pereira Agudelo Juan Ignacio. **Wednesday**. Start time: **14:50**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Wear processes result of chemical-physical-mechanical phenomena: material transformation, particles detachment and material flows at the contact interface. Tribological scenarios are defined by different factors: materials properties, chemical environment, thermo-mechanical stresses as a result of loading and contact conditions, leading to the balance between the different matter flows (source, internal, re-circulation or ejection out of the contact). Experimental evidence highlights that dry sliding contacts are characterized by the presence of a third body, i.e. a layer of solid material, trapped in the contact interface. But the dynamic behavior of this third body in the case of dry contacts is difficult to study in situ, as a contact is a confined system, inaccessible to direct local measurements. The idea, therefore, is to study those materials outside a contact, with controlled loadings and under (thermo)mechanical conditions representative of a contact. The HPT (High Pressure Torsion) test, a severe plastic deformation process, is used for this purpose. It has the advantage of reproducing, in the samples, conditions close to those found locally in contacts, i.e. shear and pressure, for continuous materials (2-5) but also for granular materials (6-8).
A custom-built HPT test bench has been designed at LaMCoS to be implemented on a double X-ray tomograph (DTHE). X-ray tomography has the advantage of being a non-destructive method for reconstructing the composition and internal structure of an object in three dimensions from several X-ray images. The coupling of these 2 methods, HPT and tomography, allows to monitor *in situ* the local evolution of a model interface sheared under pressure, from the point of view of its flow and structural (re)organization (segregation, density gradients, mixture formation, etc.).

In this communication, the experimental results with 3 different granular model third bodies (a poly-dispersed steel powder, a mixed of steel and carbon powder, a mixed copper and tungsten carbide powder, ie.e. Cu 85wt% / WC 15wt%) are presented. The tests are performed under ambient air, 5 contact pressures up to 1 GPa, 3 rotation speeds. The volume of material sheared is consistent with that of the third body found in the contacts. The chemistry, shape, size, mechanical properties, surface properties, etc. of selected particles are related to real contacts. Rheological properties and microstructural organization and modification are analysed as a function of deformation paths and initial particle properties. The 4D reconstruction procedure is also discussed.

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Insights into Solid Lubrication Processes of DLC Films thanks to Analytical Tribology

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Speaker: Fontaine Julien. **Wednesday**. Start time: **15:10**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Diamond-Like Carbon coatings may behave as very good solid lubricants, providing a good combination of tribological environment and coating composition is ensured. For instance, highly hydrogenated amorphous carbon (a-C:H) films may lead to super low friction regime ($\mu <$ 0.01) under ultra-high vacuum, at least for a limited time. What are the tribological phenomena that allow for such performance, and what brings an end to this unique regime?To answer such questions, a traditional approach consist in performing some surface analysis after the experiments, inside and outside the wear tracks. These analyses are frequently morphological, structural or chemical, sometimes mechanical. While these informations are paramount for the understanding of the surface degradations during sliding, they don't provide information about the respective roles of these degradation on the evolution of the tribological response of the contact.In this work, we use a high resolution environment-controlled tribometer, based on a six axes force sensor, to probe the tribological response of a steel pin / a-C:H film contact, either by crossing existing wear tracks or by shifting the tracks to slide on pristine surfaces. This original approach helps understanding the respective role of surface modifications on the a-C:H coated flat or on the facing steel pin on the achievement of superlow friction. These experiments are combined with more traditional analytical means, like in situ XPS, AES and REELS analyses or ex situ SEM or AFM observations.The growth of a carbon-rich tribofilm on the steel counterpart appears necessary, but not sufficient to reach superlow friction. Changes on the topography and chemistry of the a-C:H film seems also paramount, with a smoothening of the a-C:H asperities and an increase of the sp2 Carbon content. The respective role of these phenomena on the solid lubrication process of a-C:H film will be discussed.

How hydrogen influences wear and friction under tribocorrosion conditions

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Speaker: Igual Munoz Anna. **Wednesday**. Start time: **15:30**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Tribocorrosion is an established field dealing with tribological contacts in reactive environments (i.e. biological fluids, hydrogen or CO2 atmospheres, seawater, ammonia). As a consequence of the interaction between chemical and mechanical phenomena, wear mechanisms are of particular interest, especially when facing new technological challenges such as hydrogen powered economy, renewable energy sources, personalized health or electrical transportation. In this talk the current state-of-the art of tribocorrosion mechanisms of the involved phenomena and modelling will be given together with the specific application to understand which is the effect of hydrogen intake on wear and friction of carbon steel under different tribocorrosion conditions. To do that, an electrochemical hydrogen charging method was used followed by tailored tribological experiments in aqueous solutions under well controlled surface conditions (presence or absence of oxide film on the carbon steel). The electrochemical charging consisted on applying a cathodic current density of 24.3 mA/cm2 during 24 h in a 0.5 M Na2S solution at room temperature. The effect of the hydrogen intake on the material properties was identified through the measurement of the fracture energy by carrying out Charpy tests. A decrease in fracture energy from 8 J to 4 J was obtained after the hydrogen charging.
The tribocorrosion results show how the effect of hydrogen intake on friction and wear depends on the applied potential (driving force for the electrochemical reactions), in particular on the fact that the carbon steel forms a passive thin film or not.

Coatings that manufacture themselves: Formation and performance of protective coatings in situ via tribosintering

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Speaker: Carpick Robert. **Wednesday**. Start time: **15:50**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Metal oxides powders typically require temperatures > 1000◦ C to coalesce into dense solids. Remarkably, metal oxide nanocrystals, including ZrO2 and TiO2, when dispersed in lubricants can sinter at room temperature due to tribological stresses (compression and frictional shear) in a process known as tribosintering. In this process, the nanoparticles forming solid, surface-bound films that we call tribocoatings. We show that such tribocoatings prevent wear and other common tribological failure mechanisms under a wide range of harsh conditions, rendering this approach promising for applications where harsh mechanical conditions are present. The competition between growth and wear (removal) mechanisms will be discussed, including the role of debris generation vs. gradual atomic scale wear, which appears to play a role in determining the overal tribocoating formation kinetics.

Insights on the humidity influence on graphite-phenolic resin solid lubricants in highly loaded contacts

Zouina Omar (1), Dienwiebel Martin (1)

1 - Karlsruhe Institute of Technology (KIT), Institute for Applied Materials (IAM), MicroTribology Center μTC, (Germany)

Speaker: Zouina Omar. **Wednesday**. Start time: **16:10**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Friction and wear in the moving components which constitute a significant share of the mechanical systems we use can lead to important energy and materials losses. That is why it is of paramount importance to develop lubricants that withstand harsh conditions for extended periods of time. In fact, solid lubricants have proven to exhibit favourable tribological properties where liquid lubricants tend to be of restricted use. Graphite, notably as a solid lubricant coating, has shown fabulous lubricating properties under high mechanical loads and in the presence of relatively high humidities (1). However the lifetime remained quite limited. On the other hand, our previous work has shown that when graphite is mixed with phenolic resin as a binder it has exhibited a remarkable tribological behaviour. Indeed, the addition of phenolic resin to graphite improved the lifetime 50-fold meanwhile keeping a comparable lubricity to the one reported with pure graphite. Though, it is well established that the lubricity of graphite is humidity-dependent (2), this leaves us with an open question: is there a humidity influence of the tribological properties of graphite-phenolic resin blend? If yes, how? In this work we attempt to bring in further insights and understanding of the influence of humidity of the aforementioned solid lubricant by conducting highly loaded tribological tests when tested on a ball-on-flat reciprocating motion in controlled environments. We employ surface-analytical tools as well to further characterise the obtained tribofilm, hence, unveiling the underlying lubricating mechanisms of these solid lubricants.

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Tribological Insights into Supercritical CO2 and MQL in Titanium Alloy Machining for Sustainable Manufacturing

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Speaker: Xu Nan. **Wednesday**. Start time: **16:45**. Room: Bureau Forum 2 LVL-2. Link to abstract.

The use of emulsion coolants at high flow rates is widespread in machining processes such as milling, turning, and drilling. While effective, this practice poses substantial environmental, economic, and health challenges. Recent innovations, such as minimal quantity lubrication (MQL) and cryogenic machining with supercritical CO2 (scCO2), offer sustainable alternatives by reducing coolant consumption by up to four orders of magnitude while enhancing tool life and lowering manufacturing costs. However, a lack of understanding regarding lubricant selection, lubrication mechanisms, and heat transfer in mixed scCO2+MQL systems hinders their broader industrial implementation.
This study employs a bespoke high-speed, high-load pin-on-disk tribometer to simulate cutting conditions and monitor tribological behaviours at the tungsten carbide pin/Ti64 disc interface, including friction forces, heat generation, and pin wear. Real-time temperature data at the pin/disk interface is captured using a thermocouple, enabling detailed investigation under conditions that closely replicate machining environments. The experimental matrix includes parameters such as sliding speed, temperature, coolant properties, flow rates, and MQL types and concentrations.

Additionally, the study investigates surface films formed during testing using advanced characterization techniques. 3D optical profilometer and Focused Ion Beam Transmission Electron Microscopy are used to evaluate physical properties, such as thickness, distribution, and nanostructure, while Scanning Electron Microscopy and Energy Dispersive X-Ray analysis provide insights into chemical composition.
This research advances understanding of how scCO2 and MQL influence tribological performance under simulated cutting conditions. By exploring mechanisms governing tool wear and surface interactions, it establishes a mechanistic model that correlates tribological behaviour with scCO2 and MQL parameters. These findings provide critical knowledge to optimize sustainable machining systems, contributing to environmentally conscious manufacturing advancements.

Use and understanding of the new abrasion test bench for the study of emergency landing with retracted landing gear

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Speaker: Lammens Bastien. **Wednesday**. Start time: **17:05**. Room: Bureau Forum 2 LVL-2. Link to abstract.

In the event of an aircraft performing an emergency landing without deployed landing gear, the aircraft's underside may skid along the runway for several hundred meters. This extended skid gives rise to various physical phenomena, including wear and heat generation within the structural components of the aircraft's underside. Unchecked, these phenomena could compromise the integrity of the structure, posing a significant threat to passenger safety. In response to these challenges, ONERA, in collaboration with the Mechanics, Multiphysics and Multiscale Laboratory, has directed its efforts towards characterizing the tribological behaviour of aeronautical structures under extreme conditions through the PHYSAFE project, which was launched by the French Civil Aviation Authority (DGAC).
Tribology, the science of friction, wear, and lubrication between bodies in contact and relative motion, is complex, involving an array of physicochemical phenomena. Traditionally, wear characterization has relied on a tribological system consisting of two contacting solids, a third body (debris or reaction products), and the surrounding environment. The wear behaviour of such a system is governed by its tribological circuit, which is sensitive to each component's properties. During contact, most of the dissipated energy manifests as heat, potentially altering material properties through thermodynamic reactions like oxidation (as per Quin's theory). This thermal effect complicates the formulation of an accurate energy balance, as highlighted by Uetz and Fohl.

Despite existing standards for tribological system characterization, none specifically address emergency landings with retracted landing gear. Laboratory tribological tests must also account for representativeness at larger scales, a challenge that can be approached by using dimensionless numbers, such as the Reynolds number in fluid mechanics. Kline suggests that experiments are similar when their respective dimensionless numbers match across different setups. In recent years, Deletombe et al., working with the Mechanics, Multiphysics and Multiscale Laboratory, have developed a prototype abrasion bench specifically tailored for emergency landing scenarios.

This prototype was completed and installed at ONERA's Lille facility in early 2024. It allows for experiments involving spiral trajectories, facilitating controlled contact between a surface representative of an aircraft and a "clean" runway surface, free from debris or aircraft material remnants. The objective of this study is to introduce this novel abrasion test bench, detail its operational principles, and present findings from initial testing.

The prototype comprises two main components: a "runway" represented by a rotating disk driven by a brushless motor, capable of reaching 2,700 rpm; and an "aircraft" component embodied by a test specimen made from the material under investigation. The disks, which can measure up to 400mm in diameter, enable the test piece to achieve speeds approaching 60 m/s, typical of civil aircraft during runway contact. Constructed from gabbro, a rock with concrete-like properties but greater resistance to ensure operational safety and prevent disk explosion, these disks provide a robust testing platform. A six-axis robot arm, equipped with a three-axis load cell and a heavy mass, is employed to bring the "aircraft" test specimen into contact with the rotating disk. The robot's control system allows for precise positioning of the test piece at various radius on the disk, enabling both circular and spiral trajectories that simulate different contact scenarios. With adjustable arm speeds ranging from 0.025mm/s to 320mm/s, a wide array of trajectories can be realized, facilitating comprehensive material testing under diverse conditions.

The prototype's versatility in executing various trajectories, thanks to precise disc and robot controls, has enabled the study of different materials in multiple configurations. Among these are aluminum 2024Ti53 and two advanced materials from Pyromeral: Tactylit and Pyrosic. In addition to the load cell, which

measures normal and frictional forces, an optical displacement sensor was used to measure sample wear during the experiments. A high-speed infrared camera assesses surface temperature increases of the tested materials, with data corroborated by thermocouples affixed to each specimen's surface. A visible camera captures real-time degradation of the samples upon contact with the disk.
Preliminary results on circular trajectories highlight a difference in wear behaviour between contact at an inner radius and an outer radius (at the same speed seen by the test specimen), with more significant wear at the edge of the disk than its center, leading to a higher macroscopic friction coefficient in the first case. These initial tests have allowed the familiarization with this new abrasion prototype. The comparison of circular and spiral tests is the next step in this research.

Single-asperity friction and wear in seismic faults

Clerc Adriane (1), Mollon Guilhem (1), Ferrieux Amandine (1), Lafarge Lionel (1), Saulot Aurélien (1)

1 - Laboratoire de Mécanique des Contacts et des Structures (LaMCoS) (France)

Speaker: Clerc Adriane. **Wednesday**. Start time: **17:25**. Room: Bureau Forum 2 LVL-2. Link to abstract.

Understanding earthquakes mechanisms still represents a challenge, motivated by the large consequences of the numerous earthquakes occurring each year. A number of uncertainties remain concerning the complexity of the fault structure, the constitutive properties of materials and the fault rheology. To address those points, different models coexist to conceptualize a fault. We choose to model a seismic fault as two rough surfaces in contact through a series of asperities, in the presence of wear particles (called granular gouge in geophysics or third body in tribology). In other words, we borrow from the tribological approach the pin-on-disk experiment so that the fault concept previously described is downscaled to a single asperity sliding on a rough surface. The single asperity response to shearing induced by sliding and the evolution of friction are studied closely to understand the different stages undergoing by the asperity and the consequences on the fault behaviour during co-seismic events.

The original experimental apparatus consists in a centimetric pin with a hemispherical extremity representing the fault asperity while a large flat rotating disk stands for the opposite surface of the experimental fault. Both pieces are made in the same rock with controlled roughness. The experimental downscaled fault is submitted to co-seismic conditions: contact size of 0.1-5 mm, contact normal stress of 10-200 MPa, sliding velocity of 0.01-1 m/s. The originality of the experiment device compared to usually used geophysical triaxial or rotational devices is the length of imposed sliding distance (up to 100 m in our experiments so far). A number of high-sampling-rate sensors are used to constrain the observation of the asperity contact during the simulated seismic events. Complete post-mortem analyses of the pin and the wear tracks with optical microscopy, SEM and roughness images allow to quantify the regime features, from centimetric to submicron clues. Thanks to this fine analysis, friction scenarios can be reconstructed in accordance with the time-series acquired during tests.

For tests conducted on Carrara marble, with a low velocity (linear velocity $<$ 0.1 m s-1.), we observe that, independently of the normal load applied, the friction coefficient exhibits a clear transition between an idealized lab conditions regime and a mature interface with the formation of granular gouge, as a function of the sliding distance. The longer the sliding distance, the more the track becomes uniformly rough and the more the pin is abraded and cover of granular particles. Surprisingly, the wear rate increases while the pin's contact surface increases while abrading, so that the apparent normal stress decreases. The post mortem analyses of the pin's contact surface allow to understand the evolution of the microstructures as displacement increases, especially how the wear changes in relation of the circulation of the third body with in the contact. The granular gouge is analysed independently in order to determine the specific surface and to build an energetical balance of the shear induced by sliding.

For high velocity test (linear velocity $>$ 1m.s-1) on Carrara marble, the dynamic weakening observed is supported by mirror like surfaces on the contact interface created by frictional heating. Those surfaces mark a sharp contrast between the granular gouge or the intact minerals found in other tests. Thus, a close attention to the post mortem surfaces and their nanometric features inform us of the abrasion and deposition modes of the third body created during sliding.

Miniatured wheel-rail contact in lubricated conditions

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1 - IRT Railenium (France), 2 - Laboratoire de Mécanique des Contacts et des Structures [Villeurbanne] (France)

Speaker: Lesage Thibault. **Wednesday**. Start time: **17:45**. Room: Bureau Forum 2 LVL-2. Link to abstract.

KEYWORDS
Wheel-rail contact, Rolling contact fatigue, Lubrication

Abstract
Wheel/rail contact management is one of the main challenges in railways and impact both operation performances, cost and maintenance. This contact is fundamentally multi-parameters with factors coming from very distinct fields such as rolling stock nature, track geometry, traffic conditions, weather... In order to further comprehend the impact of a specific parameter, laboratory scale testing is a typical way to isolate one or a set of parameters. In this respect, both low scale (pin-on-disk, twin disk...) and full-scale benches (Deutsche Bahn's rig test A, Grenoble's Wheel...) are possible solutions, each of them proposing distinct advantages and drawbacks.

TriboRail test bench, developed during this project, lies between these two scales and offer representative contact conditions at 1/10th scale, with considerations for both materials solicitation and railways dynamics. Compared to full-scale tests benches, the test duration, cost and maintenance complexity are significantly lowered, which allows more systematic investigations.

The main objective of this work is to study Rolling Contact Fatigue (RCF) defects formation in a tight curve solicitation, depending on lubrication conditions. Contact conditions are defined using as reference an actual track localization where defects are often to be found. Contact conditions are monotonic, which maximizes RCF defects occurrence and, hereby, lower test duration. The impact of lubrication on wheel-rail contact is followed *in-situ*, in particular by friction coefficient evolution, as well as characterized after testing, by investigating wear and fatigue by surface and microstructural analyses. The impact of lubrication conditions on both wear and RCF resistance are then discussed in order to quantify its impact on rail service life.

Acknowledgments
The authors would like to gratefully thank Dr. H. Chollet, Université Gustave Eiffel - GRETTIA for initial TriboRail test bench conception. This work is part of LubRail project, co-founded by SNCF-Réseau.

Observations of a Carbon/Carbon composite interface under thermal and tribological solicitations

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Speaker: Bergère Hugo. **Wednesday**. Start time: **18:05**. Room: Bureau Forum 2 LVL-2. Link to abstract.

KEYWORDS
Wear; Friction; Pin on Disk Tribometer

Introduction
To assure the efficiency of aeronautical braking operations, high performance break disks made of Carbon/Carbon composites are usually used.
This material is notably characterized by its low density and the stability of its mechanical and thermal properties at very high temperatures.
Studies around the tribological behaviour of C/C composites have been led to understand the wear mechanisms induced by the friction. Goudier et *al.* (1) and Kasem et *al.* (2) have studied the physicochemical reactions occurring during the transition of the friction coefficient. As temperature influences the wear rate, thermal contributions also need to be included.
In this context, this work aims to link thermal and tribological contributions to the wear mechanisms of C/C composites.

2. Methods
To reproduce a Carbon/Carbon composite interface, a Pin on Disk tribometer has been used. Different conditions have been experimented as the setup allows to impose various pressures, rotation speeds and initial temperatures. The experiments are limited to a unique environment (air, 50% relative hygrometry).
Measurements of both thermal (temperatures in the pin and the disk by thermocouples) and tribological (normal and tangent efforts used to determine a macroscopic friction coefficient) are performed all along the experiments.
Images of the friction interface are also captured by both high-speed and IR cameras. Those observations allow to study the contributions of the interface's components.

3. Results
By measuring the friction coefficient under various conditions, the influence of both mechanical (pressure, rotation speed) and thermal (interface temperature) can be determined.
Then, local observations have shown the contributions of the microstructure and the third body on the friction.

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MS8.4 - Fundamentals of Friction

Organisers: Clelia Righi (University of Bologna), Lucas Frérot (Institut Jean Le Rond D'Alembert) and Denis Mazuyer (Ecole Centrale Lyon)

Tailoring the Steel/Amorphous Carbon Interfacial Shear Strength by Doping Amorphous Carbon with Rare-Earth Elements

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1 - The University of Texas at Austin (United States)

Speaker: Mangolini Filippo. Keynote. **Thursday**. Start time: **14:15**. Room: Rhône 5 LVL1. Link to abstract.

Dopants and alloying elements are commonly introduced in amorphous carbon (a-C) materials to tailor their mechanical and tribological properties. While most published studies have focused on doping and/or alloying a-C coatings with metals or metalloids, doping a-C films with rare-earth elements has only recently been explored. Notably, our understanding of the shear-induced structural changes occurring in rare-earth element-containing a-C films is still elusive, even in the absence of any liquid lubricants. Here, the friction response of Eu- and Gd-containing a-C films with low hydrogen content was evaluated in open air and at room temperature. The normal pressure-dependent friction measurements indicated that the introduction of Gd ((2.3 ± 0.1) at.%) and Eu ((2.4 ± 0.1) at.%) into the a-C matrix results in a significant reduction of the shear strength of the sliding interfaces ((41 ± 2) MPa for a-C, (16 ± 1) MPa for a-C:Gd2.3 at.%, and (11 ± 2) MPa for a-C:Eu2.4 at.%.). Notably, these interfacial shear strength values for a-C films sliding against steel are favorably comparable with the values obtained from atomistic simulations of self-mated H-passivated a-C:H contacts, thus suggesting that the macroscale response of the sliding contact is determined by the shear response of colliding nanoscale asperities. NEXAFS spectromicroscopy experiments provided evidence that no stress-assisted sp3-to-sp2 rehybridization of carbon atoms was induced by the sliding process in the near-surface region of undoped a-C, while the amount of sp2-bonded carbon progressively increased in a-C:Gd2.3 at.% and a-C:Eu2.4 at.% upon increasing the applied normal load in tribological tests. The formation of an sp2-bonded carbon-rich surface layer in a-C:Gd2.3 at.% and a-C:Eu2.4 at.% films is postulated to induce shear localization within the sp2-carbon rich layer and the transfer film formed on the countersurface, thus decreasing the interfacial shear strength. These findings open the path for the use of Gd- and Eu-containing a-C even under critical conditions for nearly hydrogen-free a-C films (*i.e.*, humid air).

Relating atomic-scale surface structure to friction via multiscale simulations: the cases of PTFE and B-doped diamond-like carbon

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Speaker: Moras Gianpietro. **Thursday**. Start time: **14:55**. Room: Rhône 5 LVL1. Link to abstract.

Friction in dry and boundary lubrication conditions is strongly influenced by the atomic structure of the sliding surfaces. In general, a stable passivation of surface dangling bonds is a prerequisite for low friction and wear. However, even subtle changes in surface chemistry can cause the friction coefficient of passivated interfaces to vary by an order of magnitude (1). In this talk, I will present the results of multiscale simulation studies that combine density functional theory, non-reactive molecular dynamics and contact mechanics to shed light on the relationships between the chemical structure of surfaces and friction.
The first case study involves fluorinated carbon materials. Some of these materials, like PTFE, have exceptional tribological properties. However, their chemical stability poses serious problems because of their accumulation in the environment and in biological systems. Therefore, regulations in this area aim to their replacement and understanding the mechanisms responsible for their friction properties may help in this non-trivial process. The results of our multiscale simulations allow us to answer some fundamental questions in this context: Why are perfluorinated carbon materials polar and hydrophobic (2)? Why are they more slippery than their hydrogenated analogues (3)? Why is PTFE non-sticky but forms transfer films on PTFE-lubricated steel surfaces (4)?

In the second case study, I will focus on friction of boron-doped diamond-like carbon coatings in humid air. While boron typically reduces wear in cutting applications, some B-doped coatings show poor tribological performance compared with undoped films. Our simulations suggest that the friction increase could be related to a subtle change in surface chemistry caused by boron atoms (5). Hydroxyl groups that normally passivate carbon surfaces in humid environments can be activated by boron and form B–O dative bonds across the tribological interfaces, leading to a mild friction increase.

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Synergistic effects of nitrogen-containing functionalized copolymer and silicon-doped DLC for friction and wear reduction

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Speaker: Pedretti Enrico. **Thursday**. Start time: **15:15**. Room: Rhône 5 LVL1. Link to abstract.

Lubrication systems based on polymer additives and diamond-like carbon (DLC) coatings have long been recognized for their potential to reduce friction and wear in industrial applications. However, achieving optimal compatibility between additives and DLC surfaces has remained a challenge due to the low reactivity of traditional lubricants with DLC. Recent advancements in chemical modifications, such as silicon doping in DLC and functionalization of copolymers with nitrogen-containing groups, offer a promising pathway to address this limitation.
This study investigates the synergistic effects of functionalized copolymers and silicon-doped DLC (Si-DLC) films in reducing friction and wear. Experimental tribological tests reveal that the nitrogen-functionalized copolymers significantly improve lubrication, reducing friction and wear by forming a tribofilm on Si-DLC surfaces. Ab initio simulations highlight the critical role of N-Si interactions in promoting chemisorption of the additives, a key step in tribofilm formation. These findings demonstrate how tailored chemical modifications to both lubricants and substrates can enhance tribological performance, paving the way for innovative lubrication solutions in automotive and manufacturing industries.

(1) Omiya, T., Pedretti, E., Evaristo, M., Cavaleiro, A., Serra, A. C., Coelho, J. F. J., Ferreira, F., & Righi, M. C., Synergistic effects of nitrogen-containing functionalized copolymer and silicon-doped DLC for friction and wear reduction. Tribology International vol. 200 110183 (2024) (https://doi.org/10.1016/j.triboint.2024.11

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Tribochemical Phenomena at Diamond-Silica Interfaces by Ab Initio and Machine Learning Molecular Dynamics

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Speaker: Ferrario Mauro. **Thursday**. Start time: **15:35**. Room: Rhône 5 LVL1. Link to abstract.

The diamond-silica interface is a system of high relevance for the chemical mechanical polishing of diamond and other technological applications. It can be also seen as a reference platform for assessing the behavior of diamond in terms of friction and wear under tribological conditions. We employ ab initio and machine learning molecular dynamics calculations for evaluating the impact of different diamond surface terminations and orientations, along with boron (B) doping, on the tribologically-induced interactions at the diamond-silica sliding interface. The Pandey-reconstructed C(111) surface behavior is found to be dominated by weaker van der Waals interactions and Pauli repulsion at the interface in all cases, while the C(110) surface is the most prone to wear. Among the different passivating species considered, F and H+OH terminations are the most efficient means of reducing friction and increasing interfacial separations. On the other hand, B dopants at the diamond surfaces are able to promote chemical interactions at the interface and more prone to be detached to silica. The study of large systems on the nanosecond timescale with quantum accuracy is made possible thanks to a workflow for smart configuration sampling (SCS) in active learning that permit to obtain machine learning interatomic potentials that are enough robust and accurate also in the characteristic harsh conditions generated by high loads and shear rates. These results are part of the "Advancing Solid Interface and Lubricants by First-Principles Material Design (SLIDE)" project that has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (Grant Agreement No. 865633)

Why Static Friction Decreases From Single to Multi-asperity Contacts

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Speaker: Roch Thibault. **Thursday**. Start time: **16:30**. Room: Rhône 5 LVL1. Link to abstract.

The key parameter for describing frictional strength at the onset of sliding is the static friction coefficient. Yet, how the static friction coefficient at the macroscale emerges from contacting asperities at the microscale is still an open problem. Here, we present friction experiments of silicon-on-silicon contact, in which the normal load was varied over more than three orders of magnitude, so that a transition from a single asperity contact at low loads to multi-asperity contacts at high loads was achieved. We find a remarkable drop in static friction coefficient with increasing normal load, which can be captured by a simple stick-slip transition model, analogous to a fiber bundle model, based on the local normal contact stress map obtained from boundary integral contact calculations without adjustable parameters. We identify the presence of pre-sliding and subcritical contact points as the cause of smaller static friction coefficient at increased normal loads. Our measurements and model bridge the gap between friction behavior commonly observed in atomic force microscopy (AFM) experiments at microscopic forces, and industrially relevant multi-asperity contact interfaces loaded with macroscopic forces.

Physical origin of friction relaxation after interrupted sliding

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Speaker: Boulet Baptiste. **Thursday**. Start time: **16:50**. Room: Rhône 5 LVL1. Link to abstract.

One of the most generic friction laws is the so-called rate-and-state friction law (1). It combines the time-evolution of the static friction coefficient and the sliding-velocity-dependence of the dynamic friction coefficient. It is parametrized by two empirical parameters, which can be calibrated using macroscopic tests: the slide-hold slide and the velocity step tests.
In the slide-hold-slide test, the friction coefficient relaxes during hold (when the contact is left at rest after interrupting full sliding). The physical origin of the relaxation remains unclear: is it a bulk relaxation, an interfacial slip-based relaxation or a mixture of both? In this work, we address this fundamental question in the case of dry elastomer/glass contacts. Our strategy is to monitor experimentally the displacement field at the contact interface when sliding is stopped, based on image correlation techniques. Doing this, the amount of slip that occurs after stopping the motion can be quantified.

We performed experiments on an elastomer sphere / glass plane contact during interrupted shear tests for different waiting times. The sphere is made, for optical purposes, of polydimethylsiloxane (PDMS), and has a curvature radius R=9.42 mm. As close as possible to the PDMS sphere surface, a thin subsurface layer of particles is added to enable in operando evaluation of the shear displacement field thanks to digital image correlation (DIC) analysis (2) and/or particle tracking (3). The obtained fields allow to study the local behavior at the contact interface and in particular to identify the sticking and slipping zones during the post-shearing relaxation.

We have quantified the time-dependence of the contact area and of the slip field, as functions of the normal force and of the shear distance before the stop. We could thus conclude about the combination of mechanisms involved in post-shear relaxation, shedding fundamental light into the origin and contact history dependence of the static friction force.

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Concurrent slow and fast frictional ruptures

Shi Songlin (1), Fineberg Jay (1)

1 - The Hebrew University of Jerusalem (Israel)

Speaker: Shi Songlin. **Thursday**. Start time: **17:10**. Room: Rhône 5 LVL1. Link to abstract.

Frictional motion is triggered by interface failure, akin to earthquakes that occur along faults. As in rapid earthquakes, these ruptures generally accelerate rapidly, eventually propagating at velocities approaching the Rayleigh wave speed. Slow ruptures, however, may occur in both laboratory and natural fault settings, but the mechanisms that drive them are not fully understood. Here we experimentally show, by direct measurements of the real contact area and local strains, that both extremely slow (cm/sec) and fast (km/sec) ruptures can repeatably propagate within the same frictional interface. We demonstrate that a dynamic equilibrium between loading rates and velocity-dependences of both interface resistance and fracture energy enable slow ruptures to nucleate and propagate at very low applied shear stresses. In the same interfaces, fast ruptures also occur, but only when their nucleation becomes possible at higher stress conditions. We find that the dynamics and structure of both rupture classes are well-described by Fracture Mechanics. Their existence results from close interplay between interface properties and rupture velocity. These results provide a fundamental understanding of the mechanisms driving both slow to fast ruptures and their transitions and offer key insights into fault mechanisms and frictional motion.

Friction sound: A fundamental mechanism of dissipation at the origin of friction force

Le Bot Alain (1), Assemien Modeste N'guetta (2)

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Speaker: Le Bot Alain. **Thursday**. Start time: **17:30**. Room: Rhône 5 LVL1. Link to abstract.

Friction sound is generated when two solids in contact are rubbed on against each other. Among several types of friction sound, we may separate those whose origin is local or global mechanical instability, such as squeal noise, squeak noise that appears in doors, breaks, tyres, belts... and those whose origin is the mechanical interaction of rough surfaces at the microscopic level. In this study, we examine the fundamental mechanism generating the so-called *roughness noise*, the second class of friction sound.
We show that the generation of vibration is due to mechanical impacts between surface asperities of antagonist surfaces. These light shocks, appearing at the scale of micrometer, constitute a large population of fundamentally unpredictable events. Application of statistical mechanics is therefore the appropriate theoretical tool for its study. We show that the vibration induced by roughness noise is disordered, exactly like the vibration of atoms but confined in the audio frequency band, and then may be considered as heat. An estimation of the modal energy stored in mechanical modes of the solids highlights that the vibrational energy has an acoustical temperature of order of 10^{15} K. Fortunately, this temperature localized in a narrow band of low frequencies of order of kilohertz, is not in thermal equilibrium with physical temperature of order few hundreds kelvins but localized in a wide band of frequencies beyond gigahertz (the natural frequency of the molecule H_2O is 22.3 GHz).
We propose to interpret roughness noise as a transfer of mechanical energy of the sliding solid into vibrational energy of surfaces. This transformation may be viewed as a dissipation mechanism of the kinetic energy. A such, this dissipation is responsible of the emergence of a force to maintain constant the speed of the sliding solid. From experimental results, we have measured the power required to produce a roughness noise. This power is converted in a force standing in the way of the motion, and compared it with the friction force. It results that roughness noise is responsible of a very small part of the dissipation by friction but not so small considering the narrowness of the audio frequency band.

Experimental and numerical study of the thermomechanical and tribological mechanisms involved in dry friction brake emissions

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Speaker: Caradec Quentin. **Thursday**. Start time: **17:50**. Room: Rhône 5 LVL1. Link to abstract.

Context

The braking function on land vehicles relies, at least in part, on friction to dissipate kinetic energy. It is well-known that frictional braking systems are a major source of nuisance, especially in urban areas. For instance, the brake pad-disc system may experience friction-induced vibrations, which generate high-intensity, high-frequency noise known as squeal. This phenomenon is seen as an important issue by manufacturers due to the costs associated with customer claims. In addition, it is now established that friction brakes are the cause of significant air pollution related to the emission of fine particulate matter, which poses serious human health risks. The mechanisms behind these friction brakes pollution and emissions remain poorly understood due to their dependence on complex tribological and thermomechanical interactions.

The study of brake emission mechanisms is made difficult by the virtual impossibility of accessing the interface under operating conditions. Consequently, studies to understand the phenomena involved in noise and particle emissions often rely on parametric experimental studies, highlighting the role of loading parameters such as temperature. To go beyond global information, studies are often carried out on simplified experiments such as pin-on-disc systems, and involve in-depth thermal and mechanical measurements as well as surface observations. Various experimental studies have shown, for example, that microscopic and macroscopic contact conditions play a key role in the appearance of emission phases (1). In particular, thermomechanical effects, such as thermal expansion and wear, have a major influence on the location of the contact loading zone on a macroscopic scale (2). Experimental evidence suggests that these effects can be understood by considering the temperature level measured near the surface, which may be a relevant indicator of both squeal occurrences and particle emission rates (3). A great deal of work has also gone into analyzing surfaces and describing the tribological circuit whose morphology and constitution act on excitation mechanisms and wear mechanisms of which particles are a part. From these analyses, load bearing areas can be identified which relate to the contact loading zones identified as relevant indicators. However, surface analyses are carried out post-mortem, which makes it difficult to relate them to the solicitation history.

Objective and strategy

The aim of this work is to reconstruct the local load history, i.e. the bearing capacity zones resulting from thermomechanical and tribological mechanisms, and to relate them to the particle emission and squeal occurrence phases. The strategy is to conduct highly instrumented experiments to monitor the load bearing areas close to the contact surface (subsurface). Surface analysis (observation and profilometry) are performed before and after each test. Finally, for interpretation purposes, inverse analysis methods are used to derive surface information from the measurements, and direct thermomechanical modeling is also carried out to illustrate some of the phenomena involved.

Methods: Experiment

A pin-disk experiment is used, specially designed to reduce dynamic complexity (minimization of contact joints and adapted geometry) and to facilitate instrumentation (cubic pin). Instrumentation includes measurements of forces, displacements, accelerations, etc. For contact mapping, near-surface thermal instrumentation is included. 16 thermocouples are embedded within the pin, located 2 or 4 mm beneath the contact surface. On the other surface, on the disk side, thermal monitoring is performed using an infrared camera. Additionally, two three-dimensional piezoelectric force sensors and three eddy-current displacement sensors enable a tracking of the pin dynamics. Noise emissions are recorded using a micro-

phone located 1 meter away from the pin-on-disc system. To analyze particle emissions, the contact is encapsulated within a chamber in which an air flow is generated to collect a part of the particles ejected out of the contact. The air flow with the collected particles is directed to an Engine Exhaust Particle Sizer (EEPS) device which analyzes the quantity and size distribution of the collected particles.

Two optical profilometers with focus variation are installed on the test bench for discrete surface monitoring. Between each contact phase, the pin support is rotated to make the 2 contact surfaces accessible for measurement. High-resolution profiles and optical maps are then obtained.

Methods: Models
Models are used to support experiments and interpret measurements. Inverse numerical analysis is first used to trace information from subsurface thermocouples to surface heating and heat flow dissipation areas, which are then associated with contact surfaces. Additionally, to gain deeper insight into the thermomechanical mechanisms involved, a three-dimensional finite element model of the pin-on-disc system is used to perform quasistatic simulations of the thermomechanical coupling. The friction energy dissipation is used as a surface heat source in the contact interface, and the resolution of the transient thermal problem yields the temperature evolution in the pin and disc. This thermal resolution is alternated with a quasistatic resolution of the frictional contact problem accounting for the thermal expansion of the solids, which alters the contact area and distribution of friction energy dissipation over the surfaces, allowing in return to update the source heat flux for the thermal problem. This numerical approach offers detailed insights into the thermomechanical conditions that promote noise and particle emissions. This type of analysis makes it possible to separate the phenomena of contact localization resulting from thermoelastic deformation and thickness variations including wear.

Results
Series of tests were carried out with a variation in speed, force and duration. Evolutions of the squealing phases and particle emissions events are observed with a sensitivity to the first order of the temperature, as expected but also with an influence of the loading history, i.e. previous tests. The overall request information of speed, forces, temperatures nevertheless remain insufficient given the variation in noise and emissions phases. The processing of experimental data made it possible to reconstruct the evolution of the load bearing zones showing significant and very variable variations from one test to another. This information is processed in support of the discrete analysis of the surfaces, on the basis of observations before and after testing, making it possible to reconstruct the history of the evolution of the surface, from initial surfaces which differs from a test to another. It is shown that areas of accumulated powders and compacted plateaus can be associated to the initial surface, before test, and load bearing areas history. Finally, the thermomechanical modeling data, associated with the experiments, make it possible to establish the scenario of the thermomechanical and tribological processes involved. This history is linked to that of the noise occurrences and the emission phases showing that they are related to specific behaviors of the macroscopic contact localization. For example a distinct cyclic radial shift of the contact localization is observed, presumably leading to periodic contact openings and closures. These specific conditions are found to be closely correlated to important emission episodes.

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Friction mechanisms of water-rubber multi-asperity interfaces

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Speaker: Mazuyer Denis. **Friday**. Start time: **10:00**. Room: Rhône 5 LVL1. Link to abstract.

Many mechanical systems involve water-rubber interfaces such as joints sealing, tire/road or wiper blade/windscreen contacts. Their friction mechanisms rises from the combining three major sources which relative contribution depends on the environment of the contact and the water phases:
- The proper viscoelastic dissipation of the rubber itself ;
- The adhesive nature of the contact which is governed both by the molecular structure and the surfaces roughness ;
- The dynamics of the multi-asperity interface.

In this framework, the challenge is the investigation of the water-rubber interfaces over a macroscopic scale that covers a sufficient amount of contact spots in order to develop a statistical approach. In this talk, the latter is highlighted through two particular examples:
- The stick-slip of an elastomer/glass contact immersed in liquid water : thanks to a model, based on a single degree-of-freedom mass-spring-damper oscillator we defined a stability criterion combining on the elastomer intrinsic material damping and the friction-velocity dependence. The origin of the instability is explained the physical nature of the contact spots in which we pointed out the prior importance of adhesion capillary forces. A friction law based on the surface topography analysis of the rubber has been established ;
- The unexpected coupling between adhesion, elastomer viscoelasticity and thermal effects in the frictional behavior of an ice/rubber contact: thanks to a in situ contact area measurements, a dimensionless friction master curve was obtained with the sliding velocity, regardless of the temperature and the material properties. A predictive friction model was proposed to explain the bell-shape friction-velocity curve for which the classical WLF transform is not relevant.

Multiscale Investigation of Tribological Interactions at the Rubber/Ice Interface

Dalavale Kaiser Pinto Anderson (1), Mazuyer Denis Cayer-barrioz Juliette

1 - Laboratoire de Tribologie et Dynamique des Systèmes (France)

Speaker: Dalavale Kaiser Pinto Anderson. **Friday**. Start time: **10:20**. Room: Rhône 5 LVL1. Link to abstract.

According to the U.S. Department of Transportation, 24 percent of annual car accidents are attributed to snow or ice on roads, encompassing both minor and severe collisions. Additionally, the International Union for Conservation of Nature reported that tires accounted for 28 percent of microplastic pollution in oceans as of 2017, making them the second-largest source of such pollutants.
This study addresses two critical challenges - enhancing road safety on icy surfaces and mitigating environmental pollution - by investigating the interfacial friction response of ice/rubber contacts under a broad range of environmental conditions. Experiments were conducted at temperatures as low as -28∘C and sliding velocities ranging from 50 μm/s to 1 m/s. Rubber samples, provided by Michelin, varied in composition, surface topography, and mechanical properties. The ice used in the experiments was homogeneous, transparent, and prepared through a controlled machining and thermalization process.

A novel in-situ contact area measurement methodology was developed to capture the static and dynamic behavior of the ice-rubber interface during mechanical loading, unloading, and sliding. By combining in-situ visualization of contact areas with friction force analysis, the study elucidated the complex interplay between adhesion, viscoelastic, and thermal effects in governing frictional behavior. These mechanisms were examined as functions of sliding velocity and temperature, providing insights into the dynamics of the ice-rubber interface in real-time.
Building on the foundational work of Schallamach and later developments by Chernyak and Leonov, a friction model was proposed to account for molecular-level interactions. This model incorporates the time-temperature dependence of the formation and rupture of molecular junctions at the rubber-ice interface, offering a comprehensive framework for understanding and predicting frictional performance under diverse conditions.

Investigating the effect of size, shape, and strain on the sliding behavior of bilayer graphene using a continuum-based approach.

Yadav Gourav (1), Gupta Shakti S. (1), Sauer Roger A. (2) (3) (4)

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Speaker: Yadav Gourav. **Friday**. Start time: **10:40**. Room: Rhône 5 LVL1. Link to abstract.

Two-dimensional (2D) materials like graphene, hexagonal boron nitride (hBN), and transition metal dichalcogenide (TMD) exhibit exceptional individual properties(**1-2**). However, even more exciting phenomena emerge when similar or dissimilar 2D materials are stacked to form layered crystalline structures. These materials possess significant interfacial properties, along with local and global structural modulations influenced by strain engineering and junction types. These factors govern various critical properties such as superlubricity, superconductivity, directional friction, and interlayer stiffness. These features are crucial for applications in MEMS/NEMS devices, sensors, composites, flexible electronics, and optoelectronics(**3-4**).
The superior properties of stacked 2D materials arise from the coupling of strong intralayer elastic interactions with weak interlayer van der Waals forces. Over the past decade, several studies using molecular dynamics (MD) simulations and density functional theory (DFT) have explored the effects of size, shape, lattice mismatch, and external loading on these materials(**5-6**). While these methods have provided results consistent with experimental findings, there remains a need for theoretical and continuum-based approaches to establish generalized relationships and reduce computational costs.

To address this, we developed a continuum-based numerical model to study the interfacial sliding properties of bilayer graphene. Our model investigates the effects of size, shape, lattice mismatch, and loading conditions on the behavior of these materials. The study highlights surface reconstruction phenomena, which are critical for electronic devices, and identifies directional sliding stiffness with potential applications in sensors. For example, in gas sensors, the van der Waals absorption of gas molecules on the layered structure's surface can alter the interfacial vibrational frequencies of the sheets. Our approach offers a computationally efficient and cost-effective means to understand and predict the behavior of layered 2D materials, paving the way for advancements in various technological applications.

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Metainterfaces with specified friction laws : new designs from numerical optimization

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Speaker: Scheibert Julien. **Friday**. Start time: **11:00**. Room: Rhône 5 LVL1. Link to abstract.

Many devices, including touchscreens and robotic hands, involve frictional contacts. Optimizing these devices requires fine control of the interface's friction law. We have recently proposed a generic surface design strategy to prepare dry rough interfaces that have predefined relationships between normal and friction forces (1). Such metainterfaces are made of assemblies of spherical asperities that, collectively, produce an emergent macroscopic friction law. The individual height of each asperity is prescribed through inversion of a suitable upscaling model. In (1), the inversion was analytical, which strongly limited the number of accessible friction laws. Here, we use genetic algorithms to identify complex designs that meet previously unaccessible specifications. For instance, we apply this method to obtain friction laws with a true proportionnality between friction and normal forces at large normal forces. This method therefore offers ways to create metainterfaces with on-demand values of the friction coefficient, without changing the pair of materials in contact. Our new designs are validated experimentally on glass/polydimethylsiloxane (PDMS) metainterfaces. Overall these results lay the foundations for automated ways of designing soft contact interfaces with a large breadth of desired friction behaviour. (1) A. Aymard, E. Delplanque, D. Dalmas, J. Scheibert. Designing metainterfaces with specified friction laws. *Science* **383**, 200-204 (2024)

Friction dynamics in the presence of a third body - Application to earthquakes

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Speaker: Mollon Guilhem. **Friday**. Start time: **11:20**. Room: Rhône 5 LVL1. Link to abstract.

The initiation of a sliding motion in the frictional interface between two elastic solids in generally believed to obey the main principles of Liear Elastic Fracture Mechanics (LEFM). In this view, more attention is paid to the fracture energy of the interface than to the details of its frictional behavior. Many experimental, theoretical, and numerical works support this view, but they all rely on the assumption of scale separation that ensures that the contact interface and the process zone at the crack tip are infinitely smaller than the dimensions of the whole system. While this assumption is acceptable in a laboratory context where clean and smooth surfaces are generally considered, it remains to be validated in more practical cases of worn and mature contacts, which typically exhibit a third body. This is in particular the case in the major field of application of such theories: earthquake science. Indeed, this is the context where the dynamics of the porpagation of a sliding rupture have the most dramatic effects, and this is also a situation where we know that interfaces are not clean. The geological third body present in a seismic fault is called "gouge" in the geological terminology, and is the product of rock abrasion and comminution that occured during past slip events on the same fault. We may therefore question the assumptions and results of LEFM in this context.

For this purpose, we built a numerical model of a meter-scale laboratory earthquake. This model couples discrete and continuum mechanics in order to represent in the same numerical framework (i) the elastic continuum formed by the intact rock surrounding the fault, which is able to store and release strain energy and to transmit seismic waves during the fault failure, and (ii) the granular/powdery gouge that fills the fault and controls its frictional rheology. We elaborate on previous smaller (20 mm in length) models, which were purely granular (with micrometric grain sizes). These models investigated the various ways sliding can be accommodated within such an interface depending on the local gouge properties (e.g. grains sizes and shapes, contact friction, cementation, porosity, etc.), and derived slip-weakening friction laws associated with these different configurations. This granular model is now considerably upscaled (64 cm of length instead of 20 mm, with the same thickness), and coupled with the elasto-dynamics of the surrounded medium. This allows to load this interface until its frictional peak (thereby storing large amounts of strain energy in the surronding rock), and to trigger a spontaneous frictional instability in the center of the system.

Results show that this instability slowly nucleates before taking the form of a pulse-like rupture front: a laboratory earthquake. The rupture front propagates in an irregular way, activating various localization patterns (e.g. inclined Riedel bands, boundary-sliding ,etc.) in the regions of the granular gouge layer that it progessively reaches.The early stages of this propagation occur at a velocity lower than the Rayleigh wave speed, but activate supershear (i.e. approaching the P-wave speed) failures after a certain propagation distance, producing visible mach cones in the surrounding continuum. A comparison with a simpler model replacing the gouge layer by an equivalent friction law leads to different results, with a crack-like friction front and an immediate supershear transition. This difference is attributed to the heterogeneous rheology of the granular layer and to its inherent dilatational behavior. It illustrates that the propagation of fault rupture fronts may be more complex that what LEFM predicts, and that friction is not only fracture.

MS8.5 - Fretting Wear & Fretting Fatigue

Organisers: Siegfried Fouvry (Ecole des Mines de Paris), Tomasz Liskiewicz (Manchester Metropolitan University) et Sylvie Descartes (LAMCOS)

The cohesive zone crack analogue for torsional fretting under mild wear conditions

Giannakopoulos Antonios (1), Lindley Trevor (2), Zisis Athanasios (1)

1 - National Technical University of Athens [Athens] (Greece), 2 - Imperial College of Science, Technology and Medicine (United Kingdom)

Speaker: Giannakopoulos Antonios. Keynote. **Thursday**. Start time: **14:15**. Room: Saint Clair 3B LVL3. Link to abstract.

Torsional fretting fatigue may appear in mechanical components that are in contact under vibrational twisting moments, inducing oscillatory frictional stresses. Fretting fatigue cracking is important, with its initiation being difficult to estimate. This work extends a well-known fretting fatigue model, the crack analogue model that examines fretting fatigue induced by circular contacts of metallic surfaces. This is done by inserting a mode III type cohesive zone at the contact edges. In our previous works on fretting fatigue of complete contacts, we proposed mixed mode I and II cohesive zones because of the nature of the stress fields around the contact edges. The proposed cohesive zones address several issues related to the mechanics of friction and wear, by combining them in the case of mild wear where asperity plastic shakedown is the dominant inelastic mechanism. Thus, the micromechanical behaviour of the surface topology and its evolution are naturally introduced into the analysis. The surface roughness becomes an internal variable that evolves with the cyclic loading, establishing a steady state friction coefficient. Alternatively, friction evolution can be established pointwise by monitoring the accumulated micro-slip. The work of friction dissipates the mechanical work and at the same time becomes the precursor of large scale wear. A predictive methodology for fretting crack nucleation is proposed through the fatigue threshold stress intensity factor used in ordinary fatigue.

Experimental study and modelling of fretting-fatigue-corrosion of galvanised steel in power lines.

Medrala Clément (1) (2) (3), Arnaud Pierre (1), Duhamel Cécilie (1), Fouvry Siegfried (1) (4), Maurel Vincent (1), Said Julien (5)

1 - Centre des Matériaux (France), 2 - Laboratoire de Tribologie et Dynamique des Systèmes (France), 3 - Réseau de Transport d'Electricité [Paris] (France), 4 - Laboratoire de Tribologie et Dynamique des Systèmes (France), 5 - Réseau de Transport d'Electricité [Paris] (France)

Speaker: Medrala Clément. **Thursday**. Start time: **14:55**. Room: Saint Clair 3B LVL3. Link to abstract.

Electrification and energy transition is challenging all the Transmission System Operators (TSO) with a significant increase demand for electrical energy. RTE is the French TSO responsible for trading electricity with its European neighbors and operating and maintaining the French grid. Electricity is partly transmitted by overhead conductors (unburied lines supported by pylons). At present, the lines are designed to be renewed after 85 years of service, which implies major renewals by 2030-2035. RTE is therefore seeking to develop tools within its R&D asset management department to prioritize the replacement of lines. ACSR (Aluminium Conductor Steel Reinforced) cables are one of the cable technologies used to transport electricity. They are constituted of galvanized steel strands in the core and aluminium strands around the edge to ensure good mechanical properties and electrical conductivity respectively. The strands are subject to fatigue due to their own weight and the action of the wind. In addition, this assembly allows slight relative movement between the wires, resulting in fretting within the conductor. The combination of these mechanical loadings, known as fretting-fatigue, induces cracking and wear and is particularly critical compared to fatigue alone. Finally, since the cable is not insulated from the environment, rain and condensation induce the presence of water in the conductor, inducing corrosion. The aim of this study is to characterise the effect of fretting-fatigue-corrosion on the conductor strands near suspension clamps (critic zones). Another, objective is to observe the influence of the aqueous environment on the corrosion products in a contact or on crack propagation. The development of a fretting-fatigue-corrosion test rig was a part of this thesis. In order to apply representative loadings and lead the tests parameters, a so-called 'global' finite element simulation of a clamp/conductor system was carried out. It models one meter of a 51 wire strand. The contacts in the strand at the exit of the clamp are detected and the forces are extracted for each wire. This post-processing provides a distribution of the contact parameters in the strand. With these results, fretting-fatigue tests on steel-steel contacts in ambient atmosphere and fretting-fatigue-corrosion tests in salt solution are carried out to understand the effect of mechanical loading (normal force, displacement amplitude, fatigue stress...) and atmospheric parameters on the lifetime of a contact (frequency effect, solution...). The evolution of the galvanized layer in the contact is also observed. All these data are used to install a 'local' modelling of a single contact which is representative of the specimen in the test bench. This modelling is based on a finite element model combined with post-processing using a non-local approach and multiaxial fatigue criteria. The purpose of this model is to estimate the lifetime of a contact in a conductor.

In-situ monitoring of crack initiation and propagation for additive manufactured 316L stainless steel under fatigue loading

Ozdogan Cansin (1), Mohammadi Sangjouey Bijan (1), Malekan Mohammad (1)

1 - Centre for Industrial Mechanics, Department of Mechanical and Electrical Engineering, The Faculty of Engineering, University of Southern Denmark (Denmark)

Speaker: Ozdogan Cansin. **Thursday**. Start time: **15:15**. Room: Saint Clair 3B LVL3. Link to abstract.

Fatigue cyclic loading is one of the most challenging fields in different industries, including automotive and aerospace industries. The lifespan and crack propagation of the metallic structures are still intriguing and critical topics. In this research, the lifetime and crack growth rate under uniaxial fatigue loading are being investigated for additive manufactured (AMed) 316L stainless steel. The samples are manufactured using a machine based on laser powder bed fusion. The central cracks are cut at lengths of 5 mm and 10 mm through the rectangular plate as a straight line and inclined at 45 degrees. These samples are subjected to uniaxial fatigue loading under different frequencies (10 and 20 Hz), stress ratios (R = 0.1 and 1) to investigate the fatigue and fracture behavior of AM 316L stainless steel material. During the loading, an infrared thermal camera is being used to record temperature variations and to capture areas where the heat is released because of plastic deformation and crack growth. Similarly, the crack extension versus time is recorded through a portable high-resolution camera to evaluate the crack growth rate under loading conditions. This advanced test setup is considered to present more controllable and practical way to generate S-N curves and calculate m and C coefficient values of the Paris law equation. Additionally, comprehensive microstructure studies are being carried out to discover and support multiple reasonings behind the fatigue failure mechanism. For instance, scanning electron microscope, electron backscattered diffraction, and ATEC profilometer are employed to illustrate the internal features such as crack initiation sites, crack propagation, final failure regions, lack of fusion, grain boundaries, solidification patterns, surface roughness and residual stress distribution. The porous percentage and void formation are monitored via an X-ray computed tomography equipment for different cycles by interrupting the experiment. As a result, the effects of crack geometry, frequency, stress ratio, stress amplitude, and surface roughness on lifespan and crack growth pattern of the AM material are enlightened in detail.

A reverse identification of the friction coefficient operating within crack lips through a complete elastoplastic simulation of 3D fretting fatigue cracks

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Speaker: Arnaud Pierre. **Thursday**. Start time: **15:35**. Room: Saint Clair 3B LVL3. Link to abstract.

Fretting fatigue involves mechanical loading characterized by oscillating friction and displacement, often leading to crack nucleation or wear depending on displacement amplitude. In industrial applications, such as overhead conductors for high-power transmission, fretting fatigue plays a critical role in determining component lifespan. These conductors consist of helically stranded aluminum wires, where misaligned contacts under external forces create elliptical contact areas. Low aluminum yield stress induces significant plasticity, enlarging the contact area and modifying local stress distributions. This cyclic loading can lead to crack growth and eventual failure, with lifetime reductions widely reported in the literature. This study builds upon experimental and numerical strategies developed to assess crack growth and arrest in aluminum wires under fretting fatigue. Using three-dimensional finite element analysis (FEA) incorporating 3D cracks, the investigation evaluates elastic and elastoplastic behaviors to replicate experimental results. It was found that purely elastic assumptions fail to capture the critical conditions for crack arrest. Incorporating elastoplastic behavior revealed stress intensity factor (SIF) evolution consistent with experimental observations, enabling a more robust numerical framework for studying crack propagation. Particular attention is given to the friction between crack lips. A reverse analysis method allows for the estimation of the coefficient of friction (COF), yielding values consistent with COF obtained by fretting experiments. These insights clarify the interplay between crack closure, local plasticity, and friction in determining whether cracks arrest or propagate to failure. This work highlights the necessity of considering plasticity and friction effects to predict fretting fatigue damage accurately. By combining numerical modeling with experimental results, the study provides a robust framework for understanding and mitigating crack propagation in critical applications, improving the predictive assessment of the mechanical behavior of aluminum wires.

Experimental and numerical study on the effect of interference on shrink-fitted assemblies under fretting-fatigue solicitations

Fourcin Morgan (1) (2), Fouvry Siegfried (1), Arnaud Pierre (1), Bridier Florent (2)

1 - Centre des Matériaux (France), 2 - Naval Group (France)

Speaker: Fourcin Morgan. **Thursday**. Start time: **15:55**. Room: Saint Clair 3B LVL3. Link to abstract.

Shrink-fitting is a common process used to assemble mating components such as axles, wheels, or sleeves, with significant applications in the railway and maritime industries. These assemblies are exposed to complex multiaxial fatigue loadings, including rotary bending, compression, and torsion. Moreover, differential deformations between the two parts can induce local fretting damage, which may lead to wear or crack initiation.
This study aims to explore the impact of interference values on fretting-fatigue behavior and consequently on the lifetime of such assemblies. Currently, no consensus has been reached in scientific literature regarding this issue. Modifying the interference value directly affects contact pressure, which in turn influences local stresses and sliding amplitudes, which are the driving factors of fretting. However, the impact on lifetime appears to depend strongly on the range of induced contact pressure, which remains notably low in the studied application due to the conforming contact configuration. Both experimental and numerical studies will be conducted to address this issue comprehensively.

The experimental investigations will focus on a simplified rotary bending loading case using two specially designed test benches. The test specimens consist of steel shafts with shrink-fitted bronze sleeves, representing a scaled model of a maritime drive shaft. Tests will be performed over a wide range of interference values to obtain fretting-fatigue S-N curves. Damage characterization will primarily address fretting wear debris and cracks. The third body layer, believed to control crack initiation, will be precisely quantified using a new disassembly-free protocol to enhance measurement precision.
In parallel, finite element analysis (FEA) modeling will be conducted to deepen the understanding of the phenomenon and to develop a life prediction model. The simulation will consider interference fitting and bending, as well as friction at the interface, to extract local contact variables such as slip and surface shear. Wear will also be integrated into to ensure accurate modeling of the fretting fatigue process. Multiple tribological and multiaxial fatigue criteria will be applied in post-processing to quantify fretting-fatigue damage.

In-situ measurement of the Fracture Toughness of Fretting obtained TTS in Ti6Al4V

Lefranc Vivien (1)(2) , Gandiolle Camille (1), Héripré Eva (1) (3), Fouvry Siegfried (2) (4), Aubin Véronique (1)

1 - Laboratoire de Mécanique Paris-Saclay (France), 2 - Centre des Matériaux (France)

Speaker: Gandiolle Camille. **Friday**. Start time: **10:00**. Room: Saint Clair 3B LVL3. Link to abstract.

Mechanical assemblies are often subjected to vibrations that generate micro-friction at the contacts: fretting. These slight displacements can lead to cracking and/or wear, reducing the service life of the assembly. Numerous models and tests exist to predict contact life, but there is still considerable room for improvement, based on a poor understanding of what happens in the contact. Indeed, most models use a continuous, homogeneous interface, whereas the actual contact area, pressure distribution and friction coefficient depend on the local state of the contact. Access to the evolution of the interface over time, as well as to its damage through wear and cracking, is therefore necessary to further the understanding and simulation of mechanical assemblies. An in-situ tomography test has been designed with this aim. It is instrumented to quantify local information (friction, stiffness, slip) during loading. It has been validated against the fretting vibration test under controlled load, with many cycles. It also makes it possible to reproduce the damage generated on conventional macroscopic test benches. The final design combines technical and material choices that enable good reconstruction. With this innovative in-situ test, the first 3D deformation fields were obtained for fretting contact and compared to FE simulation. The local coefficient of friction is fitted using contact shear displacement.

Identification of the tangential contact stiffness from reciprocating sliding tests

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1 - Delft University of Technology (Netherlands), 2 - Delft University of Technology (Netherlands), 3 - Technical University of Munich (Germany)

Speaker: Zheng Yi. **Friday**. Start time: **10:20**. Room: Saint Clair 3B LVL3. Link to abstract.

Tangential contact stiffness is a critical parameter derived from reciprocating and fretting friction tests. However, the process for determining this stiffness from friction hysteresis loops lacks standardization and clear physical interpretation. It's usually defined as the slope in the stick phase assuming a linear relationship between the tangential friction force and displacement (1). This study aims at identifying the tangential contact stiffness from reciprocating sliding tests, by taking advantage of the Mindlin-Cattaneo solution for partial slip conditions. The identified contact stiffness during partial slip is represented by the ratio between the contact radius and the equivalent shear modulus of the material pair in contact. The proposed method is used to post-process the reciprocating friction test data between various wood species and bearing steel balls (E52100, a high carbon and a high chromium allow), measured under gradually changing normal force conditions. A tribometer was used to conduct the friction test between azobé (*Lophira alata*), European beech (*Fagus sylvatica*), spruce (*Picea abies*) and balsa (*Ochroma pyramidale*) wood blocks and a bearing steel sphere. In addition to the identification of tangential contact stiffness, a statistical picture of the identified coefficient of kinetic friction is also shown, by taking into account the influences of wood surfaces and sliding planes. The results demonstrate that the proposed method can effectively capture all the most representative parameters of the reciprocating sliding tests with changing normal forces. For validation purposes, the aforementioned results are also compared for tests carried out for a set of constant normal forces, and a fairly good qualitative agreement was found in terms of observed trends. A comparative study between the identified Cattaneo-Mindlin stiffness parameter and a more conventional method, based on directly extrapolating the tangential contact stiffness from the slope of the partial slip phase, highlights that the proposed method can be used to interpret the partial slip phase in reciprocating sliding tests.

Furthermore, in Ref (2), it was shown that the ratio between the contact radius and the equivalent shear modulus is equivalent to the stiffness parameter in the Dahl model. Thus, the identified Cattaneo-Mindlin stiffness parameter is then integrated into the Dahl and LuGre model, in order to reproduce the measured friction hysteresis loops. Results show that the friction hysteresis loops, measured under varying normal forces, can be reconstructed using the identified tangential contact stiffness and the coefficient of kinetic friction.

Finally, few test cases during which squeal occurred after a surface degradation process will be shown. To interpret the squeal data, hammer tests and modal analysis are used, in order to extract the modal properties of the test-rig. Hence, the squeal occurrence is explained through a minimal mode-coupling and sprag-slip model, highlighting the relevance of the contact stiffness for the occurrence of friction-induced instability.

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Investigation of fretting wear damage in the cooling channel of Europe's Demonstration Fusion Reactor DEMO: effect of normal force fluctuation

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Speaker: Baydoun Soha. **Friday**. Start time: **10:40**. Room: Saint Clair 3B LVL3. Link to abstract.

Nuclear fusion is predicted to be a promising renewable clean energy source as it would provide a large-scale sustainable and predictable energy which is indispensable for reducing carbon footprint. DEMO (Europe's Demonstration Fusion Reactor DEMO) is the most ambitious nuclear fusion project aiming at assessing the applicability and the economic viability of thermonuclear fusion. The divertor targets in DEMO, sustaining a heat flux up to 20 MW/m^2, are made of pure tungsten armouring actively water-cooled CuCrZr pipes. The cooling capacity of the divertor targets can be improved by adding a Cu-OFHC swirl tape in the cooling channel. Under DEMO cooling conditions, the insertion of the swirl tapes in the pipes triggers fretting wear damage due to flow-induced vibrations of the swirl tape within the hosting pipe which may reduce the lifetime of the divertor components and their thermal efficiency. Hence, the objective of this study is to compare the fretting wear response of CuCrZr/Cu-OFHC contact under constant and fluctuating normal forces involving contact detachment. Surface damage evolution is followed by using different analysis techniques as 3D profilometry and SEM-EDS. Wear kinetics is quantified using energy wear rate (α) which is the ratio of the wear volume (V) and the accumulated dissipated friction energy ($\sum$Ed). Results show that under constant normal force the main damage is a mixed abrasive-adhesive wear mechanism is detected leading to a relatively high coefficient of friction, with an average value of 1.5. The evolution of friction coefficient as a function of fretting cycles reveal increase followed by decrease of friction coefficient suggesting a continuous process of formation and destruction of adhesive junctions. These results will be compared to tests under fluctuating normal force to assess its impact on wear response.

Wear mechanisms in oscillating bearings: A semi-analytical method to study radial fretting and false brinelling

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Speaker: Duquesne Rémy. **Friday**. Start time: **11:00**. Room: Saint Clair 3B LVL3. Link to abstract.

Oscillating bearings, unlike conventional bearings used in most applications, operate under small reciprocating motions rather than continuous rotation. Those bearings can be found in industrial applications such as crane slewing bearings or wind turbines pitch bearings (1). These unique operating conditions lead to significant challenges in terms of lubrication. Indeed, oscillating bearings operate under boundary or mixed lubrication regime due the low relative velocity between the contacting surfaces. This limits the establishment of a sufficient lubricant film which can lead to metal-metal contact and wear (2-4). These wear mechanisms are known as false brinelling for lubricated contacts and fretting corrosion for dry contacts (5,6). These wear phenomena can significantly impact the operational lifespan and reliability of oscillating bearings. In addition to lubrication challenges, oscillating bearings are often subjected to high time-varying loads, which contribute to fluctuating normal loads in the contacts. These variations induce relative tangential motions between the contacting surfaces resulting in complex fretting behaviors.
The aim of our work is to propose a fast and efficient calculation method to study fretting mechanisms in oscillating bearings: rotational fretting defined as the relative motion in a reciprocating rolling contact (7), and the radial fretting caused by the relative motion due to a variable normal load (8). To capture these phenomena, a two-step methodology is proposed. First, a bearing calculation code which considers the kinematics (9) and the loading conditions was developed to calculate the micro-slips inside the contact zone, commonly referred as creepages. Then, those creepages are used in a semi-analytical contact model based on the Discrete Convolution and Fast Fourier Transform (DC-FFT) (10). This computationally efficient model is used to calculate the shear stresses inside the contact and to identify the stick vs. slip zones.

Another key aspect of our work is the experimental determination of the coefficient of friction to provide a realistic value reflecting the real operating conditions in terms of materials and lubrication. This experimental campaign was conducted using a fretting sphere-on-flat test rig, where the tangential load was measured during fretting cycles under a constant normal load. The fretting loops obtained from these experiments provided a reliable means to extract the friction coefficient which was used in the numerical simulations to enhance their realism and predictive accuracy.

By combining advanced numerical techniques with experimental tests, this methodology provides a robust framework for understanding and mitigating fretting-induced wear phenomena in oscillating bearings. This work follows on from several previous studies conducted at the Contact and Structural Mechanics Laboratory (LaMCoS), aimed at developing semi-analytical methods for contact resolution based on DC-FFT (11-13). Future work will focus on integrating the role of wear on the modification of the geometry over fretting cycles.

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Fretting of DLC coating systems: Analysis of H/E ratio, contact pressure, surface roughness and oil lubrication

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Speaker: Mcmaster Samuel. **Friday**. Start time: **11:20**. Room: Saint Clair 3B LVL3. Link to abstract.

Diamond-like Carbon (DLC) coatings are often used for protection against fretting wear due to their low friction and wear properties. DLCs are metastable, allowing them to graphitise under applied load to create a graphitic transfer layer resulting in lowered friction. High residual compressive stresses allow DLC to resist cracking under fretting.
This work analyses the nanomechanics of the coating systems to predict fretting wear performance and further explores the effects of contact pressure, surface roughness and lubricated conditions.

Three DLC coating systems (a-C:H, Si-a-C:H, a-C:H:W top layers) and their uncoated substrates (316L stainless steel and hardened M2 tool steel) were studied. Loads of 20 N and 40 N were applied with $\pm$ 50 μm amplitude at a frequency of 5 Hz for 15,000 cycles. 10 mm diameter 52100 steel balls were used as the counterface in a bespoke electrodynamic shaker unit. Gross slip fretting was attained in all tests with a Hertzian contact pressure of 1.1-1.5 GPa. A Group III mineral oil (with and without MoDTC) and fully formulated variant (with and without MoDTC) were utilised for lubricated conditions.

This study shows that for dry conditions, the coating' tribological performance could be ranked by their H/E ratios with the a-C:H coating performing consistently well with low friction and low wear. Surface roughness and contact pressure had a significant effect on the running in behaviour. The addition of lubrication reduced the dissipated energy in the contact thereby decreasing wear.
Using a systematic evaluation method as in this study, the design/operating parameters for the coating can be selected for optimal tribological performance of DLC systems.

Effect of high-pressure hydrogen on the tribological behaviour of a 304L stainless steel contact subjected to fretting sliding

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Speaker: Fartas Mohammed. **Friday**. Start time: **11:40**. Room: Saint Clair 3B LVL3. Link to abstract.

Hydrogen is increasingly regarded as a key solution for achieving carbon neutrality, offering promise in energy storage, transport and application across sectors like automotive, aerospace and heavy industry. This widespread industrial adoption requires the development of robust materials capable of enduring high-pressure hydrogen environments. Metals like stainless steel are commonly used in pipelines, storage tanks, and reactors for hydrogen infrastructure. However, the presence of hydrogen leads to a degradation of the mechanical properties of materials subjected plastic deformations like endured during fretting sliding. Despite this interest in the H2 industry, there has been limited research conducted in the field of tribology to investigate the wear and friction of materials and surface treatments for friction components exposed to gaseous H2 environments, such as valves and compression pistons. In this study, a dedicated fretting wear test operating in a pressurized vessel has been developed at CDM laboratory . The contact consists in a sphere/plane homogeneous 304L stainless steel interface. Different hydrogen pressures from 3 bar up to 250 bar have been tested, and the results compared to reference tests conducted in ambient air (1bar). The findings reveal that, under equivalent fretting loading conditions, the coefficient of friction increased in the presence of hydrogen compared to air. At the same time wear degradation are more severe in H2g. When the hydrogen pressure reaches a threshold value (i.e. above 10 bar), typical "ball bearing like wear debris" are formed reducing the coefficient of friction but still decaying the wear rate due to an easier wear debris ejection process. In addition to establish the fretting wear rates of the 304L/304L interface as a function of the H2g pressure, careful surface scar analyses involving SEM, EDX, micro raman and SIMS investigations are performed to better interpret the ongoing wear scenario and the dynamics of the surface damages.

MS8.6 - Tactile and Perception

Organisers: Marie-Ange Bueno (ENSISA) Mark Rutland (KTH), and Francesco Massi (University of Rome)

Effect of Surface Textures on Tactile Perception. A numerical model for friction-induced mechanoreceptor stimulation with application to the tactile perception of topical films.

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Speaker: Masen Marc. Keynote. **Thursday**. Start time: **16:30**. Room: Roseraie 1 LVL3. Link to abstract.

Through contact of our fingers against the objects and surfaces around us, mechanical stimuli propagate to the sites of our tactile mechanoreceptors. Through changing the material, geometric and interfacial properties of these countersurfaces, it can be possible for product designers to modulate the elicited mechanical stimuli in order to deliver more functional and desirable sensations to consumers. In this investigation, a numerical, two-dimensional, viscoelastic, hyperelastic, multilayered, microscale finite element model representing finger skin was compressed and translated against a variety of rigid sinusoidal surface textures. A parametric study was conducted in which the wavelength and amplitude of these surface textures were systematically and independently varied whilst the strain energy density at the high spatial resolution (Type 1) Merkel and Meissner receptors within the finger model was recorded. It was found that when surface wavelengths were commensurate (similarly sized, but not necessarily identical) to that of the fingerprint, elevated and highly oscillatory strain energy density signals were experienced at each of the receptor sites. Furthermore, in these scenarios, increases in surface amplitude further elevated the strain energy density reported at each site. The stain energy density signals propagating to the receptor sites were substantially attenuated when the finger skin model was compressed against surfaces whose wavelengths did not approximate the fingerprint wavelength. These results may be used in conjunction with perceptive data to develop surfaces and in particular modify the skin's surface to elicit or tune specific targeted sensations amongst consumers in cosmetics and dermatology.

Fingertip friction and tactile perception of materials

Bennewitz Roland (1), Fett Yan (1), Fehlberg Maja (1), Saikumar Sairam (1), Infante Victor H.p. (1)

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Speaker: Bennewitz Roland or Fett Yan. **Thursday**. Start time: **17:10**. Room: Roseraie 1 LVL3. Link to abstract.

Friction plays a key role in the perception of materials upon active tactile exploration. We will present fingertip friction data for participants who explored surfaces with microstructures of varying, parameterized scale. On the one hand, we explore the relative importance of skin physiological parameters for the measured friction coefficients. On the othe hand, we explore if human participants can perceive friction differences. These friction differences arise from different structure sizes in the microstructures (1), from varying sliding speed (2), or from lubrication by viscous liquids. Our results indicate a perceptual constancy, which allows participants to correctly rank friction coefficients at varying speeds and normal loads. We will discuss the analysis of large sets of friction data by advanced data processing methods such as UMAP.

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Evaluating tactile interactions with fine textures obtained with femtosecond laser surface texturing

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Speaker: Schuhler Guillaume or Rutland Mark. **Thursday**. Start time: **17:30**. Room: Roseraie 1 LVL3. Link to abstract.

Tactile perception deteriorates with age, resulting in a negative impact on life quality. A clinical assessment of this decline could help to reduce its effects. Such a clinical apparatus for fine texture does not yet exist. Femtosecond laser surface texturing (LST) is capable of manufacturing fine textures on materials that are sufficiently robust for clinical requirements. This presentation starts by addressing how LST can be used to manufacture surfaces for tactile tests, i.e. of sufficient dimensions to permit interrogation, and with a minimum quantity of uncontrolled surface features. Vibrotactile interrogation tests on textured surfaces demonstrate that the surface textures have controllable tactile signature and thus underline the suitability of the process for generating fine textures for tactile perception assessment.

Skin Model Development for the Study of Complex Skin/Textile Interactions in Dry and Humid Conditions

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Speaker: Pinateau Astrid. **Thursday**. Start time: **17:50**. Room: Roseraie 1 LVL3. Link to abstract.

Skin damage, such as pressure ulcers and blisters, often results from a complex interplay of factors including pressure, friction-induced shear, moisture accumulation, temperature, and the duration of strain on various skin layers. Paraplegics are particularly susceptible, with approximately 30% affected by pressure ulcers. These ulcers manifest when blood vessels in the dermis experience compression, coupled with moisture build-up in the epidermis and shear forces at the dermis-epidermis interface. Unfortunately, these wounds exhibit slow healing, often becoming chronic. Consequently, considerable efforts have been directed towards preventive measures like pressure-distributing mattresses and low-friction bedsheets. However, establishing the efficacy of such products proves challenging due to the necessity for large clinical trials to demonstrate statistically significant benefits.
Hence, there is an urgent need for basic and still realistic skin models useful for textile companies during the product development process before clinical campaign. Notably, these models must represent the skin's elastic anisotropy and be able to sweat to analyze mechanical stresses under dry and wet conditions, during friction and compression against textile materials.

The present project aims to develop such a model in the form of a slider able to measure friction and compression through a deformable optical sensor: a polymeric optical fiber (POF) inserted into a knitted fabric, whose performance has been studied in previous works. The knitted fabric serves both as support for the sensor while bringing perspiration by capillarity. Finally, the skin simulation will be provided by the polydimethylsiloxane (PDMS) material already used in skin models for its stiffness and compression behavior similar to skin.
The final structure was validated through finite element analysis as well as compression tests. It was then tested under both dry and wet friction conditions, showing results close to the friction coefficient of skin in both environments. The model was compared with another innovative model capable of adjusting its stiffness by inflation, as well as with other artificial skins. These encouraging results demonstrate that this friction simulator could be used as a realistic skin model.

Analyzing the Touch Quality of Formulations on Human Hair and Skin

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Speaker: Luengo Gustavo S.. Keynote. **Friday**. Start time: **10:00**. Room: Roseraie 1 LVL3. Link to abstract.

Tactile touch is becoming more and more key in the perceived value of formulas in cosmetics for their efficacity when applied to hair or skin in vivo. This creates the necessity of having an objective and quantitative way to characterize and evaluate a formulation and its corresponding tactile perception when applied on hair on skin. The goal is to finely analyze the tactile sensation of human hair under different skin and hair preparation conditions and make the link with the formula characteristics (surface modification, rheology of the formula, etc.).
We used a connected and augmented patented technology: "TouchyFinger"(i) to perform this study. This device (instrumented by force and vibration sensors.) is used to be adapted on the human finger and measure the contact force and vibrations generated by friction during its movement. A particularity of this device is that it allows to work in vivo on free gestures that are closer to those used by consumers, for example, kneading wet strands of hair or applying a cream with a circular movement. It is equipped with a vibration frequency analyzer that can identify the average vibration level in decibels (dB), time frequencies and wavelengths of vibrations in each frequency band of the mechanoreceptors. The spectral analysis developed makes it possible to sample the average vibrational level in the mechanoreceptors located at the boundary between the epidermis and the dermis: Merkel ($0.3 - 3$Hz), Meissner ($3 - 50$ Hz), as well as the deep mechanoreceptors located at the level of the dermis: Ruffini (50-300 Hz) and Pacini at the level of the hypodermis ($300 - 1000$ Hz). On each of the frequency bands, the average vibration level in dB, the frequency centroid and the vibration wavelength in the same frequency band are quantified. All of these three parameters make it possible to reconstruct the vibration signal in the frequency band of each mechanoreceptor and to quantify an indicator of the tactile acuity of the hair.

Initially, we analyzed the surface roughness with a multi-scale wavelet analysis method(ii) Then we measured the tactile sensorial properties of the samples using "TouchFinger".The experimental protocol was conducted on a diversity of samples : strands of hair of different sensitization level and in vivo on hair and skin traited with several products. To stablish the protocol of frequency-touch correlation, a first evaluation of the touch of the samples was done by a small panel of 3 people, aged 22 to 30 years, trained to the same gesture. They performed 3 succesive touches and replicated the measurement 2 times.

The average values obtained of the La (dB) parameter for each of the mechanoreceptors were analyzed in correlation with the treatment used and the surface topography. The results show the richness of the spectral analysis and allow for the first time to quantify indicators of the stimulation of cutaneous mechanoreceptors that are sensitive to contact and friction of complex textures in cosmetic treatments.

(i) Patent FR3099359
(ii) S. Mezghani, H. Zahouani, J.-J. Piezanowski, Multiscale characterizations of painted surface appearance by continuous wavelet transform, Journal of Materials Processing Technology, Volume 211, Issue 2, 2011, Pages 205-211.

Rendering and comprehending texture perception by a vibrational tactile device

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Speaker: Felicetti Livia. **Friday**. Start time: **10:40**. Room: Roseraie 1 LVL3. Link to abstract.

The sense of touch is one of the channels that allows humans to perceive the external environment. Unlike sight and hearing, where stimuli are detected from a distance, touch requires contact between the skin and the explored object. This contact generates various mechanical stimuli, such as forces, vibrations and heating flows which are detected by the mechanoreceptors present in the skin. These stimuli are converted into electrical signals and transmitted to the brain for processing and interpretation. Discovering the complex processes occurring at the contact between the skin and a surface is crucial to understand touch mechanisms. In particular, when skin moves across a surface, Friction-Induced Vibrations (FIV) are generated; these vibrations come into play to determine how different textures are perceived and differentiated. Recent findings suggest that humans rely on specific characteristics of FIV to identify and distinguish between various type of surface textures. As an example, the frequency distribution of FIV appeared to be fundamental to discriminate periodic textures, while FIV amplitude is the key FIV feature to discriminate isotropic textures. This work focuses on a better understanding of the role of FIV features in touch sense, by exploiting a vibrotactile rendering device, named PIEZOTACT, to simulate vibrational stimuli and alter specific FIV features, in order to investigate their specific role in the perception of different textures. Using a piezoelectric actuator, the device simulates the vibrations produced when the finger moves across a surface, allowing users to experience tactile sensations without direct physical contact with the real surface. By altering specific characteristics of the FIV stimuli, ”fake” textures have been generated to better understand how changes in FIV features affect texture discrimination. Campaigns have been conducted with panels of volunteers, evaluating if the introduced signal modifications could mislead participants in discriminating between surfaces. The results of these experiments confirmed that participants' perception of the textures was consistently influenced with the FIV modifications. The ability to replicate tactile sensations without direct contact opens new outlines for a range of applications, in virtual environments, remote surgery, online commerce and beyond. The presented approach highlights the potential of tactile devices in simulating or even creating new tactile textures for technological purposes.

Finite Element Analysis of Surface Strains in Fingertip Mechanics

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Speaker: Duprez Guillaume. **Friday**. Start time: **11:00**. Room: Roseraie 1 LVL3. Link to abstract.

This study combines numerical modeling and experiments, aiming to better understand tactile perception. Using finite element modeling (FEM), we investigate whether and how the biomechanics of subcutaneous tissue influences skin surface deformations under flat plate loading. Tactile sensation arises from subcutaneous mechanical sensors detecting strains in the skin. Although fingertip surface strains can be measured with high accuracy during normal and tangential loading (1,2), the monitoring of subsurface strains remains challenging. This limitation complicates the interpretation of surface strains in relation to tactile perception (3).
The finite element model of the fingertip incorporates a realistic heterogeneous resistance to deviatoric strains as a function of depth (4) and mechanical anisotropy of the subcutaneous tissues due to collagen (5). The model is compared to experimental data measuring 3-D surface deformation of a fingertip and an inflated rubber membrane under similar condition, enabling validation and identification of the key factors driving the development of skin surface strains.

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(2): D. Doumont, A. R. Kao, G. J. Gerling, A. Browet, B. Delhaye and P. Lefèvre (2023). "3-D reconstruction of the fingertip deformation during tactile interactions." Worldhaptics conference. In Worldhaptics Annual Meeting.
(3): B. P. Delhaye, E. Jarocka, A. Barrea, J. L. Thonnard, B. Edin and P. Lefèvre (2021). "High-resolution imaging of skin deformation shows that afferents from human fingertips signal slip onset." eLife 10:e64679
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(5): G. H. C. Duprez, B. P. Delhaye and L. Delannay, "Collagen Induces Anisotropy in Fingertip Subcutaneous Tissues During Contact." in IEEE Transactions on Haptics, doi: 10.1109/TOH.2024.3406251.

Long-lasting biosourced wear engines based on PolyHydroxyalkanoates for high-performance cosmetic deposit

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Speaker: Waltz Victoria. **Friday**. Start time: **11:20**. Room: Roseraie 1 LVL3. Link to abstract.

All day wear is a key expectation of makeup consumers, with only petrochemical solutions available today on the market, especially silicone-based ingredients.
In cosmetic products, the wear performance is typically achieved through a film-forming agent highly concentrated in the deposit. This "performance engine" ensures long lastingness of the deposit by providing both mechanical resistance (resistance to rubbing, transfer) through a good balance between adhesion on skin and cohesion within the film, and chemical resistance (resistance to water, sebum for the face, olive oil for the lips).

In a context of growing need for sustainability (1), it is essential to identify new, entirely biosourced wear engines to develop innovative makeup products offering both long-lasting and comfort throughout the day, capable of replacing petrochemical based products.

To achieve this objective, the polyhydroxyalkanoate family was investigated (2) and a "performance engine" was built around a naturally biosynthesized polyester belonging to this family: poly(3-HydroxyNonanoate), also known as PHn. It appeared as the first green lipophilic polymer exhibiting a high level of cohesion within the film, thus demonstrating strong film-forming properties and high resistance to both water and oil. With the help of automated formulation and performance evaluation platforms, experimental plans were designed and performed to break through PHn's lack of adhesion while maintaining its high cohesion. Winning combinations with natural origin ingredients were identified, achieving in vivo performance equivalent to petrochemical benchmarks which unlocks a new path for tomorrow's high performing makeup products.

(1) L'Oreal. L'Oréal for the Future. Our Commitments for 2030. Available at: https://www.loreal.com/en/nordics/pages/oreal-for-the-future/ (accessed 06/01/25)
(2) Portal, J., Garcon, R. Cosmetic composition comprising a polyhydroxyalkanoate in an oily medium, FR patent 1873652 assigned to L'OREAL (2020)

Influence of finger movement direction on friction induced vibrations and perception of textured surfaces

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Speaker: Bueno Marie-Ange. **Friday**. Start time: **11:40**. Room: Roseraie 1 LVL3. Link to abstract.

Natural tactile exploration of a surface can be considered as a procedure to make a classification in a thermal dimension, i.e. warm/cool, and in three mechanical dimensions, i.e. softness/hardness, roughness/smoothness and stickiness/slipperiness. From this exploration, we are able to discriminate and recognize materials and textures. During tactile evaluation, finger can act in different ways, it can be static or scan the surface with various trajectories, velocities or normal forces.
By varying finger movement, finger-surface interaction changes and can be observed by skin deformation depending. The fingerprints interaction with the surface texture can be more or less significant depending on the hardness of the texture and on the spatial periods of the fingerprints and texture.

A previous study has shown the finger induced vibrations are higher for a lateral than for an anteroposterior movement below a frequency threshold approximately at 75 Hz, and lower for higher frequencies (1). However, this result was observed for a given velocity, normal force and finger angle.

This study has been extended to characterize the difference of finger induced vibrations for back and forth movement for both lateral and anteroposterior directions by considering the influence of sliding velocity but also finger angle perpendicularly to the surface and normal load. With the difference of finger induced vibrations, the perception of textured surfaces can also differ. In this study, the ability to discriminate textured surfaces is assessed using lateral and anteroposterior movement.

(1) Camillieri B, Bueno M-A. Influence of Finger Movement Direction and fingerprints Orientation on Friction and Induced Vibrations with Textile Fabrics. Tribol Lett. 2021;69:143.

Posters

A bio-mechanical model to explore the influence of the cell-matrix interactions as a key factor for cell motility

Louviaux Nicolas (1)

1 - Biologie Computationnelle et Modélisation (France)

Speaker: Louviaux Nicolas. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Cell motility is the ability of cells to move spontaneously. It is often triggered by factors like chemical gradients (chemotaxis) or surface topography (durotaxis). It involves intracellular factors such as regulatory pathways and cytoskeletal structure, as well as extracellular factors like cell-cell and cell-environment interactions. Recent research, especially using traction force microscopy, focuses on how cells interact with and exert forces on the matrix during migration, which is crucial for understanding cancer invasion and tissue repair. However, the large gap between in-vitro and in-vivo conditions complicates studying these forces. This work presents a biomechanical model of a single cell on a deformable 2D substrate, simulating cell-matrix interactions through focal adhesions. The model explores different cell migration behaviors and compares them to experimental data. It also simulates durotaxis and biased migration on patterned substrates, offering insights into cell behavior and biological hypotheses.

A geometric nonlinear length scale in the fracture of elastic materials

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Speaker: Lazo-Molina Raúl. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Soft materials like hydrogels and rubber are crucial for a wide range of applications, ranging from biomedicine to advanced engineering, mainly due to their ability to withstand large deformations without failure. These materials generally exhibit nonlinear mechanical responses, which intensify around the tip of a crack. This has motivated several experimental, theoretical, and numerical investigations, which have revealed that crack propagation instabilities, such as oscillations, are related to nonlinear length scales. For instance, the weakly nonlinear theory (1) made an important contribution to estimating the nonlinear length scale for a neo-Hookean material. This was later used to formulate a dynamic crack-tip equation of motion capable of predicting the oscillatory instability (2). On the other hand, geometric nonlinearities (GNL) have also been studied using a St. Venant-Kirchhoff material under fracture mode I (3), showing that crack propagation speeds can exceed Rayleigh's theoretical limit and reach the supershear range. Consequently, both material and geometric nonlinearities have been identified as key factors in explaining different aspects of dynamic fracture phenomena. Therefore, given the limitations of traditional linear elastic fracture mechanics (LEFM) in explaining these effects, we aim to elucidate the fundamental role of nonlinearities in the fracture process of elastic materials.
This work presents a combined numerical and theoretical investigation into the effects of geometric nonlinearities on a static crack under mode I loading. Our findings reveal that a geometric nonlinear length scale, inherent to elastic materials, can be directly computed from the stress intensity factor. Furthermore, we show that the crack tip opening displacement (CTOD) serves as a valuable tool for extracting essential nonlinear parameters to characterize fracture in elastic materials, highlighting its potential as a laboratory tool. As such, this research establishes GNL as a foundational requirement for the development of a nonlinear elastic fracture mechanics theory (NLEFM) and provides the starting point for investigating dynamic fracture instabilities.

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(1) Eran Bouchbinder, Ariel Livne, and Jay Fineberg. Weakly Nonlinear Theory of Dynamic Fracture. Physical Review Letters, 101(26):264302, December 2008. doi: 10.1103/PhysRevLett.101.264302.
(2) Eran Bouchbinder. Dynamic Crack Tip Equation of Motion: High-Speed Oscillatory Instability. Physical Review Letters, 103(16):164301, October 2009. doi: 10.1103/PhysRevLett.103.164301.
(3) Mohit Pundir, Mokhtar Adda-Bedia, and David S. Kammer. Transonic and Supershear Crack Propagation Driven by Geometric Nonlinearities. Physical Review Letters, 132(22):226102, May 2024. doi: 10.1103/PhysRevLett.132.226102.

A multiplicative decomposition for the folding of active viscoelastic tissue

Jallon Antoine (1), Etienne Jocelyn (2)

1 - CNRS - Université Côte d'Azur (France), 2 - CNRS - Université Grenoble Alpes (France)

Speaker: Jallon Antoine. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

During morphogenesis, the process by which organisms acquire their shape, tissues can fold, thus exhibiting active internal stresses due to molecular motors such as myosin. The fruit fly (*Drosophila Melanogaster*) embryo, notably due to its relative simplicity, short generation time, transparency allowing imaging and since it allows the use of the most advanced genetic tools, is a model system for tissue folding. It forms a nearly ellipsoidal single layer of _~1000 cells surrounding a viscous compressible yolk where a furrow appears due to a localised increase of myosin activity. Myosin puts under tension the actin cytoskeleton, which surrounds each cell.
This cell monolayer can be modelled as two concentric closed shells, formed by the continuum of actin at the outer apical surface and at the inner basal surface of the epithelium. These two shells are in mechanical interaction, notably through the lateral actin cytoskeleton. We have previously shown that the initiation of this folding corresponds to the purely elastic buckling of the outer surface only of this epithelium under anisotropic tension (1). However, the dynamics of the subsequent flow during which the tissue actually folds, happening on longer timescales, remains elusive. Biological tissues undergoing morphogenesis are known to exhibit rapid elastic stress relaxation and plastic-like flows, leading to a viscoelastic liquid rheology. The challenge is thus to combine this complex rheology, active internal stresses and shape changes.
The 3D dynamics of these viscoelastic active shells can be conveniently solved using a multiplicative decomposition of the deformation gradient, a technique that has been widely used in thermoelasticity, elastoplasticity, as well as biomechanics, specifically for growth in tissues. As is the case for growth, the anelastic contribution of contractility can be understood as a dynamic prestrain (2). We derive an evolution equation for this anelastic deformation such as to recover an active gel model, namely the upper-convected Maxwell constitutive equation with an active term corresponding to this dynamic prestrain (3). Using this model, we address the dynamics of thin shells actuated by internal contractility.

(1) Fierling, J., John, A., Delorme, B. *et al.* Embryo-scale epithelial buckling forms a propagating furrow that initiates gastrulation. *Nat Commun* **13**, 3348 (2022)
(2) Erlich, A., Étienne, J., Fouchard, J. and Wyatt T. How dynamic prestress governs the shape of living systems, from the subcellular to tissue scale. *Interface Focus* **12,** 20220038 (2022)
(3) Jallon, A., Recho, P., and Étienne, J. Mechanics and thermodynamics of contractile biopolymer networks. *J Elasticity* (in press)

A Multiscale Approach to Modeling Regional Coronary Perfusion and Myocardial Function

Sasidharan Sumesh (1), Huyghe Jacques (2), Nath Kunal (2)

1 - Aix Marseille University (France), 2 - University of Limerick (Ireland)

Speaker: Sasidharan Sumesh. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The disruption of regional coronary blood perfusion is a critical factor contributing to the pathophysiology of cardiac failure. Regional perfusion deficits compromise the oxygen and nutrient supply to cardiomyocytes, triggering ischemia and subsequent necrosis. The loss of viable myocardial tissue results in structural and functional deterioration of the heart, manifesting as irreversible myocardial damage and compromised cardiac output. Given the complex interplay between coronary perfusion and myocardial function, accurately modeling regional blood flow dynamics is paramount for advancing the understanding of cardiac pathologies and improving therapeutic strategies. To address this challenge, the incorporation of regional coronary perfusion as a dynamic parameter within finite element (FE) models of the human heart has become indispensable in cardiac computational simulations. FE models offer a powerful platform for simulating the mechanical behavior of the heart under various physiological and pathological conditions. However, their predictive accuracy is significantly enhanced when coupled with detailed representations of coronary perfusion, which directly influences myocardial contractility and viability. This study presents a comprehensive methodology for integrating regional coronary perfusion as a field variable into a patient-specific cardiac model. The approach begins with the reconstruction of the 3D coronary vascular geometry, derived from high-resolution medical imaging data. The vascular architecture is then stratified into subendocardial and subepicardial layers, reflecting the transmural heterogeneity in coronary blood flow. By averaging the vascular geometry within these layers, the conductances of distinct coronary compartments are quantified, accounting for variations in vessel diameter, length, and branching patterns. These conductance values are then embedded into a continuum coronary model, which serves to simulate regional perfusion by solving the governing equations of blood flow under varying hemodynamic conditions. This coupling of coronary perfusion with myocardial mechanics facilitates a fully integrated simulation environment, where the interplay between coronary flow dynamics and cardiac tissue deformation can be explored.The resulting virtual framework provides a robust and versatile tool for the preclinical evaluation of cardiac interventions. By simulating scenarios such as coronary artery occlusions, revascularization procedures, or pharmacological therapies, this model enables the prediction of treatment outcomes and the optimization of intervention strategies. Ultimately, this approach represents a significant advancement in the field of cardiac biomechanics, offering insights into the mechanistic underpinnings of coronary perfusion and its role in cardiac health and disease.

Aging-Induced Embrittlement in Short-Fiber Reinforced Thermoplastics: A Micromechanical Approach Using Numerical Homogenization

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Speaker: Ashour Mahmoud. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Aging studies are critical for ensuring that engineering plastic components can endure physico-chemical degradation under operating conditions. The degradation kinetics can be assessed by exposing parts to aging environments and testing them afterwards. However, this empirical approach is time-consuming and costly. An advantageous approach would be to simulate those aging tests. The aim of this research program is to develop a simulation method for virtualizing the aging tests of injection-molded thermoplastic parts, specifically addressing aging of the mechanical behavior at the component level. To achieve this in the framework of finite element (FE)-based mechanical simulations, it is crucial to establish failure criteria based on local aging descriptors. This work is focused on the hydrolytic degradation of polyamide 6.6, reinforced with 30 wt.% short glass fibers. Hydrolytic aging of 4 mm thickness PA66-GF30 part results in non-limited diffusion hydrolysis leading to an uniform reduction in molecular weight of the polymer matrix, causing progressive embrittlement, which manifests as a reduction in strain at break during uniaxial tensile tests. To achieve accurate simulations, the research aims to develop a failure criterion based on local aging descriptors. Using micro-mechanical analysis of a 3D representative volume element (RVE), the study links local degradation effects (such as molecular weight reduction) with the overall mechanical response of the composite. This approach allows finite element (FE) simulations to predict aged component failure. The study also discusses the construction of the RVE, which accounts for fiber microstructure, and the identification of the elastoplastic constitutive law for the PA66 matrix. The focus is on proposing a physics-based failure criterion that correlates with damage initiation under various levels of hydrolytic degradation.

AI-Based Model Reduction for Real-Time Predictive Simulation in Solid Mechanics

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Speaker: Mekhfioui Mohcin. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The rise of machine learning techniques offers new opportunities for model reduction in solid mechanics, particularly for applications requiring real-time predictions. This study presents a hybrid approach that combines classical model reduction techniques, such as Galerkin projection and proper orthogonal decomposition, with deep neural networks to enhance computational efficiency and accuracy.
We introduce a supervised learning architecture designed to extract optimized latent representations of stress and displacement fields from high-fidelity simulations. The use of convolutional neural networks (CNNs) and deep operator networks (DeepONet) significantly accelerates computations by efficiently capturing the underlying dynamics of complex materials and structures.

The performance of our approach is evaluated on benchmark structural mechanics problems, including heterogeneous materials and complex boundary conditions . Our results demonstrate a substantial improvement in computational speed compared to traditional methods while maintaining a high level of accuracy.

This methodology paves the way for the integration of intelligent reduced-order models into embedded systems, interactive simulations, and real-time structural optimization.
Keywords: Model reduction, machine learning, neural networks, solid mechanics, real-time simulation.

Analysis of Bending Curve and Intelligent Design of Carbon Fiber Composite Fishing Rod Based on VFIFE

Lin Hang (1), Chen Deshen (1), Wang Huajie Qian Hongliang (1)

1 - School of Civil Engineering [Harbin] (China)

Speaker: Lin Hang. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The analysis of force response in carbon fiber composite fishing rods faces challenges due to their complex material properties and strong geometric nonlinearities.Deformation performance is the most critical metric for evaluating the quality of fishing rods. Traditional fishing rod design relies heavily on experience, resulting in low efficiency and high costs. To achieve standardization and intelligence in fishing rod design, the following research was conducted.Carbon fiber composite fishing rods are fabricated by rolling multiple layers of carbon fiber cloth with varying fiber orientations onto a conical mold. Given the complexity of their geometric models, Grasshopper was utilized for precise modeling of the fishing rods to obtain accurate material properties.Since the deformation of fishing rods involves strong geometric nonlinearities, the application of conventional finite element methods can easily lead to ill-conditioned matrices and convergence issues. Therefore, the vector form intrinsic finite element method was adopted to simulate the bending curves of carbon fiber composite fishing rods. The proposed numerical computation method was validated through experiments on the bending curves of fishing rods.The geometric modeling and bending curve calculation procedures for fishing rods were integrated to form a unified program for fishing rod modeling and bending curve computation. This integrated program was used to generate bending curve data in batches.A prediction model for the bending curves of fishing rods based on BP neural networks was developed. The trained neural network model can replace complex modeling and calculation procedures, providing fast and accurate bending curves.The trained neural network model was used as the fitness function in a genetic algorithm, with NSGA-II employed for multi-objective optimization. Based on the target bending curve of the fishing rod, the shape parameters of the carbon fiber cloth can be reverse-searched, with material-saving solutions considered.This study provides a set of efficient, accurate, and intelligent methods for the design of carbon fiber composite fishing rods, offering strong practical guidance and economic significance for the production of these products.

Automated Ritz method for the analysis of bi-directional functionally graded deep beams

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1 - King Fahd University for Petroleum & Minerals [Dhahran] (Saudi Arabia)

Speaker: Algahtani Husain. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The paper investigates the structural performance of bi-directional functionally graded beams (BDFB), The beam is made of an elastic material with varying properties in both the longitudinal and transverse directions. The beam's material composition gradually changes from one surface to the other, as well as across its depth, following a specific grading law, such as the power-law distribution. This research focuses on analyzing the mechanical response of BDFBs under various loading and boundary conditions. The beam is modeled as a plane stress problem and the analytical solution in terms of polynomials is obtained using Ritz method. In order to reach accurate solutions, the equations resulted from the principle of minimum potential energy is cast in a matrix form. This task is achieved using indicial notations. The integration of various elements of the obtained matrix is performed using Mathematica. For that purpose, an automated integration scheme is implemented in the Mathematica code. The proposed integration scheme enables the inclusion of as many polynomial terms as required for the convergence of the solution. The accuracy of the solution is verified by Finite element analysis.

Basis problem in the stability loss problem of the plate with a hole under uniaxial tension

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1 - Higher School of Economics (Russia), 2 - St. Petersburg State Institute of Technology (Russia)

Speaker: Voloshinova Stanislava. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

This paper studies the question of techniques for solving the variational problem by the Ritz method, in particular the definition and influence of natural boundary conditions in the problem of stability loss of a thin plate with an circle/elliptic inclusion. We investigate whether the natural conditions for the free edge should be taken into account and how this affects the convergence of successive approximations to the answer of the problem. The paper also discusses the matrix approach in the calculation of the total energy and the reasoning behind the choice of basis.
In order to find the critical load at which the loss of equilibrium (escape from the plane form) of a plate with a hole or an insert in tension occurs, it is necessary to solve the variational problem. And if in the case of a circle it can be done without using some tricks, in the case of complicating the geometry of the cutout or insertion, the cumbersomeness of the calculations increases significantly, and the accuracy obtained is questionable. This paper studies the question of techniques for solving the variational problem by the Ritz method, in particular the determination and influence of natural boundary conditions in the problem of stability loss of a thin plate with an elliptic insertion. We investigate whether the natural conditions for the free edge should be taken into account and how this affects the convergence of successive approximations to the answer of the problem. The paper also discusses the matrix approach to the calculation of the total energy and discusses the choice of basis.

The research was supported by the Russian Science Foundation (project no. 25-21-00202).

Biaxial tensile testing of stretchable micro-LED display using mechanical metamaterials

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1 - Korea Institute of Machinery and Materials (South Korea)

Speaker: Jang Bongkyun. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Micro-LEDs (Light Emitting Diodes) are tiny inorganic devices, typically less than 100 micrometers in width and only a few micrometers thick. Displays based on micro-LED technology are regarded as the next generation of display innovation, offering significant advantages such as superior color gamut, higher contrast ratios, faster response times, and longer lifespans compared to conventional liquid crystal displays (LCDs).
Stretchable micro-LED displays are fabricated by transferring micro-LED devices onto flexible substrates. By incorporating kirigami-inspired mechanical metamaterials, these displays achieve high stretchability and uniform deformation (1,2). However, the evaluation of their mechanical properties remains challenging due to their unique deformation behavior.

In this study, we developed a biaxial tensile testing method specifically for stretchable micro-LED displays based on mechanical metamaterials. The tensile testing apparatus applies biaxial loads to the display while it remains operational. By measuring strain distribution, we can assess both stretchability and deformation uniformity. This research aims to advance the development of wearable and curved displays, particularly for biomedical applications.

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Casting the Future: A Versatile and Cost-effective Approach to Metallic Components

Juarez Ortiz Valentina (1), Al-ketan Oraib (1), Shahin Khaled (1)

1 - New York University Abu Dhabi (United Arab Emirates)

Speaker: Juarez Ortiz Valentina. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Foam-filled tubes offer a promising approach for enhancing mechanical performance, particularly in applications demanding lightweight yet high-strength components. Their advantageous properties include increased strength-to-weight ratios, sound insulation, effective thermal management, and enhanced energy absorption capabilities. However, the widespread adoption of additive manufacturing (AM) for producing such structures is hindered by high production costs, limited material availability, and resolution constraints.

To overcome these challenges, we introduce an innovative hybrid manufacturing process combining additive manufacturing with lost-wax investment casting, namely AM-assisted Investment Casting. This hybrid technique significantly expands the range of available materials, improves achievable resolutions, and reduces overall manufacturing costs. Additionally, to thoroughly understand and optimize this novel method, we conducted computational simulations of the casting process using Flow3D. These simulations provide critical insights into fluid dynamics and solidification phenomena, guiding process optimization and ensuring structural integrity and consistency.

Our initial findings indicate that this hybrid method has the potential to produce complex designs and enhance the mechanical properties and functional versatility of foam-filled tubes, making them suitable for advanced applications in aerospace, automotive, and structural engineering sectors where lightweight yet high-strength components are crucial. This study contributes to both the practical and theoretical understanding of AM-assisted Investment Casting, highlighting its potential to revolutionize the production of complex, high-performance materials.

Chatter Prediction of Curved Thin-walled Parts Considering Variation of Dynamic Characteristics Based on Acoustic Signals Acquisition

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Speaker: Damous Mohamed. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

High-speed milling of thin-walled components with complex curvilinear profiles often faces challenges related to machining instability, commonly known as chatter. This phenomenon results from dynamic interactions between the cutting tool and the workpiece, intensified by the low rigidity and the varying dynamic characteristics of the part along the tool path. This research introduces a dynamic model specifically designed to predict machining stability for curved thin-walled parts. Utilizing the semi-discretization method, the tool trajectory is segmented into small, straight elements to locally approximate the behavior of an inclined plane. Dynamic characteristics for each segment are derived from experimental modal analysis and incorporated into the simulation model to generate global stability lobe diagrams. Model validation is performed through cutting tests, measuring acoustic intensity to detect instabilities. The acoustic pressure emitted by a structure correlates with tool displacement, enabling the use of a microphone as a sensor to predict chatter instability. In stable cutting conditions, the dominant frequencies correspond to the spindle speed and its harmonics and the tooth passage frequency. Detecting a peak at an additional frequency serves as a clear indicator of chatter. The microphone's ease of use avoids the positioning challenges associated with other sensor types. To mitigate the effects of ambient noise, numerical band-pass filters and frequency analysis methods, such as FFT, are employed. Experimental data closely match the predicted stability limits, validating the model's accuracy and effectiveness. This work provides a robust approach to enhancing machining stability predictions, ultimately improving the efficiency and quality of high-speed milling operations for thin-walled components.

Combining two strategies to modulate the tumor microenvironment and optimize efficacy of nano-immunotherapy

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Speaker: Angeli Stella. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Introduction

Desmoplastic cancers are characterized by interactions between cancer cells, stromal cells, and the fibrotic matrix, leading to increased tumor stiffness and the buildup of mechanical forces that compress tumor vasculature. Mechanotherapeutics and ultrasound sonopermeation have been used as independent mechano-modulation strategies to alter the tumor microenvironment (TME) and improve therapeutic outcomes (1,2). This study aims to determine the optimal conditions for combining these approaches to enhance perfusion and the effectiveness of nano-immunotherapy in vivo, using sarcoma models.

Methods

In vivo experiments were conducted using MCA205 fibrosarcoma and K7M2 osteosarcoma murine models in C57BL/6 and BALB/c mice, respectively. Therapeutic ultrasound sonopermeation was applied using a clinical diagnostic ultrasound scanner. The treatment regimen included mechanotherapeutic ketotifen, sonopermeation, Doxil nanomedicine, and anti-PD-1 immune checkpoint inhibitor (ICI).

Results

The initial focus was on identifying the optimal mechanical index (MI) and number of cycles (NoC) to maximize the effectiveness of sonopermeation in modulating tissue stiffness and enhancing perfusion and drug delivery in fibrosarcoma tumors. Tumors of an average size of 300 mm^3 underwent Shear Wave Elastography (SWE) and Contrast Enhanced Ultrasound (CEUS) to measure stiffness and perfusion before and after sonopermeation (Fig. 1A, B). The combination of MI=0.6 and NoC=32 significantly increased tumor perfusion without altering the elastic modulus (Fig. 1C, D). This parameter set also maximized the delivery of fluorescent particles to the tumor (Fig. 1E).

Subsequently, the combination of ketotifen and sonopermeation was evaluated for its ability to enhance perfusion and the therapeutic efficacy of nano-immunotherapy in osteosarcoma tumors. While monotherapies did not significantly reduce tumor volume (Fig. 2A, B), the combination of Doxil and ICI with either ketotifen or sonopermeation led to a marked decrease in tumor volume. Notably, the combination of ketotifen with sonopermeation before nano-immunotherapy resulted in the greatest therapeutic benefit, including reduced tissue stiffness, increased perfusion, and decreased interstitial fluid pressure compared to ketotifen treatment alone (Fig. 2C-E).

Conclusions/Implications

The integration of mechanotherapeutics and sonopermeation exhibits a synergistic effect in modulating the TME, leading to enhanced outcomes of nano-immunotherapy in sarcoma models. This approach offers a promising strategy for improving treatment efficacy in desmoplastic cancers.

Crack propagation analysis using the peridynamic approach in the Cosserat pseudo-continuum framework

Nosal Przemysław (1)

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Speaker: Nosal Przemysław. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The classical formulation of continuum mechanics does not explicitly account for the internal structural composition of materials. Consequently, when simulating materials characterized by discontinuities or significant microstructural influence, effects lacking a clear physical interpretation often arise. To address this, higher-order gradient theories, such as the Cosserat theory, are frequently employed. In this study, a peridynamic model based on a simplified Cosserat theory (SCPD) is proposed to investigate the impact of microstructure on crack propagation. Within SCPD, the peridynamic (PD) forces and moments are derived using a bond-based correspondence model, where PD forces and moments are linked to stress and coupled stress components. The effect of microstructure on crack propagation is analyzed by varying the characteristic length scale. Additionally, the results obtained using the SCPD model are compared with those from a bond-based peridynamic model. The SCPD model demonstrates closer agreement with experimental observations, particularly in capturing the qualitative and quantitative characteristics of crack propagation.

Depot visualization and tissue back-pressure measurement of large volume subcutaneous injections

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Speaker: Baquié Aurélien. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Introduction

Subcutaneous (SC) injection is a route of administration positioning drug formulations in the hypodermis and offering numerous advantages for the patients (1, 2). Such injections induce a tissue backpressure which opposes these injections (3). This backpressure is dependent of the formulation spreading in the hypodermis, which is controlled by mechanical phenomena.

For the injection of small volumes The identification of those mechanical phenomena and of the factors impacting backpressure during large volume SC injections is needed, since backpressure prediction is required for drug delivery devices dimensioning. Those devices must overcome backpressure to ensure the total administration of the targeted formulation volumes (3). Such identification should play a part in enabling patients to self-administrate subcutaneously new active ingredients, such as monoclonal antibodies, which must be associated to larger volumes for stability, and delivery reasons (6).

Also, tolerable injection condition limits for SC injections of large volumes are unknown, although authors considered that backpressure at the injection point should be a great indicator of how tolerable an injection is (7).

There is thus a need for better understanding skin deformation, formulation diffusion, and tolerable injection condition limits for SC injections of large volumes.

To determine them, we propose first to estimate upper tolerable injection rates for given formulation viscosities. We propose then to carry out SC injections of placebos representative of drug formulations (1) in the animal anatomical zone presenting the most similar hypodermis compared to human abdomen (8), measuring backpressure and visualizing formulation depot post-injection thanks to contrast absorption X-ray microtomography.

Methods

Placebos and tissue samples

Two types of placebos were used.

To determine tolerable injection condition limits, a hyaluronan dermal filler (Stylage Hydro®, Vivacy Laboratories) diluted at 20% v/v in NaCl 0.9% has been chosen (2).

To carry out formulation depot imaging post-injection, solutions with viscosities of 1, 10, 20 and 100 mPa.s and a Newtonian rheological behavior were used. To obtain them, dextran 40 kDa (Apollo Scientific, UK) was diluted at different concentrations in a contrast solution (Iomeron®, Bracco Imaging, Italy).

Both previous placebo types were injected at room temperature in fresh *ex vivo* belly flank pork samples (containing skin, hypodermis, and deep muscle in their thickness).

Experimental set-up and backpressure measurement

A device containing a push-syringe, a syringe, a tubing and a catheter was used to carry out the SC injections. A catheter (24G) was inserted in the tissue sample at 90◦ to the skin surface and at a depth of 9 mm, thanks to a specific support glued to the skin surface. To measure the pressure during SC injection according to time, an in-line pressure sensor was positioned between the syringe and the tubing.

Injection conditions

The maximal tolerable backpressure during a SC injection was determined reproducing as much as possible injections which caused tolerability issues for patients (2.5 mL of hyaluronan placebo at 15 mL/min (2)).

The maximal injection rate associated to each viscosity of dextran/contrast agent placebos was then determined to not induce larger backpressures than maximal tolerable value, thanks to relations found by Allmendinger et al. (1). The lower injection rate was chosen as the lower injection rate preference of some

individuals within clinical trials (_ ~0.3 mL/min). The same volume, sufficient to reach the backpressure stabilization for each viscosity and injection rate combination was used for all injections.

X-ray computed micro-tomography
Two absorption contrast X-ray micro-tomography scans were carried out. One with the radio-opaque cannula already inserted for each sample before injection. Another after the SC injection. Each scan required an acquisition duration of 35 minutes with a Phoenix Nanotom S® (GE and Inspection Technologies). Cubic voxels of side 30 μm were reached. Each scan was then reconstructed with 3D Slicer.

Analysis
To determine the hypodermis thickness and the location of the injection point relative to hypodermis substructures and deep muscles, the segmentation of the tissue layers was carried out with a thresholding segmentation, after applying a 3D median filter. The segmentation of the formulation depots was also carried out thanks to a Chan-Vese segmentation, to visualize and measure depots, and to quantify the amount of formulation positioned in each hypodermis substructure. Orthographic projections were finally generated to study formulation depot homogeneity according to locations in the depots.

Results
Experimental study is still on-going; first results show that the formulation with lower viscosity was positioned in membranous hypodermis substructures (septas) post-injection, as for smaller volumes of similar viscosity (5). Hypodermis permeability was also anisotropic and impacted by the presence of specific hypodermis substructures.

Discussion and conclusion
It is thus expected that the nature of the hypodermis substructures in which the formulation is positioned post-injection and the mechanical phenomena involved in the formulation spreading should be identified for all the injection conditions studied here, representative of large volume SC injections. Focus will also be put on relations between backpressure reached, hypodermis properties (thickness, substructures), injection point, viscosity, and injection rate. Such results will facilitate the creation of numerical models predicting the backpressures generated by SC injections of large volumes for the different injection conditions tolerated by patients.

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Design of control signal of a tactile device for textile fabric rendering

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Speaker: Martin Emilie. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Tactile simulation of textile fabrics holds significant potential in various applications, such as e-commerce of garments, furnishing, seat or wall covers for home or transport, etc or virtual prototyping. However, the tactile rendering should be sufficiently close to real surfaces, and the designer or the manufacturer should be able to easily simulate the surfaces, i.e. should be able to build or complete its own tactile database. Therefore, the process used to build the database, i.e. to add a control signal for the given tactile simulator, should be systematic, from the real surface characterization to the control signal, and without any interaction with a human as a tactile sensor. This needs a specific protocol to be established, independently from the human, but according to the choice of the tactile simulator.

In this project, the tactile device, named STIMTAC (1), is similar to a touchpad; it's principle used the ultrasonic vibration technology inducing a change of the friction between the finger and the surface of the stimulator relative to the finger displacement and then simulating a texture.

A set of 6 textile fabrics representing a wide range of textile surfaces has been chosen and characterized in a tribological point of view following a specific method of measurement using an artificial finger previously developed (2). Then, an adapted signal processing procedure has been developed to convert the normal and friction forces relative to time in a command signal for STIMTAC creating at the end 6 virtual tactile surfaces
In another part, sensorial analysis campaigns were conducted: firstly, to cluster the real fabrics according to their tactile attributes and the most discriminative was the rough/smooth and to compare real and virtual fabrics, and finally to compare real and virtual fabrics as regarding their roughness.

Development of an FDM 3D printer capable of additive manufacturing on arbitrary curved surfaces

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Speaker: Nagumo Yo Nagumo Yo Yo. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

This study aims to develop a Fused Deposition Modeling (FDM) 3D printer capable of additive manufacturing on curved surfaces. It is well known that conventional FDM 3D printers produce additive models on flat surfaces, but the device developed herein makes it possible to produce models on arbitrary curved surfaces. To achieve this goal, a small displacement sensor is attached to the head of the 3D printer to measure the shape of the curved surface. Based on the recorded data, the movement of the head is controlled using Python to perform additive manufacturing along the curved surface. In addition, a numerical model is constructed to enable 3D finite element analysis of FDM under additive manufacturing conditions. A highly accurate death-birth technique is used to reproduce the additive manufacturing process. This method can accurately simulate the change in temperature and residual stress with time that occurs in the model under different additive manufacturing conditions. As a result, it becomes possible to determine the optimal additive manufacturing conditions, such as filament temperature and head speed, of a curved surface compatible 3D printer, enabling efficient operation. Our work expands the applications of FDM 3D printers by modifying the printer itself. In addition, by modeling the additive manufacturing process, it compensates for the currently limited data on optimal printing conditions for curved surface additive manufacturing. This plays a critical role in promoting the use of this 3D printer.

Development of deep processing technology and equipment for vacuum freeze drying of mare's and camel's milk

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Speaker: Rakhmatulina Ayaulym. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

INTRODUCTION

Mare's and camel's milk is a very common food in Asia. It is currently possible to preserve all the useful properties, as well as the freshness of this product, with the help of the so-called vacuum freeze drying. Powdered milk has a number of advantages over liquid milk. Firstly, the shelf life of such a product increases. Secondly, negative temperatures are not required during storage (cold storage), the powder should be stored at a certain humidity. At the same time, there are unresolved issues in the technology of production and storage of dry milk.

The purpose of the program: Development of new equipment for vacuum freeze drying, meeting the requirements of the quality standard.

LITERATURE REVIEW

The main approaches to research: improvement of milk drying technology, mathematical modeling (development of methods and programs) to solve the problem of optimal equipment design. The equipment, technological processes and products developed because of scientific and technical research will meet the quality standards (1-4). They are considered a therapeutic product and are used in the treatment of metabolic disorders, as a means of preventing colds and contributing to the cure of oncological diseases (5-7).The researchers of this program know the methods of development and design of such equipment, drives of technological machines (8-27). Kazakh scientists are conducting research on the development of optimal technological parameters for the production of dry whole camel milk regarding the optimization of biotechnological parameters of the fermented milk product (8, 9, 10), and the method of production of milk in capsules (14-17).

METHODS

The research strategy includes the sequential implementation of three main stages, which will ensure a consistent approach to the research goal:

Stage 1 – determination of the main qualitative indicators and significant indicators of the technological process of mare's and camel's milk and freeze-drying equipment. Creation of a mathematical tool (development of methods) for solving the problem of optimal design of freeze drying equipment ;

Stage 2 – determination of optimal parameters (numerical implementation of methods), development of layout and control system (tasks 8-10);

Stage 3 – model adjustment and technical task development, optimal design and experimental study of freeze drying equipment (tasks 10-12).

RESULTS

Table 1.Modes of sublimation drying of camel milk

Dynamic Investigation of a Mechanical Metamaterial Beam: A Numerical Study

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Speaker: Bashmal Salem. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The unique properties of mechanical metamaterial (MM) make them an exciting area of research for vibration attenuation applications in engineering fields including structural engineering and mechanical systems. In this research, the dynamic investigation of a simple and MM cantilever beam is presented using finite element analysis in ANSYS software. A simple and MM beam having attached resonators were modelled using beam element in design modeler ANSYS. Then the natural frequency and mode shapes of resonator, simple and MM beam were found out using modal analysis ANSYS. The numerically found first natural frequency of simple beam and resonator are found to be in close agreement with the available analytical results, hence validating the numerical model. To find out the response of the simple and MM beam modal analysis ANSYS was used. The displacement frequency response functions were calculated numerically for both simple and MM beam in modal analysis ANSYS. During the numerical simulations, appropriate mesh size and boundary conditions were used. Fixed boundary condition and force boundary condition were used during modal and harmonic analysis. It was found that the vibration displacement amplitudes of the MM beam having attached resonators is attenuated to greater extent as compared to original simple beam operating at its first natural frequency. It was found that the MM beam can attenuate the vibration amplitude in wide frequency range.

Effect of Temperature on the Mechanical Performance of Woven Carbon Epoxy Composites Under Dynamic Compression

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Speaker: Kumar Rohit. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Carbon woven composites, with their high strength-to-weight ratio, are used in aerospace, automotive, and other civil structure applications, making temperature effects important. The current study investigates the mechanical performance of carbon woven composites under varying temperatures, with a particular emphasis on their dynamic compression behaviour. Compression moulding was employed to make rectangular panels of 4 mm carbon-epoxy woven composite. For dynamic compression investigations, cylindrical specimens were made through the thickness direction utilizing water jet cutting. The split-Hopkinson pressure bar arrangement for reproducing high strain rate compression studies at temperatures ranging from -40∘C to 70∘C yielded significant results. Analysis of various mechanical properties, including elastic modulus and ultimate strength, revealed a dependence of the material on strain rate within the specified temperature range. Increased temperature reduces composite compressive strength by 20% at 70∘C relative to ambient temperature. At -40∘C, the strain rate sensitivity factor may rise by around 10-15%, increasing compressive strength at sub-zero strain rates, while leading to brittle and catastrophic failure modes.
Deformed specimen fracture surfaces were examined using a DVM6 digital microscope. The epoxy matrix becomes soft at high temperatures, causing ductile failure with fibre pull-out, polished matrix surfaces, and enhanced delamination. The matrix's load-transfer efficiency is reduced by fibre exposure on fracture surfaces due to decreasing binding strength. The epoxy matrix becomes brittle at low temperatures, causing acute fractures and clean fibre ruptures. However, this reduces durability and increases catastrophic failure.

Energetically exhaustive homothetic tests of hyperelastic isotropic materials: analytic tools and experimental characterization

Falope Federico Oyedeji (1) (2) (3), Lanzoni Luca (3) (1), Tarantino Angelo Marcello (1) (3)

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Speaker: Falope Federico Oyedeji. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The mechanical characterization of hyperelastic, homogeneous, and isotropic materials is typically carried out by fitting a stress component or resultant of one or more states of stress. Uniaxial tension/compression, biaxial, torsion, and shear tests are some of the most common experimental methods for obtaining constitutive parameters. Once the material law is assumed (*Ariano, R. (1925)*, *Truesdell, C. (1956)*, and *Signorini, A. (1959)*), the target of the fitting procedure is the determination of the material constitutive parameters. Yet, it is possible to directly track the 2D or 3D behaviour of the derivatives of the energy function (DEF) of incompressible or compressible materials, respectively.
Depending on the choice of the deformation invariants and the experiment, three families of homothetic tests can be recognized (*Falope et al. (2024)*): energetically exhaustive, partially exhaustive, and non-exhaustive tests. A test is said energetically exhaustive if its matrix form is equivalent to a determined system of equations in the unknowns DEF. The strength of the unequal-biaxial test is discussed, showing that it is able alone to directly characterize the form of the DEF. Experiments of this type are presented and design tools for these tests are proposed. The outcomes of the unequal-biaxial tests on three different rubber-like materials bring to light two unexpected results. First, two empirical (E-)inequalities do not describe the behaviour of two tested materials, while the *Backer-Ericksen* inequalities (1954) are fulfilled. Second, new alternative forms of the BE-inequalities are presented together with a new *hierarchical empirical inequality*.

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Enhancing PEEK Implant Performance: Role of Hydroxyapatite Coatings and Mechanotransduction in Osseointegration and Cell Response

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Speaker: Labadi Cerine. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Background and objectives

Polyetheretherketone (PEEK) is emerging as a promising material for bone replacement applications, especially in cases of degenerative joint diseases and bone fractures. Its high biocompatibility and elastic modulus of approximately 4.5 GPa, which is closer to that of natural bone (ranging between 4 and 20 GPa), make it a favourable choice compared to other implant materials. However, PEEK's limited osseointegration often leads to implant failure over time. This study aims to enhance the PEEK-bone interface by applying a hydroxyapatite coating, which is expected to improve osseointegration and potentially reduce inflammation associated with implants.

Materials and Methods

Stoichiometric hydroxyapatite feedstock (MEDICOAT) was applied to PEEK as supplied through a cold spray deposition technique. Four PEEK surface types were evaluated: grinded PEEK, sulfonated PEEK (SPEEK), hydroxyapatite-coated PEEK (HA-PEEK), and sulfonated, hydroxyapatite-coated PEEK (S/HA-PEEK). Unmodified PEEK samples were polished with SiC P600 abrasive paper. SPEEK samples were prepared by polishing PEEK samples with SiC P600 abrasive paper, followed by immersion in 95% (v:v) sulfuric acid (H_2SO_4) for 90 seconds. HA- PEEK samples were polished with SiC P600 and then coated with HA. Lastly, S/HA-PEEK samples were polished with SiC P600, treated with 95% sulfuric acid for 90 seconds, and then coated with HA.

To assess the cytocompatibility and bone tissue formation potential of these surfaces, murine embryonic chondrocytes (1) were cultured on direct contact with the four PEEK samples. Cells (0.5×106 cells/sample) were seeded onto the PEEK sample surfaces maintained in a biotriboreactor under dynamic culture conditions for 21 days, with a cyclic compressive load applied at a frequency of 0.5 Hz and an amplitude of 75 μm. Both static and dynamic culture conditions were assessed, measuring metabolic activity, cytotoxicity, mineralization, and rheological properties. Additionally, histological analyses were conducted to provide deeper insights into cellular responses and to predict tissue behaviour.

Results

Initial static culture results after 24 hours of contact demonstrated good biocompatibility across all materials, with cytotoxicity levels remaining very low ($< 5\%$). Although no significant differences in cell viability were observed between materials, sulfonation unexpectedly resulted in a higher cell rate, whereas HA-coated samples, which were expected to promote cell proliferation, did not exhibit a similar increase (2). While cell proliferation continued in static cultures, dynamic cultures exhibited a marked reduction in metabolic activity without affecting cell viability. This decline may suggest the initiation of a differentiation process induced by mechanotransduction, as has been documented in previous studies involving mesenchymal stem cells (3). Mechanical loading applied between days 3 and 10 was shown to stimulate extracellular matrix (ECM) production. Confocal imaging revealed substantial extracellular matrix (ECM) formation under dynamic conditions, despite a lower cell proliferation rate compared to static cultures. This suggests that mechanotransduction could play a key role in promoting a well-structured ECM, reinforcing tissue integrity and encouraging collagen synthesis.

Comparisons between materials in both static and dynamic cultures showed that HA coatings did not outperform uncoated materials in terms of metabolic activity or cytotoxicity. Interestingly, sulfonated materials exhibited the highest cell proliferation rate under both culture conditions, suggesting that sulfonation may be more effective than HA in enhancing cell adhesion and proliferation under the current experimental conditions.

Rheological assessments revealed a 10-fold increase in ECM storage modulus from day 3 to day 21. Early measurements showed variability in amplitude and phase shift across samples, indicating a predominantly viscous behaviour. In contrast, later measurements demonstrated converging amplitudes and minimal phase shifts, suggesting progressive matrix stiffening.

Despite these promising *in vitro* findings, commercially available HA coatings did not meet the expected performance, highlighting the need for more effective biomimetic coatings. The observed decrease in metabolic activity under dynamic conditions suggests that changes in cell signalling related to differentiation rather than cytotoxicity may be occurring, an area that warrants further investigation.

Conclusion and Perspectives

This study provides an initial framework for analysing cell behaviour at the bone-implant interface in response to mechanical stimuli. The findings suggest that mechanotransduction plays a role in supporting bone tissue formation, although cell proliferation is less pronounced under dynamic conditions. While neither sulfonated nor coated materials demonstrated significantly superior performance, there is potential to enhance the current coatings. Future research should include a more comprehensive comparison of coating effects using additional sample types. Another important avenue for investigation would be the tribological properties of the samples, as these are critical for understanding performance at the bone-implant interface. Insights into how these materials behave under mechanical loading and friction could provide valuable information on their long-term stability and integration. Notably, the release of PEEK particles due to suboptimal tribological behaviour may trigger an inflammatory response, potentially leading to implant rejection, an issue highlighted by Milinkovic et al. (2022) (4).

Key words: Polyetheretherketone (PEEK), Bone-Implant Interface, Hydroxyapatite Coating, Osseointegration, Mechanotransduction, Cytocompatibility, Rheological Properties.

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Friction behaviour of meso-scaled textured metallic surfaces using numerical and experimental methods

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Speaker: Rogkas Nikolaos. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Meso-scale surface texturing, incorporating features such as grooves, pillars, or bumps, has traditionally been studied to enhance the performance of tribosystems, primarily by improving lubrication characteristics (1). Recently, surface texturing has demonstrated the potential to control the friction coefficient between flat and textured surfaces, laying the groundwork for the development of frictional meta-interfaces (2). To further investigate the capability of controlling frictional behavior within tribopairs, this study explores a range of meso-scale textures, including bio-inspired designs that mimic surface structures of geckos and desert scorpions (3), alongside conventional geometries such as bumps, sinusoidal patterns, and rectangular textures. The frictional properties of these textures are evaluated through a dry sliding contact model between two metallic surfaces, a rigid cylindrical indenter and an elastic textured surface, using a 2D finite element analysis (FEA) model developed in COMSOL Multiphysics. This metal-to-metal contact analysis focuses on frictional forces, stress distributions, and contact areas. The simulation results are compared to assess the influence of each texture on frictional behavior, contact stresses, and the overall contact surface. Furthermore, prototypes of the textured surfaces are fabricated using the Selective Laser Melting (SLM) method, aiming also to explore the capability of this manufacturing process to accurately fabricate meso-scaled textures. These prototypes are then tested experimentally with a pin-on-disk tribometer in dry and lubricated conditions in order to verify the simulation results and to provide a comprehensive understanding of the frictional performance of the textures.

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Friction between lubricated soft contact lens and eyelid from free responses measurements

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Speaker: Perret-Liaudet Joel. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Keywords: Soft Contact Lenses (SCL), friction, dynamic free response, dynamic oscillating tribometer, damping

1. Introduction

Friction coefficient is considered as a measurement for clinical comfort of soft contact lenses (SCLs). The comfort of soft contact lenses is affected by many factors, including those related to the patients and to contact lens material (1). This study aims to evaluate the friction at the soft contact lens-eyelid contact. In order to evaluate precisely the ultra-low friction at this contact, an original technique developed at the Laboratory of Tribology and System Dynamics (LTDS), called "Dynamic Oscillating Tribometer" (2), is used. A variety of soft contact lenses are tested with some lubricants under many physiological conditions. The results are discussed and compared with those in the literature.

2. Methods

A variety of soft contact lenses materials is tested in contact with a flat surface made of polyethylene terephthalate (PET) material with saline solution with and without hyaluronic acid under different physiological conditions. Different percentages of hyaluronic acid is tested in order to understand the effect of hyaluronic acid with saline solution on the soft contact lenses.

3. Experimental Setup

The dynamic oscillating tribometer consists of a pin-on-plane contact. This tribometer is based on a single-degree-of-freedom (SDOF) mass-spring oscillator system supporting the sliding contact. This tribometer allows us to measure the dynamic free responses at the contact between the SCL and PET. The friction is analyzed from the decaying envelope of the free response (3). Using a pseudo-polynomial friction law, the different friction contributions are identified by solving the non-linear equation of motion (4).

4. Operating conditions

The experiments are performed at room temperature with applied normal loads between 50 and 250 mN and sliding velocities varying from 0 to 230 mm/s. The sliding speed corresponds to the blinking speed when closing and opening the eyelid. The applied normal load corresponds to the contact pressure of the eyelid on the cornea.

5. Conclusion

This research shows the feasibility of measuring friction at the eyelid-lens contact using the oscillating dynamic tribometer. The results have demonstrated that the precision is very high for low friction coefficient. This study presents the friction coefficient for different soft contact lenses. In this work, the effect of Hyaluronic acid in the saline solution has been discussed as well as the influence of different operating conditions.

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High shear thrombi formed in vitro stop blood flow by cables of VWF and platelets

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Speaker: Ku David. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Arterial thrombi formed in regions of high shear rate (> 6,000/s) must withstand strong pressure and shear forces to occlude an artery as in myocardial infarction or ischemic stroke. The present study uses a combination of scanning electron microscopy and light microscopy to characterize the structure of platelet-rich thrombi formed in a microfluidic device.
We show by SEM that the occlusive portion of the thrombus consists of a thick, transverse cable that completely spans the channel width. The cable is made of hundreds of parallel strings of platelets where the platelets are joined by yarns of Von Willebrand Factor (VWF) fibers identified by immunofluorescence microscopy. The elements of cable, strings, yarns, and fibers, are oriented in the direction of tensile forces created by pressure gradient to confer high breakage strength and stability. A mechanical analysis reveals that Platelet-VWF bonding would provide a rupture force of 4500 pN. In comparison, VWF-VWF bonding would provide a minimum rupture force of 414 pN compared to the macro ultimate strength of which is greater than the yarn rupture force of 550 pN. The structural hierarchy supports VWF as a potential target for the prevention and lysis of occlusive arterial thrombi.

Impact of Static Strain Ageing on the Fracture Toughness Properties of C-Mn Steel Welds in the Secondary Circuit of Pressurized Water Reactors

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Speaker: Riverie Ronan. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Pressurized water reactors (PWRs) include a secondary cooling system composed of steel piping elements joined by C-Mn steel welds. Under specific conditions, these weld joints may undergo static strain ageing (SSA), a phenomenon driven by the segregation of interstitial atoms, such as nitrogen, to dislocations at the microstructural scale. Laboratory demonstration of SSA requires a two-step thermo-mechanical treatment: first, pre-straining to generate a high dislocation density, followed by an ageing heat treatment to enable the migration of interstitial atoms to dislocations via thermal diffusion. Macroscopically, this phenomenon induces changes in mechanical properties. In terms of impact toughness, embrittlement manifests as a shift in the ductile-to-brittle transition curve towards higher temperatures when comparing the strain-aged state with respect to the strained state. However, the influence of SSA on fracture toughness transition curves of C-Mn steel welds has been little studied in the literature.
Therefore, the project is divided into two parts. The first focuses on a detailed description of the microstructural mechanisms involved in SSA. The second, which is discussed here, aims at evaluating its consequences on the fracture properties in the transition domain. Numerical studies are also performed to improve the mechanical modeling of the components while accounting for SSA. The as-welded state is considered in this project to exacerbate the phenomenon.

The mechanical analysis is grounded in an extensive experimental campaign. Blocks are extracted from a full-scale welded pipe mock-up to replicate industrial conditions as closely as possible. These blocks are divided into three groups representing the as-welded, strained, and strain-aged states. From each group, two types of specimens are machined: standard Charpy V-notch and four-point single-edge notch bend (SENB) specimens, to study the effects on both impact and fracture toughness properties. Pre-straining is achieved by compressing the blocks to 5% plastic strain in the weld direction, while the strain-aged state is obtained with a subsequent heat treatment at 250∘C for 30 minutes. Afterwards, toughness tests are conducted to determine transition curves for each state. Fracture toughness is analyzed using the Master-Curve approach.
In parallel, finite element simulations using the Beremin model are conducted to compare numerical results with experimental data. These simulations incorporate the Estrin-Kubin-McCormick (EKMC) constitutive law to accurately model the material's behavior under SSA conditions.

In Situ SEM Experimental Studies on the Mechanical Properties of Two-Dimensional Materials

Yan Yabin (1)

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Speaker: Yan Yabin. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Two-dimensional (2D) materials represented by graphene and Ti3C2Tx have broad applications in flexible electronics, electromechanical devices, and structural membranes due to their unique physical and chemical properties. Here, by optimizing the sample preparation, cutting, and transfer protocols, we perform the direct in-situ tensile tests on monolayer Ti3C2Tx nanosheets using nanomechanical push-to-pull equipment under a scanning electron micro- scope. The effective Young's modulus is 0.484 ± 0.013 TPa, which is much closer to the theoretical value of 0.502 TPa than the previously reported 0.33 TPa by the disputed nanoindentation method. Moreover, during the process of tensile loading, the monolayer Ti3C2Tx shows an average elastic strain of _~3.2% and a tensile strength as large as _~15.4 GPa. In addition, we conducted in situ mechanical experiments on double-layered graphene using a scanning electron microscope and obtained its force-displacement response curve. The measured Young's modulus was approximately 0.829 TPa, which is highly consistent with the theoretical value. We also observed that the cracks fractured brittlely along the direction perpendicular to the tensile direction. This study proposed a reliable, direct and quantitative method that solves the problem of measuring the mechanical properties of two-dimensional materials and provides a solution for general atomic-scale nanomechanical testing.

In Vitro Validation of a 4D Ultrasound Strain Imaging Approach for the Identification of Patient Specific Anisotropic Elastic Material Properties of Abdominal Aortic Aneurysm

Hegner Achim (1) (2), Wittek Andreas (1), Derwich Wojciech (3), Oikonomou Kyriakos (3), Huß Armin (1), Gámez Antonio J. (2), Blase Christopher (1)

1 - Frankfurt University of Applied Sciences (Germany), 2 - Universidad de Cádiz = University of Cádiz (Spain), 3 - Frankfurt University Hospital (Germany)

Speaker: Hegner Achim. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Introduction:
Biomechanical computational models should be largely patient-specific to provide deeper insight into the pathophysiology of abdominal aortic aneurysms (AAA) and to be relevant for future clinical diagnostics. The identification of individual material properties is of central importance, but they are usually unknown and difficult to determine in vivo. Time resolved 3D ultrasound combined with speckle tracking (4D-US) is a non-invasive imaging technique that provides full-field information of heterogeneous aortic wall strain distributions in vivo. These strains are cyclic strains with respect to diastole. We here present a substantial new development of an in vivo 4D-US strain imaging approach that was presented previously by our group. It identifies the parameters of a nonlinear and anisotropic material equation, while using only information that can be collected in vivo. For this approach we perform an in vitro validation using an intact tubular section of a porcine aorta in an inflation-extension experiment.

Material and Methods:
A porcine aorta from the thoracoabdominal region was obtained from a local organic butcher, cleaned of attached tissue, and marked for global deformation measurements. The specimen was immersed in 0.9% (w/v) NaCl solution at 37∘C and tested with a custom inflation-extension device. Both ends were clamped in holders, while cyclic length and pressure changes were applied at a frequency of 0.84 Hz. Saline was pumped through the fixed lower holder connected to a pump cylinder, while a linear motor adjusted the upper holder to simulate physiological length changes. Motors synchronized using a trigger signal simulated a pulse cycle. Axial force and transmural pressure were recorded at 50 Hz. Deformations were captured with two orthogonally mounted CMOS cameras and the 4D-US device in parallel.
On the one hand, specimen deformations were determined from camera images and stress-stretch curves were calculated from wall thickness and recorded force/pressure values. The parameters for the anisotropic Holzapfel-Gasser-Ogden (HGO) material equation were identified by fitting to calculated stress-stretch curves.
On the other hand, from the 4D-US images a finite element analysis model was created. Since only diastole and systole can be used as load cases in vivo, only experimentally measured values from these two states were used for parameter identification. Boundary conditions from the experiment were applied to the model: lower end was fixed, upper end could move only in axial direction, transmural pressure was applied to the inner surfaces, and sensor force was applied to the upper end. Our newly developed in vivo 4D-US strain imaging approach uses an evolutionary self-adaptive Differential Evolution (JADE) algorithm as optimization strategy. It iteratively calculates the material-dependent load-free geometry and, based on this, the diastolic and systolic geometries using diastolic and systolic force/pressure values. Cyclic strains are then calculated with respect to diastole. Parameters are identified by minimising an error function that compares cyclic measured strains using 4D-US and the calculated cyclic model strains.
Results:
Identified material behaviour from mechanical data and 4D-US showed very good agreement. Comparison of stress-stretch curves calculated using the identified parameters show coefficients of determination in the range $R^2 = 0.952$ - 0.990.

Conclusion:
We successfully performed an in vitro validation of a new developed 4D-US strain imaging approach for the identification of patient-specific parameters of an anisotropic material equation using only informa-

tion that can be collected in vivo. Also, performance could be increased by factor seven.

Influence of Microvoids and Grain Heterogeneity on Ultrasonic Longitudinal Wave Propagation in Polycrystalline Metal

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1 - Indian Institute of Technology Kharagpur (India)

Speaker: Yadav Anuj. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The field of ultrasonic non-destructive testing (NDT) has seen significant advancements, with much of the research focusing on material microstructural characterization, particularly the determination of mean grain size, grain size distribution, and elastic modulus in polycrystalline metals. However, limited literature is available regarding the characterization of microvoids within the microstructure using ultrasonic NDT (1,2). Microvoids often form during additive manufacturing and casting processes, posing a critical concern as they can act as precursors to crack growth. Early detection of these voids is essential to ensure the structural integrity and reliability of metallic components. The present study investigates the scattering of ultrasonic longitudinal waves caused by microvoids combined with grain heterogeneity in polycrystalline metals using a finite element (FE) method. Initially, 2D microstructure geometries of Inconel 600, measuring 30 mm $\times$ 10 mm, are generated using Neper software. Realistic imperfections are introduced by incorporating irregularly shaped microvoids at random locations within the microstructure using in-house code. Multiple models are developed with varying mean void diameters (40 μm to 70 μm in 10 μm increments), grain sizes (300 μm to 600 μm in 100 μm increments), and porosity levels (random values ranging from 0% to 7%). These microstructure models are then imported into ANSYS APDL for finite element-based wave propagation analysis. Simulations are conducted on a high-performance computing platform in parallel computing mode. To excite longitudinal waves, a Hanning tone burst load with a central frequency of 1 MHz is applied to all models. The simulations capture the combined scattering effects of grains and voids heterogeneity. The numerical results for zero-porosity models with varying mean grain sizes are first validated against the existing unified theory (3,4), showing good agreement. The analysis reveals that longitudinal waves effectively detect microvoids when wave scattering due to grains is less significant compared to voids. Results indicate that increasing porosity reduces longitudinal wave velocity and increases wave attenuation. Additionally, wave characteristics are significantly influenced by the increasing mean diameter of microvoids. These findings highlight the sensitivity of ultrasonic waves to microstructural imperfections and their potential for non-destructive evaluation. The study provides valuable insights into the interaction between ultrasonic waves and microstructural features, paving the way for advanced assessment of material porosity and grain boundary integrity in engineering applications.

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Investigation of Structural Stability and Mechanical properties for full Heusler alloy: Co2FeGa

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Speaker: Salima Labidi. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

By using the full potential linearized augmented plane wave (FP-LAPW) method within the density functional theory (DFT). The physical properties such: structural and mechanical properties for the full Heusler alloy Co2FeGa are investigated and discussed. The exchange-correlation potential was treated using two of approximations where the WC-GGA is used to calculate the stable state of the material for both Fm -3m and F43-m space groups from the FM, NM, and the AFM states by calculating all of their structural parameters from the lattice parameter a (Å) to the enthalpy ΔHf and to calculate also the elastic constants. The three-dimensional plots of different mechanical moduli exhibit that the bulk modulus is isotropic, whereas Young's modulus, Poisson's ratio and shear modulus of Co2FeGa compound are highly anisotropic. The effects of temperature and pressure on the heat capacity, thermal expansion coefficient and Debye temperature are also studied.

Magnetically Tunable Defective Phononic Crystal Microbeams: Wave Propagation and Energy Harvesting Characteristics

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Speaker: Zhang Gongye. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

This study explores the wave propagation and energy harvesting capabilities of magnetically tunable defective phononic crystal (PnC) microbeams, incorporating microstructure effects. A theoretical model for a sandwich-structured PnC beam is established using modified couple stress theory. Parametric analyses are performed to investigate the impact of microstructure, external magnetic fields, and defect lengths on bandgap formation and defect band characteristics. Numerical simulations demonstrate the influence of defect mode shapes on elastic wave localization, offering insights for optimizing energy harvesting efficiency. Transmission curves under varying magnetic field intensities and defect segment lengths are evaluated using the spectral element method, alongside the voltage output of a piezoelectric layer attached to the defect region. The findings highlight the potential of external magnetic fields for non-contact tuning of bandgap and defect band frequencies, providing a framework for enhancing energy harvesting devices based on PnC defect structures.

Mechanical Behavior and Energy Release in PTFE/Al Composites Enhanced with Ammonium Perchlorate Micro-Particles

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Speaker: Benattallah Sofiane or Makaoui Ramzi. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Reactive materials have gained significant attention as energetic materials, particularly in shielding applications. One notable example is the Polytetrafluoroethylene (PTFE)/Aluminum (Al) composite, which exhibits significant energy release when subjected to high-velocity impacts or extreme strain rates, along with notable mechanical properties. This study investigates the influence of Ammonium Perchlorate (AP) micro-particles on the mechanical performance and energy release capabilities of PTFE/Al mixtures through experimental approaches. Four sets of samples, with 0%, 1%, 2%, and 3% AP content, were subjected to calorimetric bomb testing. The results demonstrated a 13% increase in the calorific power of PTFE/Al with the incorporation of 3% AP, suggesting its potential as an improved reactive material. Scanning electron microscope (SEM) analysis revealed a homogeneous and fibrous structure in the sintered PTFE/Al/GO composite, with a uniform coating of Al and AP particles by PTFE. Compression tests highlighted a transition from ductile behavior in the sample without AP to increased stiffness and toughness with higher AP content. Furthermore, high-velocity impact testing using a split Hopkinson pressure bar (SHPB) demonstrated enhanced energy absorption and elasto-plastic behavior with increasing AP levels. Overall, this study provides novel insights into the integration of AP into PTFE/Al composites, showcasing enhanced reactivity and mechanical properties.

Keywords:
Reactive materials; PTFE/Al composite; SHPB; Mechanical properties; Energy release.

MICROMECHANICAL MODELING AND EXPERIMENTAL ANALYSIS OF MAGNESIUM ALLOY WE43, FOR MEDICAL IMPLANT APPLICATIONS

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Speaker: Karamifard Fatemeh. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

INTRODUCTION

Bioresorbable materials are a critically important part of the next generation of medical implants, where the implant can degrade and resorb harmlessly into the body once it has completed its function (1). Bioresorbable metals, such as magnesium (Mg) alloys, hold great promise for cardiovascular and orthopaedic implant applications where tissue structural support of is needed while the tissue heals and recovers normal function. Mg alloys provide great structural support on implantation. However, they tend to have relatively high degradation rates in the bodily environment, resulting in the premature loss of structural support, and researchers have been actively exploring ways to retard degradation rates (2,3). The overall objective of this work is to develop micromechanical models of WE43 alloy capable of representing the mechanical performance and bioresorption (corrosion) behaviour of the material. The modelling methodology proposed here is novel and has not been achieved before.

MATERIALS AND METHODS

Magnesium alloys have distinct deformation behavior compared to other metals. This distinction stems from their hexagonal-close-packed (HCP) lattice structure (4). The micromechanical modeling utilizes crystal plasticity finite element (CPFE) modeling of the HCP crystal structure. The plastic deformation of a single crystal is assumed here to arise from crystalline slip and twining. A UMAT subroutine is used to model the plastic deformation. In the first stage, a 2D unit cell model including 10 grains (Fig.1-a) was developed, and periodic boundary conditions were applied to this model. Experimental analysis in this study involves the use of 3D Diffraction Contrast Tomography (DCT), available using an in-house Zeiss Versa 620 system to determine typical grain size and shape statistics. The scanning images allow the construction of the CPFE models that will realistically represent the microstructure. DCT scans have been performed for samples with dimensions of $0.5\times0.5\times2$ mm that machined from different locations in a 50 mm-diameter extruded bar. For each sample, three sections at different lengths were individually modelled in 3D. Fig.1-b shows one section with dimensions of $0.304\times0.304\times0.304$ mm, containing 88 grains. NEPER is an open-source software that was used to generate tessellation corresponding to the polycrystal and to mesh it for FEM simulation (Fig.1-b). In this case, each grain has its own ID and specific crystallographic orientation.

RESULTS

Results for typical models in 2D Fig.1-a and 3D Fig.1-b are shown in Fig.1 for loading in tension, where the 3D models were generated from the DCT scan data as described above. The contours of strain provide valuable insights into the distribution and magnitude of strain across the entire sample.

Micromechanical properties of ion irradiated hard anodized layer developed on Al6061-T6 alloy: A micropillar compression and splitting tests study

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1 - CEA- Saclay (France), 2 - Laboratoire Georges Friedel (France)

Speaker: Sao Joao Sergio. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

This study aims to quantify the changes in micromechanical properties induced by ion irradiation of an alumina-based anodized layer for its potential nuclear applications.
A hard anodized layer of average thickness 49.1 ± 1.9 μm was developed on Al6061-T6 alloy via anodization in oxalic acid solution followed by sealing in boiling water. SEM and TEM examination revealed a typical U-shaped columnar structure in longitudinal cross-section and a flaky/gel-type structure on the top surface. XRD and TEM confirmed the layer's amorphous nature. Si ion irradiation at energies of 3.5–0.5 MeV resulted in a damage dose of _~6–7 dpa up to _~2 μm depth and Si implantation of _~0.6 at.%. Post-irradiation microscopic examination showed curly/rolled features on the top surface and a smoother surface within the irradiated zone; the irradiated region remains amorphous.

In situ SEM micropillar compression and splitting tests were carried out to compare the plasticity and fracture toughness between non-irradiated and irradiated layers. Micropillar compression tests revealed a hardening of approximately 30 % induced by irradiation, with a plastic flow stress of about 3 GPa. The fracture toughness (Kc) of the layers, measured by micropillar splitting, appears to be unchanged by ion irradiation, with a value of Kc $\approx$ 2.2 MPa$\sqrt{\text{m}}$. By testing more than a dozen pillars with different geometric shape factors, unrelaxed compressive residual stresses of the order of 1 GPa were measured in the irradiated layer. Finally, the *in situ* observation of deformation and cracking processes allows for a discussion of the obtained properties in relation to the previously characterized microstructure.
Keywords: Anodized layer, Ion irradiation, fracture toughness, micropillar compression, micropillar splitting.

Mise en place et optimisation du procédé hybride CNC / FFF dans le cadre de la fabrication de pièces métalliques en acier inoxydable 316L

Tejada Martinez Luis Vincent (1)

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Speaker: Tejada Martinez Luis Vincent. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

La fabrication additive, notamment par dépôt de filament fondu (FFF), se heurte encore à des limitations importantes en termes de performances mécaniques, particulièrement lorsqu'il s'agit de propriétés liées à la fatigue des matériaux. Ces limitations sont principalement attribuées à l'état de surface des pièces imprimées, qui favorise l'initiation de fissures et, par conséquent, réduit significativement leur durée de vie en service. Malgré une abondance d'études portant sur la caractérisation mécanique de pièces métalliques issues de la fabrication additive, celles-ci se concentrent souvent sur des échantillons préalablement usinés. Cette approche, bien qu'efficace pour améliorer les performances des pièces, masque les véritables défis posés par l'intégration de procédés hybrides visant à surmonter les contraintes initiales propres aux pièces brutes issues de l'impression 3D.
Dans cette optique, nos travaux s'inscrivent dans le développement d'un procédé hybride novateur, entièrement automatisé, combinant fabrication additive et usinage. Cette solution, qui repose sur des outils et des logiciels open-source, vise non seulement à optimiser la qualité des pièces produites, mais aussi à élargir les champs d'application de la fabrication additive au-delà du simple prototypage rapide. Grâce à ce procédé, il devient possible de répondre aux exigences des secteurs industriels les plus critiques, en produisant des pièces prêtes à l'emploi, avec des propriétés mécaniques et une précision répondant aux normes les plus strictes.
Les recherches menées s'articulent autour de deux axes principaux. Le premier concerne la conception et l'intégration d'un système d'usinage compact et adaptable aux imprimantes 3D FFF grand public. Ce système s'accompagne de deux solutions logicielles open-source : un post-processeur spécialement développé pour l'hybridation FFF/CNC et un module intégré au slicer, permettant une gestion transparente et intuitive des opérations hybrides. Ces outils permettent la mise en œuvre de stratégies d'usinage optimisées, spécifiquement adaptées aux imprimantes FFF, offrant ainsi une amélioration significative de l'état de surface des pièces grâce à des conditions de coupe favorables.
Le second axe porte sur le développement d'un module Python dénommé *ASAHM* (Automated Subtractive Additive Hybrid Manufacturing). Ce logiciel, conçu pour générer automatiquement des trajectoires G-code hybrides destinées à des systèmes multi-outils, est conçu pour être à la fois polyvalent et compatible avec une large gamme de technologies de fabrication additive. Il intègre des stratégies avancées, notamment pour le contournage et le surfaçage des surfaces complexes, permettant de traiter efficacement des géométries imprimées en 3D, tout en garantissant une flexibilité d'utilisation au sein de divers environnements industriels.
En parallèle, des efforts de recherche ont été déployés pour améliorer davantage les capacités du procédé hybride. Ces efforts incluent le développement de trajectoires adaptées aux outils à dentures sphériques ainsi que la conception d'outils de coupe spécifiquement optimisés pour répondre aux contraintes de l'hybridation FFF/CNC. De plus, des avancées dans le domaine de la fabrication additive métallique, notamment à travers des techniques de frittage économiques et performantes pour le procédé MIM-Like, permettent d'étendre l'application de cette approche hybride à des matériaux tels que l'acier inoxydable 316L.
L'ensemble de ces travaux, validés par des analyses approfondies des microstructures, des essais mécaniques et des tests de fatigue, démontre la capacité de ce procédé à produire des pièces métalliques de haute qualité, conformes aux normes industrielles les plus exigeantes. Ces résultats ouvrent ainsi la voie à une adoption à grande échelle du procédé hybride, offrant une solution technique et économique prometteuse pour relever les défis actuels de la fabrication additive.

Mixed variable system Monte Carlo tree search for sizing and shape optimization of truss structures

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Speaker: Ko Fu-Yao. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Structural optimization has attracted considerable interest over the last three decades due to limited energy and material resources (1). For combined sizing and shape optimization of truss structures, the design variables are the nodal coordinates of the joints and the cross-sectional areas of the members (2). This optimization problem has been recognized as a more important task than purity sizing optimization because it can provide more reduction in weight (3). However, this problem is considered to be more challenging because of the different natures of the two types of variables. Combining these may produce a different rate of convergence and ill-conditioning problems. Because the constraints and objective function become more complex, it may lead to solutions far from the global optimum or even in infeasible domains (4). To solve these difficulties, two classes of optimizers are used to solve structural optimization problems of truss structure, including mathematical programming approach (5) and metaheuristic algorithms (6).
Reinforcement learning (RL) is an area of machine learning, which trains an action taker called agent to take appropriate actions to maximize the cumulative numerical reward signal. RL task must be formulated into a Markov decision process (MDP). The MDP is a mathematical tool used for sequential decision making where state transition and reward function solely depend on the current state and action and are independent of the sequence of events that preceded it (7). RL method has achieved remarkable success in game playing, autonomous driving, intelligent control, and planning and scheduling (8). However, few studies focus on the area of engineering optimization and its applications.

Recently, RL method has been successfully implemented in structural optimization problems. Hayashi and Ohsaki (9) presented a combined approach using Q-learning and graph embedding for binary truss topology optimization for volume minimization under stress and displacement constraints. Huynh et al. (10) integrated Q-learning into differential evolution algorithm. This method was validated by truss optimization on sizing and shape with multiple frequency constraints. All design variables are considered in continuous search space (CSS). Kupwiwat et al. (11) proposed a combined method of deep deterministic policy gradient (DDPG) and graph attention network for geometry optimization of latticed shells described by Bézier surface. Kupwiwat et al. (12) developed a novel method using multi-agent RL and DDPG and applied to multi-objective optimization problems of truss structures. RL approach can be used for structural design problems where the optimal solution is not known beforehand because it does not need input–output pairs as training data. However, the disadvantage of this method is the high computational load for training the agent (13).

An RL algorithm based on Monte Carlo tree search (MCTS) is proposed to solve the truss layout optimization problems in the last three years. Luo et al. (14) proposed an RL algorithm named KR-UCT to handle continuous variables for solving truss layout design problems using kernel regression. Luo et al. (15) developed a novel MCTS-based RL method known as AlphaTruss to produce the optimal truss layout considering sizing, shape, and topology. AlphaTruss uses a two-stage strategy to determine the optimal solution and does not introduce accelerating technique. Therefore, it tends to get trapped in local optimum and cannot be directly used for practical engineering problems. Both KR-UCT and AlphaTruss are applied to CSS. Ko et al. (16) presented an RL approach called Improved Monte Carlo Tree Search (IMCTS) for discrete sizing optimization of truss structures. This technique with update process and accelerating technique for discrete variable, the best reward, and terminal condition utilizes the search tree with multiple root nodes. This method is employed to minimize the weight of the truss subject to stress and displacement constraints. The results show that IMCTS can determine the globally optimal solution within a reasonable time, stably produce optimal designs, and solve large-scale truss structures and multi-objective optimization problems. IMCTS only deals with one type of design variable with discrete case. Few studies employ RL methods to deal with different types of design variables with mixed continuous/discrete system.

In this paper, Mixed Variable System Monte Carlo Tree Search (MVSMCTS) is proposed to handle sizing and shape variable at the same time. MVSMCTS revolves around two important characteristics: update process and accelerating technique in CSS and combined scheme in single and mixed system. The substantive contributions of this paper are the following:

(1) Search region is defined as certain part of the CSS. The main aim is to find the optimal solution. Search region is determined by the design variable of the initial state in current round, which is calculated from the design variable of the final state in previous round.

(2) Search region is composed of all possible points in the CSS. Three important points, including the left endpoint, the midpoint, and the right endpoint are specified in search region. The midpoint is chosen as the design variable of the initial state to achieve global optimality.

(3) Nonuniform meshes are generated in search region to add the child node in the search tree. The meshes are randomly distributed. In other words, the interval between two adjacent meshes is not a constant. The optimal solution found by nonuniform meshes are slightly better than that by uniform meshes.

(4) Accelerating technique incorporates decreasing the size of the search region and the width of search tree as the update process proceeds. The width of search tree is based on the number of meshes generated for the current search tree.

(5) Three types of accelerating techniques including geometric decay, linear decrease, and step reduction are discussed. Regardless of the size of the search region and the width of search tree, geometric decay performs better than linear decrease and step reduction concerning computational efficiency.

(6) In combined scheme, the search tree couples different types of design variables to solve mixed variable structural optimization (MVSO).

(7) MVSMCTS proposes MDP framework, four steps in search tree, UCB, the best reward, policy improvement, update process and accelerating technique for discrete variable, and terminal condition to guarantee to find an optimal solution path.

The results demonstrate that this approach can find the optimal solution within a reasonable time, stably produce optimal design, and solve real-sized truss structures. In conclusion, RL-based MVSMCTS is a powerful optimization technique for MVSO. This study also shows evidence that this algorithm has the potential to solve optimization problems with mixed continuous/discrete system for practical engineering problems.

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Modelling of the permanent strain of a titanium plate riveted to a composite plate under the exposure to a kerosene flame

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Speaker: Krauskopf Paul. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Aircraft lightening has been carried out with a view to increase efficiency of fuel consumption. In that aim, light-weighted and efficient materials such as polymer matrix composite and titanium are used in aerospace designs (1). In particular, in the vicinity of aircraft engines, Interfaces for electrical and hydraulic routing are titanium plates assembled among composite structure. In this area, carbon-epoxy composites are a major challenge for safety requirements in terms of fire resistance (2). Hence the need to perform fire tests on components to meet safety regulations (3). Basically, carbon-epoxy titanium riveted plates assembly specimen (230x230 mm^2, carbon/epoxy laminates simply overlapped with titanium T40 plates, thickness=0.6mm) are exposed to a flame from an air/kerosene burner (cylindrical tube 50mm, flame at 1100 +/- 80 ∘C, heat flux of 116 kW/m^2) (4), (5). Flame penetration through the sample or flame on the unexposed rear side before 15 minutes will cause the test to fail. The experimental set up, at laboratory scale, includes the temperature monitoring of both sides by means of IR cameras. The results show the importance of the thermomechanical response of the titanium plate (from both the thermal expansion and the fixed boundary conditions) and the assembly parameters (overlapping length and fastening pitch) on meeting the certification requirements. High thermal stresses (stemming from the flame exposure) on the titanium plate result in a thermally-induced buckling between rivets after a 30 seconds exposure. The V-shaped deformation of the Ti plate allows hot gases to pass through the assembly, ultimately leading to the ignition of pyrolysis gases on the back surface and the failure of the validation test.

These observations have raised the question of the physics involved in this phenomenon which, although explainable, was not expected to occur with that dramatic consequences. This has motivated the development of a numerical modelling with the first aim of identifying what mechanisms are necessary to explain the phenomenology and what are their respective effects on it. The second aim was to evaluate the ability of the modelling to quantitatively reproduce the phenomenon. To start, the modelling is based on a purposely simplified configuration: only the section of the titanium plate lying between the rivets is represented. It is supposed to be clamped at the rivets contact surfaces and it is subjected only to a thermal aggression reproducing the one measured experimentally. The constitutive behavior is supposed to be thermo-elasto-plastic, with a weak coupling between thermal transfers and mechanics. The geometry of the section is a slightly curved rectangle. This curvature is meant to promote the bending in the direction of the flame. Most of these choices made for the preliminary steps of the development (boundary conditions, 2D, mesh refinement, curved rectangle) are, in the process of evaluating the modeling, the subject of dedicated analyses.

The first step consists in characterizing the mechanical behavior of Ti plates as a function of temperature. Some parameters (coefficient of thermal expansion, Young modulus and yield strength) could be found in literature on limited temperature ranges (6). Thermo gravimetric and Differential Scanning Calorimetry analyses were carried out to investigate phase transitions with temperature (7). To determine the temperature-dependence of mechanical properties (Young's modulus, yield and ultimate strengths), tensile tests were performed up to 750∘C by means of a testing machine equipped with a high-temperature oven. These tests are utmost important to determine the thermal and mechanical models' parameters.

The second step relies on the 2D simulation of the thermo-mechanical response of a Ti plate (through-the-thickness). Preliminary analyses show that the small strain assumption is not suitable to reproduce experimental results. A temperature ramp (from 0 to 840∘C) is applied uniformly on one surface of the plate (flame-exposed surface) during 30s, followed by a 10s cooling down to room temperature (20∘C). The back surface is subjected to natural convection at room temperature. The value of some parameters (convective heat transfer coefficient, strain hardening coefficient and initial curvature) was identified

based on the model's sensitivity study. Convective heat transfer coefficient and initial curvature shows that their effects on the simulation results were negligible according to the final curvature.

Ultimately, three fastening pitches (25-35-45mm) were simulated. Maximum curvature after cooling have been compared to experimental measurements, showing very similar results for the 25mm pitch. Larger values of pitches did not correlate well with experimental measurements (_~50% difference). This simple numerical model provides useful knowledge on the influence of geometrical parameters of the assembly on the Ti plate buckling during kerosene flame exposure. Thus, the plate's deflection may be minimized to prevent flame quenching. Further investigations are required to – (i) improve the representativity of the geometrical and numerical models by considering 3D representations of the assembly and temperature distribution – (ii) validate the model capabilities to estimate the out-of-plane displacement of the Ti plate.

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Molecualr Dynamics Study on the Strain Rate-Dependent Tensile Deformation and Failure Behavior of Single-Crystal β-Sn

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Speaker: Wang Xiaoyuan. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Lead-free solder, particularly β-Sn, is critical for maintaining the structural integrity and functional reliability of integrated circuits. Understanding the mechanical properties and fracture behavior of β-Sn is therefore of great significance. In this study, molecular dynamics simulations using the modified embedded atom method were conducted to explore the mechanical properties and crack propagation of single-crystal β-Sn under varying strain rates. The results reveal that with increasing strain rates, single-crystal β-Sn exhibits higher yield strength, fracture strength, and fracture strain, accompanied by a decrease in elastic modulus. At elevated strain rates, pronounced strain hardening occurs due to a significant increase in internal dislocation density, which inhibits plastic deformation. These findings provide atomic-level insights into the strain-hardening mechanism and enhance the understanding of the mechanical behavior of single-crystal β-Sn. This study offers valuable guidance for optimizing the design and application of lead-free solder materials in the electronics industry.

Nanocrystalline Nickel Synthesis by Pulsed Current

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Speaker: Boukhouiete Amel. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The synthesis of nickel by pulse electrodeposition has attracted much attention during the last decades. Pulse electrodepotion has been reported to improve the deposition process and deposit properties such as porosity, ductility, hardness, and surface roughness. It has been reported that pulse plating strongly modifies the properties, the structure, the surface morphology and the macroscopic characteristics of nickel coatings. In the present research, nickel deposits were produced by pulse current electrodepositing from watts bath. The optimization of the conditions of deposition was established and the influence of pulse parameters, on the grain size, surface morphology and crystal orientation was determined. The morphology of the coatings was characterized by observations in scanning electronic microscopy (SEM). X-ray diffraction in symetric mode was also used to evaluate the structure and principal crystallographic orientations of the deposits. The results obtained, showed that the development in pulsed induced a marked improvement in the morphology and grain refinement

NON LINEAIR ANALYSES FOR A HYDRODYNAMIC JOURNAL BEARING

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Speaker: Meramria Ouafa. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

the present work with lubrication theory to the problem of steady-state characteristics of hydrodynamic short bearings considering deference values of eccentricity ratio using a finite deference method the steady- state film pressures are obtained by solving modified Reynolds and non linear model for temporal discretisation for equations of rotor motion by the help of Euler's explicit method the results show that are devious changes en film pressure distribution, the highest film pressure, film thickness distribution, the least film thickness the presence of parameters of couple stress exhibits better stability in comparison with Newtonian fluid.

Non-affine lattice dynamics approach to measure viscosity in polymeric systems

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Speaker: Singh Ankit. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Viscosity, a fundamental rheological property of liquids, quantifies the resistance to relative motion between molecular layers and plays a critical role in understanding material behavior. Conventional methods, such as the Green-Kubo (GK) approach, rely on time integration of correlation functions, which becomes computationally intensive near the glass transition due to slow correlation decay. A recently proposed method based on non-affine lattice dynamics (NALD) (1) and instantaneous normal mode analysis offers a promising alternative for estimating viscosity. In this study, we apply the NALD approach to compute the viscosity of the Kremer-Grest polymer system over a range of temperatures and compare these results with those from the GK method and non-equilibrium molecular dynamics simulations. Our findings reveal that all vibration modes, including the instantaneous normal modes, contribute to viscosity. Furthermore, we investigate the role of microscopic friction in determining viscosity. This work presents an efficient framework for calculating viscosity across diverse systems and opens the avenue to understanding the role of different vibrational modes linked with structure, facilitating the design of materials with tunable rheological properties.

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Novel indentation methods to investigate the tribomechanical behavior of ceramic-based dental materials

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Speaker: Borrero-Lopez Oscar. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

We present recent advances in the application of the indentation method to characterize the mechanical properties and wear resistance of ceramic-based materials used in dental implants. Investigated systems include zirconia, glass-ceramics, and ceramic-polymer composites. Controlled tests with varied indenter shapes and configurations (axial, sliding, rotational) at different length-scales enable the determination of key mechanical properties such as fracture strength, toughness, friction, and wear rates. Experimental findings are analyzed within the framework of indentation and fracture mechanics, highlighting the influence of material microstructure. These efforts aim to predict short- and long-term mechanical degradation in dental prostheses and provide insights for developing more durable materials.

Numerical investigation of viscoelastic solid deformation induced by bubble collapse

Son Gihun (1)

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Speaker: Son Gihun. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Bubble collapse is critical in various fields such as manufacturing, medical and environmental applications, including water electrolysis enhancement, drug delivery and water treatment. The strong pressure waves generated during bubble collapse can significantly affect nearby solid or biological structures. A comprehensive understanding and prediction of bubble collapse and the resulting solid deformation is essential for optimizing practical applications. Despite extensive studies, a general predictive model for bubble collapse and solid deformation has not yet developed due to the challenges in tracking microscale multi-interface interactions. In this work, a numerical approach is developed for ultrasound-driven bubble collapse and viscoelastic solid deformation. The level-set method is extended to track multiple bubble and solid surfaces in compressible multiphase flows, further enhanced to capture viscoelastic solid deformation using an Eulerian formulation of the left Cauchy-Green deformation tensor for neo-Hookean materials. Simulations of ultrasound-driven microbubble collapse in water demonstrate solid deformation throughout the entire bubble oscillation cycle. The effects of acoustic pulse amplitude, frequency and material properties on bubble motion and solid deformation are quantified. * This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT)(RS-2024-00350110).

On the localization of a new phase domain in the vicinity of a crack

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Speaker: Kabanova Polina. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Summary. *Evolution of new phase domains induced by phase transformations of the martensitic type in the vicinity of a hole as a stress concentrator and a crack is considered with the use of numerical simulations. The propagation of the interface is described by a kinetic equation that relates the velocity of the interface with a configurational force equal to the jump of the normal component of the Eshelby stress tensor. Various scenarios for the evolution of the new phase domains are demonstrated. At first, it is studied how the elliptic hole can induce interface propagation even at external strain, which is insufficient for the existence of a new phase in the absence of the stress concentrator. It is examined how the elasticity parameters of the phases and the transformation strain affect the distribution of the configurational force along the interface as well as the localization of the new phase domain. Then the interconnections between a new phase domain growth and kinetics of the crack growth are considered.*

A coupled problem of the evolution of a new phase domain as a result of stress-induced phase transitions in an elastic body with a crack is considered. An example of such transitions are martensitic transformations, which are accompanied by transformation strain as a result of changes in the shape and size of the crystal lattice. A consequence of martensitic transformations are shape memory effects, which are used in the design of structural elements that react non-trivially to external thermomechanical actions (1,2). The transformation of austenite into martensite is associated with the formation of a process zone (a zone of material with changed properties) in the vicinity of the crack tip - an additional source of energy dissipation during crack growth, which subsequently continues to propagate along with the crack. This leads to the need to take into account the interconnections between crack growth and the new phase domain as a process zone.

There are various approaches to analysing the interconnections between the stress-strain state and phase transitions. Some models imply the introduction of additional parameters characterizing the average structural features of the material, for which special constitutive relations are formulated. A limiting phase transformation surface in stress space can be defined similarly to yield surfaces in plasticity with the use of various criteria and correction factors (3–5).

Other models assume the explicit introduction of interfaces and describe the evolution of new phase domains. Phase field approach and sharp-interface approach can be distinguished among the models. Phase field approach implies considering the interface as a transition layer of finite thickness where material properties vary smoothly. The changes of properties are specified by introducing order parameters, the evolution of which is described by additional Ginzburg– Landau-type equations (6–8).

In the present work a sharp-interface approach is implemented in which the thickness of the interface is neglected. The constitutive equations are written in each phase separately and additional kinetic equation or equilibrium condition is formulated for the interface. The sharp interface propagation is described within the framework of the mechanics of configurational forces (9–11). A kinetic equation relating the velocity of the interface with a configurational force equal to the jump in the normal component of the Eshelby stress tensor is used (12,13).

A numerical procedure for simulating the evolution of the new phase domain in an elastic solid is developed and verified. The stress-strain state is determined using the finite element method. The interface is considered as a surface, which passes along the edges of the mesh elements, and the remeshing of the geometry takes place on each time step.

First, various scenarios for the evolution of the new phase domain in a homogeneous body under external

strain are demonstrated. It is shown that the new phase domain can itself act as a stress concentrator that promotes further phase transformation (14). Then the variety of the interface behaviours in dependence on the distance between the interface and the stress concentrator, and the form of the concentrator is demonstrated based on considerations of the configurational force distribution along the interface (15). It is examined how the elliptical hole can induce interface propagation even at external strain, which is insufficient for the existence of a new phase in the absence of the stress concentrator. After that, it is studied how the shape and degree of localization of the new phase domain in the vicinity of the tip of the elliptical hole, as the prototype of the process zone in the vicinity of a crack tip, depend on the material parameters of the phases (see also (16)). It is also discussed how the new phase growth causes stress relaxation in a body, based on examinations of stress distribution.

Finally, developed algorithms are used both for studying of interface propagation in the vicinity of a static crack and investigating the joint propagation of the crack and new phase domain. Crack kinetics is determined by the Paris law. The influence of material parameters, external strain, and the distance between the crack and the interface on the stress intensity factor and crack growth are considered.

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On the role of body couples in linear-elastic fracture of polar dielectric continua

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Speaker: Lennart Behlen. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Linear-elastic fracture mechanics deals with unbounded stresses at the tips of sharp cracks due to external loading by introducing stress intensity factors quantifying their characteristic square root singularities. While the theory of polar fracture mechanics furthermore accounts for couple stresses, whose singularities at the crack tip are likewise described by corresponding intensity factors, body couples equally inherent in this extended theory are usually neglected. However, while explicit examples of body couples of mechanical origin are indeed scarce to nonexistent in literature, those arising in polarizable media due to electrostatic action of force have been well-known for decades. They fundamentally differ from mechanical couple stresses insofar as, in contrast to the latter, whose order of magnitude crucially depends on an internal length parameter, their distribution is uniquely determined by the macroscopic electric polarization and electric field. Depending on the electric boundary conditions of the crack faces, both of these fields may suffer square root singularities at the crack tip. As a consequence, possibly significant body couples are induced in the context of electromechanical crack problems. This work explores the impact of body couples on crack tip loading at the example of an infinite anisotropic dielectric plate with central crack subjected to remote stresses and electric fields. Upon discarding couple stresses for the sake of clarity, balances of angular and linear momentum reveal that body couples, on the one hand, directly determine the antisymmetric part of the stress tensor and, on the other hand, indirectly influence its symmetric part analogously to a body force. While the former is strictly associated with mode II loading in the problem at hand, the latter corresponds to both crack opening modes; therefore, body couples are found to generally go hand in hand with mixed mode loading.

On the vertical shift function in the frequency-temperature superposition mastercurves of thermo-rheologically complex polymers: multiaxial constitutive modeling, numerical implementation and experiments

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Speaker: Iaccarino Paolo. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The aim of this work is to define and identify viscoelastic constitutive laws for thermo-rheologically complex polymers, focusing on the open problem of the vertical shift function (alongside the traditional horizontal shift function) in the Frequency-Temperature Superposition (FTS) mastercurves. More precisely, we investigate the feasibility and the interpretability of incorporating a vertical shift function from both theoretical and experimental perspectives, aiming to shed light on the phenomena occurring at the micro-scale. For this study, we have adopted polypropylene, a semi-crystalline and thermo-rheologically complex polymer, as the base material. First, we have experimentally assessed the possibility of producing consistent FTS mastercurves by introducing a vertical shift function using dynamic mechanical tests carried out under various loading scenarios (tensile, shear, torsion). To support these experiments, we have complemented our analysis with calorimetry measurements and with comparisons with available literature data. We found that such vertical shift function seems to have strong physical bases related to structural transitions of the interphase between crystals and the amorphous phase. We then propose a simple multiaxial constitutive model to represent the linear viscoelastic behavior of thermo-rheologically complex polymers. The model is built on a generalized Maxwell framework, explicitly incorporating both vertical and horizontal shift functions. We detail the numerical implementation process (in both the frequency and time domains) and the parameter identification procedure (in the frequency domain). Model parameters are hence identified, and the model is validated in the time domain (in creep and stress-relaxation scenarios) comparing the results with experimental data, finding a good qualitative and quantitative agreement. Finally, we provide predictions of the material behavior at various temperatures in the frequency domain. This work could serve as a foundation for the development of nonlinear, physics-based continuum mechanical models for thermo-rheologically complex polymers.

Optimizing Biaxial Test Protocols for Hyperelastic Material Characterization in Lode Invariant Space

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Speaker: Mondal Pranay. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The choice of an invariant basis for the strain energy density function W for an isotropic hyperelastic material is as crucial as getting an appropriate form for the function. The conventional approach of employing the principal invariants of the Cauchy-Green tensor, though mathematically simple, does not provide direct insight into the mode-dependent mechanical response of the material. The Lode invariants (K1, K2, K3) of the Hencky strain tensor quantify the magnitude of dilation, the magnitude of distortion and the mode of distortion respectively. Consequently, it yields an orthogonal tensor basis for the Cauchy stress tensor that does not propagate the measurement error during biaxial experiments. Further, these invariants are better suited for analytical inverse procedures for the determination of W from mechanical data. To that end, obtaining mechanical data that sufficiently span the K2-K3 space, in addition to fixed-mode tests such as uniaxial and equi-biaxial tests, is essential to better characterize the material. This work focuses on designing the test protocols in such a way that it spans most of the K2-K3 space with as few planar biaxial tests as possible. Intermediate K3 values are achieved by performing unequal-biaxial tests. Digital Image Correlation(DIC) method is utilized to calculate the values of K2 using data obtained from experiments on hyperelastic silicon rubber. These data points are then used to construct a grid in K2-K3 space along with their corresponding normal stresses. We demonstrate that the derivatives of the energy density function with respect to Lode invariants are much well behaved in the neighborhood of the origin compared to the same with principal invariants. By systematically exploring the Lode invariants and their role in constitutive modeling, this work offers valuable insights into material behavior under diverse and complex deformation states.

Keywords: *Energy Density Function; Lode Invariants; Hyperelastic Rubber; Isotropy; Biaxial Test; Digital Image Correlation*

Post fracture surface roughness in the SmartCutTM technology

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Speaker: Salomon Grégoire. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Light ions implantation in crystalline silicon substrates leads to the formation of nanometer sized cracks when the implantation fluence is high enough. These cracks are often named "platelets". Due to the stress related to implanted ions, the *platelets* are preferentially parallel to the surface and tend to grow when annealing is applied (1). The platelets grow first via Ostwald Ripening mechanism (2), then by successive coalescences (3). When a silicon substrate is bonded on the top of the implanted silicon substrate, platelets can expand up to the micrometer scale (micro-cracks). Finally, a crack propagation is observed through the whole wafer leading to the transfer of a thin silicon layer to the bonded substrate. The SmartCutTM technology takes advantage of this multiscale crack evolution in order to fabricate silicon-on-insulator (SOI) substrates (4). Nowadays, advanced technology nodes require extremely tight tolerances on thickness variations. Understanding the mechanisms that generate surface non-uniformities is therefore key to meet such a restrictive criteria. In this paper we aim at understanding the mechanism of surface roughness formation at the different length scales involved during the defects growth.
Bonded pairs of wafers presenting various conditions of implantation were annealed until fracture occurred. Their post fracture surface was then characterized by the association of three techniques widely used in wafers characterization: Atomic Force Microscopy (AFM), White Light Interferometry (WLI) and Mechanical Profilometry (MP). AFM measurements with the use of a super sharp probe allow imaging the samples surface with a resolution down to one nanometer, which reveals the surfaces opened by the platelets during the very first stage of their growth. The WLI and MP techniques permit larger scale observations and reveal topography patterns associated to both the micro-cracks coalescences and the final fracture that opens the remaining surface. For all measurements, spectral analyses were conducted via the computing of the 2D Power Spectral Density (PSD) and the Height-Height Correlation Function (HHCF), two tools widely used to characterize self-affine surfaces (5), (6). The PSD obtained with the different techniques were merged to obtained a single curve of post-fracture SOI wafers (7), which enables the investigation of the physical mechanisms implied in the defect growth – and hence – the roughness generated during the fracture annealing.

The PSD curve highlights two different wavelengths domains in the overall roughness. At small length scales, the growth of platelets generated surface deviations (roughness), with a Hurst exponent H≈0.8. This is a classical value in fractal analysis of post-mortem cracked surfaces for different materials (8). It could indicate that the growth of platelets is driven by coalescences(9). The upper bound ξ of this domain was estimated precisely with both PSD and HHCF, and is observed to be the diameter of the larger platelets on the surface. The relationship between the size distribution of surface features and ξ is in agreement with the observation of characteristic lengths on engineered surfaces (10). This bound is therefore directly set by the implantation conditions as observed previously (7). A second growth regime of the PSD appears at distances larger than ξ. The latter prints typical patterns on the surface, either due to the coalescences of micro-cracks or to the final fracture that passes through the wafer. The measurements showed that the out-of-plane deviations associated to this second regime are small compared to the ones due to the growth of platelets. Indeed, a low value of H was obtained, which indicates that, at this scale, the surface opening paths are overall confined in the vertical width where the platelets have grown.

To conclude, the roughness of post-fracture SOI samples was investigated with several characterization methods. The results show that the growth of platelets prints important roughness on the post-fracture surface of SOI wafers. At larger scales, both the coalescences of micro-cracks and the passage of fracture through the wafer were found out to generate few additional roughness.

Probing the mechanical and thermal properties of bilayer graphene stacks

Zhao Pei (1)

1 - Zhejiang University (China)

Speaker: Zhao Pei. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The assembly of two-dimensional (2D) materials into homogenous van der Waals (vdW) stacks has opened new avenues for fundamental scientific studies in the past decade, such as bilayer graphene with a magic angle, in which the interfacial vdW interaction has been extensively recognized as playing the most critical role in determining the innovative properties. Besides most previous work that has focused on the electronic properties, the mechanical and thermal coupling between the layers of 2D vdW stacks is also important in governing their structural integrity (durability) and mechano-thermo-electronic performances. However, until now a reliable measurement technique with high accuracy to measure the mechanical and thermal properties of these homogenous 2D stacks is still lacked, due to the difficulties to distinguish the signal from each layer. In recent years, Raman spectroscopy has been widely used for strain and thermal measurement in 2D materials by the shift of their spectral peaks, owing to that it can relate the phonon modifications of a crystal with its spectral feedback. However, when this technique is used for a homogeneous 2D stack, even consisting of only two layers, their Raman signals will totally overlap. Considering the width of a spectral peak, the accurate information of the two layers cannot be obtained until the peak from one layer is shifted "out" from that of the other layer by a large enough spectral difference. Inspired by the success of using isotope to study the growth mechanism and doping level of graphene, we develop an isotope-labelling-assisted Raman spectroscopy for bilayer graphene to differentiate the measured signals from the two layers. We present the study using this technique on the interlayer shear and thermal coupling of bilayer graphene, as well as establish the related theories for them. We believe that this universal measurement method can be extended to more 2D systems and help advance the development of 2D material applications.

Pyrough: a new tool to model sample roughness in atomistic and finite element simulations

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Speaker: Amodeo Jonathan. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Surface roughness has a fundamental impact on the mechanical properties of materials as it plays a key role in several fields of applications including friction, lubrication, machining, and polishing. In this study, we introduce *Pyrough*, a new open-source tool developed to design virtual samples with surface roughness for atomistic simulations and finite-element modeling. From the main aspects of the targeted 3D sample (sample shape, crystal structure, *etc.*) and roughness parameters, a 3D mesh is processed based on the classical roughness theory. This first outcome is generated as an *.stl* file compatible with most FEM programs. *Pyrough* being fully coupled with the Atomsk atomistic library, it optionally provides an atomic position file in the format of the user's choice useful for molecular dynamics or DFT simulations. Several 3D shapes are currently available including classical particle shapes (cubes, spheres, Wulff-shapes), cylindrical or faceted wires, plates, thin films but also bicrystals with wavy grain boundaries or the capability to analyze the surface roughness of experimental images.

Solid Marangoni stresses

Nicolas Bain (1)

1 - Institut Lumière Matière (France)

Speaker: Nicolas Bain. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Despite its importance in any adhesion and wetting phenomena, there is a fundamental property that is not yet understood in soft solids: surface elasticity. Also called the Shuttleworth effect, surface elasticity is intimately linked to the solid physico-chemistry and can be boiled down to one question. Does stretching the surface of a soft solid change its surface tension? In 2021, we demonstrated that the mechanical response of a textured silicone gel could only be explained by an elastic surface(1). It is, however, still unclear whether the measured surface elasticity is a true material property or a mere consequence of the surface preparation. This presentation will focus on a novel experimental setup that exploits Marangoni stresses and local TFM techniques to characterize the surface mechanics of pristine surfaces.

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Stress and local structure evolution in the sol-gel thin-films during high temperature annealing

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1 - Surface du Verre et Interface (France), 2 - SIMM (France), 3 - Saint-Gobain Recherche (France)

Speaker: Bringuier Jean-Baptiste. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

To provide thermal comfort and reduce carbon footprint, many functions are provided to glazing by coating, for applications related to buildings, transport or decoration. In some cases, these glass products must undergo thermal tempering to give the glass better mechanical strength. The development of functional coatings resistant to high temperatures (> 600◦C) is thus a major challenge that sol-gel coatings can contribute to address. Indeed, the inorganic nature of the precursors is compatible with temperature resistance and allows good covalent adhesion to glass substrate. However, one of the limitations of these materials is the cracks generated in the layers due to the high tensile stresses that occurs during the condensation of the network and the evaporation of solvents. In addition, two known phenomena occur during tempering: the diffusion of alkali ions from the substrate to the layer and the passage of the melting temperature of the glass, which complicates the mechanics of the problem. This leads to a serious limitation in the achievable thicknesses of coatings and reduces the field of possible applications for the design of new products. The objective of this work is to better understand the relationships between the glass substrate, the structure, and the mechanical properties of the silica-based sol-gel layers during this complex tempering process. This poster will focus on the methodologies developed to establish the link between the evolution of the microstructure of the layer, the apparition of stress during the tempering coupled with the mechanical properties' evolution. Particular attention will be paid to the mechanical measurements based on nanoindentation in temperature (in-situ), separation of substrate and coating response from nanoindentation and cracks observation.

Surface microstructural evolution during Rolling Contact Fatigue of Rolling Element Bearing steels

Goigoux Aurore (1), Cazottes Sophie (2), Ville Fabrice (3), Véron Muriel (4), Douillard Thierry (1), Dubois Pierre-emmanuel (5), Sidoroff Christine (5), Biboulet Nans (6)

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Speaker: Cazottes Sophie. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Background incl. aims

To reduce CO2 emission and comply with European legislation, automotive market implements new electrical powertrain. It implies changes in the operating conditions of its bearings requiring new material development (grades and/or thermochemical treatments) for bearing manufacturers. A typical mode of failure for bearings operating in contaminated lubricant is surface-initiated spalling on a dent(1,2), such as in gearboxes. The denting process creates micrometer-scale shoulders, intensifying localized stress (3) and leading to plastic deformation over the operational lifespan. Therefore, cracks are often observed to be initiated at the vicinity of the shoulder. However, the life cycle of the bearing was observed to be dependent of its initial microstructure(4). To guide the development of new materials, a better understanding of the link between microstructure of the material and its performance in contaminated conditions is needed. Understanding the influence of each microstructural constituent on microstructural evolution, fracture development, and propagation is paramount for the development of more durable materials.

Methods

This study presents a multi-scale characterization of martensitic 100Cr6 bearings before and after RCF under standard test conditions. Samples were collected from bearings before and after the tests. Observations were realized at different locations (outside the dent area, under the dent, under the shoulder) using techniques such as SEM, SEM/FIB, EBSD, TKD and TEM-ASTAR.

Results

Prior to RCF, finishing operations leads to the formation of a 0.5 μm thick surface layer consisting in refined martensite and spread primary carbides. After RCF, away from the dent, no further grain refinement was observed along the raceway; the refined surface layer being resistant enough to plastic deformation during fatigue. Surprisingly, at the bottom of the dent, were large plastic deformation occurred during the indentation phase, no significant additional alteration of the microstructure was observed.

The major microstructural evolutions were observed beneath the dent shoulder where plastic flow occurred during the indentation and running-in, and where the stress is localized during the rolling process. First a fibered region is observed below surface, with a thickness of around 1μm. In this region, martensite grains are refined so that nano-grains are observed, and primary carbides are sheared. Below and down to 3 μm deep, far from finished surface, an ultra-fine grain layer is observed, mixing coarse and fine martensite. The martensite morphology, size and disorientations maps suggest that martensite undergoes refinement through twinning and continuous Dynamic Recrystallisation

Crack initiation was preferentially observed in the nano-grain layer, at carbides/matrix interfaces. Above the crack, another refined grain region is detected that was interpreted to be due to high deformation and stresses through crack propagation.

In all characterized areas, nanosized austenite islands were observed. The initial retained austenite does not completely transform during fatigue in this case while it is known to transform under surface-RCF (5). The major microstructural evolution observed is related to the refinement/reorientation of martensite grains that occurs through twinning and/ cDRX depending on the initial orientation of the grains.

Conclusion

The multiscale characterization of such localized deformed area, in non homogenous pieces (indentation being a random process) is a complex and tedious task to achieve. However, it gave crucial information about the microstructural deformation mechanisms. We infer that a material producing dents with smaller shoulder and less primary carbides at its surface would improve its lifetime.

Keywords

Steel, Rolling Cycle Fatigue, Microstructure, EBSD, ASTAR ACOM,

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Synergetic Effect of Cryogenic Treatment and Minimal Quantity Lubrication of WC Cutting Inserts on Machinability of EN24 Steel

Nissar Tabin (1)

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Speaker: Nissar Tabin. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

The life and productivity of cutting tools are directly impacted by cryogenic treatment. The increase in tool wear, dimensional inaccuracy, surface roughness and increased production cost is encountered by cryogenic treatment of tool materials. The current study examines the synergetic effect of cryogenic treatment and MQL on the machinability characteristics of EN24 steel. The tests were designed using an L18 orthogonal array, with the cutting speed, test condition, and kind of cutting insert serving as control variables. It was examined how these control factors affected the cutting temperature, tool flank wear, and workpiece surface roughness. According to the results, MQL decreased cutting insert average flank wear by 59.47%. Additionally, compared to cutting inserts that were not treated, the average flank wear dropped by 26.06% after cryogenic treatment and by 72.78% following cryogenic treatment with MQL. When compared to untreated inserts, cryo-treated inserts that are subjected to MQL during machining show the most percentage reduction in surface roughness 62.45%. When compared to dry cutting, MQL resulted in a 66.81% drop in average cutting temperature.

Temperature and Time-Dependent Mechanical Behavior and Optimized Bolt Preload Management in HDPE Piping Systems with Steel Flanged Connections

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Speaker: Barsoum Imad or Awad Sherif. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

High-density polyethylene (HDPE) is a widely used material in industrial piping systems, known for its cost-effectiveness and versatility. However, HDPE's mechanical properties are highly sensitive to temperature, which impacts its tensile, compressive, and relaxation behavior over both short- and long-term applications. This study investigates the effects of temperature on HDPE's mechanical performance and its influence on flanged connections with steel backing rings, commonly used in large-diameter HDPE pipelines.
Experimental analysis of HDPE at temperatures between 23∘C and 80∘C demonstrates that both tensile and compressive moduli, as well as yield strength, decrease linearly with rising temperatures, underscoring the need for temperature consideration in HDPE component design. Long-term stress relaxation tests reveal that HDPE's relaxation modulus is also significantly temperature-dependent. A nonlinear viscoelastic plastic model, the three-network model (TNM), was calibrated with these findings and implemented in finite element analysis (FEA) simulations, where it accurately predicts HDPE's time- and temperature-dependent mechanical response. Validated by three-point bending tests, this model provides a reliable basis for predicting HDPE's performance in various loading scenarios and environmental conditions.

Further, the TNM was applied to assess the performance of HDPE flanged connections under different temperature conditions over a simulated service life of one year. Results reveal that these connections are prone to leakage due to stress relaxation and bolt preload loss, which are exacerbated at higher temperatures. A realistic annual temperature profile was applied to evaluate leakage progression, leading to recommendations for periodic bolt re-torqueing to mitigate leakage. These findings highlight practical guidelines for enhancing the long-term durability of HDPE flanged connections under variable temperature conditions.
In addition to temperature effects, this study explores the elastic interaction between HDPE pipes and steel flanges, focusing on the impact of stiffness contrast on bolt preload and flange tightness. Through FEA simulations, two bolt-tightening methods were compared to optimize load distribution and contact pressure. The Tetra-Parametric Assembly Method (TAM) achieved superior results, particularly in configurations with high bolt counts and significant stiffness contrast. Applying a 30-30-40 tightening sequence proved effective for HDPE-to-steel connections, promoting uniform preload retention and contact pressure distribution across the assembly. These insights support improved design and maintenance practices for HDPE piping systems, enabling more reliable performance in demanding environmental and operational conditions.

Temperature Dependence of Incipient Plasticity in Tungsten

Tropper Florian (1), Ohmura Takahito

1 - National Institute for Materials Science (Japan)

Speaker: Tropper Florian. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Tungsten being a BCC metal is known to exhibit a brittle to ductile transition. Below the transition temperature, tungsten shows brittle fracture because ductility enabling mechanisms like kink-pair-formation of screw dislocations are mostly suppressed. Particularly in safety-critical applications tungsten shall yield instead of fracture. By pushing the yield stress to lower values, we can extend the ductile regime of tungsten and thus lower the temperature for transition. To design tungsten-based materials that can undergo plastic deformation in an extended temperature range, we need to gain a deep understanding of driving mechanisms of ductility. Classical impact tests show the macroscopic material behavior but do not allow insights into the governing mechanisms. Therefor an approach capable of investigating on the nanoscale is required. In present work we analyze yielding in defect-free sample volumes of tungsten via nanoindentation considering crystallographic orientations. Over a thermal range, a wide set of parameters related to the onset and process of plasticity is studied. While hardness expectedly decreases with temperature, the critical load where pop-in occurs seems unaffected or even increasing. This suggests a fundamentally different activation mechanism for hardness and pop-in. In our understanding, pop-in is governed by dislocation nucleation whereas dislocation mobility is the main mechanism determining hardness. For pop-in to occur, a high local stress close to or at the theoretical stress limit is required. Therefore pop-in might be predominantly stress-dominated and less dependent on thermal activation. Analysis of critical stresses and activation parameters is performed to elaborate on the atomic mechanisms. Subsequently, plasticity data like strain hardening behavior is extracted from pile-up around indents. Experimental micromechanical data is accompanied by SEM imaging techniques to analyze the deformation state. The results provide fundamental insights into thermally activated mechanisms essential for tailoring plasticity in future material development.

The elastic field in the vicinity of a cylindrical defect with nanosized irregularities under plane stress

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Speaker: Vakaeva Aleksandra. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Stress concentrations caused by various structural and material defects are one of the main reasons why devices fail. Most modern materials used for structural and functional purposes are elastically heterogeneous. Typical examples of heterogeneous materials include fiber composites with metal, polymer, and ceramic matrix, which can have voids, holes, or specialized geometric shapes. Carbon fiber, known for its high strength and rigidity, is commonly used in the aviation industry. Other examples include aluminum alloys with pores and steel alloys that contain holes shapes. At the nanoscale, we find polymer nanocomposites with nanotubes, where the nanotubes are embedded within a polymer matrix to enhance strength, stiffness, and thermal conductivity. Additionally, graphene with defects and nanowires that contain voids are also notable examples of these materials. In these materials, fibers with different scales are distributed in different ways. The fibers range in diameter from hundreds of microns to several nanometers. The stability, strength, and physicochemical properties of these materials depend on the stress-strain state of the nearsurface and boundary layers. The classical theory of elasticity cannot accurately assess real deformations and stresses when dealing with micro- and nanoscale inhomogeneities.
Due to the rapid development of nanotechnology, it is necessary to study the mechanical behaviors of nanoscale structures used in manufacturing electromechanical devices such as vibration shock sensors, biosensors, accelerometers, resonators, etc. Modeling their behavior is made possible by the tools provided by continuum mechanics. Without loss of generality, we can say that classical methods of mechanics in conjunction with models of surface elasticity (1) make it possible to simulate the behavior of nanostructures of a wide variety of nature. In recent years, the theory of elasticity has been widely used, taking surface and interfacial stresses into account (2, 3). The appearance of surface stresses in solids is associated with different conditions of equilibrium for atoms inside the body and near its surface. In a way, there is free surface energy, which leads to the appearance of surface stresses introduced by Gibbs (4).

In this work, we present the problem of a nearly circular defect in a nanoplate in a case of plane stress (5), allowing for the surface elasticity and residual surface stress by the Gurtin - Murdoch model (2, 3). The problem on a plane stress of a plate in the presence of the surface stresses differs essentially from the corresponding problem on a plane strain of a body, as the elastic parameters of the plate depend on the elastic parameters of the surface and plate thickness. The boundary conditions are derived according to the corresponding generalized Laplace – Young law. With the help of Goursat – Kolosov complex potentials and Muskhelishvili representations, the solution of the problem is reduced to the singular integro-differential equations. The algorithm of solving the integral equations is constructed in the form of a power series, as in (6). Based on the explicit forms of the analytical solution, we present numerical results for the stress field near the boundary of the nanopore given by the cosine function. The effect of plate thickness on the stress field at the surface of the pore and the role of surface tension at this surface is shown.

Acknowledgements
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Traitement d'enrobage des faisceaux de fibres d'ananas avec de l'huile de palmiste et de la cire d'abeilles pour la Fabrication d'enduits composites de gypse

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Speaker: Manfouo Tchoupmene Cheryle. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

Face aux enjeux de durabilité dans le secteur de la construction, cette étude explore l'amélioration des fibres naturelles et des composites biosourcés. Elle examine l'impact du traitement organique des fibres d'ananas avec de l'huile de palmiste et de la cire d'abeille sur leurs propriétés physiques et mécaniques, ainsi que sur les performances des composites à base de gypse. Les fibres traitées et brutes ont été caractérisées selon leurs propriétés morphologiques, hygroscopiques et mécaniques. Un biocomposite de gypse a été élaboré avec différentes fractions volumiques de fibres, et ses propriétés ont été analysées. Le traitement organique modifie la structure des fibres, réduisant leur capacité à absorber l'eau tout en améliorant leur ductilité. Bien qu'il améliore la résistance à la traction dans certaines conditions, un enrobage excessif peut altérer les interfaces fibre-matrice. Dans les composites, le traitement des fibres renforce la stabilité en milieu humide en limitant l'absorption d'eau et en réduisant les pertes de résistance après exposition à l'humidité. Ces résultats mettent en avant l'intérêt des traitements organiques pour améliorer les performances des fibres d'ananas et des composites à base de gypse, ouvrant des perspectives pour des applications durables dans la construction, notamment pour des enduits muraux adaptés à des environnements exigeants

Tribological behavior of a contact between a glass plane and a PDMS ellipsoidal asperity

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Speaker: Gabriel Kashala Djibril. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

In order to control the friction behavior of dry soft contact interfaces, a method for designing and creating elastomeric interfaces with quantitatively controlled friction laws has recently been developed (1). To achieve this, the method considered a simplified topography containing many different spherical microasperities. The developed strategy requires robust characterization of an individual asperity contact in order to feed the upscaling model that relates the macroscopic friction behavior to that at asperity scale. To access richer tribological macroscopic responses, we propose to use asperities with more degrees of freedom than the sphere, namely ellipsoidal asperities.
In this context, we have calibrated the contact between a glass plane and an ellipsoidal asperity in polydimethylsiloxane (PDMS). This calibration was conducted in three phases. Firstly, we performed a characterization of the compression response of the contact, which allowed us to describe the relationship between the real contact area and the normal indentation (δ). Secondly, the shear responses of the contact in two directions (along the two principal axes of the elliptical contact) were characterized, enabling the description of the changes of as the tangential force F is increased at fixed normal force (P). Third, we measured the friction stress of the interface.
These elements constitute necessary inputs for the construction of a multi-contact model which allows to predict the macroscopic tribological behavior of an assembly of many such elliptical microcontacts. Such model will be instrumental to design multicontact interfaces with specified anisotropic friction properties, e.g., the friction coefficient may depend on the direction of shear.

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Two-dimensional time-domain finite-difference analysis for dynamic thermoelastic equations coupled with dual-phase-lag heat conduction model

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Speaker: Masui Kaito. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

This report presents the results of applying the time-domain finite-difference technique to numerically solve a two-dimensional plane problem based on the dynamic thermoelastic equation combined with a two-phase lag heat conduction model. Two-dimensional discretized equations consisting of particle velocity, stress, and temperature components were formulated, and a stability analysis was then performed to ensure the accuracy of the solution obtained herein. Since the well-known von Neumann stability analysis cannot be applied to our problem, the effect of the combination of the number of time steps (M) and the number of space steps (N1, N2) on the numerical solution error was investigated. Based on the numerical results, a stability formula suitable for our problem was derived. Then, the propagation and reflection behaviors of heat and elastic waves were analyzed under the stability formula for a problem involving a crack-like defect in a two-dimensional plate. These results will lead to a promising technology to improve the high-precision detection of microdefects in semiconductors, for example, which has become a problem in recent years.

Influence of amorphous thermoplastic polymers behaviors on the filling of micro cavities during hot embossing process

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Speaker: Barrière Thierry. **Monday**. Start time: **18:00**. Room: FORUM 1 and 2. Link to abstract.

An important challenge in the simulation of the Hot Embossing process is the modeling of the unfilled shaped mould. The fact that the unfilled area exists is due in many cases to an inappropriate behavior law applied to embossed polymers. This study investigated the influence of the elastic-viscoplastic behaviour on the filling efficiency of two amorphous polymers during the micro–Hot Embossing process. For two amorphous polymers (PMMA and PC), mechanical tests were performed at 20∘C and 30∘C above their Tg. The viscoplastic parameters are characterized based on stress–strain curves from the compression relaxation tests under different strains and strain rates. The 2D numerical models were applied in FEM simulation with different temperatures to analyse the filling efficiency of micro cavities. The effects of temperature, imposed displacement and pressure, associated with the friction coefficient on the filling ratio were investigated with two polymers. The replication of a micro cavity was effectuated on the polymer plate by using a metallic micro-structured mould. The hot embossing process was performed under various loading conditions. The micro features were successfully replicated on the polymer. The comparison between the experimental and numerical results confirmed the efficiency of the numerical approach.

Keywords: micro–Hot Embossing, Two-Layer Viscoplastic model, numerical modelling, micro cavity, experimental validation.