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Abstract Book

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EXTRAPOLATION IN SIZE, TIME AND RISK ANCHORED BYASYMPTOTIC MATCHING

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The lifetimes of concrete structures have been inadequate, and their failures far too common. The causes are two: 1) the randomness of loads such as those from traffic, natural hazards, environment and random vibrations, and 2) the uncertainty of material properties and of failure mechanisms. Although major progress has occurred in the former, progress in the latter has become significant only recently. The durability of concrete structures is typically curtailed by some kinds of corrosion, which are always initiated by the development of cracks wider than about 0.1 mm that allows ingress of water with corrosive ions and thus controls the lifetime. The frequency of failure events of large bridges has historically been about 1 in 1000, which is unacceptable. As generally agreed, the failure probability of bridges, nuclear containments, aircraft, etc., must not exceed 1 in a million, which is the probability of being killed by a falling tree, lightning, or wild animal. Hence, a rational formulation of design code provisions requires huge extrapolations of experimental evidence. For example, in shear failure of reinforced concrete, the worldwide database consists of about 800 tests, but 95% of them pertain to cross section depths under 0.4 m while sections up to 15 m occur in practice. For the creep and shrinkage of concrete, which controls durability of bridges and other structures, the existing database contains over 50,000 data points but 96% of them were obtained by 6-year tests and 99% by 12-year tests, while the lifetime of 150 years is often specified in design. Laboratory testing and stochastic finite element codes cannot provide information on failure probability lower than about 1 in 20, and so the extrapolation to 10^{-6} cannot be done without a theory, verified indirectly. This lecture argues that an effective approach for scaling is to determine asymptotic laws at opposite ends of the range of size, time and risk. Such laws, which can be calibrated experimentally at the low end of the range, are much simpler than the intermediate transition. It suffices to use asymptotic matching, which has been a common practice for a long time in fluid mechanics. The asymptotic matching, which can employ a variety of methods, is explained by a few typical examples – 1) the size effect law for scaling of quasibrittle and ductile fracture, 2) the scaling and shear failure of RC beams, 3) the time scaling of shrinkage, autogenous shrinkage, self-desiccation, swelling and creep of concrete in presence of moisture diffusion and long-time hydration, and 4) the extrapolation of basic failure statistics to failure probability 10^{-6} based on a probabilistic model for alternating series and parallel connections that resembles a fishnet pulled diagonally, and describes the transition between the Weibull and Gaussian distributions.

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FIBER-REINFORCED BIOSOLIDS: INTERACTION OF MICROSTRUCTURE WITH MECHANICS

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Fiber-reinforced biosolids are composed of a matrix material, which is reinforced by fibers of one or more families or by distributions of fibers with different orientations. In fibrous tissues such fibers are collagen, and typically the matrix material consists of elastic fibers. For example, for arterial walls the matrix can be considered as an isotropic (neo-Hookean) material, while the collagen fibers, which are in general not perfectly aligned but are arranged in a rather dispersed structure, generate anisotropy (for a review see, e.g., [1]). Collagen and elastic fibers form a unique microstructure that is particularly involved in the biomechanical response during a cardiac cycle and also continuously rearranges itself to adapt to (patho)physiological stimuli. It is important to note that the collagen and elastic fibers can be damaged/disrupted by various diseases.

A method of choice is to base constitutive models on a multiscale approach, where it is important to integrate simulations and experiments to achieve a detailed understanding of the influences of the different constituents. We briefly present a rotationally symmetric dispersion model based on the bivariate von Mises distribution, which is used to construct a structure tensor. The latter is incorporated into a strain-energy function that accommodates both the mechanical and structural features of the material [2]. In a finite-element example, we analyze the non-homogeneous stress distribution for circumferential and axial strips under fixed extension. Next, a multiscale model of fiber recruitment and damage using a discrete fiber dispersion method is presented [3]. This model summarizes the fiber contributions from elementary areas and gives the resultant fiber strain energy, which can easily accommodate the exclusion of compressed fibers. Fiber recruitment, softening and damage are considered. Finally, a phase-field approach is introduced to model fracture of arterial walls with a focus on aortic tissues [4].

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MECHANICS-GUIDED 3D ASSEMBLY OF COMPLEX MESOSTRUCTURES AND FUNCTIONAL DEVICES

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A rapidly expanding research area involves the development of routes to complex 3D structures with feature sizes in the mesoscopic range (that is, between tens of nanometres and hundreds of micrometres). A goal is to establish methods to control the properties of materials systems and the function of devices constructed with them, not only through chemistry and morphology, but also through 3D architectures. However, existing approaches of 3D assembly/fabrication are only compatible with a narrow class of materials and/or 3D geometries. In this talk, I will introduce a mechanics-guided assembly approach that exploits controlled buckling for constructing complex 3D micro/nanostructures from patterned 2D micro/nanoscale precursors that can be easily formed using established semiconductor technologies. This approach applies to a very 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). To enrich the class of 3D geometries accessible to the proposed assembly approach, we devised a set of mechanics-driven design strategies, such as kirigami/origami designs of 2D precursors, heterogeneous substrate designs and loading-path controlled shape morphing strategies. I will also introduce a series of mechanics models for the direct postbuckling analysis, as well as inverse design methods that map target 3D topologies onto unknown 2D precursor patterns, which could provide an important theoretical foundation of the rational 3D assembly. The compatibility of the approach with the state-of-the-art fabrication/processing techniques, along with the versatile capabilities, allow transformation of diverse existing 2D microsystems into 3D configurations, providing unusual design options in the development of novel functional devices. I will demonstrate a few examples in this presentation, including biomedical devices conformally integrated with organoids/tissues/organs, 3D MEMS capable of efficient energy harvesting of low-frequency vibration, bioinspired electronic systems, and 3D microfluidic devices.

SHAPE AND TOPOLOGY OPTIMIZATION OF STRUCTURES BUILT BY ADDITIVE MANUFACTURING

G. Allaire

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Additive manufacturing (or 3-D printing) is a new exciting way of building structures without any restriction on their topologies. However, it comes with its own difficulties or new issues. Therefore, it is a source of many interesting new problems for optimization. I shall discuss two of them for which I propose original solutions. Of course, it is a to these problems, but there is still a lot of room for improvement!

First, additive manufacturing technologies are able to build finely graded microstructures (called lattice materials). Their optimization is therefore an important issue but also an opportunity for the resurrection of the homogenization method. Indeed, homogenization is the right technique to deal with micro-structured materials where anisotropy plays a key role, a feature which is absent from more popular methods, like SIMP. I will describe recent work on the topology optimization of these lattice materials, based on a combination of homogenization theory and geometrical methods for the overall deformation of the lattice grid.

Second, additive manufacturing, especially in its powder bed fusion technique, is a very slow process because a laser beam must travel along a trajectory, which covers the entire structure, to melt the powder. Therefore, the optimization of the laser path is an important issue. It turns out that devising an optimization strategy for the laser path is not enough, but it must be coupled with the usual shape and topology optimization of the structure. Numerical results show that these two optimizations are tightly coupled.

This is a joint work with several colleagues, including two former PhD students, P. Geoffroy-Donders and M. Boissier.

MICROMECHANICS AND MULTISCALE MODELING OF HETEROGENEOUS MATERIALS WITH COMPLEX AND EVOLVING MICROSTRUCTURES

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In this presentation, different micromechanical approaches and homogenization techniques will be discussed with application to thermo-mechanical behavior and effective properties of different materials. Particular focus will be on the of the effects of the microstructural features of the considered materials, the effects of the microstructural evolution, as well as the effects of the loading conditions on the mechanical response and properties. The first part will address the large viscoplastic deformation and microstructure evolution in polycrystalline metals with different crystalline structures. In this, we will discuss different homogenization techniques to predict the mechanical response as well as texture evolution in metals. In a second part, micromechanics of yielding and elastic properties will be addressed for polymers and polymer nanocomposites. We will particularly discuss the cooperative model for yielding as well as the composite modeling for the prediction of the effective elastic properties and mechanical response of these materials. In a third part, we will discuss multiscale homogenization techniques with the consideration of interface conditions to predict the effective properties and mechanical response of biological tissue with complex microstructures.

3D MICRO/NANO PRINTING

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Multiphoton Lithography is a laser-based additive manufacturing technique which allows fabrication with resolution down to a few tens of nanometres. Based on nonlinear absorption, Multiphoton Lithography has unique capabilities that no-other technique can provide. It has been implemented with a variety of materials and several components and devices have been fabricated such as metamaterials, biomedical devices, photocatalytic systems and mechanical models

The unique capability of Multiphoton Lithography lies in that it allows the fabrication of computer-designed, fully functional 3D devices. In this talk, I summarize the principles of microfabrication, and present recent research in materials processing and functionalization of 3D structures. Finally, I discuss future applications and prospects for the technology.

A NEW PROBLEM OF OLD: SYNTHESIS OF METAMATERIALS

THEORY, NUMERICS AND EXPERIMENTS

F. dell'Isola

University of L'Aquila

The demands coming from the problem of designing innovative Metamaterials lead to Novel technological challenges. As a consequence new challenges are presented to mathematical physics that formulates consequently the problem of metamaterials synthesis.

The need to design novel materials on demand requires the capacity of synthesising micro-architectures that, at macro level, behave as engineering applications require.

The mathematical modelling effort must face complex theoretical problems, long numerical simulations and difficult production and experimental challenges.

In this context, generalized continuum mechanics, a theory started in 1848 by Gabrio Piola and then developed by Paul Germain, needs to be further developed to give a macroscopic description of a wider class of mechanical behaviors. Moreover, optimization techniques need to be applied to determine the micro architectures that once homogenized are suitably described by the chosen macro models.

In this presentation, some results in this novel and fascinating subject are shown. Starting from some methodological considerations, some new synthesis problems are formulated and their solution is shown by using a combination of numerical methods and theoretical general results.

Experimental evidence is shown that proves that the theoretical effort is producing interesting and useful knowledge whose applicability seems very close, also due to the establishment of modern 3D printing technology.

Mini Symposia

MS-3 Nonlinear vibrations of continuous systems
Francesco Pellicano (University of Modena and Reggio Emilia, Italy), Rinaldo Garziera (University of Parma, Italy) and Marco Amabili (McGill University, Canada)

Dynamic phenomena in Non-Newtonian Fluid-Structure Interaction
F. Pellicano, A. Zippo, G. Iarriccio

System identification of geometrically nonlinear electromechanically coupled free sandwich plate
P. Balasubramanian, T. M. P. Silva, G. Ferrari, G. Franchini, C. Hameury, M. Amabili, M. Al Teneji

Tunning of nonlinear Sliding Mode controller via Particle Swarm Optimization on electromechanically coupled systems
T.M.P. Silva, P. Balasubramanian, , G. Ferrari, C. Hameury, M. Amabili, M. Al Teneiji

Nonlinear TSA for identification of dynamic properties of pathological tremor
A. Zippo, F. Pellicano, G. Iarriccio

Nonlinear vibrations of circular cylindrical shells: a bifurcation analysis
M. Amabili, P. Balasubramanian, G. Ferrari

DYNAMIC PHENOMENA IN NON-NEWTONIAN FLUID-STRUCTURE INTERACTION

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Fluid structure interaction (FSI) phenomena are of interest for several engineering fields as well as in medical science, and, of course in bio-engineering or bio-mechanics. One can find countless examples of FSI problems in engineering, e.g. flutter of airplane wings, galloping in powerlines and bridge cables, supersonic panel flutter, pipes flutter, fully or partially filled tanks, heat exchangers. In the field of Medical Sciences an important example is the human aorta, where the fluid is highly viscous and non-Newtonian and the artery wall is hyper-elastic, this is a combination of exceptionally difficult problems.

The FSI cause a dramatic change in the dynamic response of the system, for example flows can cause instabilities, static and dynamic; still fluids typically give rise inertia effects that change the natural frequencies and sometimes the mode shapes, these inertial effects can be accompanied by an increment of damping.

In the presented study the nonlinear vibrations of a fluid-filled circular cylindrical shell under seismic excitation are investigated. A PET thin shell with an aluminum top mass is harmonically excited from the base through an electrodynamic shaker in the neighborhood of the natural frequency of the first axisymmetric mode. The dilatant fluid is composed of a cornstarch-water mixture with 60% cornstarch and 40% water of total weight. The preliminary results show a strong non-linear response due to the coupling between the fluid and structure and the shaker-structure interaction that leads to a very interesting dynamic response of the system.

The specimen is a polymeric circular cylindrical shell, see Figure 1: an aluminum cylindrical mass is glued on the shell top edge; conversely, the bottom edge of the shell is clamped to a shaking table. Three triaxial accelerometers placed on the top mass at 120°, a monoaxial accelerometer at the base of the shell, a laser vibrometer to measure the lateral velocity on the mid-height of the shell.

The test article has been excited in the axial direction through a harmonic load, with a step-sweep controlled output, the voltage signal sent to the shaker amplifier is closed-loop controlled; to avoid interaction between the control system and the specimen under study, no controls have been used for controlling the shaker base motion.

The harmonic forcing load consists of a stepped-sine sweep of frequency band 100-500 Hz with a step of 2.5 Hz. All the tests have been performed with the shell full filled with quiescent fluid.

The dynamic scenario is carefully analyzed by means of time histories, spectra, phase portraits and Poincaré maps. The experiments show the onset of complex dynamics: subharmonic and quasiperiodic responses, Chaos.

SYSTEM IDENTIFICATION OF GEOMETRICALLY NONLINEAR ELECTROMECHANICALLY COUPLED FREE SANDWICH PLATE

P. Balasubramanian [1], T M P. Silva [1], G. Ferrari[2], G. Franchini [2], C. Hameury [2], M. Amabili [1,2], M. Al Teneji[1]

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Experimentally obtaining the electromechanically coupled equation of motion for real-world structures to reduce vibrations is still advantageous over many modeling techniques. Most modeling techniques fail or become cumbersome when the structures have complex geometry/ boundary conditions, nonlinearity, multiple physical domains, or combinations. An experimental identification procedure was developed for identifying the electromechanically coupled equation of motion of a composite plate equipped with piezoelectric actuators and sensors. The chosen composite plate is a free rectangular foam core sandwich plate with two orthogonal layers. These boundary conditions have been considered because mode shapes cannot be expressed with simple trigonometric functions.

A set of experimental responses due to a punctual harmonic load from electrodynamic shaker and piezoelectric actuators were measured using a laser Doppler vibrometer and data acquisition system. The plate was also excited around its fundamental natural frequency with sufficient force to produce the geometrically nonlinear response with jump-ups and downs. The parameters of the nonlinear electromechanical equation of motion were identified using the least square fit.

The validity of the identified equation of motion was verified in two parts. First, the numerically obtained responses were compared with experimental results, both in the linear and nonlinear domains. The agreement between the experimental and numerical result were Secondly, an optimized Positive Position Feedback (PPF) controller was developed to reduce the vibrations based on the identified model. The parameters of the PPF were implemented experimentally and found that it is very effective in reducing the plate's vibrations.

TUNNING OF NONLINEAR SLIDING MODE CONTROLLER VIA PARTICLE SWARM OPTIMIZATION ON ELECTROMECHANICALLY COUPLED SYSTEMS.

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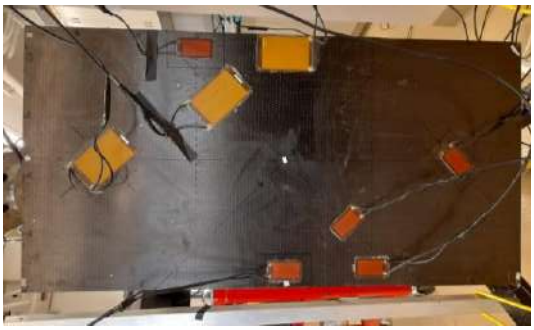
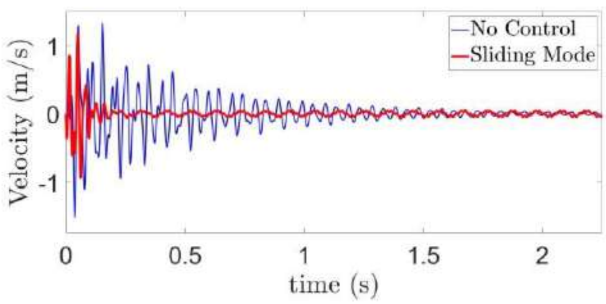
Sliding mode (SM) controllers are known for being robust and easy to implement in a wide range of applications. These controllers are based on a nonlinear switching process which drives the system to oscillate on a prescribed trajectory, named sliding surface, which readily reduces vibrations. Since SM controllers are nonlinear, the tunning of parameters is not trivial, demanding extensive mathematical derivations or time-consuming trial-and-error methods. To overcome these limitations, this work presents an iterative approach to determine the optimal parameters of a SM controller based on Particle Swarm Optimization (PSO). The PSO method proves to be an effective and fast way to optimize the nonlinear controller.

In this work, the SM controller is used to reduce vibrations on a rectangular composite plate with a foam core and with piezoelectric materials attached on the top surface, as shown in Figure 1a. A free-free boundary condition is considered, and the system is excited using an electrodynamic shaker placed near the geometrical center of the plate. The input of the SM controller is the voltage produced by piezoelectric materials employed as a sensor, and the output is an electrical voltage driven to piezoelectric materials used as actuators. The efficiency of the nonlinear controller to reduce vibrations is measured by observing the velocity of the plate's corner, which is experimentally measured by a laser Doppler vibrometer. With the proper tuning of the SM controller (using PSO method), vibrations are significantly reduced, as shown in Figure 1b.



a)



b)

Figure 1: a) composite plate with piezoelectric materials attached on the top surface and b) the plate's tip velocity when no control is used (blue curve) and when the Sliding Mode controller (tuned with PSO method) is used in the system (red curve).

NONLINEAR TSA FOR IDENTIFICATION OF DYNAMIC PROPERTIES OF PATHOLOGICAL TREMOR

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Nonlinear time series analysis and control modelling is a stimulating task, the experimental measured data will allow the identification of the electro-muscular system for a future implementation of a control model. The characterization and identification of pathological patterns detected through the sEMG (surface electro-myographic) and accelerometric signals of muscle activity are an interesting challenge: methodologies for data analysis, time series analysis and human skills must be combined to detect and extract characteristics for pathological identification. The complexity lies in the very nature of the experimental activity since each patient has slight differences due to the various positions of the electrodes, the different pathologies and the stage of the pathology itself and the intrinsic complexity of biological systems. The vibrational phenomena studied in this work regards the arm and forearm vibration with the purpose to detect and recognize the dynamic properties and correlations of onset of pathological tremor in patients affected by Parkinson disease. This pathology affects skeletal muscles and presents a typical characteristic vibration frequency between 1Hz and 12Hz, this property is monitored in out-patient tests. The natural electrical activity, like EMG or sEMG signals, are shown to have considerably complex patterns under a distinctive combination of conditions. Moreover, the autonomous and non-autonomous control mechanisms in central and peripheral nervous system within the complex biological system produce the high level of nonlinearity, nonstationarity, and noise in the signals. The showed case presents electrodes location in Arm - Biceps Brachii with posture seated, holding light object (small box) and has been analyzed using multiscale recursive analysis methodologies through the TISEAN package, the state space plot of accelerometric signal, fig.1, display the complexity of this response confirmed also by the recurrence plot see figure 2.

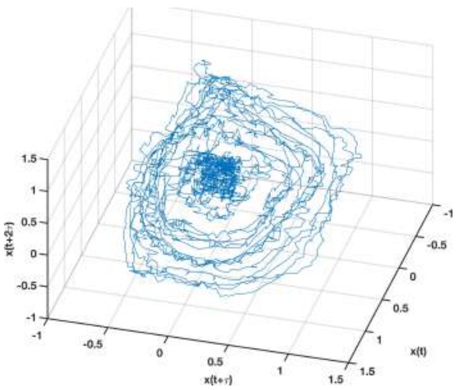

Figure 1. State space of accelerometric signal

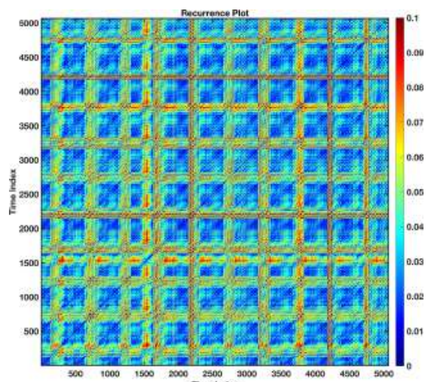

Figure 2. Recurrence plot emg signal

NONLINEAR VIBRATIONS OF CIRCULAR CYLINDRICAL SHELLS: A BIFURCATION ANALYSIS

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The nonlinear vibrations of a water-filled circular cylindrical shell subjected to radial harmonic excitation in the spectral neighbourhood of the lowest resonances are investigated [1]. The problem is discretized by using the Lagrange equations. The resulting equations are numerically studied. Experiments are carried out on a seamless aluminium sample in order to validate the results. The presence of exact one-to-one internal resonance, giving rise to a travelling wave response around the shell circumference and non-stationary vibrations, is experimentally observed and the nonlinear response is numerically reproduced. The traveling wave is measured by means of state-of-the-art laser Doppler vibrometers applied to multiple points on the structure simultaneously. Chaos is detected in the frequency region where the travelling wave response is present. The reduced-order model is based on the Novozhilov nonlinear shell theory retaining in-plane inertia and the nonlinear equations of motion are numerically studied (i) by using a code based on arclength continuation method that allows bifurcation analysis in case of stationary vibrations, (ii) by a continuation code based on direct integration and Poincaré maps that evaluates also the maximum Lyapunov exponent in case of non-stationary vibrations. Pitchfork and Niemark-Sacker bifurcations are detected as a route to chaos. The comparison of experimental and numerical results is particularly satisfactory.

References

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MS-4 Dynamics and control of MEMS and NEMS
Dumitru Caruntu (University of Texas Rio Grande Valley, USA), Eihab Abdel-Rahman (University of Waterloo, Canada), Mohammad Younis (Binghampton University, USA), Laura Ruzziconi (eCampus University, Italy), and Mergen Ghayesh (University of Adelaide, Australia)

MS-6 Unusual Dynamics and Active Control
Elvio Bonisoli (Politecnico di Torino, Italy) and Maryam Ghandchi Tehrani (University of Groningen, Netherlands)

Superharmonic resonance of third order of electrostatically actuated mems cantilevers
D. I. Caruntu, C. I. Reyes

Complex modal analyses for human cardiovascular system
E. Bonisoli, M. Amabili

Experimental outcomes of magnetic nonlinearities in rotordynamics
E. Bonisoli, S. Venturini, S. P. Cavallaro

Robust Control of a Nonlinear System by the Receptance Method using Eigenvalue Sensitivity Minimization
G.M. Tehrani, E. Bonisoli

Impact-induced internal resonance in mems
L. Ruzziconi, N. Jaber, L. Kosuru, M. Younis

SUPERHARMONIC RESONANCE OF THIRD ORDER OF ELECTROSTATICALLY ACTUATED MEMS CANTILEVERS

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This paper investigates the amplitude-frequency responses of superharmonic resonance of third order of electrostatically actuated micro-electromechanical (MEMS) cantilever resonators. The MEMS resonator system consists of a ground plate and the cantilever beam parallel to the ground plate. They are under alternating current (AC) voltage in the range of hard excitations. The AC frequency is near one sixth of the natural frequency. This leads to superharmonic resonance of third order. The amplitude-frequency response is investigated for this superharmonic resonance.

The electrostatic force is modeled to include the fringe effect described by Palmer's formula. Reduced order models (ROMs) are used to investigate the amplitude frequency responses of the electrostatically actuated MEMS cantilevers. Methods used to solve these ROMs are (1) method of multiple scales (MMS) for ROM with one mode of vibration, (2) Homotopy analysis method (HAM) for ROM with one mode of vibration, and (3) direct numerical integration for ROM with two modes of vibration or 2T ROM.

The amplitude-frequency response depicts a softening effect and the bifurcation points. The MMS and HAM methods were found not to accurately predict the occurrence of end points of the stable branches where the system loses stability and the pull-in phenomenon. Additionally, it is observed that the MMS and HAM methods accurately predict the behavior of the resonator for amplitudes less than 0.5 to 0.7 of the gap and for dimensionless voltage values less than 0.80. Beyond these values, the MMS and HAM begin to disagree with the results obtained from the time responses of the ROM with two modes of vibration.

As the damping is increased the bifurcation points disappear and the system experiences a linear behavior. As the voltage and fringe values increase the bifurcation points are shifted to lower frequency values and higher amplitudes.

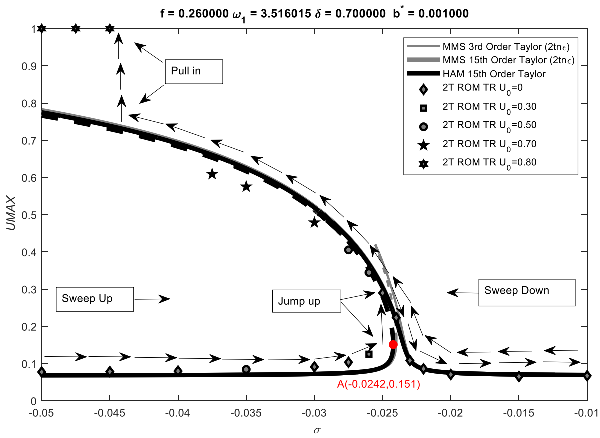

Figure 1: Superharmonic resonance of third order. MMS, HAM, and 2T ROM Time Responses.

COMPLEX MODAL ANALYSES FOR HUMAN CARDIOVASCULAR SYSTEM

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The paper proposes an original approach for simulating the human cardiovascular system as a vibrating multi-degree-of-freedom system based on the analogy with an hydraulic model and the Firestone equivalent electric model that correlates the blood flow rate to the current "through" electric elements, and the blood pressure drop to the voltage drop "across" each element. Hydraulic capacitances are correlated to inertial effects, resistances to damping and inductances to stiffness. The equivalent mechanical vibrating system composed of linear lumped mass-damper-spring element is able to predict the pressure dynamics of the human cardiovascular system, including central and peripheral main arteries and veins, four heart chambers, systemic and pulmonary circulations and main organs as lungs, liver, digestive track, kidneys, trunk, head, arms and legs. Also specific details are sketched as the mitral valve that connects the left atrium and the left ventricle and the aortic valve that connects the left ventricle with the aorta. Complex modal analyses describes the frequency content with global complex mode-shapes, due to non-classical damping properties, and more localised complex mode-shapes of valves in the frequency range from 1.3 Hz to 21 Hz. The model is considered sufficiently robust to be used as a time-frequency tool for innovative non-invasive sensors for future low-power monitoring systems.

Keywords: hydraulic–electric–mechanical analogy, non classical damping, time-frequency analysis.

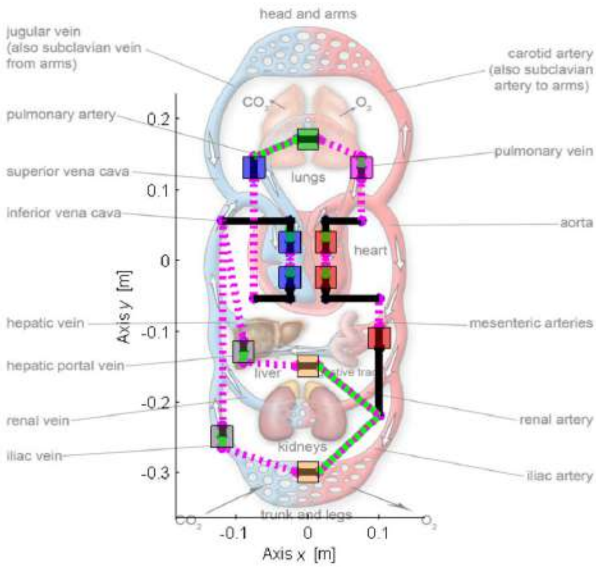

Figure – Equivalent vibrating system of the human cardiovascular system for blood pressure estimation.

EXPERIMENTAL OUTCOMES OF MAGNETIC NONLINEARITIES IN ROTORDYNAMICS

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This paper addresses the performed experimental campaign to assess the nonlinear rotordynamics of a levitating horizontal axis magnetic spinning top manufactured for educational purposes. The experimental setup, used to carry out measurements of spinning top rotordynamics, acquires angular speed and displacements, in vertical and horizontal directions at two different cross sections. This case study allows to analyse nonlinear interactions of passive magnetic bearings, behaviour at critical speeds and the influence of non-axisymmetric support configuration. Consequently, the resulting dynamic behaviour can be recognised as a Jeffcott rotor with anisotropic supports. Moreover, the acquired measurements at the studied rotor cross sections depict ovoid trajectories, which are connected to the bearing strongly nonlinear stiffness and the corresponding even and odd harmonic contributions of displacement.

Keywords: magnetic levitation, horizontal rotor, passive magnetic bearings, anisotropic supports, time-frequency analysis.

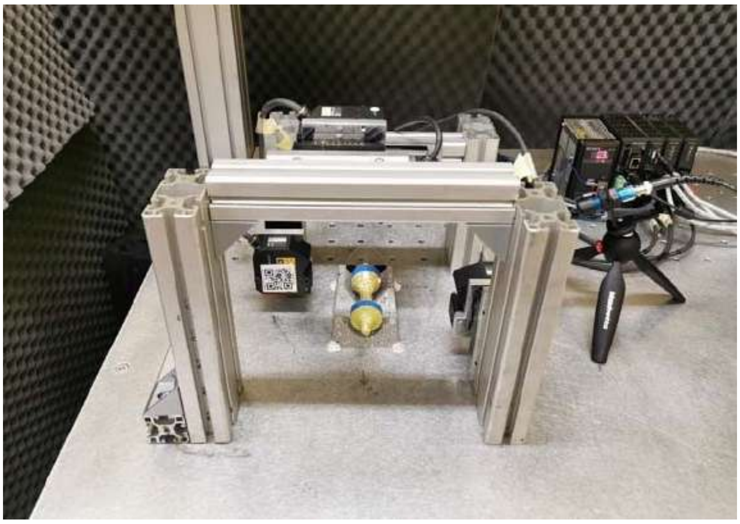

Figure – Experimental setup.

ROBUST CONTROL OF A NONLINEAR SYSTEM BY THE RECEPTANCE METHOD USING EIGENVALUE SENSITIVITY MINIMIZATION

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Robust control of a nonlinear system using the receptance method is presented. The receptance method and sensitivity equations have been established for linear systems and it is extended to nonlinear systems in this paper. Analytical formulations are derived for the eigenvalue sensitivities of the nonlinear system to parametric perturbation, which are then subsequently minimised to obtain robust vibration control. For nonlinear systems, the sensitivity equations are not only dependent on the frequency, but also on the amplitude level. The developed sensitivity equations are simultaneously used with the pole placement equations to assign both eigenvalues and their sensitivities. Since the dynamical system is nonlinear, an iterative algorithm is required to obtain the feedback gains. The closed-loop eigenvalue sensitivities are expressed as a linear function of the velocity and displacement feedback gains, allowing their minimisation with carefully calculated feedback gains. The described approach has application to control a vibrating system where variations are present due to manufacturing and material tolerances, damages and environment variabilities. A numerical example is considered to demonstrate how the method works. The mass of the nonlinear system is perturbed and the robust controller is implemented in order to assign the eigenvalues while rendering them insensitive to the mass perturbation. It is demonstrated that the closed-loop eigenvalues are assigned successfully and are insensitive to the perturbation in the parameter.

IMPACT-INDUCED INTERNAL RESONANCE IN MEMS

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Internal resonances [1] arising in MEMS/NEMS have been recently the focus of renewed interest in research studies [2]. In the present work we demonstrate that impacts can induce the activation of internal resonances.

Experimental data are conducted on a microbeam-based MEMS device. The device presents a specially deposited dielectric layer to prevent short-circuiting, which allows operating in the regime of contact dynamics. The response presents resonant and non-resonant branch exhibiting hardening bending behavior (Fig. 1). The resonant branch raises the oscillations amplitude (Region I), impacts with the substrate performing a nearly constant plateau (Region II), experiences impacting 7:2 internal resonance between the first and third mode (Region III) and disappears (Region IV). To model impacts, the theoretical model is developed in the framework of Hertz impact model and Hunt-Crossley damping model. This works demonstrates that impacts offer novel strategies to induce internal resonance. Interestingly, activation can be enabled even in regions of the driving parameters space where no bounded attractor is expected to exist in the absence of impacts.

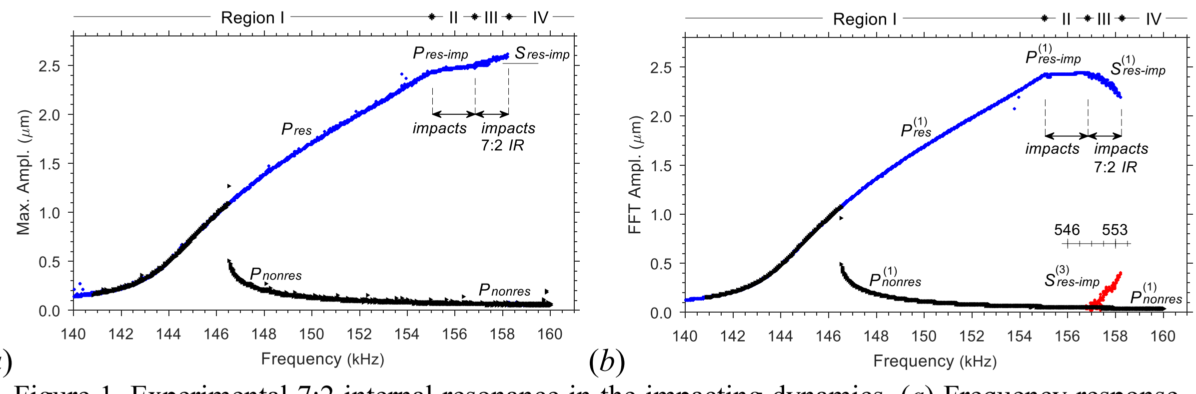

Figure 1. Experimental 7:2 internal resonance in the impacting dynamics. (*a*) Frequency response diagram. (*b*) FFT diagram.

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MS-5 Nonlinear Phenomena in Granular Solids: Modelling and Experiments
Anil Misra (University of Kansas, USA), Takashi Matsushima (University of Tsukuba, Japan), Payam Poorsolhjouy (Graz University of Technology, Austria), and Emilio Turco (Università degli Studi di Sassari, Italy)

MS-32 Emerging non-linear mechanical properties in multi-scale materials
Nicot (Université Savoie Mont Blanc, France) and Félix Darve (Grenoble Alps University, CNRS, France)

Rheology of axisymmetric grains subjected to oscillations
B. Nadler, M. Amereh

4-Cell analogical model to describe plastic shear behavior of granular solid
T. Matsushima, Y. Higo, Y. Otake

Embedding grain rearrangements in micromechanical models to make critical state emerge in the up-scaling process
N. Deng, A. Wautier, Y. Thiery, Z.-Y. Yin, P.-Y. Hicher, F. Nicot

Effect of local defects on the response of non-classical elastic materials
G. La Valle

A beam model for duoskelion structures derived by asymptotic homogenization and its application to axial loading problems
E. Barchiesi, F. dell'Isola, P. Seppecher, E. Turco

Multi-particle finite-element modelling of cohesive ductile granular systems
N. Audry, B. Harthong, D. Imbault

Multi-Scale Modeling of Fiber-Reinforced-Concrete using Granular Micromechanics Approach
P. Pirmoradi, P. Poorsolhjouy, A.S.J. Suiker

RHEOLOGY OF AXISYMMETRIC GRAINS SUBJECTED TO OSCILLATIONS

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The mechanical response of axisymmetric grains has an additional complexity associate with the microstructure alignment and orientation of the grains. These additional kinematic degrees of freedom give rise to a more complex macroscale response than observed for spherical grains. The alignment of axisymmetric grains with respect to each other and the ambient flow governs the characteristics of the grain-to-grain contacts and relative slipping in the macro-scale. The macro-scale rheological response of axisymmetric grains has been investigated recently, using experiential technics and Discrete Element Method (DEM), however, these studies mainly focus on the steady-state response rather than the transient response. When axisymmetric grains are subjected to oscillation, their corresponding alignment and orientation give rise to additional time-scale and a complex rheology.

In this presentation a mathematical model for the kinematic response of axisymmetric grains and anisotropic inertia rheology model will be used to study the transient shear-reversal response of these grains. The grains orientation is described by the structural tensor which is the second moment of the orientation density function. The anisotropic inertial rheology model which depends explicitly on the microstructure of the grain orientation is an evolving property that depends on the flow and the orientation of the grains. This gives rise to a coupled system that shows a complex transient response to oscillations.

The response of axisymmetric grains when subjected to transient shear-reversal, as predicted by the model, gives rise to transient grains reorientation that, in turn, shows shear thickening response on macro-scale. This response can give rise to directional jamming which is also supported by DEM simulations.

It is observed that the tendency for shear-thickening has strong dependency on the grain's asphericity (deviation from spheres). It is shown that shear-thickening has a nonmonotonic dependency on the asphericity, that is, the shear thickening is low for small and large asphericity, hence do not yield jamming. Jamming is observed only for mid asphericity. These results can be explained through the coupling of the rheology dependency on the asphericity and alignment of the grains, and the transient reorientation due to shear-reversal.

These results provide insight into the transient response of the microstructure, the associate transient rheology, and the conditions for jamming of axisymmetric grains. It suggests that explicit consideration of the microstructure is essential for an accurate rheological model of such grains.

4-CELL ANALOGICAL MODEL TO DESCRIBE PLASTIC SHEAR BEHAVIOR OF GRANULAR SOLID

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Constitutive modelling of quasistatic plastic shear behavior of granular solid is essential in geotechnical engineering problems. Various models describing complicated soil behaviors have been proposed mainly in the framework of phenomenological elastoplastic models as an extension of J2 flow theory in metals. Although another framework called micromechanics models have also been studied to describe the bulk behavior of granular assemblies in terms of grain scale mechanics, they are still under investigation.

This study deals with the model of the latter type as a modification of Matsushima and Chang (2007). It introduces 4-cell analogical model with which the orientational distribution of contact forces in the uniform strain model (Chang & Misra 1990) is modified to describe the plastic yielding toward critical state. The following figure shows an example of the response of the biaxial compression test under constant confining pressure in 2D granular assembly obtained by the proposed model. The transient behavior differs in different initial void ratio, and the stress ratio and the void ratio converges to the identical critical state. We also confirm that the response under constant volume test is similar to that of the undrained test of sandy soil.

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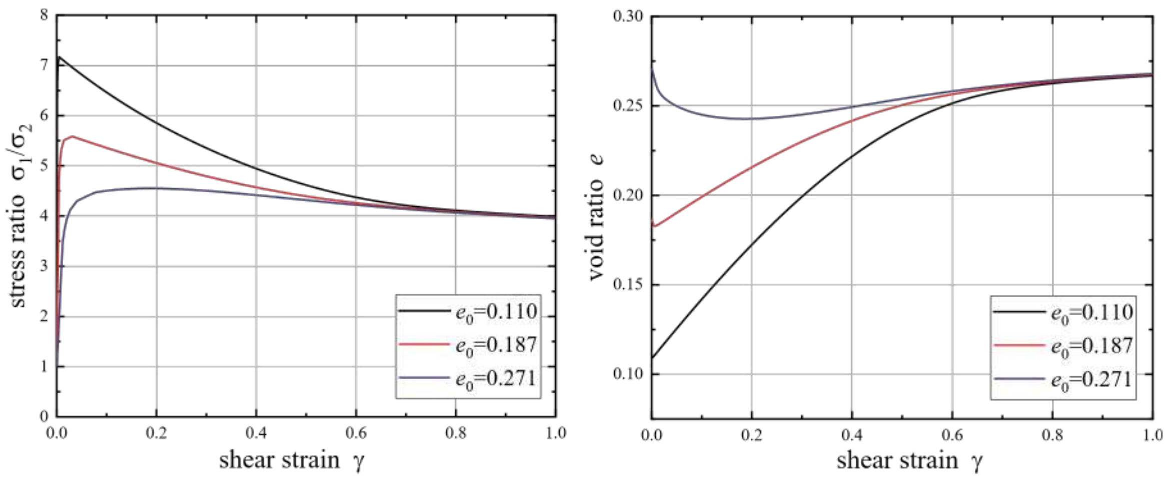

Figure: Biaxial compression response of the proposed model (stress ratio change (left) and volumetric strain change (right) in terms of shear strain

EMBEDDING GRAIN REARRANGEMENTS IN MICROMECHANICAL MODELS TO MAKE CRITICAL STATE EMERGE IN THE UP-SCALING PROCESS

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With respect to constitutive modeling of granular materials, one significant and attractive observation is the existence of stationary state (known as critical state in soil mechanics) where a multitude of conformations (local arrangements of particle structures) and conformational transitions exist for which the macroscopic stress and porosity remain constant under continuous shearing. Granular shear simulations and experiments have shown that this regime is governed by the competing mechanisms of growth/birth versus collapse/death of force chains, and these events drive evolution towards, and during, stationary states of systems under shear [1, 2, 3]. Following that, the process of grain rearrangement in granular materials under shearing has been quantified through tracking the lifespan and life expectancy of mesostructures [4]. It has been shown that the material memory rapidly fades, with an entirely new generation of force chains and grain loops replacing the old within a few percent strain [4].

In multiscale constitutive modeling, mesostructural transformations which brings vanishing and generating of mesostructures along loading is thus a central ingredient that should be included. Considering a particular micromechanical model, the H-model [5], we show how such mesostructural transformation can e included in an enriched version of the model. The original model copes with deformation from the relative displacement at the contact scale and from the particle rearrangement through deforming elementary hexagonal patterns of adjoining particles. A deactivation/reactivation procedure based on the renewal rate of mesostructures is introduced to the H-model to fully embed grain rearrangement. Results show that this is a promising strategy to improve the model to predict relative large strains and to make critical state emerge naturally without drawing support from any empirical law at the macroscopic scale.

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EFFECT OF LOCAL DEFECTS ON THE RESPONSE OF NON-CLASSICAL ELASTIC MATERIALS

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In the last decade, a lot of new materials have attracted the attention of scientists because of their mechanical behaviors. The need to forecast new exotic mechanical responses leaded to the development of non-classical elastic models characterized by increasing computational and mathematical difficulties. Among these, we can list the micropolar and higher order gradient theories.

Albeit all mechanical systems are affected by uncertainties, not many probabilistic remarks can be found in the literature on non-classical elastic models. The uncertainties can be related to geometric imperfections, material defects and non-deterministic applied loads. Moreover, 3D print defects must be also considered random quantities.

This work aims to propose a simplified approach to investigate the effect of local defects on the random kinematic unknowns of the latest micropolar and higher-order gradient theories. Firstly, a random nonlinear pantographic 2D continuum model is analyzed, and the effect of pivot and beam imperfections is studied. Secondly, a new deformation measure for the nonlinear micropolar continuum is proposed, which can uncouple classical and non-classical energetic contributions: the stretch, the micro-macro relative rotation of particles and the spatial variability of microrotations. The model involves eight constitutive parameters, which realistically are not deterministic quantities. The effect of their local randomness in the mechanical response of different samples is investigated.

The suggested procedure is computationally advantageous. It combines deterministic finite element analyses via a commercial software, a theory-driven identification of the transformation between the input-output random variables and simplified stochastic analyses. Moreover, it finds application for a large class of mathematical formulations and, consequently, for a large class of mechanical problems.

A BEAM MODEL FOR DUOSKELION STRUCTURES DERIVED BY ASYMPTOTIC HOMOGENIZATION AND ITS APPLICATION TO AXIAL LOADING PROBLEMS

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Duoskelion structures have been recently introduced by Barchiesi et al. in *E. Barchiesi, F. dell'Isola, A.M. Bersani, & E. Turco (2021), Equilibria determination of elastic articulated duoskelion beams in 2D via a Riks-type algorithm. International Journal of Non-Linear Mechanics,* as a proof-of-concept motif for a new class of metamaterials. The properties of these periodic beam-like chiral structural elements have been investigated, up to now, by means of a discrete model formulation whose predictions are obtained by numerical methods. In this paper we select a specific scaling law for micro stiffnesses aimed at deriving, via asymptotic homogenization, an internally-constrained Cosserat one-dimensional planar continuum model as the limit of a duoskelion structure. We analyze qualitatively and quantitatively the family of equilibrium configurations of the homogenized continuum when subjected to axial loading and compare the results of the analysis with those obtained by means of the discrete model formulation.

MULTI-PARTICLE FINITE-ELEMENT MODELLING OF COHESIVE DUCTILE GRANULAR SYSTEMS

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The process of powder compaction, involving deformable particles, is widely used in the industry. The purpose of this process is to produce a geometric shape thanks to the intergranular cohesion developed during the compaction. One of the major problems of this process is the cracking phenomenon occuring during the compaction phase due to locally highly deviatoric loadings near geometrical singularities. Such defects lead to the outright rejection of the manufactured parts. Although this problem is well known, there are few studies in the literature about the understanding of macroscopic failure for this type of highly deformable material. No numerical model currently allows the prediction of the creation of such defects and only lengthy trial and error procedures allow to avoid them. Experimental campaigns being often expensive and difficult to carry out for complex loading paths, the decohesion between particles for strongly deviatoric loadings, responsible for cracking phenomena, as well as the role played by the deformability of the constituent particles of the granular material, have not yet been studied at the particle scale. To overcome this limitation as well as these experimental difficulties, a numerical approach using the multi-particle finite element method appears as a promising alternative, by explicitly modelling the microstructure of an idealized granular medium. This method corresponds to a coupling between the finite element method and the discrete element method: the particles are meshed to take their deformation into account and the interactions between particles are managed using finite-element contact formulation. In such a method, the particles constitutive behaviour is accounted for by using a material model based on continuum mechanics. It is also necessary to model the interfacial behaviour at the contacts between the particles, involving contact cohesion, which is of importance for the study of failure or cracking. However, the development of cohesion at contacts between particles is not very weel understood as it results from complex interactions at the molecular scale. Therefore, a cohesive contact model involving interactions at the roughness asperity scale was adapted from the literature and implemented in the multi-particle finite-element model. This multiscale model is based on the Lennard Jones potential, expressed as a stress, weighted with the Pullen and Williamson roughness model. In this way, it is possible to locally (at each node of the finite element mesh) predict the cohesion level, evolving with the increase in the effective surface during deformation by plastic deformation of the asperities being in contact. This model is then implemented in the multi-particle finite element simulation to predict the mesoscopic properties such as yield or failure surfaces for strongly deviatoric loadings as well as the cracking phenomena appearing for this type of loadings.

MULTI-SCALE MODELING OF FIBER-REINFORCED-CONCRETE USING GRANULAR MICROMECHANICS APPROACH

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Plain concrete is a brittle material with a relatively low tensile strength and deformation capacity, which requires the application of reinforcement in order to avoid substantial cracking and catastrophic failure under service conditions. One way to enhance the tensile strength and deformation capacity is through the inclusion of short, randomly-oriented fibers. Since the fibers restrict and delay the nucleation and propagation of micro- and macro-cracks, fiber-reinforced-concrete (FRC) demonstrates an improved tensile strength, structural ductility, and toughness compared to plain concrete [1].

In this research, a multi-scale constitutive material model is developed for the analysis of FRCs. The multi-scale model is based on the so-called Granular Micromechanics Approach (GMA). Accordingly, a macroscopic FRC material point is related to a microscopic collection of grains that are connected by cement paste and fibers. The microscopic load-displacement relationships for the different constituents are formulated, and the directional density distribution functions of the grains and fibers are established. After relating the spatial average of the microscopic virtual work for a collection of grains to the virtual work in a macroscopic material point, and integrating the grain-pair constitutive interactions along all possible directions, the macroscopic constitutive behavior of the FRC is obtained [2].

The behavior of FRC materials with different types of short fibers is predicted under various monotonic and cyclic loading paths. In addition, the effects of the type and volume fraction of short fibers on the FRCs' behavior are investigated under various confining pressures. Finally, failure envelopes of FRCs with different fiber types and volume fractions are derived. The numerical results are in good agreement with experimental results reported in the literature, which shows that the proposed constitutive model is a promising candidate for the analysis of large-scale FRC structures.

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MS-7 Novel computational methods with applications in continuum mechanics
Bilen Emek Abali (Uppsala University, Sweden)

Constitutive assumptions for a continuum model of scintillators
F. Daví

Predicting stress fields in adhesive composite using deep learning
A.W. Khan, C. Balzani

A DNN-based fingertip deformation model
G. Serhat, Y. Deshmukh, K.J. Kuchenbecker

A Data-Driven Method for Building Parametric Reduced Models
M. Oulghelou, A. Ammar

Explicit asynchronous time integrator with local time stepping method for sharp elastic wave propagation - strong heterogeneous cases and irregular meshes
R. Dvorák, R. Kolman, T. Fíla, J. Falta, K.C. Park

Neural network-based modeling of the mechanical performance of functionally graded beam structures subject to distributed loads
N. Karathanasopoulos, A. Singh

Phase-Field Modeling in Generalized Damage Mechanics
B. E. Abali

A second-gradient continuum formulation for bi-pantographic fabrics
S. R. Eugster, E. Barchiesi

Continuum model for the three-dimensional pantograhpic ortho-block
M. Stilz, S. Eugster

Modeling of Inelastic Deformation of Materials in Temperature Intervals of Phase Transformations
O. Kikvidze, M. Sharabidze

CONSTITUTIVEASSUMPTIONSFORACONTINUUM MODELOFSCINTILLATORS

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A scintillating crystal or scintillator is a crystal which acts as a wavelength shifter, *i.e.* that converts incoming ionizing energy into photons in the frequency range of visible. In a previous paper [1] we modelled inorganic scintillators by the means of a continuum with structure model, to arrive at a reaction-diffusion-drift system which describes the evolution and the recombination in photons of the charged carriers. A model of this kind, first proposed for scintillators in [4], was used subsequently in many papers to get a phenomenological description of scintillation. In this and similar models the diffusion-drift part and the recombination term (which describes how the radiation-excited charge carriers recombine radiatively to generate visible photons or lose energy trough non-radiatively processes) were borrowed directly either from the kinetics of chemical reactions or from similar models for semiconductors. In [1] we showed how the reaction-diffusion-drift boundary value problem for scintillators can be obtained, in a coherent and consistent manner, by the means of the mechanics of continua with microstructure [3] for a non-deformable crystal. Moreover, we showed how the reaction term can be obtained, by using the formalism of chemical reaction kinetics, to deal with the recombination mechanisms. Further we showed that the whole boundary value problem admits a gradient flow structure: for the various mathematical aspects and results *vid. e.g.* the review in [2].

The aim of the present work is two-fold: first to extend the results of [1] to deformable continua and then to investigate the effects of different constitutive assumptions for the dissipative terms (which are represented by an entropy functional) on the recombination term. In particular we look at two possible choice for the entropy functional, namely the Gibbs (or BoltzmannGibbs) entropy and the one which is based on the Fermi-Dirac statistics. This last one seem more appropriate to describe recombination in scintillator, but this is obtained by loosing the simpler mathematical structure induced by the Gibbs entropy and which is well studied from a mathematical point of view [2]. Accordingly reaction-diffusion-drift equations based on the Fermi-Dirac statistics deserves further studies.

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PREDICTING STRESS FIELDS IN ADHESIVE COMPOSITE USING DEEP LEARNING

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Fibre reinforced adhesives are an integral part of wind energy turbine blades and play an important role in evaluation of structural integrity of the blades. Digitization of manufacturing processes and demand for fast and efficient stress analysis argues for the application of deep learning.

As a step forward in using deep learning to predict structural properties in composite, the work would explore the applicability of deep learning methods to 2D fibre reinforced composite. In this work, a composite adhesive used in wind energy turbine blades is used as an illustrative example. The composite adhesive when viewed using a CT scanner shows a heterogeneous structure with two phases, a softer matrix phase and a more stiff fibre phase.

For this purpose, several CT scan images of the fibre adhesive composite are used. Also, a strategy to generate representative images for the CT Scan images is sought using generative adversarial networks for the general applicability of the method. The images on subsequent FEA analysis serves as the training data for the deep learning framework. Once trained, the neural network would be able to predict the stress distributions in the structure (Figure 1).

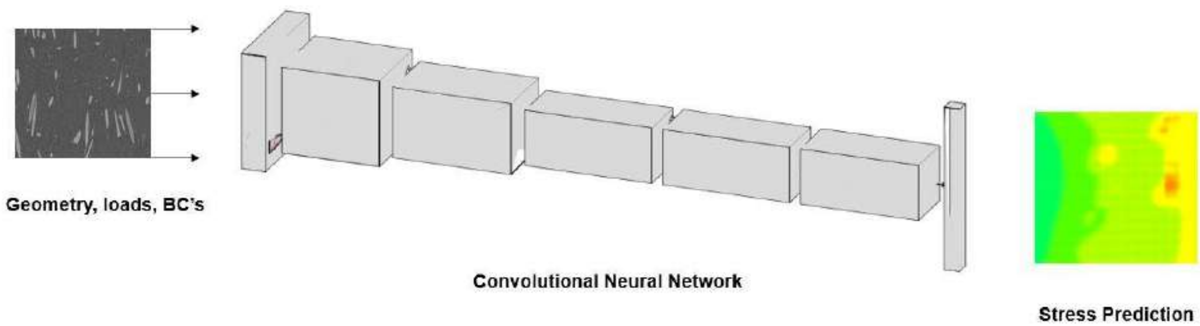

Figure 1 Stress field prediction in adhesive composite using deep learning

A DNN-BASED FINGERTIP DEFORMATION MODEL

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The human fingertip plays crucial roles in grasping, manipulation, and texture exploration. These important functionalities have inspired significant efforts to understand fingertip deformation mechanics. However, the anatomical complexity of this body part complicates modeling its mechanical behavior accurately with a reasonable computational cost.

In the literature, various finite element models with different levels of detail have been developed to simulate the deformation of fingertips with intricate geometry and non-uniform material properties. We recently introduced a high-fidelity model named DigiTip (Serhat and Kuchenbecker 2021), which includes the characteristic profile of the distal phalanx and multiple soft tissue layers comprising the stratum corneum, epidermis, dermis, hypodermis, nail bed, and fingernail. In the presence of these diverse features, achieving converged solutions required the use of more than 10,000 elements. Such a fine mesh significantly prolongs the analysis duration and limits the model's usability in practical applications.

This study introduces a fingertip deformation model capable of accurately predicting the deformation of the human fingertip indented by normal point forces. We utilize a deep neural network (DNN) as an efficient surrogate for expensive finite element analyses (Fig. 1). Our trained model can be used to simulate the displacement field and corresponding stress state in real time. One can link the obtained internal stress fields with neural models to predict human perception or design devices that provide haptic feedback. Future work will make this DNN-based model available on an open-access website, where the user can define the number, locations, and magnitudes of the indentation forces. We also plan to add the capability of computing dynamic responses for different excitation frequencies and damping levels.

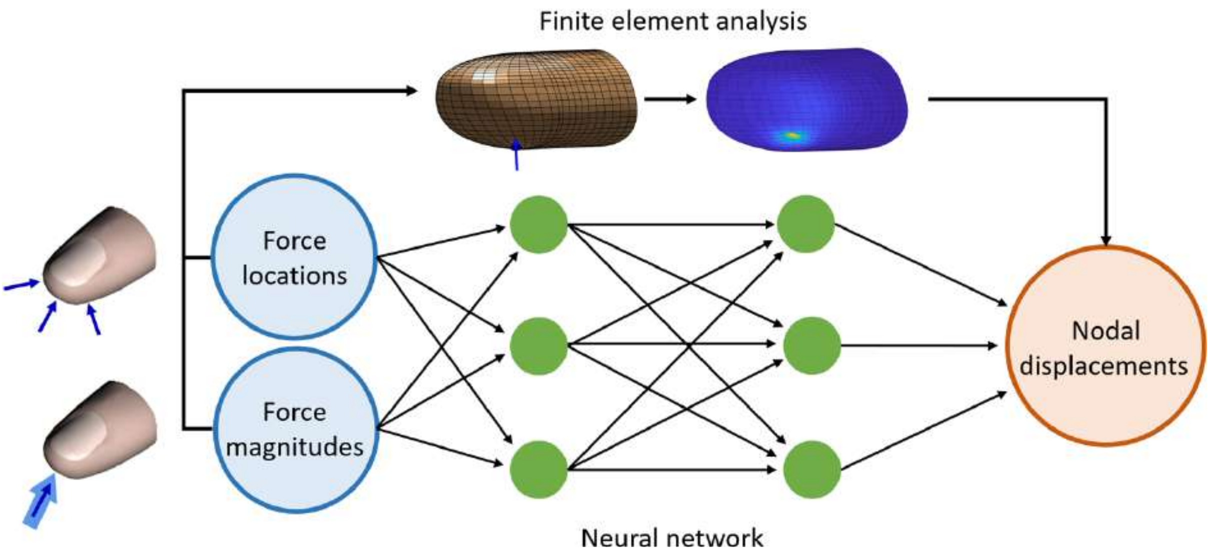

Figure 1. Mapping force input to simulated nodal displacements using a deep neural network.

A DATA-DRIVEN METHOD FOR BUILDING PARAMETRIC REDUCED MODELS

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Real-time prediction of parametric physical phenomena is essential in many industrial applications. In these cases, standard discretization techniques such as finite elements or finite volumes are not suitable and the use of model reduction techniques is necessary. The fundamental objective of model reduction is to transform a large-scale dynamical system into a reduced system of much smaller dimension, capable of accurately reproducing the dynamics of the original system. In general, such a reduced order model (ROM) is constructed by projecting the equations of the full model onto the vector subspace obtained by the Proper Orthogonal Decomposition (POD) method. A frequent problem of reduced models resulting from Galerkin projection (ROM/Galerkin) is instability. Indeed, the ROM/Galerkin can be unstable even if the original system is asymptotically stable. Moreover, the latter is only valid in a small neighborhood of the parameters for which the POD basis has been constructed. In this work and in order to overcome these difficulties, we propose an approach to derive parametric/data-driven reduced order models (PROM/DD) without using Galerkin projection. The construction of the PROM/DD is performed through optimization and interpolation on the tangent space of the Grassmann manifold. It is demonstrated on the example of the flow past a cylinder that the PROM/DD succeeds well in predicting the flow dynamics for a wide range of Reynolds number values.

EXPLICIT ASYNCHRONOUS TIME INTEGRATOR WITH LOCAL TIME STEPPING METHOD FOR SHARP ELASTIC WAVE PROPAGATION - STRONG HETEROGENEOUS CASES AND IRREGULAR MESHES

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The problem of the linear elastodynamics including domain decomposition via localized Lagrange multipliers method [2] is solved using finite element method and direct time integration. Time integration of domains is performed separately with different time steps with integer ratio. The known asynchronous integrator scheme [1] is generalized for multiple domains problem and enhanced by the use of a local variant of the pushforward-pullback method, which effectively avoids spurious oscillation in steep stress pulses response. The proposed method is applied to the rectangular step pulse propagation problem considering the linearly varying Young modulus in space as well as the bi-material interface problem. To prove the robustness and the accuracy, the comparison with analytical solution and commercial software outputs is provided.

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NEURAL NETWORK-BASED MODELING OF THE MECHANICAL PERFORMANCE OF FUNCTIONALLY GRADED BEAM STRUCTURES SUBJECT TO DISTRIBUTED LOADS

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Beam elements are structural components widely used in engineering practice. They can have either homogeneous inner material properties or follow a functionally graded internal material distribution, with varying properties along their length or through their thickness. The computational analysis of their structural response commonly requires dedicated finite element models with refined meshes and a considerable numerical cost for the accurate characterization of their deformation behavior and inner stress state. In the current work, analytical data-based neural network models are developed to compute the mechanical performance of simply supported composite and functionally graded beams subject to distributed loads of arbitrary magnitude for any beam slenderness geometry.

The neural network modeling architecture, activation functions, and the network complexity required for high-accuracy modeling of the structural performance are investigated, identifying designs that lead to highly accurate modeling predictions for the first time. The nondimensionalized numerical database is generated using a recently developed, elasticity-based, semi-analytical numerical model. It is observed that a considerably large dataset is a prerequisite for the training of a sufficiently accurate model, with a sufficient testing performance for all output displacement and stress parameters of interest. Deep neural network architectures are identified, capable of predicting the complete displacement and stress field at any length and thickness position within the beam with a test-set accuracy in the fourth decimal order for all relevant analysis parameters (Fig. 1). Moreover, the computing time and memory demands of the optimal neural network modeling architecture identified are shown to be several orders of magnitude lower than the ones required for the corresponding functionally graded, converged finite element models.

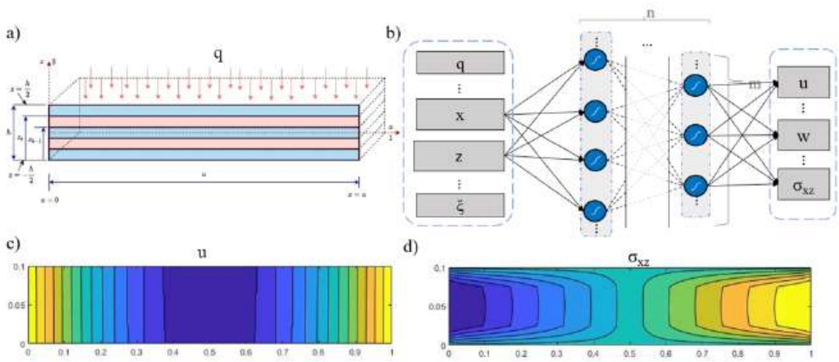

Figure 1: Functionally graded beam element with different material properties along the thickness z direction are depicted in (a). Dedicated neural network models are developed to capture the mechanical response, computing the complete displacement and stress field (b). Representative uniaxial displacement and shear stress distributions are provided in (c) and (d) respectively

PHASE-FIELD MODELING IN GENERALIZED DAMAGE MECHANICS

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Even in a composite material with fibers and matrix, there exists an internal structure. Each component in a composite material may be isotropic, but the microstructural alignment induces an anisotropic character or even a metamaterial at a macroscale. By homogenizing this microstructure at the macroscale, we may approximate the metamaterial by a strain gradient theory [1] with a great accuracy [2] in order to explain phenomenological observations across the length-scales [3]. By using such a generalized mechanics, where the deformation energy depends also on the second gradient of displacement, we start a discussion of an implementation a damage mechanics extension in metamaterials by incorporating phase-field approach [4] by using open-source packages [5].

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A SECOND-GRADIENT CONTINUUM FORMULATION FOR BI-PANTOGRAPHIC FABRICS

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Bi-pantographic fabrics are materials that are composed of two families of fibers with a microstructure. The micro-structure of a straight fiber is given by a periodic arrangement of cells that resembles an expanding barrier. The planar behavior of such a fabric is captured at a macroscopic scale by a second-gradient continuum. The corresponding strain energy function depends upon the fiber stretches, as well as upon the gradients in fiber direction of the stretches and inclination angles. In this talk, we present a continuum model that describes the planar behavior of a bi-pantographic fabric manufactured by 3D printing. Even though printed in polyamide, the micro-structure allows the architectured material to extend up to 25% within the elastic regime. The continuum formulation is obtained by an asymptotic homogenization procedure, which starts with a discrete spring system. Moreover, we give an outlook to an extension of the bi-pantographic fabric, which can be considered as a complete second-gradient material.

Article I. CONTINUUM MODEL FOR THE THREE-DIMENSIONAL PANTOGRAHPIC ORTHO-BLOCK

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There has been extensive work on pantographic structures ranging from one-dimensional beams, two-dimensional sheets to three-dimensional layered blocks. While the latter consists of interconnected parallel pantographic sheets our motivation was to extend the pantographic behavior to more than one plane.
We present a three dimensional pantographic structured material based on a simple combination of parallel and orthogonal pantographic sheets. Starting with the description of the discrete structure based on beams, its unit cell and kinematic properties, we then discuss a homogenization resulting in a second gradient material with subsequent numerical implementation and simulation results.
Similarly to other pantographic structures we find zero energy modes if perfect joints are implemented where beams interact. In simple tension test simulations the material shows a semiauxetic behavior.
The homogenization assumes a network of continuous Euler beams with a junction of four beams in every node of the continuum. For numerical comparisons of the beam structure and the homogenized model we implemented the second gradient model in a commercial code using Hermite interpolation and our in-house code with B-Spline interpolation. We further discuss the question of existence and uniqueness of solutions of the linearized continuum model.

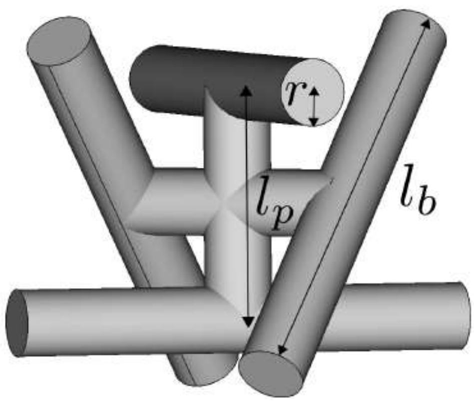

Figure 1: CAD of the primitive cell of the pantographic ortho-block with basic parameters and four beam-pivot connection and one pivot-pivot connection. The connections are depicted as rigid but joints could be implemented.

MODELING OF INELASTIC DEFORMATION OF MATERIALS IN TEMPERATURE INTERVALS OF PHASE TRANSFORMATIONS

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In temperature intervals of phase transformations with the change in temperature, inelastic deformations occur, which are essential for determining the stress-strain state of solid. The condition of the material sustainability when subjected to thermomechanical loading has been formulated and the main inequalities of inelastic deformation have been obtained. Non-gradient flow relative to the loading surface has been established and equations for inelastic strain increments have been derived. Numerical calculation of thick-walled pipe with shape memory in temperature intervals of martensitic transformations was carried out.

MS-8 Structural and finite element modeling for large deflection, post-buckling, and failure analysis of composite laminates
E. Carrera, A. Pagani, M. Petrolo (Politecnico di Torino, Italy)

MS-23 Advanced mechanical modeling of composite materials and structures
Francesco Tornabene (Università del Salento, Italy), Rossana Dimitri (Università del Salento, Italy), J.N. Reddy (Texas A&M University, USA), Matteo Viscoti (Università del Salento, Italy)

Nonlinear dynamic analyses of isotropic and composite structures using refined and unified one- dimensional finite elements
R. Azzara, M. Filippi, R. Augello, E. Carrera, A. Pagani

Microstructures of optimally designed robust composites
E. Cherkaev, J. Baker, A. Cherkaev

On the role of refined structural theories to improve the computational efficiency of nonlinear analysis of composites
M. Petrolo, A. Pagani, E. Carrera

Computational and analytical modelling of the fracturing behavior of transversely isotropic geomaterial
M. Rinaldi, R. Dimitri, M. Trullo, F.Tornabene

Static and free vibration analysis of generally anisotropic doubly-curved shells via the GDG method
M. Viscoti, F. Tornabene, R. Dimitri

A micromechanics based generalized damage initiation model for unidirectional composites
C. S. Upadhyay , Y. Sharath Chandra Mouli

Multiscale Process Modeling Analysis for the prediction of Composite Strength Allowables
M. Maiaru, Gregory M. Odegard, Sagar Shah, Michael Olaya, Sagar U. Patel

Continuum Mechanical Modeling of Woven Textile Membranes and Unique Parameter Identification based on Classical Experiments and Full-Field Data
L. Makhool, M. Motevalli, D. Balzani

A Novel Discrete, Mesoscale Modeling Framework for the Simulation of the Damaging and Fracturing Behavior of Composites
M. Salviato

NONLINEAR DYNAMIC ANALYSES OF ISOTROPIC AND COMPOSITE STRUCTURES USING REFINED AND UNIFIED ONE-DIMENSIONAL FINITE ELEMENTS.

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The present research work deals with the finite element analysis of the nonlinear dynamic behavior of isotropic and composite structures. The mathematical models of such structures are derived by exploiting the Carrera Unified Formulation (CUF). CUF represents a hierarchical formulation in which the order of the structural model is considered as an input of the analysis. Thus, no ad-hoc formulations are needed to achieve any refined generic model. According to CUF, any theory is degenerated into generalized kinematics adopting an arbitrary expansion of the generalized variables. In this work, Lagrange polynomials are employed as expansion functions. The nonlinear governing equations and the relative finite element arrays of the one-dimensional theories are formulated in terms of Fundamental Nuclei (FNs). Furthermore, geometrical nonlinear equations are written in a total Lagrangian framework and solved with an opportune Newton-Raphson method. Finally, the implicit time integration scheme employed to evaluate the nonlinear dynamic response is the HilberHughes-Taylor (HHT)-α algorithm, which allows stabilising the time integration process under highly nonlinear effects.
A preliminary analysis is performed to validate the proposed approach when compared with analytical and literature results. Subsequently, composite beams are considered, and stress distributions at highly nonlinear equilibrium conditions are evaluated. Finally, an application to a double-pendulum problem is proposed. The latter model is built in a multibody framework, joining the two different arms employing Lagrange multipliers. The results clearly show the reliability of the approach when dealing with nonlinear dynamics and evaluating the three-dimensional stress distribution. The analysis of the double-pendulum mechanism is promising for future multibody applications.

MICROSTRUCTURES OF OPTIMALLY DESIGNED ROBUST COMPOSITES

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The constructions designed to perform optimally under prescribed conditions are very sensitive to variations of the loadings. However, the applied forces are not known precisely in many engineering applications, manufacturing, and biological design problems. The optimal design should be robust and consider a possible variety of loading conditions. We formulate the optimal design problem for a robust composite structure as a minimax optimization problem. The problem requires minimizing the maximum of functional of the solution under the applied loading chosen from the admissible set. The minimum is taken over a constrained set of the design parameters characterizing the distribution of the materials in the domain.

The optimal three-dimensional robust structures are constructed by solving a minimax optimization problem for the energy stored in the domain. The maximum of the energy stored in the domain under the applied force chosen from a set of admissible forces is the principal compliance of the elastic domain; the optimization problem is formulated as a minimization of the principal compliance of the domain. This is a non-convex variational problem, and the relaxation of the problem results in the appearance of composite structures. A characteristic feature of the problem is the multiplicity of optimal extreme forces that leads to the symmetry of the optimal hierarchical structure. The optimization considers this multiplicity of extreme loadings and reinforces the material structure to resist all of them equally. Another characteristic feature of the problem is a bifurcation of the solution under a continuous change of the constraints for the set of admissible loadings or design parameters.

Optimal design of a robust thermal lens. The thermal lens problem is finding an arrangement of materials in a given domain that focuses the heat flux to the specified part on the domain's boundary. The solution to the optimization problem is a composite material with a spatially varying laminated structure that maximizes the heat flux through the given window on the boundary. In the robust design of a thermal lens, the problem is to find a composite structure that optimally directs the heat flow entering the domain to the specified boundary window without knowing exactly where the heat flux enters the designed region. To deal with this uncertainty in the boundary conditions, we reformulate the problem as a problem of maximization of the minimum of fluxes through the specified window. The optimal layout in this problem is a laminated composite.

Multiscale structure of optimal viscoelastic composites. Extension of the robust optimal design problem to viscoelastic composites is based on the analytic representation of the viscoelastic modulus. We reduce the problem to optimization of the dynamic compliance modulus, which characterizes dissipation, attenuation, and the phase delay between the oscillating stress and strain in a viscoelastic medium. We show that solutions of robust structural optimization can be constructed in a class of high-rank laminated composites.

ON THE ROLE OF REFINED STRUCTURAL THEORIES TO IMPROVE THE COMPUTATIONAL EFFICIENCY OF NONLINEAR ANALYSIS OF COMPOSITES

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This paper presents an overview of the capabilities provided by refined 1D and 2D structural models to carry out nonlinear analyses of composites. 3D FEM is mandatory in many cases in which the complete stress field is necessary to predict the nonlinear behavior, e.g., failure analysis, progressive damage, residual stress and process-induced defects. Unfortunately, the aspect ratio constraints and small thickness of plies lead to prohibitive computational overheads. 1D and 2D models have less stringent constraints, but higher-order structural theories (HOST) are necessary to incorporate the full 3D stress field. Table 1 shows a comparison between HOST and 3D for various cases. The second column reports the ratio between the number of DOF of HOST and 3D; the third column shows the error of the least accurate model; the last column indicates the model with the best accuracy. For example, in the case of low-velocity impact on a bi-metallic plate, HOST requires 1% of 3D DOF, and it is more accurate than 3D as the latter has an error of 16%. This work presents the theoretical framework to obtain such reduced models and numerical examples on various nonlinear cases.

Table 1: Computational costs and accuracy of HOST and 3D

Problem	DOF HOST/3D	Error	Best Model
Three-point bending of a sandwich beam [1]	1 %	0 %	Same
Low-velocity impact on a bi-metallic plate [2]	1 %	16 %	HOST
Large deflections in cross-ply beams [3]	1 %	7 %	3D
Disbonding in sandwich beams [4]	24 %	1 %	3D
Curing of a composite part [5]	3 %	0 %	Same

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COMPUTATIONAL AND ANALYTICAL MODELLING OF THE FRACTURING BEHAVIOR OF TRANSVERSELY ISOTROPIC GEOMATERIAL

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The present work focuses on the fracturing behavior of the Opalinus Clay (OPA) from a computational standpoint. The OPA is a kaolinite-rich formation with a low permeability and high adsorption capability, which make it a reasonable candidate as a host rock for radioactive nuclear waste geological disposal. Based on experimental results obtained in the Mont Terri Underground Research Laboratory, OPA can be considered as a transversely isotropic material because it stems from a sedimentation process, whose planes of isotropy coincide with the bedding ones [1]. In order to simulate the nonlinear cracking phenomena within OPA with a reduced computational effort, a reliable and robust method is here proposed based on the extended finite element approach [2], and a proper mixed-mode fracturing criterion [3]. A parametric investigation checks for the possible influence of the notch shapes and dimensions on the fracturing behavior of a semicircular bending test, both in terms of peak load and direction of the crack propagation. The results obtained from the computational analyses are validated against the experimental predictions from literature, as well as the classical finite elements and cohesive zone models [4,5]. A novel analytical formulation is also proposed to approximate the fracturing response of the material in terms of load-crack mouth opening displacement and peak load, starting from a predefined value of initial notch depth.

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STATIC AND FREE VIBRATION ANALYSIS OF GENERALLY ANISOTROPIC DOUBLY-CURVED SHELLS VIA THE GDQ METHOD

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Recent advances in several engineering fields require new strategies for the numerical implementation of innovative structures. Doubly-curved geometries are very often required and innovative materials are adopted [1] in an increasing number of applications.
Two-dimensional formulations have demonstrated to be reliable for the analysis of shell structures. Both Equivalent Single Layer (ESL) and Layer-Wise (LW) models are adopted employing a curvilinear set of principal coordinates. Moreover, NURBS-based blending functions [2] allow the computation of arbitrary shaped structures as well. Then, a formulation for generally anisotropic materials combined with an efficient homogenization algorithm [3] accounts for all the possible material characteristics [4]. The governing equations are derived in both the strong and the weak form, together with natural boundary conditions. Generalized constraints can be modelled handling non-uniform distributions of linear elastic springs. Moreover, a Winkler-Pasternak foundation is included in the model [1]. The numerical assessment of the fundamental relations is tackled by means of the GDQ Method. In the post-processing, the three-dimensional equilibrium equations are taken up so that the through-the-thickness profiles of stresses and strains is recovered.
A series of numerical examples outlines the validity of the formulation. The outcomes of both ESL [3-4] and LW [2] models are compared to those provided by refined 3D FEM simulations. Different geometries, material symmetries and external constraints have been considered. Very accurate results are derived, and all the possible three-dimensional effects usually predicted by high-computationally demanding simulations are well depicted.

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A MICROMECHANICS BASED GENERALIZED DAMAGE INITIATION MODEL FOR UNIDIRECTIONAL COMPOSITES

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Progressive damage modeling in composites requires a good model for damage initiation locus, under general loads. Several progressive damage models have proposed damage initiation rules based on macro-level testing of uni-directional (UD) laminates of specific ply arrangement, without paying heed to the complex micro-level stress interactions at the constituent level which lead to onset of specific modes of damage. Experimental identification of damage initiation loads is still scarce. This is in-contrast to the conventional effort to define failure envelopes for the composite lamina, either through experimental data or through macro-level models, with the Tsai-Wu or Hashin models being some of the most popular. Use of final failure data in design requires conservative knock-down factors, thus leading to under-utilization of the material. The present study proposes a comprehensive micromechanical analysis based model for damage initiation in composites, which uses the specific mechanical behavior of each of the constituent phases (i.e., fiber and matrix). The model provides a sound computational framework for developing the damage initiation locus for any combination of matrix and fiber.

The present micromechanical implementation uses the standard-mechanics model to obtain Hill's concentration factors (HCF) for three-dimensional representative volume elements (RVE's) of randomly distributed straight fiber-reinforced UD composites. The micromechanical analysis gives us effective macro properties of the material as an outcome. Further, distribution of the HCF allows us to obtain the "damage stress concentration factor" (DSCF) locally, which is a measure of damageability of the material in the RVE. The distribution of DSCF is used to identify the critical damage initiation regions (CDIR's). Averaged CDIR is used in the study to develop macro-level damage initiation model. Notably, the study emphasizes the effect of constituent properties and specific distribution of fibers in the RVE, on the scatter in damage initiation stresses. This allows us, for the first time possibly, to depict scatter bands for damage initiation envelope. For example, the damage initiation envelope of σ_{12} versus σ_{22} for AS4/3501-6 composite, as obtained from the proposed model, is shown in Fig.1. The closeness to experimental result available is noteworthy.

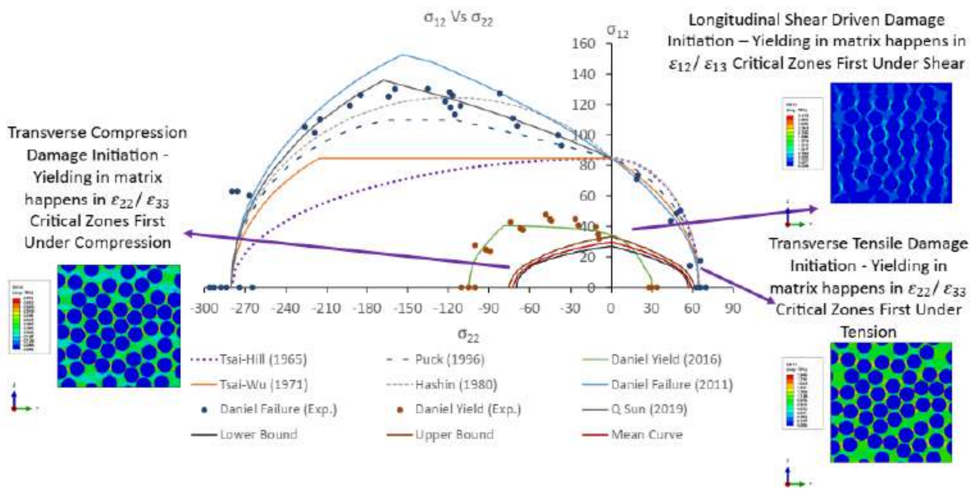

Figure 1: Damage initiation envelope of σ_{12} Vs. σ_{22} for AS4/3501-6 composite

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CONTINUUM MECHANICAL MODELING OF WOVEN TEXTILE MEMBRANES AND UNIQUE PARAMETER IDENTIFICATION BASED ON CLASSICAL EXPERIMENTS AND FULL-FIELD DATA

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Woven textile membranes are thin materials with a favorable strength-to-weight ratio, often used in various civil engineering applications, such as enclosing wide roof- and facade spans. They consist of two families of interlaced yarns (warp and fill), due to which they exhibit a highly nonlinear, anisotropic mechanical response allowing for finite deformations. This contribution proposes an accurate material model which allows for robust numerical simulation of structural problems. To this end, the strain energy density describing the hyperelastic response is additively decomposed into polyconvex terms which separately describe the behavior in each yarn direction and the interaction between the two yarn families, which is modeled by employing the concept of anisotropic metric tensors [1]. Since using of such advanced nonlinear models in engineering practice requires the appearing material parameters to have an informative physical meaning, unique identification of their values for specific materials is essential.

In this contribution, novel approaches are presented which allow for a unique and efficient identification. Two kinds of parameters are distinguished: stiffness-related *material* parameters which appear linearly in the strain energy function, and *model* parameters which are associated with the degree of nonlinearity and anisotropy. A first approach is based on data from several classical biaxial tests which will mostly follow the Japanese guideline MSAJ/M-02.1995. In the associated parameter identification approach, first, a procedure is applied allowing the model parameters to be determined independently from the material parameters and then, in the second step, the material parameters can be uniquely identified.

The second proposed approach is based on the full-field measurement of displacements and strains in a single experiment. Contrary to the conventional biaxial experiments, a non-standard experimental setup is presented where on purpose inhomogeneous strain fields are induced to activate all deformation modes required for identification of the material parameters. The measured displacement field is then directly inserted into the discretized equilibrium equation, representing the inhomogeneous experiment numerically. This enables the definition of a quadratic objective function in terms of differences of discrete internal and external forces based on the Equilibrium Gap Method [2]. The feasibility of the proposed new experiment is shown numerically by assessing the sensitivity of the proposed method to noise in the measurement data.

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A NOVEL DISCRETE, MESOSCALE MODELING FRAMEWORK FOR THE SIMULATION OF THE DAMAGING AND FRACTURING BEHAVIOR OF COMPOSITES

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Unidirectional (UD) and 2D/3D textile composites are increasingly being employed in systems acrossed many industrial sectors including aerospace, automotive, and wind energy. This is due to the excellent specific mechanical properties and tailorability of composites, paving new avenues for structural optimization and weight savings.

One of the challenges with the simulation of the mechanical response of composite materials is that their damage mechanisms depend strongly on the material micro- and mesostructures. Phenomena such as fiber micro-buckling and kinking in compression or fiber scissoring and matrix microcracking in shear in UD composites are only a few examples. Homogenized continuum models that describe these mechanisms are extremely mathematically complex, lack generality, and can only be used to fit experimental data. In fact, the constitutive equations compensate for not modeling fibers and matrix explicitly by introducing several complex equations and fitting parameters of unclear physical meaning. This makes model calibration extremely cumbersome and limits the predictive capability of the model.

In reality, the modeling of damage and fracture in composite materials does not have to be complex if the physics of the micro-and mesostructures is simulated explicitly. This is the goal of the Discrete Model for Composites (DM4C), a novel discrete mesoscale modeling framework that simulates the mechanical behavior of UD and textile composites. Specifically, this framework is only based on physical laws and does not depend on element erosion to simulate fracture. As it will be shown in this presentation, in DM4C, fibers, groups of fibers, and tows are simulated explicitly as Timoshenko beam elements while the matrix is described by vectorial constitutive laws defined on the facets of a tetrahedral mesh anchored to the nodes of the beam elements. These vectorial laws describe both the elastic and inelastic behavior of the matrix, including the traction-separation laws governing the fracture process and the friction between facets governing the compressive behavior. Thanks to the facet-based formulation, fracture is modeled in a discrete way and the need for element erosion can be avoided. Furthermore, since fibers and matrix are now simulated explicitly, the constitutive laws of each material can be physics-based, simple, and with clearly defined material parameters.

To demonstrate the predictive capability of the proposed framework, simulations of several typical damage mechanisms in composites will be compared to experimental data such as shear band formation in transverse compression, fiber micro-buckling and kinking in longitudinal compression, and sub-critical matrix microcraking in off-axis layers.

MS-9 Contact Mechanics of Interfaces
Patrick Selvadurai (McGill University, Canada), Anil Misra (University of Kansas, USA), Antoine Wautier (Aix-Marseille University, INRAE, France)

MS-16 Regularization of classical singular problems within generalized continuum theories: stress concentration, cracks, contact interactions, edge forces, dislocations
Victor A. Eremeyev (Università degli Studi di Cagliari, Italy), Sergey A. Lurie (Russian Academy of Sciences, Russia), M. Gutkin (IPMach RAS, Russia) and Yury Solyaev (IPRIM RAS, Russia)

Exact solution of free vibration of a nanobeam
N. Sonmez, E. Tufekci

Surface-dislocation interaction by varies models of surface elasticity
M.A. Grekov, T.S. Sergeeva

Multiphase Lattice Boltzmann approach for capillary bridges and associated forces
N. Younes, Z. Benseghier, O. Millet, A. Wautier, F. Nicot, and R. Wan

Instability modes resulting from hyperelastic and hypoelastic contact laws in discrete mechanics
A. Wautier, N. Challamel, F. Nicot, J. Lerbet, F. Darve

A model for composite materials with continuous fibers distribution including strain gradient effects
K. Enakoutsa

On modelling of material instabilities using von Mises truss as a structural element
V. A. Eremeyev, E. Reccia, M. Lai, A. M. Cazzani

EXACT SOLUTION OF FREE VIBRATION OF A NANOBEAM

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In today's technology, the industry is aiming for ever-so-smaller scales. Moore's Law states that the number of transistors on a microchip double about every two years. Currently, these beam-like elements stand around 7nm. For some applications, they shrunk down up to 2.5nm. It is important to understand the behavior of these nanostructures, to effectively use and develop new technologies and design novel nanodevices.

In this study, the free vibrations of a straight nanobeam with a uniform cross-section are investigated. The differential form of Eringen's nonlocal elasticity theory is implemented into the classical beam equations. The governing differential equations of free vibrations of nanobeams are obtained by using the d'Alembert principle. The axial extension, shear deformation, and rotatory inertia effects are included in the governing differential equations. The exact analytical solution of the governing differential equations is obtained by using the initial value method. The natural frequencies and the mode shapes of the beams are obtained analytically. The effect of nonlocal parameter on the natural frequencies is studied. The capabilities of the proposed method in capturing the vibration behavior of nanobeams are examined through various numerical examples. The effects of the slenderness ratio and small-scale parameter on the natural frequencies are explained.

The size effect is more significant when the nonlocal parameter is small. It is obtained that the nanoscale causes lower natural frequencies of the nanostructures. The ratio of the natural frequencies predicted by nonlocal and classical elasticity theories becomes more noticeable for lower values of the slenderness ratio of the nanobeam and also for higher modes.

It is expected that the results of this study would be very useful for dynamic analyses of beam-like components such as nanosensors or nano actuators whose discrete models have high computational and labor costs.

SURFACE-DISLOCATION INTERACTION BY VARIES MODELS OF SURFACE ELASTICITY

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A free surface of crystalline materials exerts an attractive force on a nearby dislocations arriving in the subsurface layer from the surface due to emission or from far away region When the distance of dislocations from the surface is in the range of several nanometers, the classical continuum mechanics cannot be used for analyzing the surface-dislocation interaction and needs to be modified to account for the surface energy first introduced by Gibbs. Widely used mathematical framework incorporating the effects of surface tension (residual surface stress) and surface elasticity into continuum mechanics has been developed by Gurtin and Murdoch (GM) and its generalization by Steigmann and Ogden (SO).

In the recent two decades, thousands of studies have used varies continuum models of material surface to allow for the surface energy in many practical problems involving nanostructures, fracture, contact problems, etc. At the same time, most models of surface theory of elasticity in the publications defer from the original GM and SO theories. As a rule, the author selecting the surface elasticity model which is simplified versions of GM model doesn't adduce any reasons for such simplification.

The main objective of the paper is to collect different surface elasticity models related to the original GM model and to compare the stress fields around the flat surface, that arise due to interaction of the periodic array of edge dislocations with the free surface.

It is supposed that the semi-infinite elastic body is under the plane deformation and the dislocations can reach the distance to the free surface up to several nanometers. The solution of the corresponding 2-D boundary value problem with the generalized Young-Laplace boundary condition is based in the work on application of Goursat-Kolosov's complex potentials, Muskhelishvili's representations and varies surface elasticity models including the original GM one. The way of the solution leads to the hypersingular integral equation which in the case of the dislocations array has been evaluated in terms of the Fourier as it was done in [1]. Using derived formulas, the numerical results have been obtained for the stress field and image force acting on the edge dislocations, depending on the dislocations position, Burger's vector orientation. The surface stress effect on the elastic field around the dislocations and at the surface and on the image force is analyzed comparing results of all models considered.

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MULTIPHASE LATTICE BOLTZMANN APPROACH FOR CAPILLARY BRIDGES AND ASSOCIATED FORCES

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In partially saturated granular materials, grains interact through both contacts and liquid bridges. For small water contents, capillary effects can be treated as forces between pairs of grains, and approximated by analytical solutions. For larger water contents, the liquid bridges merge between groups of grains and the mechanical interactions must be solved numerically. In the present work, a GPU based Lattice Boltzmann Method (LBM) approach is implemented to solve Navier-Stokes and Allen-Cahn equations. Using this procedure, capillary bridges profiles are readily determined. Then, capillary forces between two and three spherical solid grains are computed. A phase-field-based model and an accurate cubic wetting boundary condition are used to simulate an air-water system with a large density ratio [1]. Capillary bridges between two spherical grains for different separation distances were simulated. At equilibrium, the profiles of capillary bridges are shown to coincide very accurately with the solution of YoungLaplace equation. Furthermore, the inversion of the sign of the mean curvature H using LBM is captured, which in turn determines the shape of the capillary bridge between solid particles. The obtained results are in excellent agreement with the experimental data performed in [2], thus showing that the proposed multi-phase model converges at equilibrium to Young-Laplace equation. Moreover, numerical, experimental, and analytical calculations of capillary forces between two spherical grains match perfectly. The study is next extended to simulate capillary bridges between three particles. The capillary forces due to isolated and coalesced liquid in two and three spherical particles configurations are computed to illustrate the pendular regime and the transition to the funicular one. Numerical simulations are found to be in good agreement with available numerical data for wetting in a triplet of particles under the same configuration as in [3]. The numerical results indicate that the proposed model provides a viable framework within which the complex capillary interface evolution during the wetting of a large assembly of particles can be captured.

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INSTABILITY MODES RESULTING FROM HYPERELASTIC AND HYPOELASTIC CONTACT LAWS IN DISCRETE MECHANICS

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Granular materials can be described as simply as a set of solid bodies in interactions through contact forces. In this respect, their mechanical behavior is frequently modelled thanks to discrete element methods (DEM). As a first approximation, grain shapes are frequently simplified as spheres and contact laws are decomposed into normal and tangential contributions. For spherical grains the definition of the normal contact law is usually related their overlap which is defined unambiguously from the grain positions and radii. However, the definition of the tangential contact law is not straightforward for spherical grains. As a result, the interaction law is usually defined in a rate form [1, 4] which raises some issues with respect to energy balance, even if the contact is assume to behave elastically (e.g. leading to the ratcheting effect [2]).
In this work, several elastic interaction laws used in dicrete element modelling of granular materials are considered [1, 2, 3]. They are reviewed and classified as hypoelastic or hyperelastic laws depending on the existence of a potential energy. Among hypoelastic interactions (no potential energy exist), a distinction is made between weakly hypoelastic laws for which there exists an integral form, and strongly hypoelastic laws for which no integral form exists. Then the different contact laws are analyzed at the scale of a mesostructure formed of a four-grain cyclic granular chain (diamond pattern) loaded by a set of external forces [4, 5]. Instabilities may be predicted for large displacement of the diamond chain for all the classified models with more diverse failure modes for hypo than hyper elastic models. The mechanical responses eventually inspected from numerical simulations are shown to be mitigated by the creation of new contacts.

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A MODEL FOR COMPOSITE MATERIALS WITH CONTINUOUS FIBERS DISTRIBUTION INCLUDING STRAIN GRADIENT EFFECTS

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In this paper, we propose a constitutive model for composites materials containing continuous fibers distribution. The model accounts for the effects of structural tensor representative of the anisotropy induced by the fibers as well as strain gradient effects. We postulated an energy density function for the material that depends on the Cauchy-Green strain tensor, the gradient of the Cauchy-Green tensor as well as the structural tensor and is invariants. The energy density function is invariant under rotation and therefore can be expressed in terms of the principal invariants of its arguments thanks tensors representation theorems. We distinguished the cases where the energy density function contains the structural tensor with the case where it does not and validated the model on several small boundary values problems.

ON MODELLING OF MATERIAL INSTABILITIES USING VON MISES TRUSS AS A STRUCTURAL ELEMENT

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Material instabilities observed in many structured materials such as foams, beam-lattice materials and many others, could play an essential role in the material response [1, 2]. As an example of such material instabilities one can consider cell walls buckling in closed cell foams [2].

We discuss the material instabilities using a modified von Mises truss as a structural rheological element. First, in all details a single von Mises truss behaviour including its snap-through and snap-back behaviour is taken into consideration. Then, we analyze deformations of a discrete system of elastically connected structural elements such as the single von Mises truss. For such system one can observe a series of bucklings related to instability of each structural element.

Finally, a homogenized continuum model with a strain energy density which inherits the properties of von Mises trusses is introduced. Here we also consider a regularization of the model introducing higher-order terms in the strain energy, i.e. using a strain gradient elasticity approach.

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MS-11 Fractals and Fractional Calculus in Engineering Sciences
Martin Ostoja Starzewski (University of Illinois, USA)

On the role of fractals in heat transfer
M. R. Lancia

Fractal canopy shapes from mechanical laws
J. Rodriguez Cuadrado

Fractal and hurst effects in mechanics
M. Ostoja-Starzewski

ON THE ROLE OF FRACTALS IN HEAT TRANSFER

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We study a parabolic transmission problem in a two-dimensional domain across a highly conductive pre-fractal interface. This problem is mathematically modeled by heat equations in the bulk coupled with a second order transmission condition defined on the internal barrier. In the literature these problems are known as Venttsel-type problems.

We investigate how the shape of the fractal interface may affect the distribution of the thermal field in the bulk. We then control the pre-fractal growth exploiting the role of the barrier in the heat transmission process with the aim to obtain a uniform temperature distribution. A crucial point is to define suitable dynamics for the interface. Some preliminary numerical results, as well as some open problems, will be presented.

This work is in collaboration with M. Cefalo, S. Creo and J. Rodriguez-Cuadrado.

FRACTAL CANOPY SHAPES FROM MECHANICAL LAWS

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Trees are a fundamental part of our environment for ecological and economic reasons. Therefore, they have been extensively analyzed from the biological point of view, although their study from other relevant perspectives is lagging. In particular, the mechanical perspective is essential to determine the structural response of trees when subjected to physical loads. This induces the question of how the fractal structure of trees and the laws of mechanics are involved in the fractals present in their canopies. For this reason, in this talk we focus on determining the shape that tree fractal structures acquire in static equilibrium when corresponding canopy loads are applied to them.

For this purpose, we calculate the deformation produced in a fractal binary tree structure subjected to a uniform load at its top nodes. The deformation of the tree is given by the vertical and horizontal displacements of its nodes calculated using the Principle of Virtual Work (PVW). First, we apply the PVW to a tree with a finite number of levels, determined by the number of times its branches have bifurcated. This allows us to derive the analytical expressions for the displacements of the nodes, which depend exclusively on the mechanical parameters of the branches (length, area, inertia and elastic modulus) and the level of the tree to which they belong. Subsequently, we take the limit to calculate the displacement of the nodes of the canopy of a tree with infinite levels. We conclude that the vertical and horizontal displacements are characterized by two different fractals: the Takagi curve and a linear combination of inverses of β-Cantor functions, respectively. Consequently, the deformed shape of the canopy is given by two fractals that were not present in the initial structural configuration of the tree.

The functional forms of the Takagi curve and the β-Cantor functions depend on the mechanical parameters of the branches (length, area, inertia and elastic modulus). This implies that the shape of the canopy can be changed without changing the original shape of the tree, but simply by varying its parameters. Furthermore, this dependence on the mechanical parameters allows establishing a connection between the Takagi curve and the β-Cantor function through its fractal dimensions. This connection, originated through the binary tree, reveals a deeper connection between these fractals.

FRACTAL AND HURST EFFECTS IN MECHANICS

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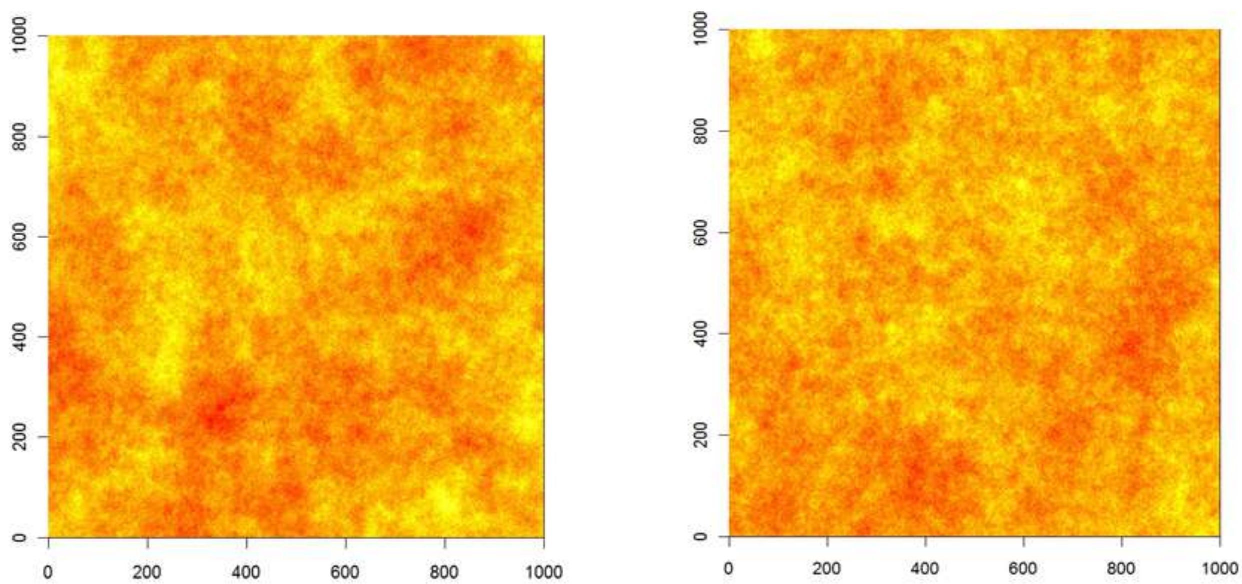
Myriad random phenomena in nature possess fractal and Hurst characteristics. Stochastic processes and fields with Cauchy or Dagum correlations enable modeling such stochastic structures in time and space. In effect, responses of dynamical systems and/or spatial problems in 1d, 2d, or 3d can be investigated in the presence of fractal and Hurst characteristics. Additionally, it is possible to examine whether mechanical systems give rise to stochastics with such intriguing features. This paper reviews quantitatively analyzed examples ranging from vibration problems, rods and beams with random properties under random loadings, waves and wavefronts, fracture, homogenization of random media, and statistical turbulence, to randomly evolving spontaneous violations of the entropy inequality in Couette flows. Common features brought out in this survey show what and how can be achieved with Cauchy and Dagum models in mechanics.



Realizations of random fields with fractal and Hurst effects generated according to Cauchy (left) and Dagum (right) correlation functions.

MS-14 Non-Linear Biomechanics in the Cardiovascular System – Modelling and Experimental Technologies
Rosaire Mongrain (McGill University, Canada), Sonia Pinto (Universidade do Porto, Portugal)

Development of Viscoelastic Vascular Tissue Models using 3D Printed Elastomer Composites
R. Mongrain, C. Yanez, Z. He, R. Leask, H. Valtchanov

Patient-specific FFR quantification using Windkessel models: Code development
S.I.S. Pinto, D. Freitas, C.F. Castro, C.C. António, L.C. Sousa

Stress tensor divergence in fluid-structure interaction based coronary biomechanics
H.J. Carpenter, M.H. Ghayesh, A.C. Zander, P.J. Psaltis

Comparison of flow-induced wall interactions in a thoracic aortic aneurysm predicted by CFD and FSI
X. Wang, M.H. Ghayesh, A. Kotuosov, A.C. Zander, Psaltis P.J.

Fluid-Structure Interaction Model of a 3D Starling Resistor Based on Large Eddy Simulations
M. Laudato, R. Mosca , M. Mihaescu

DEVELOPMENT OF VISCOELASTIC VASCULAR TISSUE MODELS USING 3D PRINTED ELASTOMER COMPOSITES

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Introduction: Vascular phantoms are useful tools to test new medical devices under reproducible and controlled conditions. They allow to investigate the impact of various mechanical properties and phenomena reproducing healthy or pathological situations. Viscoelasticity has been shown to play a key role for the proper functioning of vascular structures [1]. It controls the timing of the Windkessel effect and associated pulse traveling wave [2]. It was also argued that it could be beneficial in dissipating energy and as a result possibly decrease wall stresses. We present a methodology based on 3D printing of elastomer materials to create elastomeric composites to reproduce physiological viscoelasticity.

Methods & Results: Elastomers, that were previously used separately for phantom fabrication [3], were combined to form elastomeric composites using 3D printing (Connex3 Objet500 by Stratasys). The approach uses a soft elastomer (Tangoplus TGPF930) embedded with hard elastomer fibers (Verowhite). The fibers are generated with sinusoidal profiles.

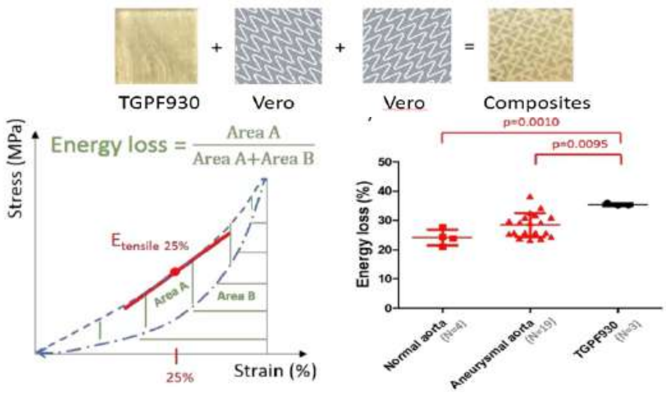

Fig 1 3D elastomeric composites viscoelasticity

Then multiple layers are overlaid to achieve the elastomeric composites (Fig 1). The elastomeric composites viscoelasticity were assessed using the hysteresis (energy loss) of the stress-strain curves under biaxial testing configuration (Electroforce ELF 3200, TA Instruments) and compared to the physiological viscoelasticity using aortic tissue collected from transplant donors and patients undergoing surgery (Fig 1). Equi-biaxial tensile testing was carried out within 24 h of the excision. Samples of human tissue or composite materials (15x15mm2) were subjected to equi-biaxial stretching at constant strain rate (0.1mm/s) in a bath at 37°C.

Conclusion & Discussion: The elastomeric composite approach allows to control the hyperelastic and the viscoelastic properties to match the physiological range. The properties are needed for manufacturing advanced dynamic phantoms. Ongoing work include the incorporation of the anisotropic properties for the differences in longitudinal and circumferential properties.

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PATIENT-SPECIFIC FFR QUANTIFICATION USING WINDKESSEL MODELS: CODE DEVELOPMENT

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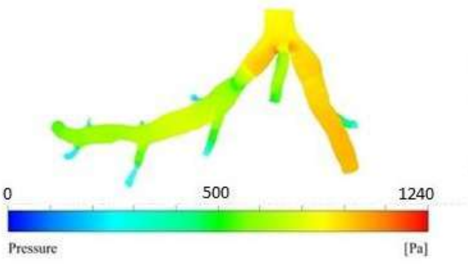
Currently, cardiovascular diseases (CVDs) are the leading death cause worldwide. Computed tomography images provided by the hospital can give information about the geometry of the artery and location of the disease; however, they cannot explain the hemodynamics with detail. Thus, a hemodynamic software can be an auxiliary tool for the prevention and treatment of such diseases. In the present work, a patient-specific left coronary artery geometry, with 40% stenosis, was generated in Mimics® software in order to perform hemodynamic simulations, using computational fluid dynamics (Ansys® software). The goal is to obtain the Computed Fractional Flow Reserve (FFR_{comp}), pressure drop in the stenosis, to reduce invasive procedures in the hospital. Thus, the FFR_{comp} will be compared with the Invasive FFR (FFR_{inv}) measured in the patient in Vila Nova de Gaia/Espinho Hospital Center (CHVNG/E).

In order to properly simulate coronary blood flow, the hemodynamic conditions for the patient must be the most real as possible: 1) patient geometry under hyperemia condition (condition of FFR measurement), 2) use of the Womersley velocity profile as boundary condition at the inlet, 3) use of the Simplified Phan-Thien/Tanner (sPTT) model for the most accurate rheology of blood, 4) implementation of the 5-element Windkessel model for the pressure boundary condition at the outlets of artery model. As far as we know, there are no works in the literature, which simulate the hemodynamics considering simultaneously the Windkessel model for the pressure condition and the sPTT model for blood. The 5-element Windkessel model takes into account parameters of the patient such as arterial microcirculation resistance and myocardial mass which the 3-element Windkessel model does not take into account (simpler model). Figure 1 shows the comparison between the FFR_{comp} and FFR_{inv} obtained for the patient. When using the 5-element model, the relative error is even lower (0.53%) than using the 3-element model (2.15%). Since the computational time is practically the same, the 5-element Windkessel model can be used in further simulations. In a near future, the validation must be done in many patient-specific cases.



Windkessel Model	FFR_{comp}	FFR_{inv}	er (%)
3-element	0.910	0.93	2.15%
5-element	0.925		0.53%

Figure 1: Pressure field of the patient for the maximum velocity using the 5-element model (left) and comparison between the Computed FFR and the Invasive FFR considering two different Windkessel models (right).

STRESS TENSOR DIVERGENCE IN FLUID-STRUCTURE INTERACTION BASED CORONARY BIOMECHANICS

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Maximum principal stress is often used to analyse risk of failure (plaque rupture) through coronary artery biomechanics. The role of stress tensor directional properties is not well understood but could play a role in coronary remodeling or the growth of plaques. Here we investigate the role of stress tensor divergence in coronary biomechanics by adapting a Eulerian method to fluid-structure interaction-based simulations. A section of a right coronary artery with a lipid rich plaque was analysed, with the divergence vector capturing the complex stress tensor directions and associating with plaque shoulder regions vulnerable to growth over time. This approach could strengthen our ability to determine how arteries and plaques may remodel and grow while improving our understanding of how lipid-rich plaques may fail.

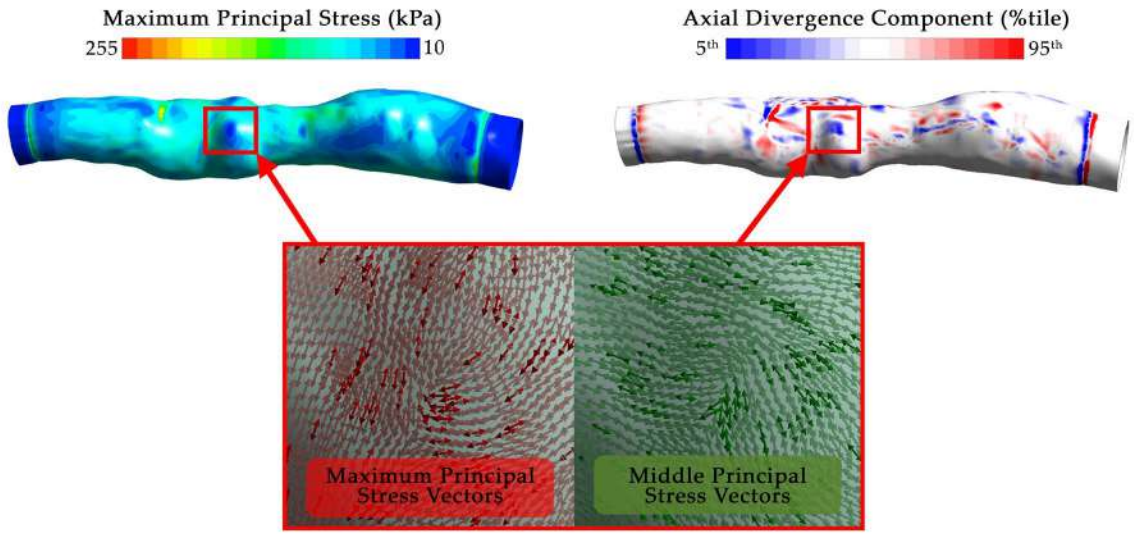

Figure 1. Comparison between the maximum principal stress contour and the axial component of the stress tensor divergence when calculated using the elemental (cylindrical) coordinate system. Inset, the maximum and middle principal stress vectors highlighting their complex directional properties and how they vary significantly, even in regions of low principal stress magnitude.

COMPARISON OF FLOW-INDUCED WALL INTERACTIONS IN A THORACIC AORTIC ANEURYSM PREDICTED BY CFD AND FSI

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Computational approaches have increasingly been employed to predict haemodynamically induced forces and stress in the progression of aortic aneurysms. This work describes the clinical importance of the structural and haemodynamic parameters in a thoracic aorta model with an aneurysm in the ascending aorta via computational fluid dynamics (CFD) and fluid-structure interaction (FSI) approaches. With the rigid wall assumption, the dynamic pulsatile flow velocity profiles and nonlinear viscosity of blood are taken into account, constituting the CFD study. While in the two-way FSI analysis, the anisotropic hyperelastic aortic wall was carried out on ascending thoracic aortic aneurysms along with other parameters considered in the CFD-only model. Prediction of wall shear stress (WSS) distributions, wall pressure and velocity field were compared between CFD and FSI studies. Results show that in both CFD and FSI simulations, the enlarged lumen zone is the preferential region to develop thrombosis, given its blood recirculation and low value of wall shear stress. Additionally, it is necessary to consider the interaction and reciprocal influence between the structural and fluid domain by taking into account the hyperelasticity of the arterial wall through two-way FSI, given that the CFD model overestimates the results for WSS and blood flow velocity. This comparison showed that differences between considering the influence of arterial wall compliance on wall shear stress are notable; however, the influence is minimal in the oscillation and time-averaged wall shear stress.

FLUID-STRUCTURE INTERACTION MODEL OF A 3D STARLING RESISTOR BASED ON LARGE EDDY SIMULATIONS

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The so-called Starling resistor is a simple yet accurate model of a collapsible tube. Due to its simple geometry it has been widely used to perform experimental and numerical studies of the fluid-structure interaction (FSI) between human vessels and physiological flows. In particular, the Starling resistor has been successfully employed as a reliable model of the human upper vocal tract in the context of Obstructive Sleep Apnoea for more than 30 years[1].
When the intramural pressure (i.e., the pressure difference between the lumen and the exterior of the tube) reaches a certain critical value, the Starling resistor undergoes a non-axisymmetric buckling (see Fig. 1). The presence of self-excited oscillations around such buckled configuration has been reported in many different experimental studies [2]. Although such oscillations are explained by lumped-parameters or one-dimensional models, the mechanism of the oscillations' onset is still to be fully understood.
One of the possible explanations is that the oscillations are triggered by a resonance phenomena between modes of oscillations in the longitudinal and transverse direction, resulting in an aeroelastic flutter. We propose a 2-way FSI numerical model of a 3D Starling resistor based on Large Eddy Simulations aimed at investigating the validity of such hypothesis. The results of the model have been compared against experimental data [2].

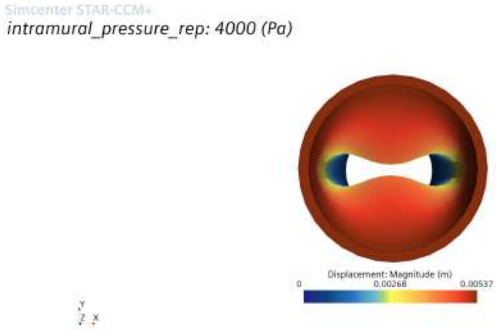

Figure 1: Non-axisymmetric buckled configuration of the Starling resistor. The system will show self-excited oscillations around such this configuration.

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MS-15 Trabecular bone remodeling vs shape and topology optimization principles
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The efficient trabecular bone remodeling numerical tool enabling multiple load case simulation
J. Polak, M. Nowak

BioniAMoto – trabecular bone remodeling phenomenon based efficient structural optimization numerical tool
J. Polak, M. Nowak

Characterization of trabecular plate and rod anisotropies
N. Rogalski, S. Laporte, C. Cluzel, I. Iordanoff

Human chest modelling with elastic truss
I.V. Alpatov, M.Z. Dosaev, V.A. Samsonov, E.A. Vorobyeva, V.A. Dubrov

THE EFFICIENT TRABECULAR BONE REMODELING NUMERICAL TOOL ENABLING MULTIPLE LOAD CASE SIMULATION

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The paper concerns a simulation of the trabecular bone remodeling process taking into account its real geometric form. The efficient trabecular bone remodeling numerical tool enabling multiple load case simulation is presented. The observation proposed by Julius Wolff - called the Wolff's law - can be described as a structural adaptation of the bone to the external forces. Thus the trabecular bone remodeling process numerical simulation has to include the very important aspect of external load, namely the variable loads. For simulation purposes it means, that the numerical tool must be able to simulate multiple load case and the geometric form of the bone must correspond to these loads. Technically the numerical system is .Net C# project designed with Inversion of Control paradigm design pattern that provides pluggable and extensible platform. In order to be able to provide general relationships between the geometric form of the structure observed in imaging studies and its mechanical properties, an accurate, three-dimensional simulation model of the trabecular bone structure is necessary. There are two elements necessary to build a computing environment - the inclusion of multiple load cases and an accurate geometric model of the trabecular tissue. The simulation approach presented in this paper uses two postulates [3] concerning the trabecular bone remodeling regulatory model, based on shape optimization studies [1, 2]. The presented trabecular bone remodeling numerical tool enables multiple load case simulation taking into account the postulates regarding the evolution of the trabecular bone. The trabecular bone remodeling regulatory model applied to an actual threedimensional trabecular structure requires the preparation of an appropriate numerical approach. Since the local change on the structural surface leads to global minimization of the strain energy for the whole structure, the fulfillment of both postulates requires energy distribution analysis on the structural surface. Thus, the most important role in such an approach must be played by a very efficient finite element mesh generator for structural computations as well as an efficient computational environment. In both cases, it becomes necessary to use parallel processing. Such a numerical tool is able to mimic the trabecular bone remodeling process by structural surface evolution. So, on the one hand it will be possible to repeat virtually the observations recorded on the micro-CT scans, and on the other hand, to better adjust the continuous models of the trabecular bone remodeling phenomenon.

The developed software promises to simulate significant fragments of trabecular bone tissue, and as equipment develops, also structures covering the entire bone. Mesh generator performance is no longer a limiting factor nor is computing power. Created algorithms are I/O-bound and the main challenge in large-scale simulations is handling of very large amounts of physical data that needs to be transferred to the FEM software. Highly optimised code enables using system on a single high-end PC while HPC grid is required only for FEM simulations.

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BIONIAMOTO – TRABECULAR BONE REMODELING PHENOMENON BASED EFFICIENT STRUCTURAL OPTIMIZATION NUMERICAL TOOL

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The paper concerns application of trabecular bone remodeling phenomenon to perform structural optimization.

Application of trabecular bone remodeling numerical tool to optimize structure of mechanical element prior Additive Manufacturing is presented. Application of Additive Manufacturing (AM) technologies creates new opportunities of manufacturing complex geometries without increasing costs of manufacturing. Additional benefits of using AM technologies could be achieved thanks to implementation of topology optimization tools during the design process. During the BioniAMoto project, new tools for manufacturing of structural nodes for the automotive industry are developed and prepared for implementation, such as bionic topology optimization and AM based manufacturing process from aluminum alloys. As a result of the project a new concept for manufacturing 3Dimensional nodes for the structural frame of vehicles is developed. The observation proposed by Julius Wolff - called the Wolff's law - can be described as a structural adaptation of the bone to the external forces. The same approach can be applied to perform structural optimization of a mechanical object under a static load. Object remodeled in the same way as a trabecular bone changes topology to increase stiffness and decrease internal energy. The simulation approach using two postulates [3] concerning the trabecular bone remodeling regulatory model, based on shape optimization studies [1, 2], is applied to structural node of a car frame. The presented structural optimization tool enables multiple load case simulation taking into account the postulates regarding the evolution of the trabecular bone. Local changes on the structural surface lead to global minimization of the strain energy for the whole structure; the fulfillment of both postulates requires energy distribution analysis on the structural surface. Original postulates have been altered to overcome limitations of both multiscale modeling approach and Additive Manufacturing process. Presented approach allows structural optimization using multiple load scenarios taking into account the postulates regarding the evolution of the trabecular bone. Additional changes were proposed to consider target material mechanical properties and Additive Manufacturing technology limitations to find optimal solution that not only is the stiffest design for given input parameters, but also is ready to manufacture using Additive Manufacturing technologies.

The developed software platform allows structural optimization based on trabecular bone adaptation phenomenon. Highly efficient, multithreaded code written in .Net allows processing of big meshes using HPC grid. Use of IoC (Inversion of Control) container and modular design allows easy extension or replacement of system components for testing new algorithms and approaches. Simple user interface, flexible configuration and use of open data formats allows definition of scenarios for both research and commercial use.

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CHARACTERIZATION OF TRABECULAR PLATE AND ROD ANISOTROPIES

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The geometric anisotropy of trabecular bone, composed of plates and rods, plays a crucial role in its mechanical performances. The reference tool for characterizing trabecular microstructure is the Mean Intercept Length (MIL), which defines an orthotropic system within a representative volume [1]. However, it does not discriminate between the specific orientations of plates and rods, which have distinct mechanical roles. The aim of this study is to propose a method for discriminating and quantifying full specific geometrical anisotropies of plates and rods at a representative volume scale.
The triangular surface meshes of 163 trabecular bone samples were reconstructed from microcomputed tomography images and several tools were used for the analysis of surface normal orientations. First, a curvature criterion was used to discriminate between plate and rod-like mesh areas. An angular filter [2], parameterized to extract rod axis and plate planes, was then applied to analyze either the complete samples, or the plates and rods specifically and the orientation rates in all space directions were visualized on polar plots.

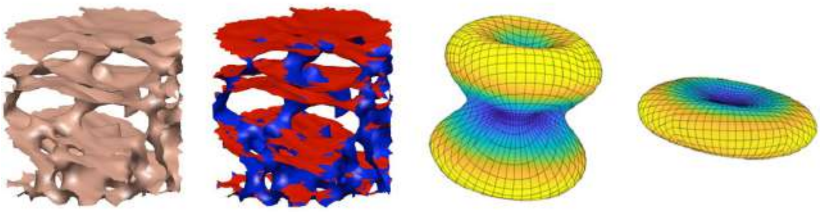

Figure 1: From left to right: trabecular bone sample, plate (red) / beam (blue) discrimination, rod polar plot and plate polar plot.

The method allowed to retrieve the orthotropic frame obtained with the MIL and to go further in the microarchitecture analysis. Of the 163 samples, 116 exhibited only one plate orientation and for these samples, the rods were found to be mostly oblique. It was previously suggested that the plates are the primary structures resisting local compressive loads, while the rods serve rather as links between the plates and allow load transfer [3]. The rod obliquity is consistent with this assumption as it allows the structure to be consolidated by supporting their shear loading. The presented method, computationally effective and functional for invivo compatible images, could be used in a clinical routine to analyze the effects of osteoporosis on the trabecular network and consolidate the diagnosis of osteoporosis, based on the sole measurement of bone density.

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HUMAN CHEST MODELLING WITH ELASTIC TRUSS

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The problem of modelling a human chest is considered for purposes of pectus carinatum treatment. Particular attention is paid to the effect of lower rib flaring that sometimes occurs in patients who received bracing treatment.

We developed two different 3D models of chest in Ansys software. The first model (Figure 1a) consists of 23 stiff beams and 28 spatial spiral springs that hinder the change of relative orientations of the beams. Here we just tried to investigate the rib flaring effect in the simplest possible model of 3 symmetric rib pairs connected by cartilage beams and sternum beam. The heads of the ribs are also connected by spiral springs with fixed spine. We applied the force to a keel point. The obtained results show that even in simple model the flaring effect appears while the sternum returns to normal position.

The second symmetric 3D model (Figure 1b) was built based on a CT scan of a real patient with pectus carinatum. It consists of 78 stiff beams and 92 spatial spiral springs. Here we also applied compressive force to a keel. The flaring effect for this model was also found (Figure 1c).

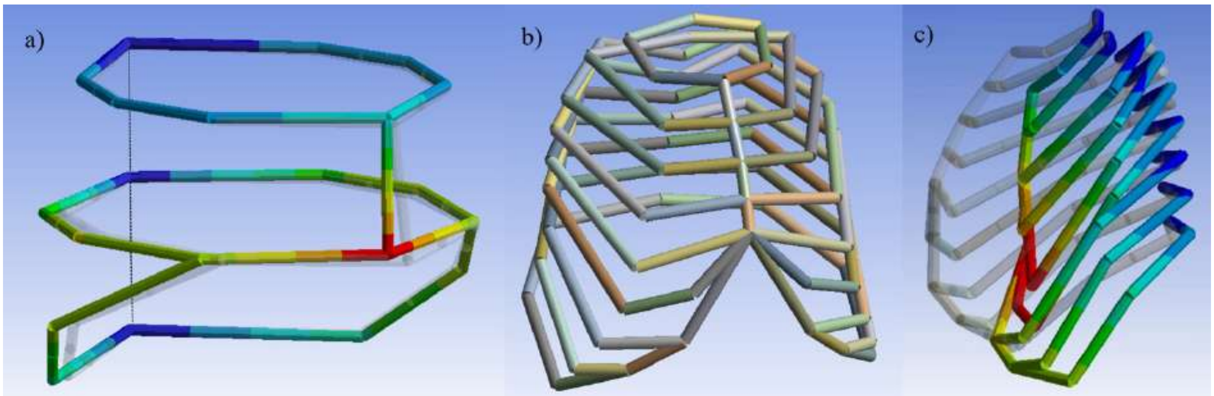

Figure 1. FEM rod model of chest. a) Simplified rod model of chest; b) Full rod model of chest; c) Deformation of the model under load applied to the keel.

We also assessed the applicability of finite element modelling of rod structures in Ansys. For this purpose, we considered the equilibrium of the system of 2 beams connected by spiral spring deformed by a compressive force. We then built the equivalent model of this system in Ansys and investigated its convergence and accuracy compared to the solution obtained in the frame of a theoretical mechanics. It is shown that the ill-conceived choice of the integration step in the calculation in the Ansys software can lead to a transition from one balance solution to another in the range of large compressive forces.

MS-17 New frontiers in regularized damage modeling
Anil Misra (Kansas University, USA), Zdenek Bazant (Northwestern University, USA), Luca Placidi (Università Internazionale Telematica UNINETTUNO, Italy), Emilio Barchiesi (Ecole Nationale d'Ingenieurs de Brest, France)

A damaged non homogeneous Timoshenko beam model for a dam subjected to the aging effects due to diffusion of a fluid
A. Scrofani, E. Barchiesi, B. Chiaia, A. Misra, L. Placidi

Implicit integration scheme in strain-gradient modelling of brittle fracture
S. Sessa, E. Barchiesi, L. Placidi

A Variational Formulation for Viscoplasticity
F. De Angelis

Lattices with enhanced resilience
A. Cherkaev, M. Ryvkin

Modeling of Stress- and Strain-Softening at Finite Strains based on Relaxed Incremental Damage Formulations
D. Balzani, M. Köhler

About the solution of a paradox related to axial pull out of a bar from a concrete cylindrical elastic domain in standard first gradient 3D Isotropic
N. Rezaei, E. Barchiesi, D. Timofeev, C.A. Tran, A. Misra, L. Placidi

Time dependent (dynamic) analysis of fracture propagation in 2D strain-gradient granular solids
V. Maksimov, L. Placidi, E. Barchiesi, A. Misra, F. J. León Trujillo

A DAMAGED NON HOMOGENEOUS TIMOSHENKO BEAM MODEL FOR A DAM SUBJECTED TO THE AGING EFFECTS DUE TO DIFFUSION OF A FLUID

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A variational method [1] for a non homogeneous Timoshenko beam model with the inclusion of the phenomenon of the aging damage due to the diffusion of a aging fluid is proposed.

In addition to the classic kinematic descriptors, such as the axial dispacement w, the transversal displacement u and the rotation θ of the section, also the concentration c of the aging fluid for every section of the beam and the damage ω [2] have been considered.

The effects of the damping, by means of a proper Rayleigh functional, has been considered introducing damping factors.

The investigated example is a dam that is subjected not only to distributed forces and couples but also to the distributed dual of the concentration (b_c^{ext}), that drives the incoming flow of the aging fluid, that is, for this purpose coupled with the damage evolution.

As an outlook we will consider the 2*D* and 3*D* cases within granular micromechanics.

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IMPLICIT INTEGRATION SCHEME IN STRAIN-GRADIENT MODELLING OF BRITTLE FRACTURE

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Adoption of non-local computational approaches in analyzing fracture propagation is a wellknown necessity required in order to overcome mesh-dependent results and to guarantee computational accuracy [1]. Among all non-local philosophies available in the literature, procedures characterizing the kinematics of the analyzed continuum by the second-gradient of the displacement (i.e. the *strain gradient*) proved to be particularly effective. Among them, recently a variational formulation involving the *strain gradient* total deformation energy functional was developed [2]. It proved to be effective in reproducing brittle crack propagation, by means of the *damage field*, in two-dimensional domains, although it can be easily extended to threedimensional cases.

Such an approach was implemented in a computational framework based on the Galerkin finiteelement method. The original implementation permitted to compute quasi-static responses by an explicit integration scheme in which the response relevant to each pseudo-time step was computed by as function of the damage field value at the previous step. As for most of the explicit integration procedures, the accuracy of the adopted scheme is strongly dependent on the amplitude of the pseudo-time steps. Hence, it was necessary to adopt dense discretizations of load paths thus increasing the computational burden.

The present contribution exploits the possibility of using an iterative procedure, based on the fixed-point theorem, thus formulating an implicit integration scheme. It adopts a sequence of trial equilibrium states and aims to minimize the amplitude of a residual. To exploit such an approach to the *strain gradient* formulation presented in [2], different typologies of residuals, defined by means of the damage field, the elastic energy and the static response, have been investigated. Numerical analyses, providing a comparison with the original explicit scheme, prove the robustness of the investigated implicit integration algorithm, its accuracy, and its benefits in reducing the computational burden.

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A VARIATIONAL FORMULATION FOR VISCOPLASTICITY

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Many engineering materials may exhibit a plastic or viscoplastic behavior when subject to external loadings. In this case it is necessary to consider the proper transition from a time independent to a time dependent constitutive material model to properly reproduce the experimental evidence shown in laboratory tests, see among others Perzyna [1], Skrzypek and Hetnarski [2], and De Angelis and Meola [3].

In the present analysis a variational formulation for viscoplasticity is considered and applied to problems of solids and structures, see e.g. Oden and Reddy [4] and Koiter [5]. A strategy is illustrated for the derivation of the proper variational principles by casting the non-linear field equations and the constitutive multivalued equations into a viscoplastic operator governing the structural problem, see, e.g., De Angelis [6].

A consistent procedure is illustrated for deriving a multifield potential in all the unknown variables of the viscoplastic structural problem and accordingly the relevant multifield variational principle is presented. The proposed procedure shows to be suitable for the consistent derivation of other variational principles in viscoplasticity with different combinations of the unknown fields, see De Angelis [6]. The property of the procedure of generating other variational principles is illustrated by deriving the extensions to viscoplasticity of the Hu-Washizu and Hellinger-Reissner principles. The presented treatment provides the support for a variationally consistent development of numerical algorithms for finite element applications in the analysis of solids and structures.

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LATTICES WITH ENHANCED RESILIENCE

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The talk discusses designs of periodic inhomogeneous lattices aiming at their maximal resilience. The specific difficulties are the uncertainty of the initial damage location and the unstable evolution of damage. The optimal lattice must robustly resist the damage spread, no matter where it started. We study damage propagation in triangular and hexagonal beam lattices and suggest a fault-tolerant design for them. The damage spread is viewed as a quasistatic process: a sequence of breakages of beams followed by an adjustment of the stresses in the remaining structure. At each step, the tensions in several beams are almost equal, which makes the choice of every next failing beam uncertain. We suggest several failure criteria to account for the stress level, imperfections of the beams, and hidden accumulated damage due to prehistory; we also introduce several quantitative parameters for measurements of the damage degree. Using the suggested criteria, simulations of the damage spread produce realistic pictures of wiggling and branching cracks. We then discuss robust design principles of breakable lattices and propose a fault-tolerant design that is an isotropic hybrid between triangular and hexagonal structures composed of beam elements with different thicknesses. Periodic redistribution of the material between the beams for the fixed lattice density leads to an optimal layout for which only thin (sacrificial) links failed at the first stage of damage propagation. Stronger links between weak elements arrest a single flaw growth, and damage develops as a cloud of separated localized flaws.

MODELING OF STRESS- AND STRAIN-SOFTENING AT FINITE STRAINS BASED ON RELAXED INCREMENTAL DAMAGE FORMULATIONS

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The numerical phenomenon of mesh-dependent solutions occurs in structural simulations which are based on various continuum damage mechanical formulations due to a loss of convexity of the underlying incremental energy density. In order to overcome the issue of mesh-dependency, a rigorous analysis of generalized convexity conditions known for hyperelasticity can be used in the incremental variational formulation setting, see e.g., [3]. A convexified (relaxed) onedimensional continuum damage mechanics fiber model was proposed in [1] for the finite strain setting. Avoiding mesh-dependencies is only one benefit of such relaxed formulations, as another advantage is the interpretability of the convexified energy as mixture of weakly and strongly damage microscopic phases and thus, damage microstructure nucleation and evolution. Although a first approach to describe strain-softening at small strains based on a simplified microstructural construction has been proposed in [4], so far relaxed formulations have only been able to describe stress-softening, restricting their practical use quite significantly. In this contribution, we expand the convexification idea to the scenario where even the individual microscopic phases are allowed to further evolve with respect to increased damage in the convexified regime. Thereby, strain-softening becomes also describable which will be shown in numerical examples. An improved convexification algorithm following [2] is used to enable more efficient calculations using three-dimensional relaxed damage models. The performance of the proposed approach in terms of mesh-independence and robustness is shown by comparing the results of different convexification models with classical damage formulations.

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ABOUT THE SOLUTION OF A PARADOX RELATED TO AXIAL PULL OUT OF A BAR FROM A CONCRETE CYLINDRICAL ELASTIC DOMAIN IN STANDARD FIRST GRADIENT 3D ISOTROPIC

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This presentation aims at resolving a paradox occurring in standard first gradient theories and related to the axial pull out of a bar from a concrete cylindrical elastic domain. In the limit of the inner cylinder radius going to zero, we have the following paradox within standard first gradient elasticity in three dimensions: the total elastic energy goes to zero for every value of the axial displacement prescribed to the bar. In the presentation, we propose to solve such a paradox by means of strain-gradient elasticity. The number of constitutive coefficients (7 in total), following Piola's ansatz and granular micromechanics, is reduced to Young modulus, Poisson ratio, and a characteristic length L. Results of numerical simulations show that this approach leads to non-zero energy for the limit of the inner cylinder radius going to zero. The energy, in such a case, is proportional to the characteristic length L. Besides, the application of the strain-gradient theory does not require the application of any double force at the boundary. This implies the possibility to confirm these results by experiments and the fact that the axial pull out of a bar from a concrete cylindrical domain could serve as a methodology for the determination of constitutive coefficients of 3D isotropic second gradient elasticity.

TIME DEPENDENT (DYNAMIC) ANALYSIS OF FRACTURE PROPAGATION IN 2D STRAIN-GRADIENT GRANULAR SOLIDS

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To explore time dependent (dynamic) fracture propagation in a two-dimensional isotropic continuum, we use certain results from the theory of irreversible phenomena. The body's elastic strain energy density is assumed to be geometrically nonlinear and dependent on the strain gradient. In the description of microstructured media, such generalized continua frequently appear. The size of internal boundary layers in these materials is determined by an intrinsic length scale. The non-locality offered by this internal length scale, in particular, prevents deformation concentration, which is common when dealing with local models and leads to mesh reliance. To characterize the internal state of structural degradation of the system, a scalar Lagrangian damage field with a range of zero to one is introduced. All standard Lamé and second-gradient elastic coefficients are assumed to decrease as damage rises, and to be locally zero if damage reaches one. This last circumstance is linked to the propagation of cracks. In the instance of a notched rectangular/square specimens exposed to extension/compression loading tests, numerical solutions are offered, and fracture propagation is examined.

MS-18 Multiscale and Multiphysics Modelling for Complex Materials-MMCM18
Patrizia Trovalusci (Università degli Studi di Roma La Sapienza, Italy), Victor Eremeyev (Università degli Studi di Cagliari, Italy), Emanuele Reccia (Università degli Studi di Cagliari, Italy), Nicholas Fantuzzi (Università di Bologna, Italy)

Verification of a strain gradient elasticity model of a beam with a 2D triangular lattice structure by experimental analysis
A. Morozov , G. Ganzosch, S. Khakalo, V. Balobanov, N. Panjalipoursangari, W.H. Müller

Interaction between defects in single-layer graphene
M. Curatolo, G. Salerno

Two-scale statistical homogenization for random particle composites as micropolar materials
M. Pingaro, E. Reccia, M.L. De Bellis, P. Trovalusci

On dynamic modelling of elastic networks within the nonlinear micropolar elasticity
A. M. Cazzani, V. A. Eremeyev, E. Reccia

Micro-shear deformation influence on macro-behavior of lattice metamaterial
M. Spagnuolo, V. A. Eremeyev, F. Hild

Numerical modelling and experimental investigations for damage and dissipation phenomena in pantographic sheets
A. Ciallella

Elastic wave propagation in non-centrosymmetric and chiral architectured materials: insights from strain gradient elasticity
G. Rosi, N. Auffray

Toward the identification of a Cosserat effective continuum for quasi-periodic lattice materials
A. Somera, M. Poncelet, N. Auffray, J. Réthoré

Finite cell method for an efficient simulation of ductile crack propagation through metal matrix composites
D. Wingender, D. Balzani

Nolinear mechanical behavior of anisotropic materials as Cosserat continuum
F. Shi, N. Fantuzzi, Y. Li, P. Trovalusci, Z. Wei

Geometrical Modeling of a Microstructured Material: A Scaled Material Modeling
M. Crespo, L.M. Le Marrec, G. Casale, L. Rakotomanana, V.H. Nguyen

VERIFICATION OF A STRAIN GRADIENT ELASTICITY MODEL OF A BEAM WITH A 2D TRIANGULAR LATTICE STRUCTURE BY EXPERIMENTAL ANALYSIS

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In the recent past, the fabrication of function-oriented structures became cheaper and therefore rather possible due to new developments in the additive manufacturing technology. Predicting mechanical behaviour of a construction element with an internal structure becomes a critical issue for the engineering science. For this purpose, we used advanced material models based on the so-called generalized continua theories, in particular a generalized Bernoulli–Euler (sandwich) beam model [1]. However, an additional material constant, namely a strain gradient parameter, needs to be determined. The main goal of this work was to obtain this parameter experimentally.

The specimens with a 2D triangular lattice structure are manufactured using two different techniques: Fused Deposition Modeling and Stereolithography. Two different materials were used, namely Polylactide and transparent epoxy resin. Furthermore, displacement-controlled extension and bending tests [2, 3] have been performed in order to determine the higher gradient parameter by means of an inverse analysis. In addition, the dependence of bending behavior on the size of the lattice structure was studied experimentally. The obtained experimental results are in good agreements with the results of finite element simulations and analytical predictions performed in [1].

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INTERACTION BETWEEN DEFECTS IN SINGLE-LAYER GRAPHENE

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Single-layer graphene is the basic structural element of several carbon allotropes, including graphite, fullerens and carbon nanotubes. The mechanical behaviour of graphene has been intensely studied in the last years [1, 2] and it has been shown that it is significantly affected by the presence of structural defects, e.g., atom vacancies in the graphene lattice, which can dramatically reduce the failure strength [3]. The presence of defects in the graphene lattice is nearly inevitable, either because of the production process or because of the environmental and operating conditions of the devices. Moreover, in some engineering applications such as the desalination of water through a graphene filter [4], atom vacancies could be deliberately introduced to achieve new functionalities. Hence, the interaction between multiple defects becomes extremely important for the overall mechanical properties in a single-layer graphene. Here, we study the mechanical behavior of perforated single-layer graphene sheet through a molecular mechanics model which is solved numerically using the Riks arc-length method. We show that the distance between multiple defects in tensile tests determines a very different failure strength of the single-layer graphene. Finally, the effect of defects is also investigated in the case of out of plane deformation of the single-layer graphene. Such analysis lays the foundations for the development of more sophisticated nano-materials that can achieve non-trivial mechanical functionalities through the presence of defects [5].

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TWO-SCALE STATISTICAL HOMOGENIZATION FOR RANDOM PARTICLE COMPOSITES AS MICROPOLAR MATERIALS

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Composite materials are used in a wide range of applications in engineering. In this frame heterogeneous materials with random distribution of particles play a central role and such examples are Ceramic or Metal Matrix Composite (CMC/MMC), fiber reinforced composites, porous media, concrete. The increase in the use of these materials has generated great interest in researchers from all over the world with the aim of best describing the mechanical behaviour and creating new innovative materials with enhanced properties and eco-compatible characteristics. Homogenization techniques are commonly recognized as suitable for investigating the mechanical behaviour of these materials defining models able to properly retain memory of the peculiar internal structure. Moreover, it has been widely recognized that in size dependent problems it is important to take into account the internal length scale and this can be done by using enriched non–local continua [1], such as the micropolar continuum [2]. In the case of material with heterogeneities randomly distributed the object of homogenization is not only the determination of the homogenized parameters but also the size of the so called Representative Volume Element (RVE) [3]. To this aim we proposed a statistical homogenization procedure [4], subsequently automatized in [5]: Fast Statistical Homogenization Procedure (FSHP). In this work the procedure has been also extended to the case of micropolar materials. A series of parametric analysis have been performed for showing the reliability of the proposed procedure in conjunction with the promising computational strategy of the Virtual Element Method [6].

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ON DYNAMIC MODELLING OF ELASTIC NETWORKS WITHIN THE NONLINEAR MICROPOLAR ELASTICITY

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Within the nonlinear micropolar elasticity we discuss effective dynamic (kinetic) properties of elastic networks with rigid joints. The model of a hyperelastic micropolar continuum is based on two constitutive relations, i.e. static and kinetic ones [1, 2]. They introduce a strain energy density and a kinetic energy density, respectively.

Here we consider a three-dimensional elastic network made of three families of elastic fibers connected through massive rigid joints as in [3]. We propose a semi-discrete model of the network using the Cosserat curve model for fibers [2, 5], whereas for joints we apply the equation of motion of rigid body dynamics. As a result, we get a system of differential equations.

In order to characterize this model with the micropolar continuum we provide a discretization of the discrete and continuum models and compare the results. Here the main attention is paid to the kinetic constitutive equations and the form of microinertia tensors. So using the same technique as in [3] we obtain the effective kinetic properties. While effective elastic properties are inherited from the geometry and material properties of fibers, the kinetic (inertia) properties are determined by the fibers and joints; in particular microinertia tensors are expressed through the inertia tensors of fibers and joints.

Finally, in order to demonstrate the peculiarities of the model we discuss the propagation of plane waves of small amplitude. Let us note that the symmetry properties of joints may significantly change the material symmetry of the effective medium. In particular, we show that the waves of microrotations essentially depend on the inertia properties of joints: indeed the waves of microrotations essentially depend on the inertia properties of joints. Moreover, one can observe coupling phenomena between translational and rotational waves.

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MICRO-SHEAR DEFORMATION INFLUENCE ON MACRO-BEHAVIOR OF LATTICE METAMATERIAL

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We present results for a lattice metamaterial with a complex microstructure composed of fibers aligned on parallel layers. Experimental evidence suggests that the fibers, in addition to their own deformations, such as elongation and bending, and to the relative rotation present between fibers lying on different layers, may also slide relative to each other under certain conditions. This deformation mechanism is taken into account and used as a key hypothesis for getting results in accord with experiments.

NUMERICAL MODELLING AND EXPERIMENTAL INVESTIGATIONS FOR DAMAGE AND DISSIPATION PHENOMENA IN PANTOGRAPHIC SHEETS

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We present a two-field model for pantographic sheets with the aim of describing the sheets mechanical behavior for: i) cyclic extension tests in elastic regimes and ii) damage initiation. The model introduced in [1] has been generalized to include a more accurate description of the deformation of interconnecting pivots [2] and structural dissipation in [3].

We compare the numerical results with two kinds of experimental tests we performed. Firstly, we tested pantographic sheets under different cyclic loads remaining in the elastic regime. In the second experiments, we extended the specimens reaching the first rupture and then continuing up to total failure.

The numerical model was calibrated in order to predict: i) the observed amplitude and shape of hysteretic cycles and ii) the most likely localization of the first rupture.

A Dahl model is introduced to describe the dissipation mechanism that has been attributed to dissipation during the pivot deformation phenomena. The primary rupture initiation is attributed to pivots' shear deformation. The results motivate further investigations about failure mecha- nisms based on a yield criterion based on pivots' shear deformation.

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ELASTIC WAVE PROPAGATION IN NON-CENTROSYMMETRIC AND CHIRAL ARCHITECTURED MATERIALS: INSIGHTS FROM STRAIN GRADIENT ELASTICITY

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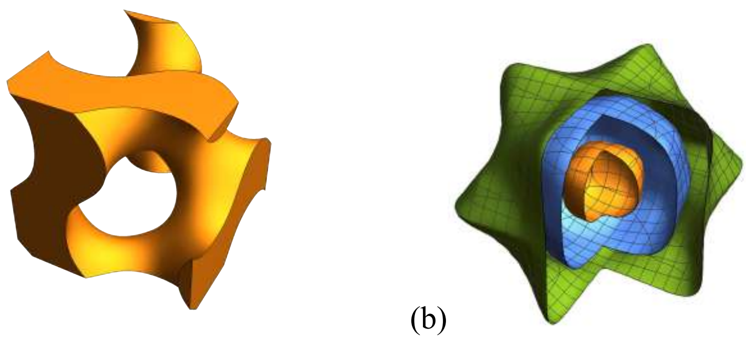
The study of elastic wave propagation is a fundamental tool in different fields, from Nondestructive Damage Evaluation (NDE) to ultrasonic imaging. Usually NDE and characterisation techniques rely on inversion methods based on homogenised theories, that are valid only when the wavelength of the perturbation is considerably larger than the characteristic size of the heterogeneities of the materials. When the wavelength approaches this characteristic size, an upscaling occurs and mesoscopic effects can be transferred to the macro-scale. In this case, classic models used in the aforementioned inversion procedures can fail to predict the correct response [1] and they need to be improved [2].

In this work, we address those architectures for which the unit cell does not have any centre of inversion (non-centrosymmetric) nor symmetry plane (chiral). It will be shown that unconventional effects, in terms of dispersion and polarisation, can be observed even for large wavelengths. We will also show that, in order to describe these materials using an equivalent homogeneous continuum, the use of an enriched or generalised theory, such as the strain gradient elasticity, is mandatory. Moreover, the analysis of the generalised acoustic (or Christoffel) tensor defined in this framework can give a useful insight on the dynamic features of the architectured material. Among others, the example of the gyroid unit cell will be detailed.



(a) (b)

Figure 1: Gyroid unit cell (a) and slowness surfaces of plane elastic waves (b).

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TOWARD THE IDENTIFICATION OF A COSSERAT EFFECTIVE CONTINUUM FOR QUASI-PERIODIC LATTICE MATERIALS

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The recent emergence of new manufacturing processes has led to the increasing use of architectured materials in industry. Quasi-periodic architectured materials are a class that promises to combine the advantages of random and periodic lattices: they are, at the same time, perfectly ordered structures [1], while being elastically isotropic and having a great toughness [2].

The democratisation of lattice materials for engineering applications requires the ability to perform rapid simulations, which often involves the use of a homogeneous overall continuum. The idea is to consider a fictitious homogeneous material which behaves, for a certain range of external parameters, like the original lattice material. For a weak scale separation, the classical Cauchy continuum model is sometimes unable to describe the effective behaviour [3]. Thus, the nature of the fictitious material to be considered is the first question to be answered. Once the continuum model defined, the second problem consists in obtaining the material parameters of the associated constitutive relation. As lattice behaviours can be classified into at least three categories - bending dominance, stretching dominance and slenderness dominance [4] - a credible hypothesis is that the effective medium depends on the lattice dominance type. In order to numerically and experimentally determine the parameters of the substitution medium, a new experimental setup is proposed. It is inspired of the Brazilian test, with the three-point loading of a ring-shaped specimen.

The objective of this contribution is to validate the proof of concept of the design using numerical simulations. Virtual experimental data are generated by use of digital twin models of the periodic and quasi-periodic architectured materials specimens, discretized using beam elements. These simulations are used as references for the identification of Cauchy and Cosserat effective behaviours using a FEMU method. It is shown that the most appropriate behaviour depends on the type of lattice dominance: Cauchy for stretching-dominated structures and Cosserat for bending-dominated ones.

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FINITE CELL METHOD FOR AN EFFICIENT SIMULATION OF DUCTILE CRACK PROPAGATION THROUGH METAL MATRIX COMPOSITES

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The mining tools of tunnel boring machines underlie wear, mainly governed by abrasion and surface spalling. As mining tools, cutting disks and chisels consisting of a metallic body armored by metal matrix composite layers are applied on the tunnel boring machine. If those are worn out, they have to be exchanged, which leads to an additional consumption of time and money. Hence, the wear strongly influences the efficiency of the tunnel drilling process. In case of the mining tools, the wear is mostly governed by abrasion and surface spalling. The latter one occurs as ductile crack propagation under cyclic loading on the microscopic level near the tool's surface. Hence, the microstructure morphology and the material properties of the constituents influence the crack propagation and thus the resistance against surface spalling.
In order to investigate this, a mesh-independent framework capable of performing simulations including finite strains, elasto-plastic material behavior and arbitrary crack paths is necessary. Here, the eigenerosion approach, which assumes the erosion of elements based on the Griffithtype criterion, as presented in [1] and its implementation for small strains in [2] are extended to an algorithmic scheme for large strains. For the ductile constituents, the finite strain J_2-plasticity formulation in [3] is applied. Here, the microstructures are given as voxel data obtained from μCT scans. To circumvent the complicated meshing procedures and for computational efficiency, the Finite Cell Method as introduced in [4] is applied. Thereby, special cell arrangements, that minimizes the number of cells and the aspect ratio of the cells' edge lengths, are constructed based on the voxel data. Considering the eigenerosion approach based on eroding subcells, the subcells of finite cells containing at least one eroded subcell are transformed into single finite elements. This enables adaptive mesh refinement. Thereby hanging nodes as introduced in [5] occur. This framework is applied on metal matrix composite microstructures based on voxel data as well as simplified artificial microstructures. By evaluating the results of these simulations, failure of the material can be investigated on a microscopic level. Additionally, suggestions for the improvement of the material morphology regarding wear can be given based on those.

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NOLINEAR MECHANICAL BEHAVIOR OF ANISOTROPIC MATERIALS AS COSSERAT CONTINUUM

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The non-local effect related to the microstructures becomes vital nowadays, due to the increasing usage of microstructured materials such as lightweight concrete and honeycomb materials. Most of such composite materials and structures result in having a nonlinear behavior under applied loads. Therefore, it is aimed to investigate the geometrically nonlinear behavior of the anisotropic material with microstructures. The total Lagrangian finite element formulations are employed for a nonlinear anisotropic Cosserat continuum. The obtained results are compared to the results of the corresponding nonlinear anisotropic Cauchy continuum and linear results of the two models are also presented. Different equivalent anisotropic materials are used by homogenizing a composite consisting of different hexagonal microstructured geometries. The scale effect, which only appears in Cosserat model, is also investigated by changing the size of microstructures with respect to the macro scale. A 2D plane cantilever beam problem is analyzed. The results show that both nonlinear Cosserat and Cauchy models can produce a more realistic behavior, especially for the large deformation case. A scale effect occurs for the microstructures analyzed using Cosserat theory. Cosserat and Cauchy models have similar behaviors for the smaller scales, as the scale increases, the difference between these two models becomes larger. Different anisotropic materials show different nonlinear behaviors due to their peculiar constitutive behaviors. In the present analysis, different nonlinear load-displacement curves are carried out according to material scales and microstructures. These curves appear to be slightly nonlinear or highly nonlinear according to the theory and material configuration selected. Convergence and accuracy of the present nonlinear total Lagrangian finite element implementation demonstrates to be valuable for the solution of the present problems.

GEOMETRICAL MODELING OF A MICROSTRUCTURED MATERIAL: A SCALED MATERIAL MODELING

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Kinematics of a microstructured material is geometrically modeled through the framework of fibre-bundle geometry. The material continuum is a fiber bundle manifold $\mathcal{M} \xrightarrow{\pi} \mathcal{B}$ where $\mathcal{B}$ is compact and orientable. At any point p of the body $\mathcal{B}$, the microstructure of a microelement is denoted by fibre $\mathcal{M}_p$ over p. For the sake of the simplicity, the discussion focuses on the special case where $\mathcal{M}$ is isomorph to $T\mathcal{B}$ (*ie.* $\mathcal{M} \sim T\mathcal{B}$). Hence microelements are interpreted as first order infinitesimal neighborhoods of geometrical points as it is commonly considered for crystal modeling. This equality means that the same mathematical object, namely $T\mathcal{B}$ is used to model different mechanical objects: the space of *velocity* of geometrical point $p : T_p\mathcal{B}$ on the one hand and the microelement at $p : \mathcal{M}_p$ on the other hand.

Accordingly, embedding of such material manifold $\mathcal{M}$ is realized in the ambient space TE. Note that this smooth and one-to-one map defines partially a material configuration, by introducing the placement $\phi : \mathcal{B} \to E$ and its differential $F = \phi_*$. In order to complete the description of a material configuration a connection and metric have to be prescribed on $\mathcal{M}$. This is obtained by pulling back the canonical metric and the connection of the ambient space into $\mathcal{M}$. For such vector-bundle morphism this involves the bundle map Υ^* where $\Upsilon : T\mathcal{M} \to TTE$ takes the generic form

$$(X, Y, Z) \mapsto (\phi(X), F(X)Y, \Omega(X, Y)Z)\,,$$

The map $\Omega(X, Y)$ is then a key-point of the geometrical description of a configuration. It concerns both the vertical and the horizontal bundle space over $\mathcal{M}$, *ie.* $V\mathcal{M}$ and $H\mathcal{M}$ respectively. It allows us to define a Sasaki metric and an Ehresmann connection on $\mathcal{M}$. These ingredients are related to the definition on angle, length and equivalence class in the neighborhood for the two types of vector involved in such a description of a micro-structured material.

In practice, the model is based on the following constraints: the restriction of Ω onto the horizontal space is $F(X)$ whereas its restriction onto the vertical space (infinitesimal changes of microelement around p) is another morphism $\Theta(X)$, a priori independent of F. Independence of F with Y imposes that $VT\mathcal{M} \to HTE$ is null, but $HT\mathcal{M} \to VTE$ is a free. It would be presented how the prescription of this transformation is related to the type of material and could involve original induced material manifold for which torsion, curvature and non-metricity may reveal the mechanism of the transformation.

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MS-19 Design, additive manufacturing, and characterization of metallic metamaterials
Georg Ganzenmüller and Aron Pfaff (INATECH, University Freiburg & Fraunhofer EMI, Additive Design & Manufacturing, Germany)

On isotropic logarithmic elasticity and Mohr's circles in 3D
K. Heiduschke

The Auxetic Friction Cell
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Manufacturing and experimental analysis of 3D printed pantographic sheets
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Auxetic behaviour of the ATC metallic lattice visualised using ultra-fast X-ray imaging
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Fast and reliable method for supports release in metal am by sandblasting-driven process
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Thermal sensing of am components through electronics embedding in LB-PBF process
G. De Pasquale

Damage localization and failure of stainless steel specimens manufactured using powder bed fusion investigated at high strain rates
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ON ISOTROPIC LOGARITHMIC ELASTICITY AND MOHR'S CIRCLES IN 3D

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Nonlinear isotropic elasticity can be decomposed into finite dilatation and finite distortion. Dilatation is modeled with an isotropic tensor of volume change (a scalar multiplied by the identity tensor I) and distortion is modeled with an isochoric tensor, a deformation tensor that is equivoluminal and does not undergo volume change. The corresponding nonlinear isotropic stress-strain relations may be based on strain-energy functions with three invariants of a deformation tensor as arguments. On the one hand, the infinitesimal linear stress-strain relations of isotropic elasticity require just two material constants (which essentially reflect dilatation and distortion) either Young's modulus E and Poisson's ratio ν or the two Lamé parameters $\lambda = \frac{\nu}{1-2\nu}\frac{E}{1+\nu}$ and $\mu = \frac{1}{2}\frac{E}{1+\nu}$. Furthermore, only two types of waves propagate through an isotropic continuum: longitudinal and transversal waves, which are called primary (pressure) waves and secondary (shear) waves in earthquake physics. On the other hand, the strain-energy function of nonlinear isotropic elasticity depends on three variables [3]. The physics behind various sets of these three variables is discussed using Mohr's circles [2], Lode's angle ϑ [1] and the projections of the symmetric Cauchy stress T and the symmetric Cauchy-Green deformation tensor $\mathsf{B} = \mathsf{F}.\mathsf{F}^{\mathrm{T}}$ onto a common surface with unit normal $\vec{n}$, where F denotes the deformation gradient and F^{T} its transpose. Moreover, the additive split of symmetric tensors $\mathsf{T} = \mathsf{T}^{\mathrm{T}}$ into spherical $\mathsf{T}'' = \frac{1}{3}\mathrm{tr}(\mathsf{T})\,\mathrm{I}$ and deviatoric $\mathsf{T}' = \mathsf{T} - \frac{1}{3}\mathrm{tr}(\mathsf{T})\,\mathrm{I}$ parts is of physical importance for the Cauchy stress $\mathsf{T} = -p\,\mathrm{I} + \mathsf{T}'$ and for the logarithmic strain tensor $\mathsf{E} = \frac{1}{3}\mathrm{tr}(\mathsf{E})\,\mathrm{I} + \mathsf{E}' = \frac{1}{2}\ln(\mathsf{B})$. It is well-known that the dilatation depends only on a pair of work-conjugate invariants, e.g., the traces $p = -\frac{1}{3}\mathrm{tr}(\mathsf{T})$ and $\frac{1}{3}\mathrm{tr}(\mathsf{E}) = \ln(\sqrt[3]{J})$, where p denotes the pressure and $J = \det(\mathsf{F}) > 0$ the Jacobian determinant, respectively. Using Mohr's circles and Lode's angle ϑ, the dependence of the distortion on the other invariants is discussed. When isotropic logarithmic elasticity is defined by the collinearity of the Cauchy stress $\mathsf{T} = \|\mathsf{T}\|\,\mathsf{n}$ and the logarithmic strain $\mathsf{E} = \|\mathsf{E}\|\,\mathsf{n}$ tensors with $\mathsf{n} = \mathsf{T}/\|\mathsf{T}\| = \mathsf{E}/\|\mathsf{E}\|$, $\|\mathsf{n}\| = 1$, the isotropic strain-energy function $\Sigma(\mathsf{E}) = \Sigma''(J) + \Sigma'(\mathsf{E}')$ can be additively split into a dilatational part $\Sigma''(J)$ and a distortional part $\Sigma'(\mathsf{E}')$, leading to nonlinear spherical and deviatoric stress-strain relations of the form $p = -\rho J \dfrac{\partial \Sigma''}{\partial J}$ and $\mathsf{T}' = \rho \dfrac{\partial \Sigma'}{\partial \mathsf{E}'}$, where ρ is the present density. Linearization of these stress-strain relations yields a constitutive finite deformation model for isotropic logarithmic elasticity with only two material constants.

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THE AUXETIC FRICTION CELL

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This work presents an approach to introduce pronounced strain rate sensitivity into additively manufactured metallic lattice structures where the base material does not have a pronounced strain rate sensitivity. Metal additive manufacturing (AM) allows to design metamaterials specifically tailored for crash and impact applications. However, the intrinsic strain rate sensitivity of the base material developed for metal AM technologies is typically weak. For maximum crashworthiness, it is prudent to not only control the structure but also the viscoelastic behaviour of the metamaterial.

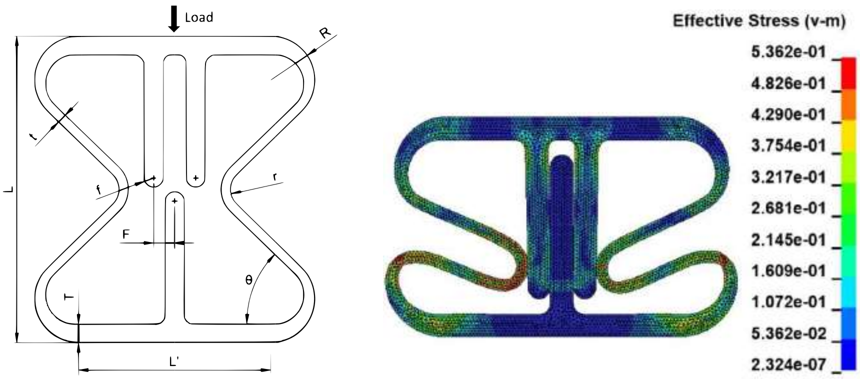

Figure 1: An auxetic unit cell equipped with friction element in its original state. The key geometrical parameters shown are to be optimized for maximum energy dissipation via friction under compressive loading (left). A simulation output image with colour fringing of von-Mises stress (GPa) under compressive load (right). The optimal set of geometrical parameters aid to efficiently exploit the frictional properties that paves a way for strain rate dependency in the structure.

This work attempts to introduce strain rate sensitivity into metallic lattice structures using friction as the governing mechanism. The friction between rough surfaces is strain rate dependent [1] [2]. The preliminary numerical and experimental results will be presented thereby quantifying the effects of the geometrical parameters. The main idea is to redirect compressive loads into an orthogonal direction and utilize large frictional contact areas between the central stems and the curved beams as in Fig. 1, thus enhancing the energy dissipation capability.

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MANUFACTURING AND EXPERIMENTAL ANALYSIS OF 3D PRINTED PANTOGRAPHIC SHEETS

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By means of additive manufacturing the fabrication of challenging lattice structures became possible in the last decade. The cost-effective production of so-called metamaterials with a complex, small-sized substructure became possible. Four different additive manufacturing techniques (Fused Deposition Modeling, Stereolithography, Selective Laser Sintering, Direct Metal Laser Sintering) have been used to fabricate differently sized pantographic sheets made of six different materials (Polylactide, Polyethylene Terephthalate Glycol, Epoxy Resin, Polyamide, Aluminum, Ceramic).
Dependent on the substructure of the metamaterial a special wanted global deformation behavior can be adjusted. For the case of a pantographic sheet, which can be described as a metamaterial with a substructure consisting of two orthogonal arrays of beams connected by internal cylinders (pivots), an exotic, large linear elastic deformation behavior was measured.
Therefore, three different experimental set-ups have been used: quasi-static extension tests, shearing tests and torsion test. 3D-digital image correlation was used to measure and evaluate the 3D-displacements of pantographic sheets in real time during all experiments.

AUXETIC BEHAVIOUR OF THE ATC METALLIC LATTICE VISUALISED USING ULTRA-FAST X-RAY IMAGING

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Auxetic materials have been investigated for many years due to their unconventional lateral contraction behaviour. As a consequence of their negative Poisson's ratio, they shrink in the lateral directions upon compression, and grow upon stretching. Historically, foams made of polymers have shown this phenomenon at low levels of mechanical performance. With the advent of the Selective-Laser-Melting additive manufacturing technology for metals, it is now possible to design such metamaterials with tailored properties, reaching high-levels of mechanical performance. As a consequence, industrial applications of these materials are now within reach and it has become important to fully understand their deformation behaviour, including damage and failure.

One of the application areas where auxetic metamaterials are expected to perform better than their conventional counterparts is protection against impact. Under a concentrated compression load, auxetic materials contract and show enhanced resistance against indentation. To date, this mechanism has been mainly experimentally confirmed for quasi-static, and comparatively slow loading conditions up to approximately 10 m/s. However, the intended usage scenarios encompass loading velocities which are higher by one order of magnitude.

This works reports experimental investigations at different velocities for a 3D anti-tetra-chiral lattice structure made form 316L stainless steel. Experiments are reported for the quasi-static regime at 10^{-4} m/s, the split Hopkinson regime at 10 m/s to, the low pressure gas gun regime at 100 m/s, and the high-pressure gas gun regime up to 500 m/s. The dynamic compaction behaviour is visualised using high-speed optical cameras, and ultrafast X-Ray imaging at the highest velocities. The image data is evaluated using global Digital Image Correlation to yield the full displacement field. We find that a homogeneous auxetic structural response can only be observed for velocities up to ~10 m/s. For velocities between 10 and 100 m/s, the homogeneous response is replaced by an auxetic wave front, similar to plastic wave fronts in shock physics experiments. For even higher velocities, the auxetic response is preempted by a structural collapse front. This effect needs to be considered when designing auxetic impact protection suitable for elevated velocities.

FAST AND RELIABLE METHOD FOR SUPPORTS RELEASE IN METAL AM BY SANDBLASTING-DRIVEN PROCESS

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The LB-PBF (laser beam powder bed fusion) process for metal alloys is largely used in industrial and academic fields for the AM (additive manufacturing) of components. However, the process is still affected by cost and time issues, which include powder and inert gas management, micromelting process, thermal post-processing, supports release and mechanical finishing. Then, the optimization of each process phase is crucial for the technology scalability. This paper focuses on the supports release and introduces the design of supports for the fast removal through sandblasting process instead of traditional manual release or release based on mechanical tooling.
The supports release by sandblasting is achieved on the AlSi10Mg alloy through: (a) the study of geometrical parameters of the supporting structures to enable more effective abrasive media flow through the supports, and (b) the study of the process parameters to modulate the structural strength of supports through controlled porosity. The best supports geometry and combination of laser power and speed is defined.
The mechanical properties of the supports material have been characterized by considering the growth direction and the geometry (Fig. 1). The combinations of supports and laser parameters are processed with a DOE (design of experiments) on a target object. The target object (Fig. 2a) is a cube with many significant features concentrated in it (holes, suspended parts, embossed details, etc.). The local deformations on samples are measured to control the process output. The sandblasting process is finally validated on the supports of a complex component represented by the cylinder of a 250cc two-stroke engine (Fig. 2b).
The sandblastability of each sample is quantified by four quality levels (Fig. 3). The sandblasting process is reported in Fig. 4 and one job of samples fabrication in Fig. 5. Finally, the proposed process demonstrate the possibility to design the supports for fast and complete release through sandblasting with high efficiency compared to traditional release methods especially for small features and holes with reduced accessibility.

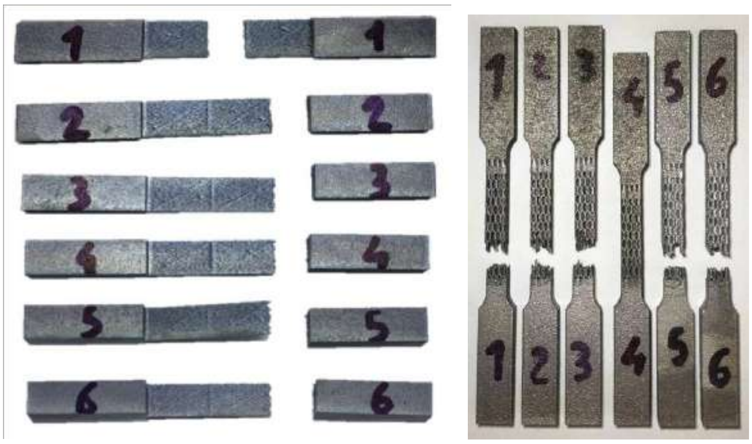

Figure 1. Samples for tensile characterization of bulk and lattice supports.

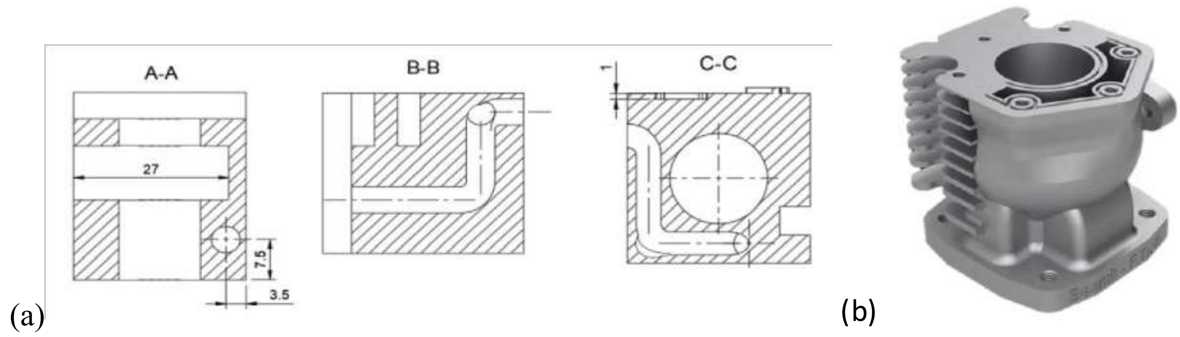

Figure 2. Target cube objet with significant features (a) and engine cylinder component (b) used for the optimization and validation of the sandblasting-driven supports release.

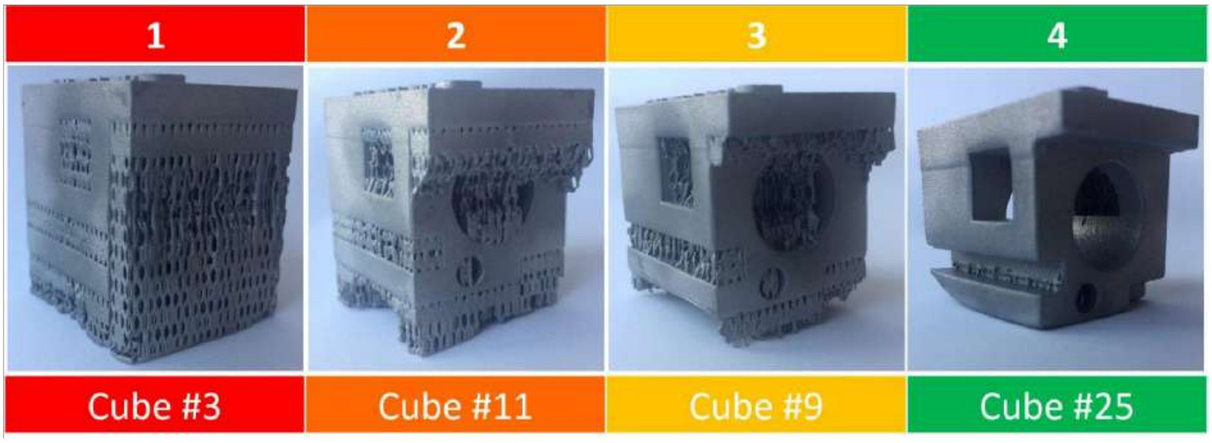

Figure 3. Qualitative scale for the efficiency categorization of the sandblasting process for supports release.

Figure 4. Sandblasting process.

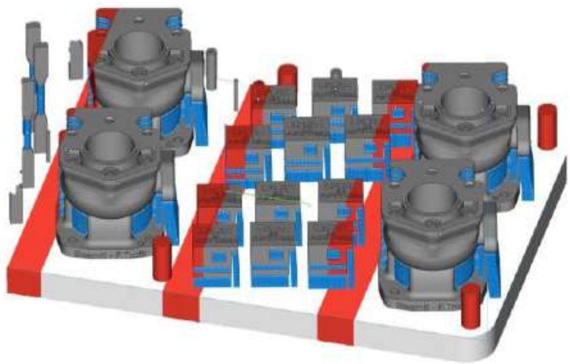

Figure 5. LB-PBF job setup for the building of samples with optimized supports.

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ADDITIVE MANUFACTURING OF MINIATURIZED PIN-JOINTS FOR NON-ASSEMBLY METALLIC METAMATERIALS

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Mechanical metamaterials show unusual macroscopic mechanical behavior and often exhibit a complex inner structure. The latter make it challenging to manufacture functional metallic metamaterials whereby laser powder bed fusion (LPBF) can offer a solution for the fabrication of filigree and complex shapes such as non-assemblies, e.g., pin-joints. By inserting real joints into the inner structure, a degree of freedom (e.g., rotation for pin-joints) can be added.

The additive manufacturing of miniaturized pin-joints and their integration in a metamaterial demand process-oriented designs and adapted processing parameters. The complex macroscopic shape of mechanical metamaterials can make it necessary for the joints to be printed with an angle to the build plate and it is well-known that cylindrical structures may lose their circularity due to inevitable deviations. Furthermore, for most metamaterials the size of the microscopic joints should be close to the manufacturing limits of LPBF to allow high density of a metamaterial's inner structure to exhibit its function.

In this study, a suitable pin-joint design (concave shaped pin and convex shaped hole) for LPBF is presented in conjunction with adapted processing parameters for Ti-6Al-4V. The pin-joints are orientated in a 45° to the build plate with small clearance (50-120 µm) and a total joint size on the mesoscale (1-2 mm^3). First, a design of experiments (DOE) based parameter optimization was conducted to determine a process parameter set that results in a shallow and narrow melting pool without invoking the effects of lack-of-fusion or balling. The developed process parameters were used to manufacture single joints as well as small pantographic metamaterials including multiple joints with varying clearance. In a second step, the macroscopic size of the metamaterial is scaled up to integrate hundreds of pin-joints in a non-assembly, the metallic pantographic structure with perfect pivots (rotational joints). The results of imaging and mechanical analysis of the manufactured samples demonstrate the advantages compared with using standard process parameters.

The presented work implies that optimization of process parameters for LPBF manufacturing are necessary to miniaturize pin-joints and to include joints in metamaterials. The obtained findings can be used to realize new metallic metamaterials.

LOW-VELOCITY PENETRATION RESISTANCE OF SANDWICH PANELS WITH AUXETIC AND NON-AUXETIC CORE USING DIRECT IMPACT HOPKINSON BAR

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Keywords: Additive Manufacturing, Sandwich Panel, Auxetic and Non-auxetic Core, Dynamic Penetration, Direct Impact Hopkinson Bar

The mechanical response of sandwich panels tailored to specific applications investigated becomes an extensively topic for research teams. Sandwich panels typically consist of a lightweight core (porous materials, meta-materials structures) and covering shell (solid or composite layer). These materials can be used as, e.g., the main component of crumple zones in vehicles or low-velocity protection in many applications, due to their high specific energy absorption and low density. An unique loading mode in dynamic mechanical testing is a dynamic indentation where combining multi-directional stress distribution in sandwich panels is not an easy task for description.

The main aim of this work is to compare sandwich panels with two different types of core (3D inverted honeycomb and conventional honeycomb structures with similar specific densities). Based material of the aforementioned cores is photopolymer resin which allows the manufacturing of complex shapes of cores by stereolithography technology. All specimens, equipped with a spreading thin layer of polyethylene shell, are subjected to dynamic penetration to evaluate the mechanical behavior, penetration resistance, and energy-absorbing capability at different impact velocities. An in-house developed direct impact Hopkinson bar is used for dynamic indentation experiments. The loading apparatus is equipped with strain gauges and the measured signals are used for the calculation of an applied force and impact velocity. A pair of highspeed cameras are used for optical inspection of the experiments. A targeted camera is used for evaluating the velocity of the projectile using the digital image correlation method (DIC) for comparison with strain-gauge measurement, and an overview camera is used for capturing the surroundings of the impact plane.

Acknowledgement

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THERMAL SENSING OF AM COMPONENTS THROUGH ELECTRONICS EMBEDDING IN LB-PBF PROCESS

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The modified LB-PBF (laser beam powder bed fusion) process introduced [1] and patented [2] by the author allows to integrate discrete packaged sensors and/or customized electronics into the metal component during its additive manufacturing (AM) growth. This technology allows producing smart components suitable for networking, data sharing and IIoT (industrial interner of things) applications [3, 4]. The main advantages of sensors embedding in metal components are insulation from contaminations, protection against tampering, efficient transducer positioning, traceability of components, etc.

This paper reports the design and fabrication of samples made with steel (17-4 PH), aluminum alloy (AlSi10Mg) and Inconel (In718) with integrated thermal sensors (k-type thermocouple and PT100 sensor) and USHX electronic connectors. The process is conducted with the EOS270 and SLM500 systems.

The integration process is based on the growth stop and restart, which generally causes mechanical and metallographic singularities at the layer interested by the interruption. The printing parameters are preliminary optimized to eliminate the mechanical effect of the process interruption. This result is achieved by non-destructive tests at the interruption level made with optical and scanning electron microscopes (Fig. 1) and by tensile tests on samples with growth interruption (Fig. 2). Thermal treatments (solubilization, ageing, etc.) are also considered. In the next step, the optimized process parameters are used to build samples with embedded devices (sensors, connectors and cables). The patented technology includes a thermal shield that is used to protect the electronics against the laser heating when the micromelting process is restarted. The sample is built from the ground platform, and the housing of the internal sensors is created (Fig. 3). The process is interrupted, the temperature reduced into the printing chamber and the electronic devices are integrated. Then, the component growth is completed up to the last layer of powder micromelting.

The final result on some samples is reported in Fig. 4, as demonstrator of the technology reliability and suitability for IoT applications and advanced structural monitoring.

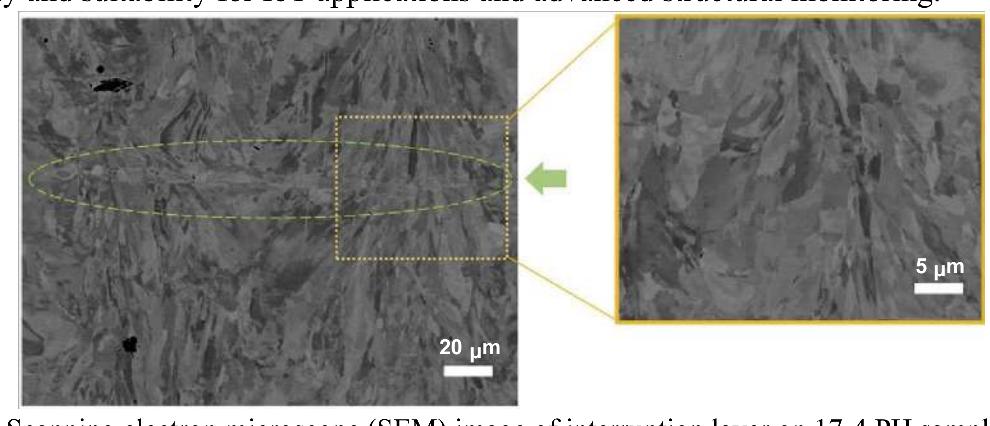

Figure 1. Scanning electron microscope (SEM) image of interruption layer on 17-4 PH sample.

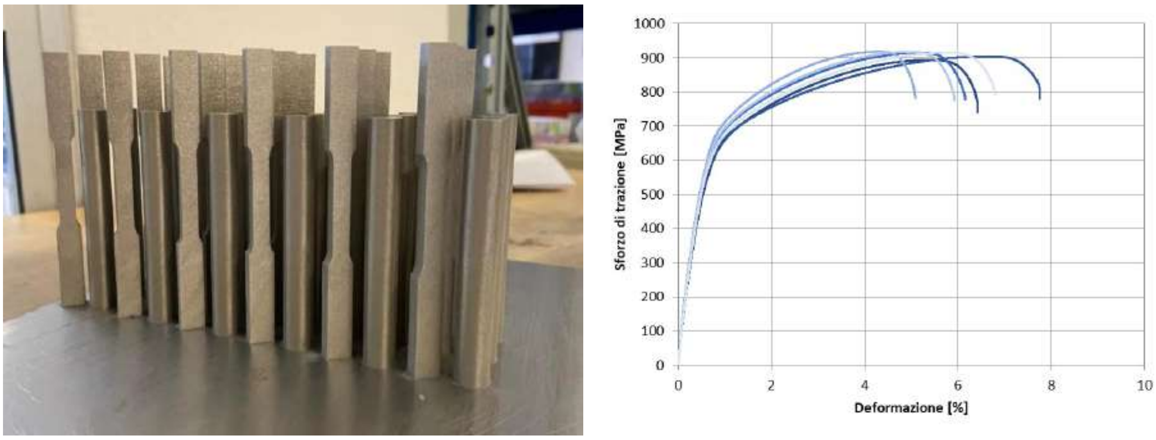

Figure 2. Tensile samples in In718 and example of stress-strain curves of the as-built material with process interruption simulating the process for sensors integration.

Figure 3. Internal view of the sample built with In718 and embedded PT100 sensor with ceramic connector USHX and electronics embedding operations.

Figure 4. Sample released in final configuration with integrated sensor and external connection.

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DAMAGE LOCALIZATION AND FAILURE OF STAINLESS STEEL SPECIMENS MANUFACTURED USING POWDER BED FUSION INVESTIGATED AT HIGH STRAIN RATES

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Keywords: Additive Manufacturing, Power Bed Fusion, Split Hopkinson Bar, Strain Rate Sensitivity, Powdered Stainless Steel, Failure

Additively manufactured materials represent an advanced type of engineering material allowing for rapid building of parts with complex design. Additively manufactured metallic materials are particularly promising for application in high-tech industry, requiring optimized parts with complex shape and high performance mechanical properties. In this area, power bed fusion (PBF) is a fast developing manufacturing technology suitable for components production in many engineering areas ranging from shape-optimized structural parts to parts for jet engines or space research. However, as components in this field are often subjected to extreme conditions and loading, an in-depth description of deformation behavior of the materials is essential. This still represents a topic that is not resolved, particularly at high strain rates.

In this contribution, the cylindrical specimens manufactured from 316L powdered stainless steel built in different orientations to the printing platform are subjected to compression at high strain rates using split Hopkinson pressure bar (SHPB). The specimens are subjected to quasi-static and dynamic compression at strain rates ranging from 1500s ^{1} to 5000s ^{1}. Changes in damage development and failure mode are investigated through combination of high speed optical imaging with data of the SHPB instrumentation. For the testing, the SHPB with high strength aluminum alloy bars, soft copper pulse shapers and two sizes of the striker bar is used. The bars are instrumented with a set of foil strain-gauges. The experiments are observed by stateof-the-art high speed camera (Photron SA-Z) with frame rate of approximately 250kfps. The camera is time synchronized with the data acquisition system. Strain localization and changes in failure mode related to the printing orientation and strain rate, particularly occurrence of the fatal macroscopic crack and identification of the corresponding failure strain, are investigated using digital image correlation (DIC). It is found out that the failure mode changes dramatically with the increasing strain rate resulting in sudden and complete failure of the specimen during high strain rate compression. The failure is dependent on both the printing orientation and the strain rate.

Acknowledgment:

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MS-20 Numerical methods for stochastic mechanics and dynamical systems
Antonina Pirrotta (Università degli Studi di Palermo, Italy), Alberto Di Matteo (Università degli Studi di Palermo, Italy)

New developments for the non-deterministic analysis of multi-cracked beams with uncertain damage
R. Laudani, R. Santoro e G. Falsone

Path integral approach with Laplace's method of integration for nonlinear systems with fractional derivative elements
A. Di Matteo, A. Pirrotta

Complex spectral moments for stochastic analysis of fractional viscoelastic beams at small-scale
F.P. Pinnola, M.S. Vaccaro, R. Barretta, F. Marotti de Sciarra

Stochastic dynamics framework for nonlinear oscillators endowed with fractional derivative elements under compatible design-spectrum seismic excitation
P. Ni, I. A. Kougioumtzoglou, I. P. Mitseas, V. C. Fragkoulis, M. Beer

NEW DEVELOPMENTS FOR THE NON-DETERMINISTIC ANALYSIS OF MULTI-CRACKED BEAMS WITH UNCERTAIN DAMAGE

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In the search field on uncertain structural systems, the problem of multi-damaged beams is a critical issue for assessing structural integrity. Since the presence of a concentrated crack makes a discontinuity that reflects into a localized reduction of the flexural stiffness of the beam in the crack proximity, one intuitive macroscopic way is to model the flexibility of the beam's cracks. Consequently, a massless rotational elastic spring connecting two adjacent cross-sections at the crack location is often used to describe the beam's open crack. Moreover, considering that the characteristics of cracks may be affected by a remarkable scattering of uncertainty, is reasonable to consider that the crack's parameters, namely the crack amplitude in terms of spring stiffness and its position, may be modeled as uncertain parameters. In view of this, for the evaluation of the structural response of multi-cracked beams, the implementation of a non-deterministic analysis is highly recommended.
Generally, to implement a non-deterministic analysis, according to the nature of the uncertain source, it is usual to classify uncertainties into random and epistemic. The two categories correspond to the probabilistic and non-probabilistic representations of the problem. In the recent literature, several studies developed probabilistic models by modeling the characteristics of the crack as random variables as well as interval or uncertain-but-bounded variables.
Overall, the aim of this work is twofold. At first, in the framework of the probabilistic methods, an approach for evaluation of the static stochastic response of cracked Euler Bernoulli beams through the Probability Transformation Method (PTM) is shown. Then, based on a recent paper developed by one of the authors for the evaluation of the response bounds of damage beams considering simultaneously uncertainties in the crack parameters treated as interval variables, a new perspective on the comparison between results from an interval analysis and a probabilistic analysis has been proposed. In particular, in the non-deterministic analysis field, new contributions on the influence of the modeling the uncertain damage has been provided.

PATH INTEGRAL APPROACH WITH LAPLACE'S METHOD OF INTEGRATION FOR NONLINEAR SYSTEMS WITH FRACTIONAL DERIVATIVE ELEMENTS

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In this paper the nonstationary response of a class of nonlinear single-degree-of-freedom systems, endowed with fractional derivative elements, subject to broad-band stochastic excitations is examined. A version of the Path Integral (PI) approach is developed for determining the evolution of the response probability density function (PDF).

Specifically, the PI approach is generally employed for evaluating the response PDF in short time steps of linear and nonlinear integer-order systems, based on a discretized version of the Chapman–Kolmogorov equation. Here the procedure is extended to nonlinear oscillators with fractional derivative elements approximately modeling the amplitude of the system response as a one-dimensional Markovian process.

Further, the proposed PI approach is here employed in conjunction with the Laplace's method of integration. In this manner, an approximate analytical solution of the integral involved in this equation is obtained, thus circumventing the repetitive integrations generally required in the conventional numerical implementation of the procedure.

Various nonlinear systems are considered in the numerical applications, including Duffing and Van der Pol oscillators. Appropriate comparisons with Monte Carlo simulation data are presented, demonstrating the efficiency and accuracy of the proposed approach

COMPLEX SPECTRAL MOMENTS FOR STOCHASTIC ANALYSIS OF FRACTIONAL VISCOELASTIC BEAMS AT SMALL-SCALE

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The statistical characterization of the nano- and micro-beam response with non-integer order damping forced by Gaussian noise is addressed in this paper. This structural problem occurs in the design and optimization of some small-size components forced by non-deterministic excitations.

In this problem the damping is related to the time-dependent costitutive law of the material of which the structural element is made. To model this particular stress-strain relation Boltzmann superposition integral and fractional-order viscoelasticity are used. While, size-effect, that arises at small-scales, is modeled by means of stress-driven nonlocal formulation. Presented analysis is performed considering as random excitation a normal noise but the outcomes can be extended for more general cases.

For the problem at hand a specific method is defined to obtain correlation and power-spectral density characterizations. Specifically, as first step, thanks to the stress-driven approach is possible to define the closed-form eigenfunctions of the problem. Next, for each eigenfunction the stationary characterization of the modal coordinate is obtained with the aid of fractional-order state variable analysis and exact complex spectral moments. These complex entities are able to describe completely the random processes at steady-state. Therefore, by the proposed formulation, the knowledge of the exact eigenfunctions, a proper set of state variables and the analytical complex spectral moments permit to define power spectral density and correlation function of displacement field of nonlocal beam with fractional viscoelastic damping. Moreover, the presented approach provides an analytical expression of the variance and cross-variance of the displacement field.

Finally, in the numerical application, a viscoelastic cantilever micro-beam forced by stochastic ground motion is considered and the outcomes of the proposed analysis are compared with those obtained by Monte Carlo simulations.

STOCHASTIC DYNAMICS FRAMEWORK FOR NONLINEAR OSCILLATORS ENDOWED WITH FRACTIONAL DERIVATIVE ELEMENTS UNDER COMPATIBLE DESIGN-SPECTRUM SEISMIC EXCITATION

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A novel approximate stochastic dynamics framework is developed for peak inelastic response determination of nonlinear systems endowed with fractional derivative elements exposed to a Eurocode 8 elastic response spectrum, without the need to resort to computationally demanding nonlinear response time-history analyses. In this setting, an elastic response spectrum compatible evolutionary power spectrum is derived for characterizing the induced seismic excitation stochastic process [1]. Next, an equivalent linear system with time-variant stiffness and damping ratio elements is generated relying on a combination of the stochastic averaging and the statistical linearization methods [2]. An efficient iterative scheme [3] is proposed to update the damping ratio of the assigned design spectrum to match with the system equivalent linear damping ratio element for the most critical time instant. It is remarkable that the time-variant equivalent linear elements, judicially used, lead to an enhancement of the associated accuracy in terms of the peak inelastic response determination, as compared with the time-invariant equivalent elements associated with an excitation consideration of the stationary kind. An illustrative application including a bilinear hysteretic nonlinear system endowed with fractional derivative elements is considered to verify the reliability and applicability of the proposed framework. Comparison with pertinent Monte Carlo simulation data is provided for assessing the accuracy of the proposed approach.

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MS-24 Nonlinear mechanics of beam, plate, membrane and shell structures: models and methods

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A new mixed isogeometric form-finding formulation for the cable structures
L. Greco, M. Cuomo, R. Ruggeri

Spatial nonlinear beam theory for soft pneumatic actuators
J. Harsch, S. R. Eugster

Strain gradient plate model for geometrically nonlinear analysis: application to cellular plates with a triangular lattice core
J. Torabi, J. Niiranen

Non-linear static analysis of laminated plates through the discontinuous Galerkin method
G.Guarino, V.Gulizzi, A.Milazzo

Mathematical model of the nonlinear dynamics of flexible rectangular Kirchhoff Nano-plates described by a modified couple stress theory
V.A. Krysko-jr., J. Awrejcewicz

Classification of beam's models for large transformations: analytical applications
L.M. Le Marrec, M. Hariz , J. Lerbet

A geometric non-linear beam analysis for the fatigue assessment of distorted thin plates
F. Mancini, H. Remes, J. Romanoff

An update lagrangian Bézier finite element formulation for the analysis of slender beams
L. Greco, M. Cuomo, A. Scrofani, D. Castello

Some issues of the theories of elastic and viscoelastic thin bodies
M. Nikabadze, A. Ulukhanyan, N. Mardaleishvili

A NEW MIXED ISOGEOMETRIC FORM-FINDING FORMULATION FOR THE CABLE STRUCTURES

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In this contribute we present a new robust isogeometric strategy for the form finding of self-weight cable structures. First the Force Density Method (FDM) [1,2] is briefly introduced, later a new mixed variational principle suitable for the form finding problem and generalizing the FDM is presented.
Starting from a reformulation of the Hellinger-Reissner principle in terms of placement and force density a variational principle suitable for the form finding of self-weight cable nets considering its inextensible limit is presented.
Contrary to the classic FDM the Newton-Raphson method is used to approach the optimum of the considered form finding problem.

Assuming for both the placement and the force density B-spline interpolations, it is shown as the proposed mixed isogeometric formulation results very efficient and presents optimal rate of convergences with higher accuracy level with respect to the classic iterative stress updating techniques of the Force Density Method as shown in [3].

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SPATIAL NONLINEAR BEAM THEORY FOR SOFT PNEUMATIC ACTUATORS

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In the emerging research field of soft robotics recent investigations examine how cylindrical beam like structures made of silicone can be described using spatial nonlinear beam theories. These structures are frequently actuated by inflating multiple eccentrically embedded pressure chambers.

This talk extends the classical spatial nonlinear beam theories [1], given in the variational framework of the principle of virtual work, by pressurized chambers. It contains the formulation of the internal virtual work contribution of the pressurized medium which is restricted to the beamlike kinematics of the enveloping material [2]. Using the principle of virtual work, which demands the total virtual work to vanish for all admissible virtual displacements, the equilibrium equations follow by an integration by parts procedure. The silicone's elastic material response is modeled by using a nonlinear Ogden-like material law for the beam's axial direction. Further, the radii of the embedded pressure chambers are linearly coupled with the applied pressure.

The unknown parameters of the proposed material laws are identified using an optimization procedure with respect to selected experimental measurements. By showing that the proposed model together with the identified parameters is capable of reproducing the results of a different unknown experiment validates the optimization procedure. Using the example of a nonlinear trajectory optimization problem, the first-class suitability of the presented formulation for use in soft robotics will be impressively demonstrated. This results in numerous potential applications of practical interest which elevates the use of nonlinear spatial beam theories to the next level throughout the whole robotics community.

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STRAIN GRADIENT PLATE MODEL FOR GEOMETRICALLY NONLINEAR ANALYSIS: APPLICATION TO CELLULAR PLATES WITH A TRIANGULAR LATTICE CORE

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The advancement in additive manufacturing technologies has led to multifunctional applications of advanced cellular metamaterials in various industrial fields and this increase demands for developing efficient models to present more numerical structural simulations. On the other hand, the complex microarchitectures in these structures make the analysis of their mechanical characteristics more computationally expensive. Hence, the main objective of this research is to introduce an effective structural model to investigate the geometrically nonlinear mechanical behavior of lattice plates with triangularly prismatic cores. The model integrates the higher-order finite element method and strain gradient plate formulation. The governing equations are under Mindlin's strain gradient theory [1] and the first-order shear deformation plate model with the von Kármán geometrically nonlinear kinematic assumptions. The results of the numerical homogenization technique [2,3] within the strain gradient theory are employed to decrease the computational cost by neglecting the fulfilled 3D modeling of detailed lattice microarchitectures. This makes it possible to model the cellular plate using the plate model just by analyzing the mid-plane of the plate which can remarkably improve the computational performance of the analysis. To this end, first, the energy functional of the problem is derived in matrix form and the nonlinear finite element analysis using the 6-node quasi C^1-continuous triangular element is presented [4]. To solve the nonlinear sets of finite element governing equations and find the nonlinear bending and free/forced vibration response of the cellular plate, the arc-length iterative technique and numerical time-periodic differential operators are implemented. The comparison studies are provided to verify the accuracy of the model. The numerical examples are also presented for the nonlinear static and dynamic problems to highlight the efficiency of the proposed model.

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NON-LINEAR STATIC ANALYSIS OF LAMINATED PLATES THROUGH THE DISCONTINUOUS GALERKIN METHOD

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This work focuses on the geometrically non-linear analysis of laminated plate structures. Starting from the principle of virtual displacements for three-dimensional solid mechanics in a total Lagrangian formulation, the problem at hand is reduced to a two-dimensional problem within the context of the Equivalent Single Layer kinematic theories, whereby variable-order known functions are used to express the components of the displacement field throughout the plate thickness. The considered plates consist of a stacked sequence of long-fiber composite layers, whose constitutive relationship is assumed to be orthotropic and linear between the second Piola-Kirchhoff stress tensor and the Green-Lagrange strain tensor.

Based on such hypotheses, a two-dimensional principle of virtual generalized displacements for plate structures is derived. The governing equations are numerically solved through the discontinuous Galerkin (DG) method. The DG method is based on the use of discontinuous basis functions and on the use of suitably-defined boundary integrals to enforce the interelements continuity as well as the boundary conditions. One of the main advantages of DG methods is their ability to naturally handle high-order polynomial basis functions, which typically lead to an overall reduction of the number of degrees of freedom required to obtain a given level of accuracy with respect to low-order schemes. The resulting set of non-linear algebraic equations is eventually addressed through a Newton-Rapson scheme.

To prove the accuracy and the efficiency of the method, numerical tests are performed on laminates with different geometries and materials and the results are compared with reference solutions taken from the literature and from Finite Element simulations.

MATHEMATICAL MODEL OF THE NONLINEAR DYNAMICS OF FLEXIBLE RECTANGULAR KIRCHHOFF NANO-PLATES DESCRIBED BY A MODIFIED COUPLE STRESS THEORY

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Nano-plates have been in high demand in modern aerospace, superfast microelectronics, nano electro-mechanical (NEMS) systems, biomedical and bioelectrical devices. Nanoplates are used as, paddle-like resonators, gas sensors and mass sensors.

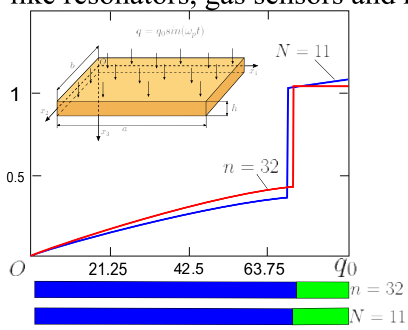

Figure 1 Convergence of the Fayedo-Galerkin method in higher approximations by signal q0 (Wmax(0,5;0,5)) for N=11 and finite differences method for Ω 32*32, where blue indicates harmonic vibrations and green indicates chaotic vibrations

Based on Hamilton's principle, a mathematical model of flexible elastic rectangular in plan Kirchhoff nanoplates is constructed, taking into account the modified couple stress theory [1]. Obtained nonlinear differential equations of Kirchhoff nanoplates are solved by two methods. PDEs are reduced to the Cauchy problem by the Fayedo-Galerkin method in higher approximations and by the finite difference method of second order of accuracy. The obtained Cauchy problems are solved by the Runge-Kutta type methods (from the 4 to the 8 order of accuracy) and the Newmark method.

The convergence of these methods is investigated depending on the number of terms in the Fayedo-Galerkin method (N) and the number of partition intervals of the area Ω n*n. This is necessary to study chaotic vibrations, since the plate should be considered with an infinite number of degrees of freedom [2]. The coincidence of the basic functions and their derivatives up to second order are required. As an example, we consider a square plate $\Omega = \left\{0 \le x_1 \le a; 0 \le x_2 \le b; -\frac{h}{2 \le x_3 \le \frac{h}{2}}\right\}$ under the action of a uniformly distributed alternating load q. Fig. 1. shows the load-deflection relation in the center of the plate. The analysis of chaotic vibrations was carried out using the methods of Wolf, Kantz and Rosenstein. For the first time, the phenomenon of dynamic loss of stability of flexible nanoplates under the action of transverse alternating load was revealed. The results obtained by both methods were almost identical. This confirms the accuracy of the obtained results.

Acknowledgements
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CLASSIFICATION OF BEAM'S MODELS FOR LARGE TRANSFORMATIONS: ANALYTICAL APPLICATIONS

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The study of a static beam under large transformation is approached in an analytical way through various models : the Timoshenko, the Euler-Bernoulli and the Kirchhoff models. It is exposed how the two last models may be seen as some asymptotic solutions of the first one in an uniform way.

Analytical solutions of a plane, quasi-static but large transformation of a Timoshenko beam is exposed. The problem is first re-formulated in the form of a Cauchy initial value problem where load (force and moment) is prescribed at one-end and kinematics (translation, rotation) at another. With such formalism, solutions are explicit for any load. The existence, uniqueness and regularity of the solution of the problem are proven. Therefore, analytical post-buckling solutions were found with different regimes driven explicitly by two invariants of the problem.

This approach was also applied to Euler-Bernoulli beam as well as Kirchhoff rod and explicit solutions were found for the three models. A comparison in terms of kinematical and dynamical variables between these different models was made. It is shown how such models are intrinsically related to asymptotic point of view from the initial Timoshenko model. Various case are exposed for which solutions of each models are qualitatively similar or, in contrary, different. Such analysis highlights configurations for which each model are valuable and may be justified.

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A GEOMETRIC NON-LINEAR BEAM ANALYSIS FOR THE FATIGUE ASSESSMENT OF DISTORTED THIN PLATES

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The interest in performing, energy-efficient solutions for large structures has promoted the use of high tensile steel and thin plates. However, plates with a thickness of 3-4 mm are prone to irregular welding-induced distortions, which may cause significant secondary bending effects. These distortions are not currently considered in fatigue design rules and recommendations for welded components, see, e.g., [1]. Accordingly, for instance, shipbuilding design codes limit the minimum plate thickness to 5 mm. In order to overcome this limitation, the effects of the non-linear behaviour of curved plates on fatigue-critical locations such as welds are under study.

The structural hot-spot stress assessment is the most used approach to account for geometric distortions in the stress state. At early design stages, the hot-spot stress is evaluated as the nominal applied stress magnified by a factor k_m, computed analytically. In the case of a butt-welded plate, concise k_m-factor formulations are drawn from the analysis of an Euler-Bernoulli (E-B) beam under axial load. The analysis applies the von Kármán kinematic assumption to include the secondary bending caused by a straight distortion (i.e., by a global angular misalignment, α_g). Thereby, the formulations do not apply to irregular distortions, typical for thin plates.

On this basis, Mancini et al. [2] extended the E-B beam model to account for a simple halfsine curvature that superimposes a local angle, α_l, to α_g, as in Fig.1. The figure also shows a rotational spring at the left end, the purpose of which is to model the weld rigidity as a non-ideal rotational constraint [3]. The beam analysis is validated with a maximum error of 3% against the geometric non-linear Finite Element analysis of a curved plate with different weld shapes that result in a varying rotational rigidity. Future studies will focus on modelling curvatures closer to the irregular distortions observed in larger components such as stiffened panels.

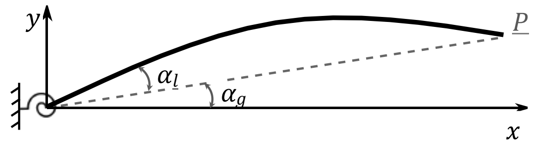

Figure 1: E-B beam model with half-sine initial curvature generating a global (α_g) and local (α_l) angular misalignment. The weld rigidity is modelled by a rotational spring.

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AN UPDATE LAGRANGIAN BÉZIER FINITE ELEMENT FORMULATION FOR THE ANALYSIS OF SLENDER BEAMS

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We present a formulation for slender space curved rods and rod assemblies that implicitly accounts for the Kirchhoff constraints and for the G1-continuity conditions (i.e., continuity of the geometric tangent) between elements. The whole formulation is developed in tensorial coordinate free form, apt to any numerical interpolation to be implemented. Analogously to [1] a symmetric tangent stiffness operator is obtained performing the second covariant derivative of the internal energy functional, for which the Levi-Civita connection of the configurations manifold of the rod is needed.

The G1-continuity conditions are fulfilled by means of a change of basis, from the original configuration parameters (position of the beam axis and rotation around the axis tangent) to a new set of configuration parameters, whose relation to the original set is non-linear. For this reason, an additional geometric term, specific for the G1-formulation, appears in the tangent stiffness matrix. The robustness and accuracy of the obtained Kirchhoff model is demonstrated with numerical examples (see [2]) that employ Bézier interpolation of the same polynomial degree for the position of the centroid curve and for the correction rotation angle.

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SOME ISSUES OF THE THEORIES OF ELASTIC AND VISCOELASTIC THIN BODIES

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In this paper, we considered some issues of a new parametrization for three-dimensional domain of a thin body and presented some geometric characteristics of this parametrization. Next, we formulated the statements of initial-boundary value problems of three-dimensional linear and some nonlinear classical and linear micropolar theories of viscoelastic bodies and some second-gradient theories of elasticity. From them, one version of the statements of initial-boundary value problems of the three-dimensional nonlinear classical theory of elastic thin bodies was obtained under the new parametrization of the thin body domain. In addition, statements of initial-boundary value problems are given for the three-dimensional linear micropolar theory of viscoelastic thin bodies and some second-gradient theories of elastic thin bodies under the new parametrization of the considered thin bodies' domain. From the last statements, in turn, we have obtained the statements of initial-boundary value problems in moments with respect to systems of orthogonal polynomials and, in particular, with respect to the system of Legendre polynomials. Statements of initial-boundary value problems are also considered in the case of the classical linear theory and gradient theories of elasticity with respect to the displacement vector, and in the case of the linear micropolar theory with respect to the displacement and rotation vectors. We presented the constitutive relations using the tensors and tensor-block matrices, as well as taking into account the canonical representations of these tensor objects. In addition, the static boundary conditions and equations of motion and equations of equilibrium were represented by differential tensor operators in the case of the classical theory and by differential tensor-block-matrix operators in the case of micropolar and gradient theories. Tensor operators of cofactors for tensor operator of motion and tensor operator of equilibrium and tensor stress operators are constructed, which allow splitting of initial-boundary value problems of linear classical and linear micropolar theories of viscoelastic bodies, as well as some gradient theories. It should be noted that all of the above is easily extended to the theories of other rheological bodies, including linear and non-linear high-order gradient theories.

Acknowledgements

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MS-25 Geometry and Continuum Mechanics

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The distance to cubic symmetry class as a polynomial optimization problem
P. Azzi, R. Desmorat, B. Kolev, F. Priziac

Carathéodory's geometric thermodynamics and beyond
J. D. Goddard

The fall of a rod constrained by a sliding sleeve subject to a periodic oscillation
F. Dal Corso, P. Koutsogiannakis, D. Misseroni, T. Papathanasiou, D. Bigoni

Material evolution foliations
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Stochastic modeling of micro-structural collagen organization in human cornea
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THE DISTANCE TO CUBIC SYMMETRY CLASS AS A POLYNOMIAL OPTIMIZATION PROBLEM

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Generically, a fully measured elasticity tensor has no material symmetry. However, many materials (such as composite/engineered materials, single crystal superalloys or rocks) have an expected symmetry, most often due to their microstructure and their elaboration process. For instance, for single crystals with a cubic lattice, or for the aeronautics turbine blades superalloys such as Nickel-based CMSX-4, cubic symmetry is expected. In practice, appealing to Curie principle ("the symmetries of the causes are to be found in the effects"), their constitutive tensors shall inherit the material symmetry (orthotropy, cubic or monoclinic symmetry for example), so that the natural question is *to determine the constitutive tensor with a given material symmetry the nearest to a given measured (triclinic) constitutive tensor.* This question has been extensively studied, from both the theoretical and numerical points of view, since the pioneering work of Gazis, Tadjbakhsh and Toupin [7], and subsequent works in the 90s [3, 5, 6]. The problem can be solved by calculating the distance of the experimental tensor to the expected symmetry class. In other terms, given an experimental tensor $\mathbf{E}_{exp}$, denote by Σ the symmetry strata regrouping all tensors having the expected symmetry of $\mathbf{E}_{exp}$, the distance between $\mathbf{E}_{exp}$ and Σ is given by

$$d(\mathbf{E}_{exp}, \Sigma)^2 = \min_{\mathbf{E}\in\Sigma} ||\mathbf{E}_{exp} - \mathbf{E}||^2,$$

hence the problem becomes to find the nearest tensor $\mathbf{E}^* \in \Sigma$ to $\mathbf{E}$

$$\mathbf{E}^* = \underset{\mathbf{E}\in\Sigma}{\operatorname{argmin}}\, d(\mathbf{E}_{exp}, \Sigma)^2.$$

The elasticity symmetry classes have been characterized by polynomial equations and inequalities in [8] (see also [1], or [4] for the case of harmonic fourth-order tensors), illustrating the mathematical property that the closed symmetry strata are semialgebraic sets [2, 9, 10]. We propose to make use of this mathematical property to formulate the distance to cubic symmetry problem as a polynomial (in fact quadratic) optimization problem, and to derive its quasianalytical solution using Euler-Lagrange's method. The proposed methodology also applies to cubic Hill elasto-plasticity (where two fourth-order constitutive tensors are involved).

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CARATHÉODORY'S GEOMETRIC THERMODYNAMICS AND BEYOND

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Maxwell's model of the Gibbs's thermodynamic surface for water. (Cavendish Laboratory)

Geometrical renditions of thermodynamics go back at least to the mathematical foundations laid down by J. Willard Gibbs, as illustrated above by the plaster sculpture by J. C. Maxwell of the volume-energy-entropy surface for water. An axiomatic topological foundation was later given by Carathéodory in his celebrated 1909 treatment of second law thermodynamics, an endeavor encouraged by Max Born.

Influenced to some extent by the treatise of Frankel[1], this paper revisits the second law of thermodynamics via certain modifications of Carathéodory's treatment. It is shown that his postulate of *adiabatic inaccessibility* represents one of several constraints on the energy balance that serve to establish the existence of thermostatic entropy as a *foliation of state space*, with temperature representing a force of constraint. To achieve the thermostatic version of the second law, as embodied in the postulates of Clausius and Gibbs, work principles are proposed to define thermostatic equilibrium and stability in terms of the convexity of internal energy, entropy and related thermostatic potentials. Comparisons are made to the classic work of Coleman and Noll on thermostatic equilibrium in simple continua, resulting in a few unresolved differences.

The most novel aspect of this work is the extension to irreversible processes by means of a non-equilibrium entropy derived from recoverable work, which generalizes similar ideas in continuum viscoelasticity. This definition of entropy calls for certain revisions of modern theories of continuum thermo-mechanics by Coleman, Noll, and others that are based on a generally inaccessible entropy and undefined temperature.

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THE FALL OF A ROD CONSTRAINED BY A SLIDING SLEEVE SUBJECT TO A PERIODIC OSCILLATION

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The concept of configurational forces, introduced to explain the defect motion within solids by Eshelby [2], has been recently extended to the framework of structural mechanics [1] by disclosing the presence of non-null sliding force at the exit of sliding sleeve whenever the constrained rod displays a non-null curvature jump at that point.

With reference to a falling rod constrained at its lower end by an oscillating sliding sleeve, the nonlinear dynamic response is investigated by means of an in-house Finite Element solver. The theoretical results reveal that the injection motion for the rod can be turned into a steady or an ejection motion, by properly tuning the constraint periodic oscillation.

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MATERIAL EVOLUTION FOLIATIONS

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For any body-time manifold R×B there exists a groupoid, called the *material groupoid*, encoding all the material properties of the material evolution. A smooth integrable distribution, the *material distribution*, is constructed to deal with the case in which the material groupoid is not a Lie groupoid. This new tool provides a unified framework to deal with general non-uniform material evolution.

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STOCHASTIC MODELING OF MICRO-STRUCTURAL COLLAGEN ORGANIZATION IN HUMAN CORNEA

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We describe a stochastic model of the structural reinforcement of the collagenous lamellae in the human cornea, derived by means of an improved perturbation method [1]. We consider the microstructural modelling approach recently formulated in [2] and introduce a Lennard-Jones potential to describe the finite elasticity of crosslinks [3] and randomness in the distribution of the orientation parameter at the lamellar level. In particular, according to the state-of-the-art literature in cornea biomechanics, two sets of collagenous lamellar structures connected through inter- and intra-crosslinks are considered. For a realistic human cornea geometry, the stochastic structural element is analyzed numerically in terms of mean displacement response. We investigate different heterogeneous distributions of the elemental stiffness characteristics representative of healthy and keratoconic corneas [4]. We show that the improved microstructural model reproduces bulging and thinning of the diseased cornea. Moreover, the perturbation method provides a good approximation of the expected displacement field even in the case of a moderately large deviation of the uncertain material parameters, requiring a limited computational time. We discuss the applicability of the stochastic analytical approach to very general distributed fibre-reinforced tissues, by linking the material models and properties to biologically based processes.

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SYMMETRIES AND CONSTITUTIVE LAWS

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The use of material symmetries from a constitutive law leads naturally to the use of algebraic/differential tools in continuum mechanics in order to study uniformity and homogeneity properties. Thus, the theory of Lie groups and G-structures (based on that of principal fibered spaces and connections) has been used. More recently, it has been seen how the structure of material isomorphisms is that of grupoids, and in the cases where differentiability is enjoyed, they are Lie grupoids. In this paper we will briefly review how these geometric structures provide an optimal description of phenomena such as growth, aging or morphogenesis.

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GALILEAN CONTINUUM THERMODYNAMICS

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The concepts of Thermodynamics were initially introduced independently of the Continuum Mechanics but these two approaches can be married as in the local versions of the two principles by Truesdell and his school. On the other hand, General Relativity (GR) is not solely a theory of gravitation but –may be above all– it is a consistent framework for the Mechanics and Physics of Continua. Another breakthrough idea is to construct a consistent theoretical framework for Relativity and Thermodynamics. As GR is widely based on differential geometry, we see this process as a geometrization of Thermodynamics. Souriau [3] and –in his footstep– Vallée [4] tried their hand at proposing such a formalism in GR.

In the same spirit, we propose a tensorial description for the Thermodynamics of dissipative continua compatible with Galileo's principle of relativity [1, 2]. The key idea is to consider a lift from the space-time to a 5-dimensional manifold in liaison with Bargmann's group.

The entropy is generalized as a 4-vector and the temperature as a 5-vector. Its gradient, called friction tensor, mixing the components of the temperature gradient occuring in Fourier's heat conduction law and the strain rate occuring in Newton's viscous flow law, is a natural candidate to provide thermodynamic forces in the dissipative phenomenologic laws. The energy momentum tensor of the Relativity is extended as a 2-rank mixed tensor gathering the energy, the linear momentum, the mass density, the heat flux and the stresses. It is divergence free and we recover the balances of energy, linear momentum and mass. This is the Galilean covariant expression of the first principle of thermodynamics.

Based on an additive decomposition of this tensor into reversible and dissipative parts, we deduce the Galilean invariance of the local production of entropy and of the second principle of thermodynamics. We extend our formalism in presence of a Galilean gravitation field. We propose the corresponding relativistic version of the second principle and we confront it against other formulations of the literature.

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BUCKLING ANALYSIS OF MICRO-STRUCTURED BEAMS

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In this work, a homogenized beam model, embedded in the three-dimensional space, is formulated for the buckling analysis of beam-like structures [1,2]. These are grid cylinders, uniformly compressed, made by a periodic and specifically designed assembly of beams. It is assumed that the micro-structure of the cylinder is composed of two families of fibers, one of which is parallel to its axis and the other belonging to the cross-section plane. The arrangement of the second family of fibers consists in a rectangular pattern reinforced by diagonal bracing elements.

The equivalent beam model is formulated in the framework of a direct one-dimensional approach [3] and its constitutive law, including the effect of prestress of the longitudinal fibers, is derived through a suitable homogenization procedure [4,5]. Accordingly, the micro-macro constitutive relations are obtained via an imposed energy equivalence between a cell of the periodic structure and a segment of the homogenized beam, undergoing same deformations. The model also accounts, in an approximate way, for micro-warping of the micro-structure, through the introduction of elastic and geometric corrective factors of the constitutive coefficients.

Buckling and post-buckling behaviors of sample grid beams are presented and discussed to validate the effectiveness and to show the limits of the equivalent model. To this purpose, results supplied by exact and asymptotic analyses of the equivalent beam model are compared with benchmark solutions given by finite-element models of grid beams.

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EXPERIMENTAL EVALUATION OF GRANULAR MICROMECHANICS INSPIRED METAMATERIALS

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Metamaterial systems with granular motif are composed of nearly rigid elements (or grains) in which the elastic strain energy is stored in deformable interconnections or interfaces between the grains. Such systems can be described using continuum models based upon the granular micromechanics approach (GMA) [1-2]. In particular, GMA, has the ability to reveal the connections between the micro-scale mechanisms that store elastic energy and lead to particular emergent behavior at the macro-scale. Recently, we have exploited the GMA paradigm to design metamaterials that follow the granular motif (see for example [3-5]). 3D printing was used to fabricate the designed systems. These were then tested under tension or compression and their deformation analyzed using digital image correlation (DIC). In this presentation, we will describe the salient features of GMA and the findings of the experimental effort, particularly in relation to the grain motions and the emergent macro-scale force-displacement response.

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A CONTINUUM FORMULATION FOR ELASTO-PLASTIC-DAMAGE STRAIN GRADIENT SOLIDS WITH GRANULAR MICROSTRUCTURE

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This presentation is devoted to the development of a continuum theory accounting for elastic [A] and some dissipative phenomena like damage and plasticity [B]. The physical object is defined as those materials having granular microstructure but can be generalized for any continuum model in the same way Navier [C] and Cauchy [D] did in their works. In other words, the continuum description is constructed assuming expressions of elastic and dissipation energies as well as postulating a hemi-variational principle, without incorporating any additional postulate like flow rules. Granular micromechanics is connected kinematically to the continuum scale through Piola's ansatz (also called Cauchy–Born approximation). In elasticity, expressions for geometrically non-linear second gradient coefficients, both in the 2D and in the 3D cases, have been identified in terms of Young's modulus, of Poisson's ratio and of a microstructural length. Besides, Karush–Kuhn–Tucker (KKT)-type conditions, providing evolution equations for damage and plastic variables associated with grain–grain interactions, are derived solely from the fundamental postulates. Numerical experiments have been performed to investigate the applicability of the model. Cyclic loading–unloading histories have been considered to elucidate the material hysteretic features of the continuum, which emerge from simple grain–grain interactions. We also assess the competition between damage and plasticity, each having an effect on the other. Further, the evolution of the loadfree shape is shown not only to assess the plastic behavior, but also to make tangible the point that, in the proposed approach, plastic strain is found to be intrinsically compatible with the existence of a placement function.

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SIMULATION OF THE VIRAL ENTRY INTO A CELL

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The present contribution focuses on the receptor driven endocytosis typical of viral entry into a cell. The process is characterized by a local increase in receptor density necessary to establish contact between the cell and the virus. While the receptors of the virus are fixed on its surface, the receptors of the cell are able to move over its membrane, which leads to a local change in their concentration. In the model developed, the receptor motion is described by the diffusion equation along with two boundary conditions. The boundary conditions represent the balance of fluxes at the front of the contact area, where the velocity is assumed to be proportional to the gradient of the chemical potential [1,2], and the energy balance behind and before the front, causing the fronts movement [3]. The model provides a basis to incorporate different phenomena such as for example cooperativity [4]. This property strongly influences the effective binder density necessary to establish contact. The moving boundary problem describing the process is numerically solved by using the finite difference method and applied to study the change of receptor density over the membrane as well as the motion of the adhesion front. Two features are investigated in particular: The process initiation is analyzed in order to obtain information on possibilities for inhibiting the viral entry, and the non-dimensional analysis is performed to minimize the number of necessary process parameters and to check their priority.

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SOAP FILMS SPANNING ELASTIC BOUNDARIES

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The Kirchhoff-Plateau problem concerns the equilibrium shapes of a system in which a flexible filament in the form of a closed loop is spanned by a liquid film, with the filament being modeled as a Kirchhoff rod and the action of the spanning surface being solely due to surface tension. We establish the existence of an equilibrium shape that minimizes the total energy of the system under the physical constraint of non-interpenetration of matter, buT allowing for points on the surface of the bounding loop to come into contact. In our treatment, the bounding loop retains a finite cross-sectional thickness and a nonvanishing volume, while the liquid film is represented by a set with finite two-dimensional Hausdorff measure. Moreover, the region where the liquid film touches the surface of the bounding loop is not prescribed a priori. Our mathematical results substantiate the physical relevance of the chosen model. Indeed, no matter how strong is the competition between surface tension and the elastic response of the filament, the system is always able to adjust to achieve a configuration that complies with the physical constraints encountered in experiments. In this seminar I will present some results concerning the Kirchhoff-Plateau problem obtained in collaboration with Eliot Fried, Giulio Giusteri, Giulia Bevilacqua and Alfredo Marzocchi.

HOMOGENISED BALANCE EQUATIONS FOR NONLINEAR POROELASTIC COMPOSITES

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Within this work, we upscale the equations that describe the pore-scale behaviour of nonlinear porous elastic composites, using the asymptotic homogenization technique to derive the macroscale effective governing equations.

A porous hyperelastic composite can be thought of as being comprised of a matrix interacting with a number of subphases and percolated by a fluid flowing in the pores (which is chosen to be Newtonian and incompressible here).

A general nonlinear macroscale model is derived and is then specified for a specific choice of strain energy function, namely the de Saint-Venant function. This leads to a macroscale system of PDEs, which is of poroelastic type with additional terms and transformations to account for the nonlinear behaviour of the material.

Our new poro-hyperelastic-type model describes the effective behaviour of nonlinear porous composites by prescribing the stress balance, the conservation of mass and Darcy's law. The coefficients of these macroscale equations encode the detailed microstructure of the material and are to be found by solving pore-scale differential problems.

The model reduces to (a) linear poroelastic composites [1] when the deformation gradient approaches the identity, (b) nonlinear composites [2] when there are no pores and (c) nonlinear poroelasticity [3,4] when only the matrix–fluid interaction is considered.

This model is applicable when the interactions between various hyperelastic phases occur at the pore scale, as in biological tissues such as artery walls, myocardium, lungs and liver.

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FINITE-SIZE METAMATERIAL MODELED AS A RELAXED MICROMORPHIC CONTINUUM FOR ACOUSTIC CONTROL APPLICATIONS

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It is nowadays clear that higher-order models should be chosen in order to better describe micromechanical effects in solids with heterogeneities or microstructures in the framework of elastic waves propagation. In order to model such materials with a continuous model, the relaxed micromorphic model is here proposed [1, 2]. Two of the most common examples of such micromechanical effects are the presence of frequency ranges for which the propagation of waves is inhibited (*band gaps*), and the change of the response of a structure while changing the ratio between its dimensions and the size of the unit cell that characterizes it (*size effects*). Relaxed micromorphic model's parameters are fitted on the dispersion curves of the material of interest (obtained via a Bloch-Floquet analysis) and finite-size structures are designed to exploit their reflective and focusing properties [2] (see one the example in Fig. 1), while also experiments on finite-size samples are performed. The mechanical behaviour of different unit cells is investigate with the intent of optimize the position and the extent of bend-gaps while tuning the magnitude of size effects. Connections between some of the geometrical and material features of the unit cell and the parameters of the relaxed micromorphic model are established.

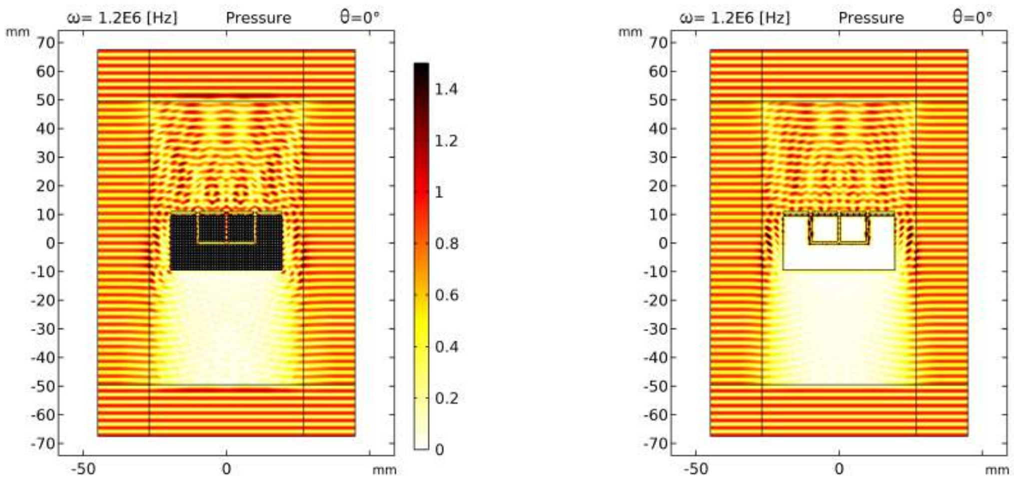

Figure 1: Norm of the dimensionless displacement field (scaled with respect to the amplitude of the incident wave) for (*left*) micro-structured material and (*right*) the equivalent relaxed micromorphic material.

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WAVE PROPAGATION IN AN ACOUSTIC METAMATERIAL MODELED AS A RELAXED MICROMORPHIC CONTINUUM

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In order to describe elastic waves propagation in metamaterials, i.e. solids with heterogeneities or microstructure, it is necessary to consider non-local or higher-order models. The relaxed micromorphic model (RMM) [1, 2] proposed here can describe these effects as a continuous material with enriched kinematics. One of the most important micromechanical effects is the appearance of *band gaps* for which waves at given frequencies cannot propagate through the material and its connection to different *size effects*. These band gaps depend on the geometry of the unit cell as well as the ratio between its dimension relative to the metamaterial's specimen.

In this work, we present a new unit cell giving rise to a metamaterial for acoustic application. The microstructure is engineered to show a band gap in the low acoustic regime (600-2000 Hz). We concentrate on the size effects to make full advantage of the particularly beneficial structure that the model provides. The RMM material parameters are fitted using a new algorithm relying on cutoffs and asymptotes (obtained via a Bloch-Floquet analysis). The dispersion curves of the considered metamaterial as well as the corresponding fitting of the RMM are shown in Figure 1. In particular, by enhancing the kinetic energy of the model with a new inertia term, we enable decreasing curves (modes with negative group velocity).

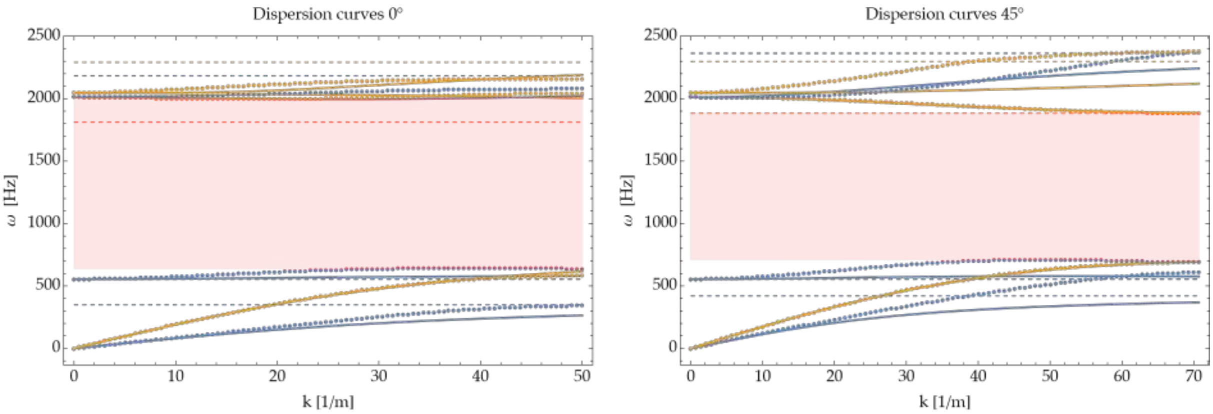

Figure 1: Dispersion curves $\omega(k)$ with pressure and shear curves colored in yellow and blue, respectively. The dots are numerical values from *Comsol Multiphysics*® obtained via BlochFloquet analysis while the solid curves show the relaxed micromorphic model.

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TOWARDS A CONSTRAINED THEORY OF GROWTH MECHANICS

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In this talk, we review some fundamental aspects of the mechanical theory of volumetric growth in continuum bodies, and we rephrase them within the framework of Analytical Mechanics.

Since our study aims at being of some mechanobiological interest, we must account for the fact that, in order for a tissue to grow, its cells must dispose of a sufficient amount of certain chemical species, such as oxygen and glucose, as is the case for tumor masses [1]. To comply with this evidence, models have been presented in which the rate of variation of mass of a given body is supplied phenomenologically as a function of the concentrations of such chemical agents (see e.g. [2]). In our talk, we shall try to harmonize growth laws of this kind with the "most purely" theoretical aspects of the mechanics of growth.

Although merging phenomenological laws with fundamental physical principles is not novel *per se*, accomplishing this task for growth mechanics may present some novel features. One of these is the critical reinterpretation of some pillars of the theories of growth that we regard as reference [3, 4, 5]. More specifically, our commitment is to view phenomenological growth laws as constraints for the analytical theory of growth that we are proposing. This yields a formulation of growth mechanics that may shed light on interactions that are not considered in other models, and it may offer new perspectives in the geometric description of growth. Above all, our approach may help put together the experimental facts observed by biologists with the theoretical paradigms which some mechanicists believe in.

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THE TRUESDELL RATE IN CONTINUUM MECHANICS

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When developing the theory of hypoelasticity, Truesdell [3] introduced the rate

$$\mathring{\sigma}^{ab} = \dot{\sigma}^{ab} - v^a{}_{|c}\,\sigma^{cb} - \sigma^{ad}\,v^b{}_{|d} + v^c{}_{|c}\,\sigma^{ab}, \tag{1}$$

of the Cauchy stress $\boldsymbol{\sigma}$, the vertical bar denoting covariant differentiation and the superposed dot denoting the substantial derivative $\dot{\sigma}^{ab} = \sigma^{ab}{}_{|c}\,v^c + \partial_t\sigma^{ab}$. This rate was intended to be *frame-indifferent*, i.e., invariant under rotations of the spatial frame. However, Hughes and Marsden [2] proved that the Truesdell rate is intimately related to the Lie derivative and thus it not just frame-indifferent, but *objective*, i.e., invariant under general *diffeomorphisms*.

We show [1] that the Truesdell rate is a far more general object, whose natural application is in Reynold's Transport Theorem. In the differential geometric picture, the Transport Theorem is applied to the integral of an r-form $\boldsymbol{\beta}$ over the current configuration $\phi(\mathcal{Q}, t)$ of an r-dimensional submanifold $\mathcal{Q}$ of the body $\mathcal{Q}$. The differential operator involved is the Lie derivative with respect to the spatial velocity $\boldsymbol{v}$:

$$\partial_t \int_{\phi(\mathcal{Q},\,\cdot\,)} \boldsymbol{\beta} = \int_{\phi(\mathcal{Q},\,\cdot\,)} L_{\boldsymbol{v}}\boldsymbol{\beta}. \tag{2}$$

In three dimensions, a three-form $\boldsymbol{\theta}$ is expressed in terms of the standard volume form $\mathrm{d}v \equiv \boldsymbol{\mu}$ and the density f as $\boldsymbol{\theta} = f\,\boldsymbol{\mu}$, and we have

$$\partial_t \int_{\phi(\mathcal{R},\,\cdot\,)} f\,\mathrm{d}v = \int_{\phi(\mathcal{R},\,\cdot\,)} \mathring{f}\,\mathrm{d}v = \int_{\phi(\mathcal{R},\,\cdot\,)} [\dot{f} + f\,\mathrm{div}\,\boldsymbol{v}]\,\mathrm{d}v, \tag{3}$$

and a two-form $\boldsymbol{\omega}$ is expressed in terms of the contraction $\langle \boldsymbol{w} \,|\, \boldsymbol{n} \rangle$ of the flux density $\boldsymbol{w}$ defined by the interior product $\boldsymbol{\omega} = \iota_{\boldsymbol{w}}\boldsymbol{\mu}$ and the normal covector $\boldsymbol{n}$ to the surface, i.e.,

$$\partial_t \int_{\phi(S,\,\cdot\,)} \langle \boldsymbol{w} \,|\, \boldsymbol{n} \rangle\,\mathrm{d}a = \int_{\phi(S,\,\cdot\,)} \langle \mathring{\boldsymbol{w}} \,|\, \boldsymbol{n} \rangle\,\mathrm{d}a = \int_{\phi(S,\,\cdot\,)} \langle \dot{\boldsymbol{w}} - \boldsymbol{l}\,\boldsymbol{w} + (\mathrm{div}\,\boldsymbol{v})\,\boldsymbol{w} \,|\, \boldsymbol{n} \rangle\,\mathrm{d}a. \tag{4}$$

The Truesdell rates $\mathring{f}$ and $\mathring{\boldsymbol{w}}$ correspond precisely to the Lie derivatives $L_{\boldsymbol{v}}\boldsymbol{\theta}$ and $L_{\boldsymbol{v}}\boldsymbol{\omega}$.

As an example, we show that the *convected derivative* used extensively in the theory of electromagnetism in continuous media [4] coincides in fact with the Truesdell rate of a flux density shown in (4).

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MINIMISERS OF THE CANHAM-HELFRICH FUNCTIONAL IN THE SPACE OF GENERALISED GAUSS GRAPHS

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The Canham-Helfrich functional is the most widely used functional to study the equilibrium of biological membranes as a result of the competition between mean curvature and Gaussian curvature. In this talk, we review some approaches to the minimisation problem for this functional and present novel results in the setting of generalised Gauss graphs. This is joint work with Anna Kubin and Luca Lussardi.

MODELLING CELL REORIENTATION UNDER STRETCH: A MECHANOBIOLOGICAL EXAMPLE

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The active response of cells to mechanical cues due to their interaction with the environment has been of increasing interest, since it is involved in many physiological phenomena, pathologies, and in tissue engineering. In particular, several experiments have shown that, if a substrate with overlying cells is cyclically stretched, they will reorient to reach a well-defined angle between their major axis and the main stretching direction. The aim of this talk will be to investigate the interplay between mechanics and cell organization. It will be shown that cells organise their internal structure to minimize an elastic energy that then drives this reorientation process. Viscoelastic effects will then be included to explain the dependence of the appearance of the phenomenon as a function of oscillation frequency.

CAUCHY'S FLUX THEOREM FOR *n*-DIMENSIONAL AFFINE SPACES

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Cauchy's theorem for the existence of the flux vector is one of the fundamental results of continuum mechanics. While for Euclidean spaces the flux is a vector field, for general n-dimensional manifolds, where no metric tensor is a priori given, the flux field is an $(n - 1)$-differential form. As such, the value of the flux field at a point is a completely antisymmetric multi-linear mapping.

In this talk, with the objective of motivating the multi-linear, antisymmetric character of fluxes, we consider functions defined on the collection of oriented $(r-1)$-simplices in an n-dimensional affine space. We show that such functions, which satisfy some natural assumptions, are multilinear and completely antisymmetric with respect to the vectors that make up the simplices. Specifically, the real-valued functions of simplices are assumed to have the following properties: (1) *Translation invariance:* The value of a function, for any given simplex, is invariant under the translation of the simplex. (2) *Homogeneity:* The value of a function is homogeneous in any of the vectors that determine the simplex. (3) *Additivity:* The function is additive under a subdivision of simplices. In addition, if an r-simplex is subdivided, then, the total flux through its boundary is equal to the sum of the fluxes through the boundaries of the simplices it contains. Under these assumptions, one can show that the flux functions are odd with respect to the orientation of a simplex and are sign-alternating under permutations of their arguments.

Next, we strengthen assumption (3) and postulate the following. (4) *Balance:* The sum of fluxes through the faces of an r-simplex is assumed to vanish. Under this additional assumption, we show that the flux functions are multilinear in the vectors that make up a simplex.

The *content* of a simplex is the property of the simplex that determines the flux through it. Mathematically, the content of a simplex is represented by the simple multivector determined by the vectors it comprises.

Once the properties of the flux function, defined on the collection of simplices, are established, its domain of definition can be extended naturally to the vector space of polyhedral chains, linear combinations of simplices. The content of a polyhedral chain is represented by a linear combination of the contents of the simplices it contains so that algebraically, it is represented by a multivector which need not be necessarily simple. Thus, the flux function belongs to the dual space of the space of multivectors—an alternating multilinear mapping or a multicovector.

THE MULTI-SCALE ROLE OF REMODELLING IN HOMOGENIZED HETEROGENEOUS MEDIA

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In this work, we employ the two-scale asymptotic homogenisation technique [1] to obtain an effective description of a heterogeneous medium, in which the internal structure evolves according to a stress-driven phenomenological law [2]. In particular, the micro-structural evolution, which we refer to as material remodelling, is identified with the production of inelastic distortions and mathematically addressed by having recourse to the BKL (Bilby-Kröner-Lee) multiplicative decomposition of the deformation gradient tensor [3], which we reformulate in a scale-dependent fashion. The study is then framed within the limit of small elastic distortions, and the presence of the inelastic distortions results in a coupling between the homogenised and the so-called cell problems. We complete our theoretical model by showing some numerical simulations.

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ON THE ROLE OF ELASTICITY IN THE QUASI-STATIC DECOHESION OF BIOLOGICAL SYSTEMS: A VARIATIONAL APPROACH

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We develop a variational framework to study the onset of decohesive processes in biological systems. In doing this, we particularise our study to focal adhesions, which play a fundamental role in guaranteeing the attachment of cells to the extra-cellular environment and sustain several cell functions [1]. In our work, we consider a three-layer scheme, consisting on three mechanical elements representing the focal adhesion, the extra-cellular environment and the integrin receptors [1, 2]. The latter ones, in particular, are supposed to transmit linear-elastic fragile forces between the other two elements [2]. With reference to a Griffith-like criterion of rupture, we analytically individuate the transition from a fully attached state of the system to the nucleation of a decohesion front, up to full decohesion [2]. Furthermore, we go into the modulation provided by elasticity, and we deduce how the relative elastic properties of the layers determine a ductile-fragile detachment transition [2]. Our model is then compared with other theoretical approaches, as those employed for the characterisation of the DNA denaturation [3, 4], and with experimental results available in the literature [5]. In both cases, the agreement is very good, both qualitatively and quantitatively.

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COUPLING BETWEEN REMODELLING AND INTERSTITIAL FLUID FLOW IN MULTICELLULAR AGGREGATES

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The evolution of living systems is affected both by external processes, e.g. the interactions with the environment, and by internal processes [1]. Multicellular aggregates represents a workaround to some aspects of this complexity that arises in the study of biological media. Their relatively simple shape (usually spheroidal) and micro-structure, along with the ease of preparation for experiments, are so that mathematical models can focus on describing the most important features of the processes involved during compression-release tests.

We propose to study, in a mechanical setting, a mathematical model of a three dimensional, elasto-plastic bi-phasic description of multicellular aggregates [2]. In particular, with respect to the setting presented in [3], we consider a more thorough model in which the extracellular fluid, for which we assume Darcian regime, can circulate inside the aggregate and can flow through the free boundary. We are interested in studying how the mechanical and hydraulic properties of the multicellular aggregate vary as remodelling occurs, that is, as the onset of plastic-like, stress-driven distortions alters the properties of the internal structure.

A contact problem is formulated to consider the exchange of mechanical actions between the compressive apparatus and the biological tissue. The evolution of the system is solved with respect to the displacement prescribed to the plates between which the spheroid is inserted. The results of the simulations show a qualitative agreement with the experimental curves in [4], and, in addition, direct consequences of the coupling between remodelling and the flow of interstitial fluid distribution can be observed.

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ISOMETRIC DEFORMATIONS:

CLOSED RIBBONS AND BEYOND

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The bending energy associated with deforming a flat material surface is proportional to the integral of the square of the mean curvature over the deformed surface. However, since such materials can only undergo isometric deformations, this energy can be dimensionally reduced so as to be written as a line integral with a suitable energy density. In the case of a Möbius band, Sadowsky [1] performed this reduction under the assumption that the strip was infinitely narrow, while Wunderlich [2] carried it out without this restriction. These models, and others, allow for the equilibrium configurations to be found by solving a system of ordinary differential equations rather than partial differential equations. Here the same dimensional reduction is performed starting with an isometric deformation of a material strip with prescribed matching edge conditions. This allows for a more complete and accurate description of the problem than in earlier works. Moreover, the outlined approach allows for the formation of orientable and nonorientable closed ribbons with any number of twists. I will also discuss some current work on isometric deformations of more general planar domains and the challenges associated with performing the dimensional reduction in this case. This is joint work with Yi-Chao Chen and Eliot Fried.

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MS-26 Nonlinear Behavior of Vaulted Masonry Structures
Antonio Cazzani (Università degli Studi di Cagliari, Italy), Antonella Cecchi (Università IUAV di Venezia, Italy), Gabriele Milani (Politecnico di Milano, Italy) and Emanuele Reccia (Università degli Studi di Cagliari, Italy)

MS-31 New trends, challenges, and visions in block-based modeling techniques for masonry
Daniele Baraldi (Università IUAV di Venezia, Italy), Antonella Cecchi (Università IUAV di Venezia, Italy), Antonio Maria D'Altri (Università di Bologna, Italy), Stefano de Miranda (Università di Bologna, Italy) and Ginevra Salerno (Università degli Studi Roma Tre, Italy)

Spatial and temporal discretizations for masonry failure
J. G. Rots, M. Pari, M. Sousamli, M. Longo, F. Messali

Limit analysis of spherical masonry domes under vertical loads: Parametric studies and statically admissible stress fields
F. Barsi, R. Barsotti, S. Bennati

On the definition of masonry strength domain: A simple procedure
G. Bertani, L. Patruno, A. M. D'Altri, G. Castellazzi, S. de Miranda

The behavior of masonry arches and vaults under fire
N. S. Burello, A. P. Fantilli

Optimized thrust surfaces for the safety assessment of masonry vaults
A. Fraddosio, N. Lepore, M.D. Piccioni

Simple heterogeneous limit analysis modelling of reinforced masonry arches
Y. Hua, G. Milani

A dynamic study of Beit-El-Din Hammam and its multi-holed masonry vaults
A. Gerges, M.C. Porcu, A. Cazzani, J. Harb, M. Dabaghi

Lower Bound model for the analysis at collapse of masonry vaults
G. Milani

Discontinuity layout optimization for the limit analysis of non-periodic masonry
M. Schiantella, M. Gilbert, C. C. Smith, Linwei H., F. Cluni, V. Gusella

Damping models for dynamic analysis of masonry vaults with discrete elements
J.V. Lemos

Understanding the behavior of masonry structures subjected to blast loads
F. Masi, I. Stefanou

On the construction stage analysis of historical masonry vaults
M. Zucca, E. Reccia, F. Stochino, A. Cazzani

*Multiscale finite element analysis of masonry vaults linking shell and 3D formulations*F.
D. Addessi, P. Di Re, C. Gatta, E. Sacco

SPATIAL AND TEMPORAL DISCRETIZATIONS FOR MASONRY FAILURE

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This contribution presents progress in understanding spatial as well as temporal discretization for computational tracking of masonry failure. Spatial discretization refers to the way in which the masonry constituents (bricks, mortar, brick-to-mortar interfaces) and their bond pattern are represented within the finite element context. Temporal discretization refers to the way in which the loading is added, in load, time, displacement, arc-length, indirect displacement or damage control in order to reach convergence.

Figure: Highly brittle and discontinuous phenomena observed in masonry failure

First, pictures of recent test results will be looked upon. We observe multiple discontinuities, sharp tensile cracks, shear friction and sliding, degrading crushed mortar, splitting, spalling, misalignment along bed joints, and even pieces of joints and bricks falling into existing cracks underneath and thus preventing them from being closed in cyclic loading.

How can we discretize this? It is not feasible to model all these micro phenomena explicitly in a detailed manner. Clearly, there is a need to smear them out and model them in a continuum sense, certainly for the compression component with multiple splitting, spalling and crushing occurring over larger volumes. Here, advances in fixed and rotating total-strain based approaches will be summarized, including double orthotropy. This will be compared with brick-to-brick micro modelling approaches, for challenging cyclic load cases.

How can we increment the loading such that equilibrium and convergence are maintained? In tests the micro-failures produce sound, jumps and brittle snaps in the static response. Here, recent work on sequentially linear event-by-event saw-tooth softening methods will be summarized, whereby the softening is discretized and damage control steers the analysis rather than load, displacement or arc-length control.

LIMIT ANALYSIS OF SPHERICAL MASONRY DOMES UNDER VERTICAL LOADS: PARAMETRIC STUDIES AND STATICALLY ADMISSIBLE STRESS FIELDS

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In the extensive scientific literature on the safety assessment of historic masonry buildings, limit analysis is present as one of the most established theoretical frameworks. As is well known, Heyman's assumptions [1], according to which the material is unable to transmit tensile stresses, the compressive strength is unbounded and no sliding failure is allowed, allow the development of simple but reliable models to identify the conditions of possible collapse. These assumptions, which the early builders had already guessed to be substantially fulfilled, and which were largely taken over by the early static theories, appear almost always justified in the case of historic buildings of monumental value. In particular, the evaluation of the safety of masonry domes and vaults carried out by searching for statically admissible distributions of internal forces 'a la Heyman' is well documented in the literature of recent years [2] [3].

This contribution proposes to evaluate the safety level of masonry domes by means of the static theorem of limit analysis, through the assessment of the smallest value of the thickness compatible with equilibrium. The dome is modeled as a thin shell made of a material that satisfies Heyman's assumptions. Statically admissible distributions of internal forces, appropriately combining membrane forces and bending moments, are sought through a specifically developed procedure. The differential equations of equilibrium of the shells are integrated by resorting to an 'ad hoc' numerical procedure. The optimal solution, *i.e.*, the one that maximizes the safety coefficient, is searched by solving a convex optimization problem.

In the present work, the developed solution method is exploited for the parametric analysis of spherical domes subjected to their own weight and having an upper opening. The correlation between the main geometrical parameters and the safety level is highlighted and discussed also in the light of existing results in the literature. The influence of a reinforcing ring around the top oculus on the safety level is also studied.

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ON THE DEFINITION OF MASONRY STRENGTH DOMAIN: A SIMPLE PROCEDURE

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Numerical modeling of masonry structures has undergone a considerable development in recent years. Particularly, block-based models appear very promising to investigate the main aspects of masonry mechanics, as they can account for the actual masonry texture.

In this contribution, in the spirit of analyzing representative volume elements (RVEs) for masonry homogenization, the role of masonry texture is analyzed and discussed in terms of strength domains. For this aim, a block-based model, characterized by zero-thickness frictional-cohesive interfaces for mortar together with a continuum damage plasticity model for blocks, is adopted.

As a result, a simple procedure for the definition of the strength domain is obtained and discussed. An arbitrary number of fracture mechanisms can be easily accounted for in the strength domain, making it suitable both for masonry and for textured continua in general.

Applications to regular masonry mechanical behavior are then considered. The main features of the procedure are highlighted and the possible extension to other masonry textures is also discussed.

THE BEHAVIOR OF MASONRY ARCHES AND VAULTS UNDER FIRE

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An experimental campaign performed on curvilinear masonry structures is described herein. For these structures, widely present in existing buildings, the structural assessment under fire conditions is not properly ruled. This is also due to the lack of experimental investigations, which are difficult to carry out on full-scale structures subjected to elevated temperatures. Therefore, new laboratory tests were performed on prototypes of barrel vault (see Fig.1), subjected to a standard fire in the intrados and to distributed loads in the extrados. The goal is to extend the calculation approaches currently used for vertical elements (i.e., walls and pillars) to arches and vaults. In particular, a simple, albeit conservative, measure of the safety of the structure can be obtained by applying the method of reduced sections in combination with the limit analysis.

Figure 1 – The barrel vault subjected to elevated temperatures

OPTIMIZED THRUST SURFACES FOR THE SAFETY ASSESSMENT OF MASONRY VAULTS

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Masonry constructions represent a significant part of the Italian and World Architectural Heritage, to be preserved for future generations since the invaluable cultural and historical value.

Despite the increasing efforts of the research community, there are not still widely accepted approaches for studying the structural response of masonry structures, especially in the case of complex-geometry structures such as historic masonry vaults.

Limit Analysis equilibrium approaches appears to be very interesting, since are substantially independent from the need of an accurate mechanical characterization of the structure, usually impracticable in real applications. Anyway, classical approaches could lead to a strong underestimation of the actual load-bearing capacity, or cannot be employed for complex load conditions like, e.g., for seismic loads. Recent studies have tried to overcome the above drawbacks, proposing Limit Analysis equilibrium approaches able to consider the complex three-dimensional structural behavior of masonry vaults, thus giving a substantially better load-bearing capacity estimate.

In this context, the Thrust Surface Method (TSM), lately proposed by the authors, represents an optimized solution-oriented application of the lower bound theorem of Limit Analysis capable of fully exploring the spectrum of statically admissible solutions for masonry vaults having an arbitrary geometry and under a general load condition. Indeed, through a convenient numerical procedure and the formulation of a suitable constrained optimization problem, TSM provides optimal solutions for any vertical and horizontal loads, including those simulating the seismic inertia effects.

Here, the effectiveness of TSM is discussed in light of some representative cases of historical masonry vault shapes.

SIMPLE HETEROGENEOUS LIMIT ANALYSIS MODELLING OF REINFORCED MASONRY ARCHES

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Heterogeneous limit analysis with infinitely resistant blocks and rigid-plastic joints reduced to interfaces is a powerful tool for the prediction of the collapse behavior of historical arch and vault masonry structures, also in presence of a reinforcement of any nature. Such analysis not only can provide the collapse mechanism and ultimate load of the structures in a quick and reliable manner in a single step, but can precisely take into account the heterogeneous nature of the masonry material most precisely. This contribution proposes a heterogeneous model for masonry arches in present of innovative strengthening (FRP/FRCM). In the model blocks are assumed infinitely resistant and joints are reduced to interfaces with cohesive frictional behavior and non-associated flow rule. The reinforcement is considered suitably modifying the admissibility conditions of the joints and imposing new compatibility constraints. First, the governing theoretical formulation of the ultimate limit state for arches is elaborated, including the equilibrium conditions, the compatibility conditions, the constitutive and flow laws, the non-negative external work condition, and the complementary condition. After that, the solution of the collapse problem employing associated or non-associated flow rules for the joints is discussed respectively. Some examples and parametric studies are considered to show the implementation of the theory and put at disposal to the reader an operative tool for design and assessment.

A DYNAMIC STUDY OF BEIT-EL-DIN HAMMAM AND ITS MULTI-HOLED MASONRY VAULTS

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Designed by an Italian architect, the Beit-El-Din Palace is an impressive Lebanese monumental complex built at the end of the 18th century with elegant Arabic style. Of particular interest within the complex is the Hammam, which is a masonry structure characterized by domes and barrel vaults pierced by holes, as in inlay work. These holes are covered by stained glass which decompose the light inside in suggestive chromatic effects. Despite its huge importance for the Lebanese heritage, this monument has not yet been studied from a structural point of view to assess its likely vulnerability to exceptional actions it may suffer during its life. The present study aims to contribute to fill this gap.

A tridimensional detailed finite element model of the Beit-El-Din Hamman was built in ABAQUS, where the presence of holes in the domes was carefully reproduced. In some cases, the holes cover almost the entire vault, which is expected to affect the stress paths somehow. To assess the influence of the holes on the local behaviour of the system, a twin model without holes was also considered in the analyses. An isotropic linear behaviour of the masonry material was firstly considered, while a non-linear behaviour was secondly assumed through a concrete plasticity model. In-situ dynamic tests under environmental excitations were made to find the first natural frequencies of the structure. An iterative identification procedure, based on comparing numerical and experimental eigenfrequencies, was then performed to find the best-fitting values of the mass density and elastic modulus to be considered in the numerical model. Linear and non-linear time-history analyses were finally carried out to assess the performance of the structure under seismic actions. The results of the study give some preliminary indications on the seismic vulnerability of the monument. Some features of the patterns of stresses in multi-holed domes and barrel vaults are also finally discussed.

LOWER BOUND MODEL FOR THE ANALYSIS AT COLLAPSE OF MASONRY VAULTS

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An equilibrated and admissible Lower Bound LB discrete element approach for the analysis at collapse of masonry vaults and domes is presented. A double curvature masonry structure is discretized into hexahedrons assumed infinitely resistant and quadrilateral interfaces with rigid plastic behavior, where plastic dissipation occurs for the contemporary presence of bending moment, torque, axial load and shear (with an in-plane and an out-of-plane component). Equilibrium is imposed inside elements and admissibility on interfaces. As far as the admissibility of the interfaces is concerned, it is interesting to point out that masonry can be modeled either as a no-tension material or with more complex surfaces, for example derived from homogenization. A simple Linear Programming LP problem is so derived, where the actual thickness of the structure is taken into account. The limit analysis problem so obtained is characterized by a quite reduced number of variables to deal with, boosting the computational efficiency and limiting premature halting to a great extent. The numerical model is validated through two structural examples, a dome and a cloister vault. A detailed comparison with alternative numerical approaches available in the literature is carried out to show the suitability of the method proposed.

DISCONTINUITY LAYOUT OPTIMIZATION FOR THE LIMIT ANALYSIS OF NON-PERIODIC MASONRY

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Historical masonry buildings are commonly composed by walls having irregular bonding patterns called non-periodic texture. The latter may be defined as quasi-periodic if it has horizontal courses, each one with a defined height, while the units within the course may have variable width. If the texture doesn't even have horizontal courses it may be called chaotic. For a periodic texture, several methods are present in literature (see [1] for a discussion). For non-periodic masonry instead, the determination of the load that the wall can carry is tough and in [2] Discontinuity Layout Optimization for a rigid block analysis has been used to determine the influence of such textures on the failure multiplier. DLO was proposed in ([3], [4]) and it allows to perform a limit analysis identifying the failure mechanism among several by means of linear programming techniques. In a recent work [5], the effect of the variation of three different textures, the variation of the size and shape of the panel and the mechanical properties have been addressed.

In this paper, a further classification for the quasi-periodic texture is provided and the textures are analysed through DLO both for a rigid block model approach and for an homogenized smeared approach. The key parameter used for the homogenized model is the Aspect Ratio of the blocks, namely the ratio between the width and the height of the element; the way it is individuated throughout the wall varies from one approach to another. Results shows that when the wall is composed by an high number of elements, the homogenized models are representative and are also a safe lower bound. Some exceptions are then identified and discussed.

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DAMPING MODELS FOR DYNAMIC ANALYSIS OF MASONRY VAULTS WITH DISCRETE ELEMENTS

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Discrete element block models provide a useful tool for the numerical analysis of masonry structures. They are particularly apt to represent the nonlinear response which is often governed by the shearing and separation of blocks taking place along the structure's joints and discontinuities. Arches and vaults have been successfully analyzed with this approach, namely under the action of earthquakes and other dynamic loads. For time domain dynamic analysis, explicit solution algorithms are the most common choice, given their ability to follow the nonlinear contact phenomena, including in the large displacement range, as the structure's failure mechanism progressively develops.

The present paper addresses the use of discrete element models for seismic analysis of arched and vaulted masonry structures. First, the issues of representation of these structures with rigid blocks is analyzed, namely in terms of accuracy and computational efficiency. Then, the issue of dissipation models during dynamic events is addressed. The standard Rayleigh damping model for time domain analysis is discussed. An alternative damping model is proposed, based on the use of Maxwell elements in the contacts between blocks. The advantages of the new model are examined, in particular its ability to achieve nearly uniform damping for a wide frequency range. The computational advantages for explicit time stepping algorithms are also evaluated, given its less restrictive time step requirements in comparison with standard Rayleigh damping. These issues are discussed by considering various applications of the models, and the damping alternatives, to barrel vaults and cross-vaults, using rigid block representations.

UNDERSTANDING THE BEHAVIOR OF MASONRY STRUCTURES SUBJECTED TO BLAST LOADS

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Masonry structures, made of bricks and stones, are vulnerable architectural assets to impulsive loading. The aim of this work is to investigate the behavior of key structural elements and buildings subjected to blast loads, arising from explosions.

Due to the inherent heterogeneous nature and an often complex geometry, vaulted masonry structures are characterized by a strong coupling between in- and out-of-plane motions. To this end, we leverage the Discrete Element Method to perform advanced numerical simulations which account for the mechanical and geometrical characteristics of the masonry, at the meso-scale. After validation against existing experimental tests, we investigate the dynamic response of planar arches as well as the influence of the geometry and the slenderness ratio [1]. Scale effects are also analyzed. Then, we consider the more interesting scenario of three-dimensional vaulted elements [2]. Parametric studies are performed to evaluate the influence of various material parameters on the overall dynamic structural response of the systems.

Despite the high degree of detail, the aforementioned simulations reveal the bottleneck of DEM and its prohibitive computational cost for the analysis of real-scale masonry structures. To this purpose, we propose a simplified macroscopic modeling approach, based on the previous studies and results. Beside its strong assumptions, the proposed model allows to mimic the meso-scale behavior in large Finite Element simulations, accounting for variations in the specific material parameters. Despite its limitations, our approach allows good estimations of the blast resistance and represents a satisfactory compromise between accuracy and associated computational cost. We show the performance of such an approach by investigating the response of a vaulted building due to explosions [3].

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ON THE CONSTRUCTION STAGE ANALYSIS OF HISTORICAL MASONRY VAULTS

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A growing interest in the preservation of historical masonry constructions led to analysing in detail the structural behaviour of masonry vaults. In the last decades, several approaches have been proposed to analyse vaults' behaviour under static and dynamic loads [1], which depends on different parameters such as shape, mechanical properties of masonry and brick pattern.

In this paper, the static behaviour of a historical masonry sail vault, characterized by a complex brick pattern and by a segmental shape, is analysed. Such typology of vaults is widely diffused in the area of Cagliari, where many of them have been built during the XIX century. Some hypotheses about the constructive techniques adopted are investigated. In particular, the role played by the arrangement of the bricks is considered. The purpose is to check whether the adopted bricks pattern allows construction of vaults without formwork [2].

Starting from a geometry model which has been reconstructed from a complete laser scanner survey, a finite element model is developed to perform a construction stage analysis. Thus, the evolution of the stresses acting on the different parts composing the vault during the construction process is studied, assuming that no formwork has been used.

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MULTISCALE FINITE ELEMENT ANALYSIS OF MASONRY VAULTS LINKING SHELL AND 3D FORMULATIONS

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Vaulted masonry structures are fascinating typologies composing the architectural heritage of many countries. Thus, preservation of their structural performance is a worldwide felt concern.

Notoriously, masonry constructions exhibit a complex nonlinear response even for low intensity loads, mainly due to the heterogeneous nature of the material, composed of bricks/blocks and mortar layers, whose arrangement and mechanical properties strongly affect the overall behavior. Particularly, masonry texture plays a crucial role in the collapse load of masonry vaults [1]. Hence, among the various methods and computational tools available [2], multiscale approach is a suitable choice, as this allows for the detailed geometric/mechanical modeling with limited computational effort.

Relying on the above considerations, this study analyzes response of masonry vaults with regular texture by using the advanced multiscale strategy recently proposed in [3]. The model connects two different structural models at the two scales, exploiting the advantages of each formulation in a combined way. At the macroscopic level a homogeneous Mindlin-Reissner shell is considered and its constitutive behavior is evaluated by the detailed analysis of the masonry representative unit cell. This latter is modeled at microlevel considering the classical threedimensional Cauchy continuum. The model is implemented in a finite element procedure, but, differently from the classical multiscale FE^2 approach, a Transformation Field Analysis method is exploited considering piece-wise uniform distributions of damage and plasticity mechanisms over the mortar joints, thus resorting to a reduced order model with indubitable computational advantages.

Numerical applications are performed by investigating response of masonry vaults in terms of maximum load and damaging paths under typical loading conditions. Results obtained with the proposed model are compared with those recovered by detailed micromechanical analyses and experimental evidences.

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MS-27 Size-dependent continua: recent advances, theory and applications
Paolo Fuschi (Università Mediterranea Reggio Calabria, Italy) and Aurora Angela Pisano (Università Mediterranea Reggio Calabria, Italy)

Asymptotic comparison of the strain-gradient and micromorphic models when loading forces are widely spread
P. Seppecher, L. Jakabcin

Coupling Navier-Stokes equations and peridynamics for the 3D numerical simulation of fluid-structure interaction with fracturing
F. Dalla Barba, U. Galvanetto, F. Picano, M. Zaccariotto

Peridynamics implementation of a space-time gauge theory for ductile damage in metals and alloys
S. Kumar, D. Roy

Periodic wave propagation in nonlocal beams resting on a bilinear foundation
S. Lenci, V. Settimi

Nonlinear mechanics of small-scale nanocomposite beams
M. S. Vaccaro, F. P. Pinnola, R. Barretta, F. M. de Sciarra

On the spectral properties of a nonlocal integro-differantial operator
S. F. Pellegrino

Enhanced forms of the Eringen's nonlocal elastic model for beams in bending
A.A. Pisano, P. Fuschi

ASYMPTOTIC COMPARISON OF THE STRAIN-GRADIENT AND MICROMORPHIC MODELS WHEN LOADING FORCES ARE WIDELY SPREAD

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It sometimes happens that different homogenization results describe the effective behavior of the same heterogeneous material either by a strain-gradient model or by a micromorphic one. These seemingly contradictory results can be reconciled. Indeed, it is well known that strain-gradient and micromorphic models are close models. In this presentation we make precise this affirmation by considering solutions of both models submitted to a periodic loading with increasing wavelength and by studying their relative asymptotic behavior. Roughly speaking we are proving that both models, when considered at a large scale, are very close to each other. Here "large" means "large with respect to the intrinsic lengths which are naturally attached to these types of models". The fact that they are close to each other is obvious as they both converge to a classical Cauchy model. What we prove is that their difference converges to zero at a higher order.

This result is obtained using Fourier analysis in tensor spaces and it applies to a large class of micromorphic models.

Interesting enough, there exist examples of micromorphic models that do not belong to this class and thus are not accurately approximated by any strain-gradient models.

COUPLING NAVIER-STOKES EQUATIONS AND PERIDYNAMICS FOR THE 3D NUMERICAL SIMULATION OF FLUID-STRUCTURE INTERACTION WITH FRACTURING

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Fluid-Structure Interaction (FSI) is a strongly non-linear problem that involves the intricate coupling between the governing equations of fluid dynamics and solid mechanics. The deformation of the immersed structures, and the consequent modification of the solid-fluid interfaces, strongly couples the dynamics of the fluid with that of the solids involved in the process. FSI problems are encountered in a wide variety of engineering applications and scientific fields, ranging from aerospace and civil engineering to planetary sciences. Advancing our capability in the modelling of this class of problems is of crucial relevance, but presents many challenges related to the complexity of the phenomena involved, their multiphysics nature and the high demand for computational resources. FSI becomes even more complex if fracture mechanics is taken into account, e.g. hydraulic fracturing (HF). In this field, improving existing numerical models would play a significant role in mitigating the environmental impact of HF and enhancing its effectiveness. In this context, we aim to present a novel methodology for simulating generic, three-dimensional fluid-structure interaction problems involving fracturing. Ordinary state-based peridynamics is used to describe the mechanical behaviour of the solid phase. The governing equations of peridynamics are coupled via a multi-direct immersed boundary method with the incompressible formulation of the Navier-Stokes equations, which are used to resolve the dynamics of the fluid phase. The synchronization of the solution is achieved with a fully explicit, weak-coupling strategy that allows for fast and efficient computations. We tested our methodology against different benchmarking test cases whose results were compared to wellreferenced and independent data available in the literature. Finally, the proposed methodology was applied to the numerical simulation of the breakup of a porous medium due to the action of a fluid stream forced to flow through it. Some qualitative results of the simulation are presented to show the potential of the proposed approach.

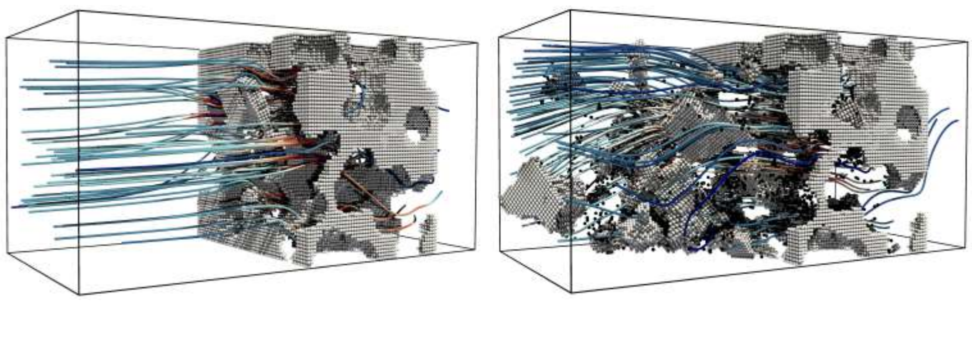

Figure 1: Snapshots of the break up of a portion of a porous medium in a laminar flow at two different time steps. Streamlines are colored according to velocity magnitude.

PERIDYNAMICS IMPLEMENTATION OF A SPACE-TIME GAUGE THEORY FOR DUCTILE DAMAGE IN METALS AND ALLOYS

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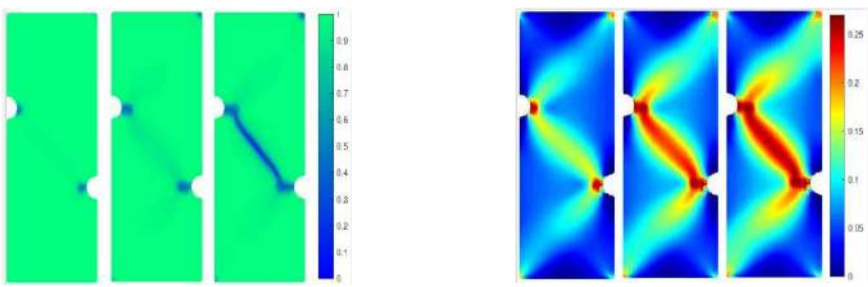
Exploiting local translational and conformal (scaling) symmetries in space-time, a gauge theoretic model is developed to explore ductile damage in metals and alloys over wide ranges of strain rate and temperature. Invariance of the energy density under local translation and scaling is preserved through minimally replaced space-time gauge covariant operators. Minimal replacement introduces two non-trivial gauge compensating fields pertaining to local translation and scaling. These are used to describe ductile damage, including plastic flow and micro-crack evolution in the material. A space-time pseudo-Riemannian metric is used to lay out the kinematics in a finite-deformation setting. Recognizing the available insights in classical theories of viscoplasticity, we also establish a correspondence of the gauge compensating field due to spatial translation with Kröner's multiplicative decomposition of the deformation gradient. Thermodynamically consistent coupling between viscoplasticity and ductile damage is ensured through an appropriate degradation function. While deriving macro- and micro-force balances, we also consider the interaction of dislocations with the surfaces formed due to micro-cracks, e.g. the effect of dislocations absorption by the crack surfaces. Subsequent application of the laws of thermodynamics yields constitutive relations and provides temperature evolution. Non-ordinary state-based (NOSB) peridynamics (PD) discretization of the model is used for numerical implementation. We conduct simulations of both homogeneous and inhomogeneous deformation scenarios (see Fig. 1) to validate the model against available experimental evidence and to assess its predictive features.



(a) (b)

Figure 1. Contour plots of fields pertaining to damage and plasticity; (a) damage; (b) equivalent plastic strain.

PERIODIC WAVE PROPAGATION IN NONLOCAL BEAMS RESTING ON A BILINEAR FOUNDATION

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Recently, periodic waves propagating in a Euler–Bernoulli beam resting on a bilinear elastic foundation have been analytically investigated [1]. Different stiffnesses of the foundation for positive and negative values of the displacements have been considered in order to realistically model embedding media with different reactions in compression and tensile conditions. The analyses have revealed several interesting behaviors, such as veering-like phenomena with changes from single wave to multiple wave solution, and cusp points in the wave path.

When moving from macro- to micro- and nano-scale, the peculiar performances of nanoscale materials and structures are proved to be strongly related to their very small size, highlighting a significant size effect in the mechanical properties, which has an important role in their static and dynamic analysis. Classical continuum elasticity, which is a scale free theory, is not able to take into account the size effect in modelling of the material behavior at the nanoscale, so that nonlocal models have to be adopted [2–4].

In this framework, a nonlocal model of Euler-Bernoulli beam resting on a bilinear elastic foundation is proposed, in order to possibly describe the behavior of carbon nanotubes embedded in elastic medium with different compression and tensile stiffnesses. The variational formulation is developed by resorting to a generic quadratic form of the elastic potential energy density. The ensuing equation of motion is governed by the sixth order spatial derivative, instead of the fourth order one obtained from the classical elasticity theory. The wave propagation is analytically investigated in order to describe the behavior of periodic waves with single and multi periodicity. The influence of scale length material parameters as well as foundation stiffnesses on the beam dynamical properties is discussed.

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NONLINEAR MECHANICS OF SMALL-SCALE NANOCOMPOSITE BEAMS

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Nowadays, a topic of major interest in Nonlinear Solid Mechanics deals with modeling of ultrasmall soft structures by exploiting computationally convenient methodologies of nonlocal continuum mechanics (see e.g. [1–3]) to properly take into account size-effects. Indeed, microand nano-structures undergoing large configuration changes can be effectively employed as basic components of new-generation miniaturized devices which exhibit size-dependent behaviors. In the present research, modeling and analysis of such systems are tackled by means of an effective nonlocal strategy. Specifically, a stress-driven nonlocal approach [4] of integral elasticity is developed to address nonlinear problems of small-scale nanocomposite [5] continua characterized by compliant mechanisms (see e.g. [6–8]). First, a proper assessment of constitutive properties of nanofillers is provided along with an accurate tuning of internal length-scale parameters. Overall stiffness of nanocomposites is then evaluated exploiting law of mixtures. A consistent nonlocal methodology based on the stress-driven elasticity [4] is adopted to formulate the structural problem of a nanocomposite beam undergoing large displacements. An iterative solution procedure is exploited and applied to evaluate effects of nanofillers and nonlocal parameters on structural responses. Outcomes of the parametric nonlinear analyses show a stiffening structural responses for increasing length-scale parameter in agreement with the smaller-is-stiffer phenomenon evidenced in [9].

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ON THE SPECTRAL PROPERTIES OF A NONLOCAL INTEGRO-DIFFERANTIAL OPERATOR

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In the framework of continuum mechanics, nonlocal integro-differential models can be used to model cracks and fractures without using partial derivatives. We study the spectral properties of a class of convolution type nonlocal integral operators in separable form both in onedimensional and bi-dimensional case and we propose a spectral method based on the implementation of trigonometric polynomials to discretize in space the model. Fourier spectral method requires the assumption of periodic solution, and to overcome such drawback we implement a volume penalization technique. Moreover, we also propose method which avoids the assumption of periodic boundary condition in the solution and can benefit of the use of the fast Fourier transform (FFT). We compare the performance of the the proposed methods both analytically and numerically.

ENHANCED FORMS OF THE ERINGEN'S NONLOCAL ELASTIC MODEL FOR BEAMS IN BENDING

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Eringen and co-workers (see e.g. [1, 2]) proposed an elasticity theory in which, leaving unaltered the equilibrium equations and the kinematic relationships, the stress-strain constitutive relation is characterized by a convolution operation upon the strain field. On addressing nonlocal boundary-value problems of beams in bending, the pertinent governing integro-differential equation turns out to be a Fredholm equation of the first kind which, as known from integral equation theory, admits multiple solutions or no solutions at all [3, 4].

An alternative differential formulation was also provided by Eringen and applied by Peddieson and co-workers [5] to model size effects of micro- and nano-beams. It was found that the model generally predicts softening effects on the stiffness with increasing the length scale parameter of the beam, but may also predict hardening, as for a cantilever beam under uniform load, or, even no size effects at all as in the so-called "paradox" case of a cantilever beam under point load at the free end; all apparently without a precise rule.

In the present contribution, after focusing on the drawbacks of the Eringen's integral and differential nonlocal models as well as on their theoretical explanation, some remedies, among other of the relevant literature able to solve the above inconsistencies, are discussed. Precisely, the so-called *strain-difference-based* nonlocal models, proposed by Polizzotto and co-workers, see e.g. [6] and reference therein, are referred to. It is shown how they provide an effective tool to address nonlocal elastic beams in bending and this both via the integral and the differential approach, [7], without inconsistencies and/or paradoxical situations. A few original benchmarks of Euler-Bernoulli beams in bending are analyzed to show the effectiveness and peculiarities of the presented enhanced forms of the Eringen's nonlocal model.

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MS-29 Damage in structural systems: innovative computational approaches
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Transient Response of Collinear Griffith Cracks in a Functionally Graded Strip Bonded between Dissimilar Elastic Strips under Shear Impact Loading
R. Singh

Artificial neural network modeling of metal plasticity
K. Enakoutsa, A. A. Adetokunbo

On computational homogenization of random elastic networks with high and low connectivity
D.A. Orlova, A. Yu Panchenko, I.E. Berinskii

Influence of response coupling on failure probability of seismic base isolated systems
S. Sessa, N. Vaiana, D. Pellecchia, D. De Gregorio, L. Rosati

A new block-based approach for the analysis of damage in masonries undergoing large deformations
C.A. Tran, E. Barchiesi

Comparison of geometrically linear and nonlinear poroplasticity for the borehole stability problem
A.V. Vershinin

TRANSIENT RESPONSE OF COLLINEAR GRIFFITH CRACKS IN A FUNCTIONALLY GRADED STRIP BONDED BETWEEN DISSIMILAR ELASTIC STRIPS UNDER SHEAR IMPACT LOADING

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This article analyses the interaction between a central and two symmetrically placed collinear Griffth cracks subject to transient response under anti-plane shear impact loading. The cracks are situated in a strip constituted by functionally graded material (FGM) bonded between two dissimilar elastic strips of equal thickness. The material properties of FGM are assumed to vary exponentially as a function of thickness. Applying integral transforms, the boundary value problem reduces to a system of singular integral equations in the Laplace transformed domain. These equations are solved numerically using the Lobatto-Chebyshev collocation quadrature approach. The inverse Laplace transform is used to find the approximate expressions of dynamic stress intensity factors (DSIFs). The striking feature of the article is the study of phenomenal changes of shielding and amplification through dynamic stress magnification factor (DSMFs) at the tips of the cracks under the sudden impact loading applied at the upper material surface. The effects of impact load applied at different surfaces, positions of cracks' axis and the thickness of the strips of the composite material on the possibilities of cracks' arrest are depicted graphically for different particular cases.

Keywords: Collinear cracks, Crack arrest, Functionally graded material, Stress magnification factor, Transient response.

ARTIFICIAL NEURAL NETWORK MODELING OF METAL PLASTICITY

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There is an increasing demand to apply artificial neural network (ANN) techniques to finite element analysis of complex engineering problems. While some of these efforts focus on data science, where available data are used to predict the behavior of any model without using constitutive laws, other efforts are based on a mixed data/modeling approach. In this contribution we assessed the feasibility of ANN for modeling nonlinear complex behaviors of materials. First, we present a constitutive model based on ANN which has the ability to capture complex nonlinear of materials. Then, the ANN is trained on a data set of stress-strain curves from numerical simulations. Finally, the trained ANN is integrated to as a UMAT subroutine into a commercial finite element code. The proposed framework is applied to several boundary values problems, the material obeying an elastic-plastic behavior.

ON COMPUTATIONAL HOMOGENIZATION OF RANDOM ELASTIC NETWORKS WITH HIGH AND LOW CONNECTIVITY

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Random elastic networks can model a microstructure of many materials, both natural and synthesized, such as biological tissues, hydrogels, textiles, and paper. A rational design of artificial random microstructure implemented with additive or some other kind of manufacturing can help achieve the desired response to the specific loading of the material, both static and dynamical. This design includes tuning the fiber properties and their arrangement. The desired data can be found using numerous lab experiments and computational simulations. However, due to a rather complex microstructure and the cost of materials and equipment, such experiments and simulations with random fibers require a lot of resources.

We propose a method of homogenization of a two-dimensional fibrous elastic network with a pre-defined structure to estimate its effective elastic properties and predict its reaction to some kinds of mechanical loading. For this purpose, a two-dimensional representative volumetric element (RVE) containing many randomly distributed elements was considered. RVE was subjected to small uniaxial displacements for the subsequent stress calculation. The resulting stress-strain relations were used to determine the corresponding continuum hyperelastic model. Finally, the elastic moduli in the direction of stretching and a mutually orthogonal direction were estimated for both discrete and continuum models. A comparison of the moduli shows that the Ogden model well predicts the average elastic properties of the fiber network. However, it neglects jumps of the moduli values due to microscopic effects such as network reconfigurations. In the series of experiments, we consider the networks with high and low connectivity. We notice that low connectivity may lead to the non-correct description of elastic properties via standard approaches and discuss the possible solutions.

INFLUENCE OF RESPONSE COUPLING ON FAILURE PROBABILITY OF SEISMIC BASE ISOLATED SYSTEMS

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Base isolation represents one of the most effective strategies for seismic protection of structural systems. It is based on the use of isolation bearings characterized by high horizontal flexibility and energy dissipation capacity. In general, most of bearings' typologies present a complex hysteretic behavior determining a nonlinear relationship between the horizontal components of displacements and reactions that should be properly modeled in order to compute accurate responses [1].

As a matter of fact, most of the constitutive models commonly used for such a purpose, including the popular Bouc-Wen [2] and Kikuchi-Aiken [3], consist in uniaxial relationships. Hence, isolation bearings belonging to three dimensional models subject to multi-component seismic excitations are often modeled by two orthogonal and uncoupled uniaxial springs. Although very popular in common practice, such an approximation does not take into account the dependency between the two horizontal components of the bearings' responses, thus underestimating the seismic vulnerability of the system.

In order to overcome such a drawback, a new biaxial hysteretic material, capable of determining in closed form the reaction associated with assigned displacements, has been recently developed [4]. Such a model proved to be accurate in reproducing the coupled responses of several devices, including isolation bearings. The present research presents a vulnerability assessment comparing the response of such biaxial model with the one relevant to two uncoupled uniaxial springs. Such a comparison is performed on a case-study structural system for which a Monte Carlo stochastic analysis is performed. Therefore, seismic vulnerability is computed by means of the first-excursion probability of the structural system and permits to estimate the modeling error relevant to the uncoupled springs, thus proving the necessity of using appropriate constitutive relationships accounting for the response coupling.

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A NEW BLOCK-BASED APPROACH FOR THE ANALYSIS OF DAMAGE IN MASONRIES UNDERGOING LARGE DEFORMATIONS

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A new block-based elasto-damage model for describing masonry structures has been recently proposed [1], where the used constitutive elastic and damage behavioural laws were inspired from granular micromechanics. Preliminary results hinted at the realistic masonry deformation modes which could be obtained, as well as the importance of the damaging characteristic lengths featured in the model.

The present work is an extension of that previous paper and presents a more detailed derivation of the model, along with a finer parametric study of the damaging characteristic lengths. Qualitative results hint at how those characteristic lengths allow to model interactions between normal and tangential deformations of the mortar, thus opening the way for future development and quantitative studies of the model.

Future applications of the presented model may lie in failure analysis of masonry structures (including complex loadings and damage-plasticity coupling), as well as other micro-structured systems (granular materials; materials which may be modelled as strain-gradient continua, such as pantographic structures; etc.)

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COMPARISON OF GEOMETRICALLY LINEAR AND NONLINEAR POROPLASTICITY FOR THE BOREHOLE STABILITY PROBLEM

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It is widely known that the determination of technological parameters, for which the wellbore maintains its stability, and risk assessment during drilling are one of the most important problems in geomechanics of hydrocarbon fields. When drilling, in general, a bit and mud generates a pressure on the rock, thereby deforming it and redistributing the stresses (superposition of generally finite strains), causing the reaction of the rock on the applied impact. This may lead to the formation and development of localized zones of plastic shear bands. Different rock's properties and their evolution during deformation should be taken into account to correctly simulate this process. In addition, the rock is usually prestressed, which is defined by the components of the generally anisotropic initial stress tensor. Real rocks are characterized by the presence of pores and a fluid that saturates them and the possibility of nonlinear inelastic deformation with the accumulation of plastic deformations and their localizations leading to the corresponding variations of dynamic porosity and permeability.

The paper presents mathematical models and numerical algorithms that can be used to solve the problems of a wellbore stability in a poroelastoplastic formulation under small and finite strains. A generalization of the classical Biot's model to the poroelastoplastic medium is considered in order to simulate a shear banding phenomena taking place around the borehole drilled in the prestressed solid leading to the change in the pore pressure in the surrounding rock as well as a redistribution of stresses and accumulated plastic strains. An isoparametric spectral element method is applied to discretize a geometric model and equations in space on curvilinear unstructured meshes of high order, which allows to precisely describe a curvilinear shape of the borehole on a relatively coarse mesh. CUDA technology is used to parallelize the implemented algorithm on the massively parallel graphics-processing unit. Several model examples of the borehole stability problem are presented and numerical results are analyzed.

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MS-33 Methods of computational mechanics and simulation oriented to civil engineering

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Micromechanical numerical model for the evaluation of the elastic properties amorphous titanium dioxide thin film
N. Cefis, M.G. Beghi

Eulerian-Lagrangian transformation of second gradient equations
R. Fedele, F. dell'Isola, P. Seppecher, S.R. Eugster

Finite element analysis of novel masonry-like composites
M. Bulgarini, N. Cefis, R. Fedele, G. Milani

Characterization and modelling of FRP-reinforced masonry triplets
R. Fedele, N. Cefis, C. Tedeschi, G. Fava, M. Cucchi

MICROMECHANICAL NUMERICAL MODEL FOR THE EVALUATION OF THE ELASTIC PROPERTIES AMORPHOUS TITANIUM DIOXIDE THIN FILM

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In this communication we present a numerical methodology for the mechanical assessment of thin films in amorphous titanium dioxide deposited by PLD (Pulsed Laser Deposition) technique on crystalline substrates. The morphology of these films includes columnar structures in amorphous titanium dioxide interspersed with empty regions. These films are widely used for several civil and industrial applications in which the photocatalytic properties of titanium dioxide are exploited when they are exposed to UV rays (evaporative systems, surfaces of buildings in urban environment, dye-sensitized solar cell [1]).

The novel numerical procedure aims at estimating the elastic moduli of nanostructured films through two subsequent steps. In the first step, starting from the SEM images of the frontal morphology, a model of the Reference Volume Element (RVE) is provided. In the second step, assuming a priori the elastic parameters for the amorphous titanium dioxide [2], a homogenization procedure with periodic boundary conditions is utilized to estimate the macroscopic response [3]. Such a procedure was implemented in Abaqus environment. The elastic parameters thus obtained turn out to be in satisfactory agreement with those provided by optical techniques based on Brillouin scattering [4].

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EULERIAN-LAGRANGIAN TRANSFORMATION OF SECOND GRADIENT EQUATIONS

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In this study, the focus is posed on the equilibrium equations for second gradient continua. As well known, for such class of materials volume, face and edge contributions to the inner virtual work can be provided by minimizing a Lagrangian energy density functional through integration by parts and repeated applications of the divergence theorem extended to curved surfaces with border [1].

In the above scenario, it is of extreme interest to find a viable route to transform the governing equations (with the relevant external loading) from the Lagrangian to the Eulerian configuration. To this purpose, three results are outlined as intermediate steps, achieved by tools of differential geometry [1]: (i) novel transport formulae are provided for the vectors normal and tangent to the boundary edge; (ii) a remarkable relationship between Lagrangian and Eulerian expressions is derived from the divergence problem, involving surface projectors; (iii) suitable relationships are specified between Lagrangian and Eulerian gradients of the placement map, and their work conjugate hyperstress tensors.

On the basis of such intermediate results, the transport of the governing equations for second gradient materials from the Eulerian to the Lagrangian configuration is finally carried out by alternative strategies [3], revealing a coupling of terms transversely to the involved domains [4].

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FINITE ELEMENT ANALYSIS OF NOVEL MASONRY-LIKE COMPOSITES

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Recent investigations in material mechanics concern innovative two-phase composites for civil engineering, able to achieve satisfactory mechanical performances while drastically reducing the cost and the environmental impact. Some studies have exploited applications of red mud from the aluminum manufacturing, by-products of the steel production process [1], ashes from factory furnaces or other types of quarry waste [2]; moreover, by-products from the palm oil. Eventually, even unfired earth bricks may exhibit some interest, since the low embodied energy involves a limited carbon footprint.

In this preliminary study, the focus is on a novel heterogeneous medium constituted of a polymer-based matrix with viscous behaviour [3], and of randomly distributed rigid aggregates with a varying size. Nonlinear finite element simulations are carried out in an Abaqus environment on a Representative Volume Element (RVE) with periodic boundary conditions [4]. Monte Carlo simulations are utilized to provide statistically meaningful results. For each finite element analysis, the average macroscopic mechanical response is computed by nonlinear homogenization [5-6].

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CHARACTERIZATION AND MODELLING OF FRP-REINFORCED MASONRY TRIPLETS

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This study concerns the experimental characterization and the mechanical modelling of masonry triplets reinforced by means of Fiber-Reinforced Polymer (FRP) strips. A wide experimental campaign was carried out on masonry triplets subjected to shear tests: both unreinforced and reinforced specimens were considered, the latter with faces partially or totally covered by a transversal FRP strip. Moreover, the bulk response of the mortar phase was assessed through three point bending experiments, under monotonic and cyclic loading conditions.

During the tests, conventional data from the point sensors (load cell, clip gauge) and full field kinematic measurements were provided [1]. Sequences of digital pictures, acquired at suitable instants during the experiments, were processed through a Digital Image Correlation procedure (2D DIC), apt to detect the in plane displacements of flat surfaces. Recourse was made to a multiscale DIC code, based on a Galerkin discretization of the displacement field [2].

To better interpret the experimental observations and correlate them to processes at the microscale, heterogeneous finite element models were developed in an Abaqus environment, enriched with user subroutines (Vumat) for the constitutive behavior [3]. As an alternative to the assumption of perfect adhesion [4], the multiple interfaces active within the triplets (between brick and mortar, and between the FRP strip and the support) were modelled as zero-thickness joints.

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MS-34 Continuum and Computational Biomechanics

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Mechanical and microstructural characterization of skin for hyperelastic anisotropic constitutive modeling
R. Alberini, G.A. Holzapfel, M.J. Sadeghinia, B.H. Skallerud, A. Spagnoli, M. Terzano

A pseudo-viscoelastic anisotropic model for soft fibrous tissues
M. Terzano, M.P. Wollner, M. Rolf-Pissarczyk, G.A. Holzapfel

Modeling the calcium-dependent and -independent contraction mechanism of smooth muscle in arterial walls
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Exploring pressure dependent permeability of brain white matter: Poroelastic theory or microstructurally-based FSI modelling?
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Homeostatic, stress driven, isotropic growth in soft tissues: a hypoelastic micromechanical framework
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P. Gaziano, G. Vairo

Control of the needle indentation into a brain tissue phantom with a piezoelectric drive
Y. D. Selyutskiy, M.Z. Dosaev, D. M. Martianov

MECHANICAL AND MICROSTRUCTURAL CHARACTERIZATION OF SKIN FOR HYPERELASTIC ANISOTROPIC CONSTITUTIVE MODELING

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The skin is a masterpiece of evolution, enclosing different essential components in a thickness of just a few millimeters. Collagen fibers are the main constituent of the dermis layer, and they are responsible for the overall membrane response under loading 0. In particular, the waviness and non-uniform planar dispersion of these fibers significantly influence the nonlinear and anisotropic mechanical behavior of skin at the macroscale [0], making numerical simulations a challenging task. Fiber-reinforced hyperelastic constitutive models can accurately reproduce the nonlinear anisotropic behavior of several soft biological tissues, including arterial walls 0 and skin 0 with few mechanical and microstructural parameters. In this work, a detailed experimental investigation is performed to quantitatively determine the orientation of collagen fibers in mouse skin samples using planar second harmonic generation (SHG) images (Fig.1). In addition, biaxial tests are conducted to extract the stress-stretch curves of the tissue. Subsequently, mechanical tissue parameters are extracted for the model with non-symmetrical fiber dispersion by Holzapfel et al. 0. This work aims to provide a deep understanding of mouse skin mechanics that can be used for correlation with human skin. The ultimate goal is the development of advanced computational tools for refined simulation of complex loading conditions encountered in reconstructive and corrective surgical procedures 0.

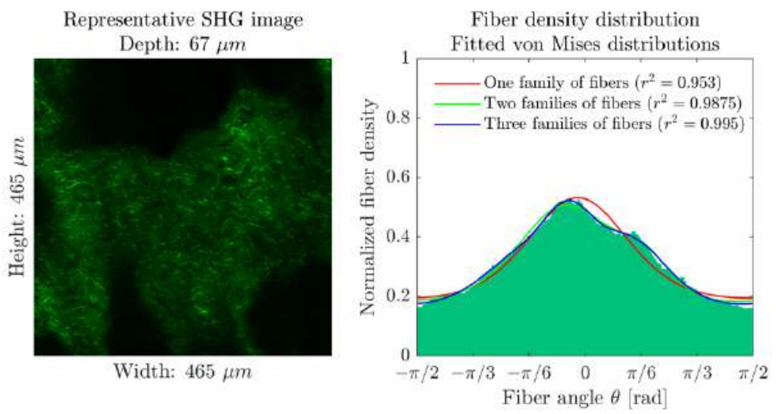

Figure 1 SHG image of collagen fibers (left) and measured fiber density distribution ($\theta = 0$ for fibers aligned with the horizontal loading axis) with fitted von Mises distributions considering 1, 2, and 3 fiber families (right).

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A PSEUDO-VISCOELASTIC ANISOTROPIC MODEL FOR SOFT FIBROUS TISSUES

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The complex response of soft fibrous tissues to mechanical loading can be efficiently described by structure-based constitutive models that integrate microstructural information about tissue morphology into a continuum framework. A three-dimensional network of elastin, collagen fibers and various cell types is observed in many soft fibrous tissues such as arterial walls [1] or the myocardium [2]. Histological images show the presence of one or more collagen fiber families thought to be responsible for the markedly anisotropic hyperelastic response commonly observed during biaxial extension. In addition, cyclic loading/unloading and stress relaxation experiments have provided evidence for stress softening and viscoelastic behavior, which is particularly relevant in the myocardium and muscular arterial tissue. Finally, supraphysiological loads, such as those experienced by the tissue during clinical interventions, are the cause of high stresses that can lead to damage [3].

In this work, we propose a new constitutive model capable of integrating the above effects into a continuum framework that is also amenable to a numerical formulation for an implicit finite element code. The hyperelastic anisotropic response is introduced by a polyconvex function expressed by the invariants of the second-order structure tensors [4]. Inelastic effects, including stress softening and permanent deformation, are expressed by a pseudo-elastic function [5] in combination with a finite strain viscoelastic model formulated in terms of internal variables [6]. As an application of the proposed constitutive framework, a large-scale finite element simulation of arterial clamping occurring during surgery is illustrated.

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MODELING THE CALCIUM-DEPENDENT AND -INDEPENDENT CONTRACTION MECHANISM OF SMOOTH MUSCLE IN ARTERIAL WALLS

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The medical inhibition of the active contraction of smooth muscle cells (SMCs) in arterial walls constitutes a well-accepted, clinical approach to prevent patients with various cardiovascular diseases from further health risks. For the optimization of medical methods, computational simulations of arterial walls in health and disease are considered promising. An accurate description of the mechanical behavior of the arterial tissue is necessary to obtain realistic distributions of mechanical fields from numerical simulations. Due to an increase of the intravascular pressure, SMCs are stretched which triggers two different mechanisms: the calcium-dependent and the calcium-independent contraction [1].

For the calcium-dependent contraction mechanism, the stretch of the SMCs leads to an inlet of calcium ions through various different pathways which activates the myosin light chain kinase (MLCK). The MLCK activity triggers the contractile units of the cells which results in the contraction. For the calcium-independent contraction mechanism, stretch-dependent receptors of the cell membrane stimulate an intracellular reaction chain which leads to an inhibition of the antagonist of MLCK, the myosin light chain phosphatase (MLCP). While the calcium concentration can change over a rather small time frame, the inhibition of MLCP lasts much longer.

We present a chemo-mechanical model which describes both, the calcium-dependent and the calcium-independent contraction of SMCs. As a basis for the mechanical description of the contractile units, the widely used model by Murtada et al [2] is considered. Furthermore, the influence of the chemical state on the mechanical behavior is described by applying the model of Hai and Murphy [3]. A new set of equations is presented to describe the stretch-dependent calcium inflow and the inhibition of MLCP as a contractile mechanism. An algorithmic framework for the implementation of the model in finite element programs is derived. Based thereon, simulation results of arteries under time-dependent intravascular pressure, mimicking the scenario during a heart-beat, are analyzed and the influence of the proposed model is shown. Quantitative comparisons with experiments show that the response of the model enables realistic numerical simulations.

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A COMPUTATIONAL MODEL OF ENDOTHELIAL CELL LAYERS

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Endothelial cells form the innermost layer of the human vascular and lymphatic systems, and thus constitute the barrier between body fluids and the surrounding tissues. They are subject to various mechanical cues such as wall shear stress due to fluid flow or normal tension due to flow pulsatility. The capability of sensing, integrating and transforming these mechanical cues into biochemical signals is called mechanotransduction, a complex process that enables active cellular responses to mechanical stimuli such as cell movement, proliferation or apoptosis.

The cells' cytoskeletal components play a particular role in the sensing and transduction of mechanical stimuli. They transmit forces throughout the cell such as between their anchoring points with the substrate and the nucleus as well as between cell-cell junctions in mature monolayers. While there is extensive knowledge on the intracellular networks of actin, intermediate filaments and microtubuli in single cells, there is considerably less understanding on the mechanobiological role of interconnected actin and intermediate filament networks formed in cell-layers. The structure of these networks and the properties of the cell-cell junctions are key factors in transducing mechanical signals through the cell layer, and furthermore, determine the mechanical characteristics of this thin "living material".

In order to study the role of these networks, and to rationalize the results of laboratory experiments with endothelial monolayers grown on deformable soft substrates, we set up computational models of both single endothelial cells and of cell clusters including their intercellular networks, accounting for the interconnectivity between cells. The model includes the cytoskeletal networks, their connections, nuclei, and cellular membranes that correspond with results from experimentally performed stretch experiments. By these means, we generate large heterogeneous "fibre" networks suitable for numerical analysis. The networks are subjected to mechanical boundary conditions at their periphery and their connections with the substrate material. In order to solve resultant boundary value problems, we employ the opensource molecular dynamics software lammps.

In our study, we present a modelling strategy and the comparison of our computational model with different experiments on single cells and cell layers.

EXPLORING PRESSURE DEPENDENT PERMEABILITY OF BRAIN WHITE MATTER: POROELASTIC THEORY OR MICROSTRUCTURALLY-BASED FSI MODELLING?

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The flow of interstitial and cerebrospinal fluids in brain white matter (WM) is key to maintain the tissue functions and health. An important class of brain disease treatments has recently emerged that allows to bypass the blood-brain-barrier by infusing drugs directly into the brain tissue via a catheter. Such procedures, which include Convection Enhanced Delivery (CED), also rely on the fluid transport property of the brain tissue. However, the intricate flow in WM is controlled by the presence of axonal bundles and the complex tissue microstructure. Given the extremely soft nature of the axons, the mechanical interaction between the flow and these anisotropic structures affects the local flow status and the overall transport property of the brain tissue, which can be characterised by the tissue hydraulic permeability. Although recent experiments have reported evidence of pressure dependent permeability of the brain, this phenomenon has not received sufficient attention from a modelling perspective. Here, we use (a) a mathematical model based on poroelastic theory, and (b) a more explicit method named microstructurally based fluid-solid interaction (MBFSI) - to model this phenomenon and compare their capabilities and accuracy in predicting the pressure dependent permeability of the WM. The results show that both methods can reproduce this phenomenon if the change of permeability is driven by axons deformation (shrinkage); however, the use of poroelastic theory is not capable of accurate predictions when displacements and interactions between axons play an important role in affecting the fluid flow.

COMPUTATIONAL CHEMO-MECHANO-BIOLOGICAL GROWTH AND REMODELING OF ARTERIAL TISSUES

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Loading conditions above physiological limits, as during trauma or surgical procedures, cause damage in biological tissues. In turn, damage initiates repair mechanisms at cell- and molecularlevel, leading to growth and remodeling (G&R) mechanisms, generally known as healing, aiming to maintain or restore a homeostatic mechanobiological state. However, the balance between functional and dysfunctional G&R is delicate, potentially transforming healing in dangerous hyperplasia. In this context, this work presents a continuum-based model coupling elasto-plastic damage mechanisms [1], molecular and cellular events activated by damage, and the repair and re-adaptation (i.e., G&R) of tissues activated by such mechanobiological mechanisms [2, 3, 4]. The model is specialized to arterial tissue applications, with the aim of developing a predictive model for the risk of in-stent restenosis, a severe complication of angioplasty or stenting procedures.

Model capabilities are assessed by means of a finite element simulation of a 3D stenotic artery segment. The presented model aims to move a step towards a predictive tool for healing processes in soft tissues in order to gain knowledge on how the delicate balance between normal and pathological healing mechanisms contribute to complications after angioplasty or stenting procedures. Future works will address the coupling with hemodynamics loads by considering the release of biochemical agents by endothelial cells due to altered wall shear stress patterns.

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A THERMODYNAMICALLY CONSISTENT GROWTH MODEL APPLIED TO THE VERTEBRAL COLUMN

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Living materials have the ability to adapt to their mechanical and biochemical environment through various mechanisms such as growth and remodeling. Although growth is primarily a physiological phenomenon, many pathologies are related to abnormal tissue growth, such as tumor invasion and over- or underloading of bones. Thus, understanding the mechanisms of growth and being able to model this phenomenon can contribute to explain the physiological and pathological development of tissues. Classical engineering tools can provide valuable information in many areas of biomechanics. However, the modeling of growth phenomena remains a major challenge in continuum mechanics.

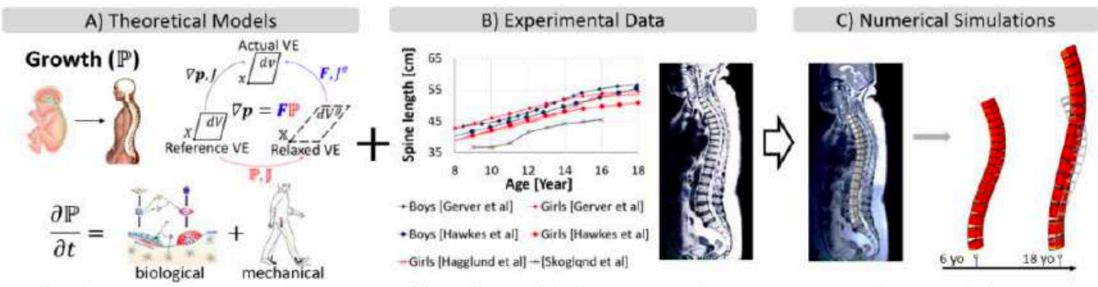

Figure 1. Diagram of the methodology. Coupling of (A) a theoretical growth model and (B) experimental data applied to (C) numerical simulations in order to study the growth of healthy and pathological spine

In continuum mechanics, the growth of a material element is often associated with a variation of its mass and shape at rest (relaxed state). This work presents and discusses a volumetric growth model implemented in the framework of the theory of generalized continuum mechanics as proposed by DiCarlo and Quiligotti. The theory is based on a multiplicative decomposition of the deformation gradient into an elastic and a growth component: $\nabla \boldsymbol{p} = \boldsymbol{F}\mathbb{P}$ (Fig. 1A). The growth law of a material element, translating the evolution of its relaxed configuration, is obtained by relying on generalized formulations of the principle of virtual powers and of the principle of dissipation that allow to account for both mechanical and physiological stimuli, while ensuring the thermodynamic consistency of the theory.

This general theory is applied to a real clinical problem, namely the pathological and progressive spinal deformation in patients with adolescent idiopathic scoliosis (AIS). Based on experimental and clinical data (Fig. 1B), we developed finite element simulations (Fig. 1C) to study the growth of the spine under both physiological and pathological conditions and to offer new insights into the AIS pathology causes and progression.

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HOMEOSTATIC, STRESS DRIVEN, ISOTROPIC GROWTH IN SOFT TISSUES: A HYPOELASTIC MICROMECHANICAL FRAMEWORK

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Growth in soft tissues is the continuous process of mass deposition/reabsorption to maintain a homeostatic mechanical state. For each constituent, the net mass production rate is proportional to the difference between current and target homeostatic stresses. As a consequence, an inelastic growth-related deformation arises. This can be computed by a properly defined evolution law for the rate of growth deformation gradient (eq. 25 in [1]).
Extending the classical growth model [1] towards the realm of truly multiscale models, we consider that each phase can experience its own deformation gradient for the total and the inelastic growth deformation. As proposed in [2], a representative volume element (RVE) of the soft tissue is made of growing spherical inclusions embedded in a soft matrix, both phases displaying a hypoelastic constitutive behavior (*Fig.1a*). The RVE is subjected to a uniform macroscopic strain rate for 15 years. The microscopic stress in each phase is computed downscaling the macroscopic load and accounting for the inelastic growth-related deformation.
Fig.1b shows the evolution in time of the microscopic inclusion stress for different gain parameters. The capability of the tissue to recall the homeostatic state improves with the increase of the gain parameter. This study shows a framework capable to model growth in soft tissues in case of an independent growth-related deformation for each constituent, representing a starting point for the micromechanical description of growth in soft tissues.

(a)

	MATRIX	INCLUSION
Young modulus	0.1 MPa	10 MPa
Poisson's ratio	0.47	0.47
Initial density m_i/V_{tot}	157.5 Kg/m^3	65.1 Kg/m^3
Initial volume fraction	0.7	0.3
Macroscopic load	$\mathbf{D} = 0.001\, \mathbf{e}_3 \otimes \mathbf{e}_3$ 1/s	
Proportionality factor	k = [0.005, 0.01, 0.05, 0.1, 0.5]	

(b)

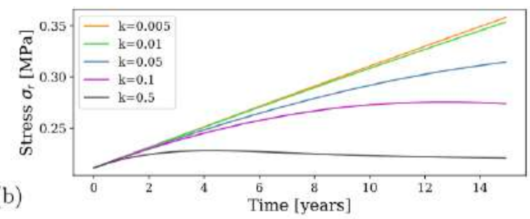

Figure 1: (a) Deatils of the model parameters; (b) microscopic inclusion stress σ_r

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ENHANCED COMPUTATIONAL MODELLING OF FEMUR FRACTURE

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Being the femur an important load-bearing bone, femoral fractures worldwide represent a major public health concern, since they generally lead to a noticeable reduction in life quality of patients, as well as to severe medical complications and even death. A crucial task for clinicians is therefore the accurate evaluation of femoral fracture risk. However, actual clinical standards suffer from important limitations, related to the adoption of qualitative indexes or parameters which, neglecting the mechanical determinants of fracture, are characterized by a low specificity. This have frequently led to clinical dilemmas about the more effective intervention strategy, resulting (not so rarely) in surgical overtreatments [1].

In the last decades, finite-element (FE) modelling techniques integrated with patient-specific diagnostic imaging tools, such as the Computed Tomography (CT), have proved to enhance the prediction of femoral fracture risk [2]. At present, the majority of the studies have mainly focussed on the prediction of femoral strength and on the onset of failure process, but not predicting the mechanical response of femur up to the fracture and the related failure mechanism. Nevertheless, these aspects are fundamental from a clinical standpoint, since a proper treatment of hip fractures strongly depends on several factors, among which the type and location of fracture are among the most determining ones [3].

Accordingly, the present contribution aims at furnishing a deeper insight on femoral failure mechanisms by investigating the mechanical behaviour of an ex-vivo femur in a FE framework. Patient-specific features in terms of both femur anatomical shape and local bone constitutive properties have been obtained from CT scan data. To simulate the progressive loadinginduced loss of structural integrity, a quasi-brittle bone constitutive relationship has been modelled through advanced continuum-mechanics-based theories including suitable regularization techniques of the free-discontinuity problem associated to fracture propagation. The model has been successfully validated by comparing obtained numerical results (given in terms of load/displacement curves and fracture patterns) to available experimental data coming from mechanical tests mimicking a single-leg stance loading condition.

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CONTROL OF THE NEEDLE INDENTATION INTO A BRAIN TISSUE PHANTOM WITH A PIEZOELECTRIC DRIVE

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Stereotactic operations are minimally invasive medical interventions that involve indentation of a needle into the tissue using the spatial coordinate system to locate the target point. Such technology is rather widely used for manipulations with the brain (such as biopsy). One of important problems now is to develop a robotic system to facilitate such operations and to support their execution in remote mode. During the process of needle insertion into the brain, it is very important to ensure a precise control of position of the needle tip. To that end, real-time information about the needle position is required. Such data can be provided by MRI, but, in such case, the robotic system (including drives and motors) should be compatible with the MRI device. Piezoelectric drives, which do not interfere with the magnetic field in MRI machine, represent an attractive alternative to conventional motors.

A phenomenological model is proposed in order to describe the force exerted by the phantom tissue on the needle. This model takes into account the viscoelastic and plastic properties of the material, relaxation processes arising in the tissue, and the presence of the surface film on the phantom that the needle pierces at the beginning of the indentation. Parameters of the model were identified using the available experimental data.

A control law for the excitation frequency is proposed is proposed intended to insert the needle into the tissue to the specified depth with a prescribed indentation speed. This control scheme is based on the needle position and speed feedback. It takes into account the interaction between the needle and the phantom tissue, as well as dependence of the driving force generating by the piezoelectric drive upon the excitation frequency and the needle speed.

Numerical simulation is performed, and the effect of feedback coefficients on the indentation process is analyzed. It is shown that the appropriate choice of these coefficients ensures good agreement with the target parameters (indentation speed and depth) and allows for avoiding the overshooting during the indentation process.

MS-35 Design of multi-scale materials, inverse solid modeling, and simulation of advanced manufacturing and sensing processes

Erden Yildizdag, Ahmet Ergin (Istanbul Technical University, Turkey) and Adnan Kefal (Sabanci University, Turkey)

Strain-gradient modeling of additively manufactured specimens and investigating the effects of infill characteristics
B.C. Sarar, E.B. Abali

Identification of constitutive parameters of a Hencky-type discrete model via experimentation on a millimetric pantographic unit cell
N. Yilmaz, A. Misra, F. Hild

Modeling of damage behavior in 3D-printed metallic pantographic structures by a hemivariation formulation
M. E. Yildizdag, L. Placidi, E. Turco

Damage detection of locally corroded structures using inverse finite element method coupled with genetic algorithm
M. Ghasemzadeh, A. Kefal

Multi-objective optimization of variable stiffness composite panels using lamination interpolation approach
P. K. Shahabad, M. R. Anamagh, G. Serhat, I. Basdogan, B. Bediz

Damage modeling and analysis of laminated composite structures using coupled multiscale models
A. Kheyabani, A. Kefal

Scrutiny of stress expressions of armchair nanotubes via doublet mechanics
H. Koc, E. Tüfekci

Modelling and characterisation of lightweight epoxy foams with high compressive strength
T. Elvan, M. Emre Demir, İ. Pir, M. Tüfekci, E. Tüfekci

Investigation of static behavior of carbon nanotubes based on doublet mechanics
H. Koc, E. Tüfekci

A Modified Trigonometric Higher-Order Shear and Normal Deformation Theory for Free Vibration Analysis of Composite Conical Shells
M. Rahmanian, P. L. Motlagh, S. Lotfan

Manufacturing and mechanical characterisation of polymeric nanocomposite membranes
S. Acarer, İ. Pir, V. Öztekin, M. Tüfekci, G. T. Demirkol, N. Tüfekci

The mechanics of 3-dimensional elastic foams
İ. Pir, M. Tüfekci, E. Tüfekci

Experimental Characterization of Impact Induced Damage on Aerospace Grade Thermoset Composites
M. Seyednourani, I. Emami Tabrizi, M. Yildiz, A. Kefal, H. S. Sas

STRAIN-GRADIENT MODELING OF ADDITIVELY MANUFACTURED SPECIMENS AND INVESTIGATING THE EFFECTS OF INFILL CHARACTERISTICS

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Infill density used in additive manufacturing incorporates a structural response change in the structure. Infill pattern creates a microstructure that affects the mechanical performance as well. Whenever the length ratio of microstructure to geometry converges to one, metamaterial emerge and the strain-gradient theory is an adequate model to predict metamaterials response. All metamaterial parameters are determined by an asymptotic homogenization and we investigate effects of infill density and pattern on these parameters. In order to illuminate the role of infill characteristics on the strain-gradient parameters, an in-depth numerical investigation is presented for one, widely used case in 3-D printers, rectangular grid.

IDENTIFICATION OF CONSTITUTIVE PARAMETERS OF A HENCKY-TYPE DISCRETE MODEL VIA EXPERIMENTATION ON A MILLIMETRIC PANTOGRAPHIC UNIT CELL

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The constitutive parameters identification of a discrete Hencky-type model for a millimetric pantographic unit cell is attempted and achieved. The procedure, which can be viewed as multi-objective and multi-experiment optimization, consists of using different types of objective functions that contain data of different nature and coming from different types of experiments. The rationale of the analysis is to develop an identification procedure in the field of pantographic materials starting from what can be considered the elementary unit of larger pantographic structure specimens. The present results represent an intermediate step: subsequent research on the relation between discrete micro constitutive parameters and macro homogenized constitutive parameters must follow.

MODELING OF DAMAGE BEHAVIOR IN 3D-PRINTED METALLIC PANTOGRAPHIC STRUCTURES BY A HEMIVARIATION FORMULATION

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In this study, to model damage behavior in pantographic layers, an hemivariational formulation is presented for spring elements included in an Hencky-type discrete model. The elastic behavior of a pantographic layer is modeled via extensional, bending and shear springs with corresponding stiff- nesses in the discrete model.

The experimental evidence shows that degradation of stiffnesses occurs until their annihilation because of the fracture phenomenon. Thus, a damage descriptor is added for each kind of spring. Such a damage descriptor is non-decreasing function of time, and there- fore, the standard variational formulation of the problem is generalized to an hemivariational one providing not only the Euler-Lagrange equations for the evolution of the displacements of all the standard degrees of freedom but also the Karush-Khun-Tucker (KKT) condition governing the evolution of damage descriptor.

For numerical example, a metallic pantographic layer which was experimentally investigated in the literature has been considered under shear test. The dissipation energy included in the hemivariational formulation depends upon six further constitutive parameters (two per each kind of spring), and the layer has been simulated with an efficient and smart strategy able to solve the nonlinear equilibrium equations coupled with the evolution of damage variables.

DAMAGE DETECTION OF LOCALLY CORRODED STRUCTURES USING INVERSE FINITE ELEMENT METHOD COUPLED WITH GENETIC ALGORITHM

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Corrosion results from the chemical interaction of metal surfaces with the surrounding environment and can occur in various engineering structures, particularly in marine structures immersed in corrosive seawaters. Pitting corrosion is the most common type of metal material deterioration, leading to cavities and spots. This type of corrosion is the most dangerous type because it is difficult to detect and predict. Thus, structural health monitoring (SHM) is vital to maintain the integrity and efficiency of offshore installations. The inverse finite element method (iFEM) is a robust tool for real-time full-field reconstruction of the structural deformation for health monitoring. In the present study, the iFEM methodology is executed to detect the corroded regions using a new damage parameter based on von Mises strain distribution. The simplified semi-sphere geometry of a corrosion pit with a defined depth and surface is considered and simulated in the FE model using commercial software of ABAQUS CAE. The high-fidelity FEM results are considered to stimulate the sensor data, which is the input of the iFEM, and verify the obtained positions of pits. In addition, a genetic optimization algorithm (GA) with practical constraints is applied to demonstrate the realistic applicability of the implemented method with a reduced number of sensors. By using the newly introduced method, iFEM accurately identified the location of corrosion pits. Hence, the coupled iFEM-GA method can be used as a highly accurate damage detection strategy in corroded structures.

MULTI-OBJECTIVE OPTIMIZATION OF VARIABLE STIFFNESS COMPOSITE PANELS USING LAMINATION INTERPOLATION APPROACH

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Fiber-reinforced laminated composites are widely used in various industries due to their excellent mechanical properties that highly depends on fiber orientations and staking sequence. Furthermore, recent improvements in composite fabrication technologies has enabled manufacturing curvilinear fiber paths within the layers. Since it is possible to spatially design the composite panel, it is feasible to advance the mechanical behavior compared to constant stiffness composites. Due to the vast design space, efficient modeling approaches are needed. For instance, lamination parameters that formulates the constitutive equations in a compact form, are widely used to perform the optimization without defining the number of layers and their thickness. In this study, we present a lamination interpolation/extrapolation approach which reduces the number of design variables significantly and simplifies the design process. Instead of defining separate lamination parameters for each sampling point, we define a predefined number of master points and their corresponding lamination parameters as design variables. Furthermore, to increase the computational efficiency, the modeling is performed based on spectral Chebyshev approach. The developed framework is used to design the composite panels considering multiple functions based on critical buckling load, fundamental frequency, and frequency gaps between selected modes. In each case study, lamination parameters distribution maps and fiber angles are plotted and the improvements compared to constant-stiffness composites are calculated.

DAMAGE MODELING AND ANALYSIS OF LAMINATED COMPOSITE STRUCTURES USING COUPLED MULTISCALE MODELS

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In the present study, a novel efficient multiscale analysis strategy is proposed for progressive damage modeling of composite materials by coupling of parametric high fidelity generalized method of cells (HFGMC) micromechanical model and the refined zigzag theory (RZT) integrated into the isogeometric analysis (IGA) framework. To this end, the HFGMC is called at each integration point to predict the continuum response of the composite based on strain and stress fields developed in the constituent materials by using a discretized repeating unit-cell (RUC). Results from the micro-scale analysis are utilized in the macro scale to achieve the overall behavior of the structure by employing the isogeometric plate formulation based on RZT (IG-RZT). To capture the matrix nonlinearity, the J2 theory of plasticity is implemented in the micro scale whereas Hashin's failure criterion is leveraged in the macro scale to define the failed material points and eliminate them from the analysis. The robustness and efficiency of the approach come from the RZT which enables the modeling of a thick composite structure as a single layer; and the IGA where an exact representation of geometry is achieved without the requirement of a refined mesh. To assess the applicability of the proposed approach, the mechanical behavior of a carbon/epoxy (IM7/977-3) composite is taken into consideration. First, the model is calibrated according to the standard mechanical tests data provided in the literature; later, the mechanical responses of different laminates are considered for validation. The efficiency and accuracy of the proposed technique are clearly demonstrated through the comparison of the obtained results with the reference solutions.

SCRUTINY OF STRESS EXPRESSIONS OF ARMCHAIR NANOTUBES VIA DOUBLET MECHANICS

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Doublet mechanics is employed for bending [1], buckling [2], and vibration behaviors [3] of nanobeams in recent studies since the value of the small-scale parameter is known certainly contrary to the size-dependent theories such as strain gradient theory [4], nonlocal theory of elasticity [5]. This study draws considerable interest to acquire macro stresses for armchair nanotube if purely axial strain is considered in the plane stress condition. The macro stresses are procured without any presumption in the micro modulus matrix. The stress $\sigma_{zz}^{(M)}$ appears besides the stress $\sigma_{xx}^{(M)}$ unlike the literature and the obtained macro stresses are specified below.

$$\sigma_{xx}^{(M)} = \frac{1}{64} E\left(64\varepsilon_{xx} + 4\eta^2 \frac{\partial^2 \varepsilon_{xx}}{\partial x^2} + \eta^4 \frac{\partial^4 \varepsilon_{xx}}{\partial x^4}\right) \tag{1}$$

$$\sigma_{zz}^{(M)} = \frac{1}{192} E\left(4\eta^2 \frac{\partial^2 \varepsilon_{xx}}{\partial x^2} + \eta^4 \frac{\partial^4 \varepsilon_{xx}}{\partial x^4}\right) \tag{2}$$

In this way, there are two choices: considering this stress or ignoring it. When this stress is ignored, the stress $\sigma_{xx}^{(M)}$ matches up to the statement of the classical theory of elasticity since the small-scale effect vanishes. So, a new formulation is also applicable in the cases where off-diagonal elements of the micro modulus matrix are non-zero, unlike the literature. If the stress $\sigma_{zz}^{(M)}$ is considered, it is thought that the results obtained may be more sensitive.

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MODELLING AND CHARACTERISATION OF LIGHTWEIGHT EPOXY FOAMS WITH HIGH COMPRESSIVE STRENGTH

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This study aims to propose a manufacturing procedure for syntactic epoxy foams, in which the volume fraction of the micro balloons can go up to 80%, as well as characterise and numerically investigate their mechanics. The characterisation focuses on the mechanical and thermal properties of the foams. In order to visualise the morphology of the foams scanning electrone microscopy (SEM) is used. Thus, the dispersion of the material/micro balloons are ensured. This is followed by theoretical and experimental density measurements, finding the volume fraction of voids in syntactic foams, and tensile and compression tests. Dynamic mechanical analysis (DMA) is also performed to observe the viscous behaviour and glass transition temperature (T_g) of the syntactic foams. Furthermore, differential scanning calorimetry (DSC) and hot disc tests are carried out, respectively, to determine the specific heat values (c_p) and heat conduction coefficients (λ) and inertia of syntactic foams. Figure 1 visualises some of the manufactured samples as well as a sample going through the compression test.

The mechanic tests suggest that the compressive and tensile strengths decreased with increasing micro balloon presence. However, the epoxy resin syntactic foams in this study stood out with their high mechanical strength and high toughness compared to foams manufactured using other resin materials presented in the literature.

Figure 1 Manufactured foam samples

INVESTIGATION OF STATIC BEHAVIOR OF CARBON NANOTUBES BASED ON DOUBLET MECHANICS

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In the doublet mechanics theory, macro stress statements are obtained by considering the axial and shear strain to examine mechanical behaviors of carbon nanotubes. The deformations are specified by the Taylor series and the first three terms in the Taylor series expansion are used throughout this study. Once the micro modulus matrix is derived without any restriction, the relation between the macro stress and strain is attained by considering the plane stress assumption. The stress $\sigma_{zz}^{(M)}$ emerges alongside the stresses $\sigma_{xx}^{(M)}$ and $\sigma_{xz}^{(M)}$ in the zigzag nanotube as well as the armchair nanotube. It can be thought that this situation is possible since the rod is modeled in the xz-plane. To the best of the authors' knowledge, a study considering the stress $\sigma_{zz}^{(M)}$ has not been published in literature before. The macro stress formula given in the literature [1-3] is used for obtaining the stress $\sigma_{zz}^{(M)}$. It is observed that acquired macro stress statements are exactly the same when the higher-order terms than the second-order of the small-scale parameter are ignored. In this case, there are two choices; considering the stress $\sigma_{zz}^{(M)}$ or ignoring it. If the rod assumptions are considered, the stress $\sigma_{zz}^{(M)}$ will be equal to zero for the zigzag nanotube, while it is non-zero for the armchair nanotube. Neglecting the stress $\sigma_{zz}^{(M)}$, macro stresses for armchair nanotube are obtained as follows:

$$\sigma_{xx}^{(M)} = E\left(\varepsilon_{xx} + \frac{\eta^2}{12}\frac{\partial^2 \varepsilon_{xx}}{\partial z^2}\right) \tag{3}$$

$$\sigma_{xz}^{(M)} = E\left(\frac{3}{4}\varepsilon_{xz} + \frac{\eta^2}{24}\frac{\partial^2 \varepsilon_{xx}}{\partial x\,\partial z} + \frac{3\eta^2}{64}\frac{\partial^2 \varepsilon_{xz}}{\partial x^2} + \frac{\eta^2}{64}\frac{\partial^2 \varepsilon_{xz}}{\partial z^2}\right) \tag{4}$$

The results obtained in this study are compared with those given in the literature.

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A MODIFIED TRIGONOMETRIC HIGHER-ORDER SHEAR AND NORMAL DEFORMATION THEORY FOR FREE VIBRATION ANALYSIS OF COMPOSITE CONICAL SHELLS

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Shell structures have been a matter of concern for structural engineers during the past two centuries due to their vast industrial applications. They are found in various forms in modern civil, mechanical, marine, and aerospace industries. In-depth knowledge of their dynamical behavior or more specifically their free vibration analysis will facilitate their mathematical description in time/frequency domains and consequently enlightens their design procedure. Conical shells have also been considered in several studies due to their general geometrical essence, reducing to cylindrical shells and annular plates as specific configurations. In the current study, a modified higher-order shear and normal deformation theory is developed for the first time. The transverse shear stress distribution is realistic across the thickness and there will be no need for shear correction factors. Moreover, the normal deformation allows the structure to deform nonlinearly along the thickness, which is a matter of concern in all soft tissue or sponge-like structures. In addition to the novelty in the mathematical theory, a unified solution algorithm is also utilized by implementing a spring penalty approach. For this solution method, the weak form equations of motion will be utilized. These equations are obtained by following the Hamilton's energy principle. Satisfaction of the geometric boundary conditions is handled independent of the trial functions by using the so-called penalty parameters. Additionally, Jacobi polynomials are taken as the admissible functions, which are the most general orthogonal functions including Legendre, Chebyshev, and Gegenbauer orthogonal polynomials as special cases. Such solution methodology ensures convergence rate and eliminates all numerical instabilities due to ill-conditionings of mass and stiffness matrices. Performing a complete convergence and verification study, the current theory is compared to the available literature on conical shells with any desired boundary condition, providing natural frequencies and mode shapes of the system.

MANUFACTURING AND MECHANICAL CHARACTERISATION OF POLYMERIC NANOCOMPOSITE MEMBRANES

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Polymeric membranes are commonly included in the procedures for wastewater and drinking water treatment. Therefore, more performance and efficiency improvements are required to make the most of this technology in the applications which is the main reason for the popularity of the membranes in the research community. Thus, in this study, polyethersulfone (PES) based cellulose nanofibre (CNF) reinforced membranes are manufactured and their mechanical properties are characterised in wet and dry conditions. The membrane samples are manufactured by employing the phase inversion method. Then, the characterisation of those manufactured samples is carried out by putting the membrane samples through tensile testing under quasi-static conditions. The results of wet and dry membranes with various reinforcement content are compared to the unreinforced membrane and the underlying reasons are discussed.

Figure 2. Membrane sample during the tensile test.

THE MECHANICS OF 3-DIMENSIONAL ELASTIC FOAMS

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Applications of foam materials are becoming more common in recent years. Especially in the industry, due to their lightweight, tailorable/improvable thermal, electrical and mechanical properties, the need for porous materials/foams is increasing. Thus, research focusing on foams is also accelerated. Hence, this study deals with the theoretical modelling/prediction of the mechanical behaviour of elastic 3-dimensional foams, that have ellipsoidal/spherical voids and the volume fraction of voids going up to 30%, employing several analytical/numerical methods including mean-field homogenisation and finite element method.

To conduct the mean-field homogenisation, Mori-Tanaka and double inclusion methods are em- ployed. To be able to perform the finite element method, a Python script is prepared. With this code, it is possible to generate the geometry with randomly positioned and sized voids. Uni- directional loading and periodic boundary conditions are implemented into the finite element software Abaqus. Some of the resulting geometries are presented in Fig. 1. The results of these analyses are nondimensionalised aiming to provide a general source of information for the material selection stage of the design process of the industrial applications. The data acquired from those analyses are compared to each other and found in decent agreement.

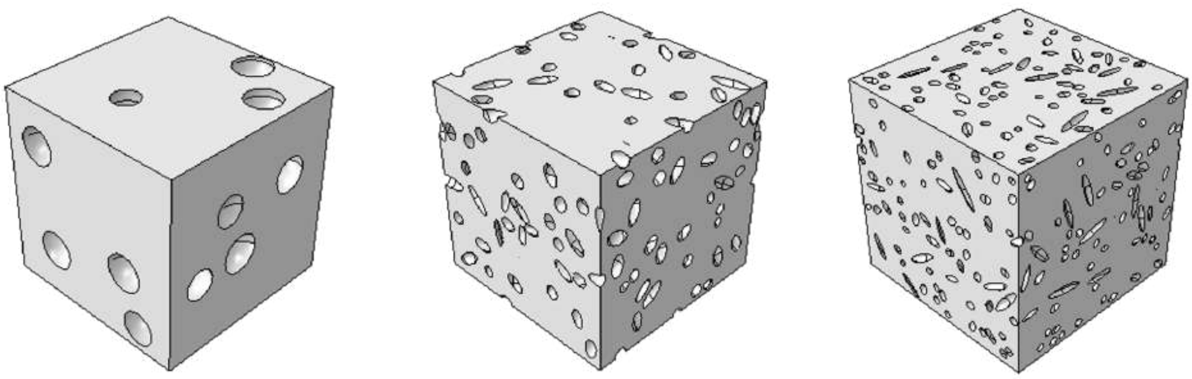

Figure 1: Foam geometries

EXPERIMENTAL CHARACTERIZATION OF IMPACT INDUCED DAMAGE ON AEROSPACE GRADE THERMOSET COMPOSITES

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Barely visible damages in the fiber-reinforced material can provoke catastrophic failure in engineering structures via damage accumulation under loads during the service life. Correlating the residual strength of the composite materials after impact incidents is a promising way to predict the damage-growth dynamics. Structural health monitoring techniques such as thermography have been used frequently for this purpose. Considering the importance of issues mentioned above for aerospace applications, this study investigates the effect of low-velocity impact on residual strength of thermoset carbon fiber reinforced laminates. Thermoset composite laminates with different lay-ups are stacked using an automated fiber placement machine (AFP) and cured using autoclave processing. Then, various impact tests are performed at different energy levels on the composite specimens, and then lock-in thermography is utilized to characterize the damage modes of laminates. Damage areas due to impact are compared for both lay-ups and quantified using image processing, which are correlated with the residual tensile strength at each impact energy level as well. It is shown that despite having a same manufacturing process, the geometry and severity of damage under various impact loading conditions will be different for cross-ply and symmetric angle-ply laminates. For each lay-up configuration, the results reveal a critical impact energy level below which the residual strength of material would not be affected.

MS-36 Mathematical models for composite materials and heterogeneous media in Engineering and applied sciences

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Continuum electrodynamics of materials - Its history and some curious recent developments
W.H. Mueller, E.N. Vilchevskaya, V.A. Eremeyev

Covering a surface with pre-stressed ribbons: From theory to nanostructures fabrication
I.R. Ionescu, A. Danescu

Exact controllability for imperfect interface problems
S. Monsurrò, A. K. Nandakumaran, C. Perugia

On the Yield of Magnetorheological Fluids: A Modified Magnetic Dipole Model and Phenomenological Modelling
H. Khajehsaeid, N. Alaghehband

Studying Various Optimization Algorithms for Parameter Determination of Metamaterials
N. Shekarchizadeh, M. Abedi, A. M. Bersani

Homogenization of elliptic problems involving interfaces and singular data
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Aggregates of Silicon Crystals: Analytical Estimates of Elastic Properties
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G. Pontrelli

Homogenization of Fokker–Planck diffusion with degeneration
M. Amar, D. Andreucci, E.N.M. Cirillo

Homogenization within the context of structured deformations
M. Amar, J. Matias, M. Morandotti, E. Zappale

Junction Problems for Landau-Lifshitz Equation in ferromagnetic Multi-Structures
L. Faella

CONTINUUM ELECTRODYNAMICS OF MATERIALS – ITS HISTORY AND SOME CURIOUS RECENT DEVELOPMENTS

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This paper wants to draw attention to several issues in electrodynamic field theory of materials and to make way for a rational continuum approach to the subject. To this end the history of Maxwell's equations will be studied to find that, in the end, the starting point are the balances for magnetic flux and electric charge, both in a very general formulation for volumes and for open surfaces, all of which can deform and be immaterial or material. The spatial point-of-view for the description of fields is favored and its advantages in comparison to the concept of material particles is explained. A straightforward answer to the question of how to choose units for the electromagnetic fields most suitably is also presented. The transformation properties of the electromagnetic fields are addressed by rewriting the balances in space-time notation. Special attention is paid to the connection between the two sets of electromagnetic fields through the so-called Maxwell-Lorentz-æther relations. The paper ends with an outlook into constitutive theory of matter under the influence of electromagnetic fields and a discussion on curious developments in context with Maxwell's equations.

COVERING A SURFACE WITH PRE-STRESSED RIBBONS: FROM THEORY TO NANOSTRUCTURES FABRICATION

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The paper deals with the fabrication of nano-shells from pre-stressed nano-plates release. Due to geometrical and technological restrictions we have to cover a given surface with threedimensional thin ribbons. We discuss the key role of the geodesic curvature in the design of such shell-ribbons. We show that including small-strains but large rotations we are able to control the metric tensor of both un-deformed (or planar) and deformed (or shell) ribbons by an appropriate choice of the width and thickness of the ribbons. Moreover, the strain tensor is controlled by the difference between the curvature of the planar (un-deformed) ribbon and the geodesic curvature of the supporting curve of the shell (deformed) ribbon. Under suitable constitutive assumptions, we deduce the field equations, the boundary conditions and the design equations. The former relate the pre-stress in the planar layer to the final geometry of the desired shell-ribbon. A fine tuning of the composition, geometry and of the pre-stress of the plate-ribon is necessary to design and fabricate the shell-ribbon. We design and fabricate a partial cover of the sphere with constant latitude ribbons starting from planar multi-layer semiconductor materials grown by molecular beam epitaxy. The details of fabrication method and its limitations are discussed in detail.

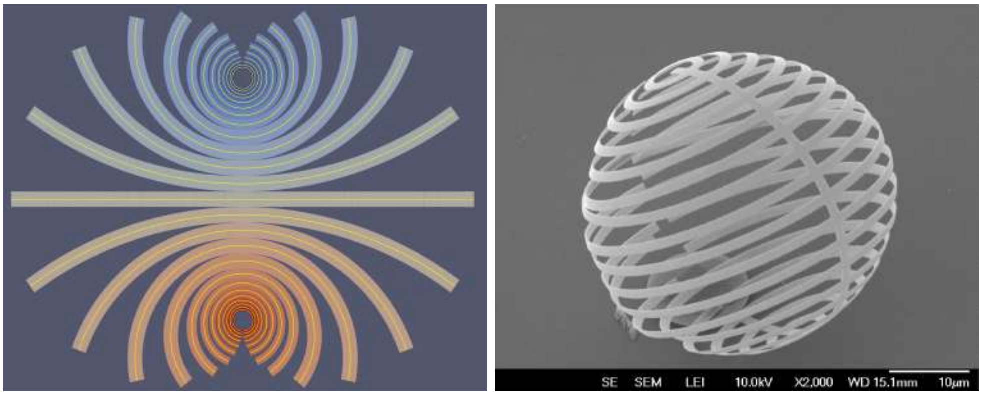

Figure 1: Left: an optimal theoretical set of planar ribbons to cover the sphere. Right: the experimental relaxation of a (non-optimal) set of planar ribbons.

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EXACT CONTROLLABILITY FOR IMPERFECT INTERFACE PROBLEMS

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We study the exact internal and boundary controllability for a second order linear evolution problem defined in a two-component domain. We prescribe a homogeneous Dirichlet condition on the exterior boundary and a jump of the displacement proportional to the conormal derivatives on the interface. This last condition is the mathematical interpretation of an imperfect interface. Our approach to exact controllability consists in proving an observability inequality by using the Lagrange multipliers method. Eventually, we apply the Hilbert Uniqueness Method, introduced by J. -L. Lions, which leads to the construction of the exact controls through the solution of an adjoint problem. Finally, we find lower bounds for the control times depending not only on the geometry of our domain and on the matrix of coefficients of our problems but also on the coefficient of proportionality of the jump with respect to the conormal derivatives.

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ON THE YIELD OF MAGNETORHEOLOGICAL FLUIDS: A MODIFIED MAGNETIC DIPOLE MODEL AND PHENOMENOLOGICAL MODELLING

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Magnetorheological fluids (MRF) are a category of smart materials. They exhibit a reversible change from a free-flowing Newtonian-like fluid to a semi-solid state upon application of an external magnetic field. In contrast to ordinary fluids, MRFs can tolerate shear stresses up to a threshold value called yield stress which strongly depends on strength of the magnetic field, magnetic particles volume fraction and temperature. Even beyond the yield, magnetic field can increase MR fluid viscosity up to several orders. Yield stress is one of the important characteristics which play role in selection/design of MRFs for a variety of applications. Thus, it is very useful to know how the yield stress changes with respect to the applied field and the magnetic particle content. For example, in order to efficiently control MR devices (like clutches and dampers), a relation which predicts the MRF's yield stress is crucial for computation of the output parameters like torque, force, velocity, etc.

In this work, effects of magnetic field intensity and magnetic particle volume fraction on the yield stress of MRFs are investigated. Four MRF samples with the same carrier fluid but different magnetic particle volume fractions are developed and experimentally analyzed to obtain the flow curves at a range of magnetic field intensity as well as shear rate. The results are then used to determine the yield stresses. A nonlinear empirical model is proposed for the yield stress of MRFs. The proposed model includes only two material parameters and despite its simple mathematical formulation, it covers a wide field strength range and captures magnetic saturation of the MR fluids. The model also includes the effect of particles volume fraction such that once calibrated, it can be utilized for different volume fractions as well.

Moreover, a modified form of the magnetic dipole model is proposed for the yield stress of MRFs. An exponential distribution function is used to describe the orientation of particle chains under the action of external magnetic field. It is shown that, the proposed modified dipole model results in a reasonable distribution of chains compared to previous similar models.

STUDYING VARIOUS OPTIMIZATION ALGORITHMS FOR PARAMETER DETERMINATION OF METAMATERIALS

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Metamaterials are referred to a group of architectured materials with peculiar properties which have a wide range of applications in various fields such as their recent utilization in medicine [1, 2]. Metamaterials are usually made of repeating structures, resulting in unprecedented mechanical properties. For capturing the effect of such complex microstructures in the material's response, it is often necessary to employ mathematical models that include higher-gradient terms. In such models, there are unknown material parameters which should be determined. As an example of metamaterials, we consider the pantographic structure [3]. The parameters of a macro-scale model are determined by fitting the deformation energy of the macro-scale model with that of a micro-scale model [4]. For this purpose, herein, we study different optimization algorithms, namely Trust region reflective (TRF), Nelder–Mead (NM), Truncated Newton (TNC), and Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithms. The Non-dominated Sorting Genetic Algorithm II (NSGA-II) has been previously applied [5].

The early results show that, among the employed algorithms, TRF outperforms the others regarding the mean squared error (MSE) and run time, and TNC has the largest MSE. BFGS and NM behave quite similarly having the longest run times among all algorithms.

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HOMOGENIZATION OF ELLIPTIC PROBLEMS INVOLVING INTERFACES AND SINGULAR DATA

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We prove existence and homogenization results for a family of elliptic problems involving interfaces and a singular lower order term. These problems model heat or electrical conduction in composite media.

THE VARIATIONAL ANALYSIS OF HIERARCHIES OF STRUCTURED DEFORMATIONS

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The theory of first-order structured deformations introduced by Del Piero and Owen enriches the purely macroscopic field theory of non-linear elasticity by taking into account the effects of dissarangements that occur at a single submacroscopic level. Nonetheless, many natural and man-made physical systems have a rich enough geometrical structure to permit the identification of hierarchies consisting of more than one physically meaningful submacroscopic level. The field theory of hierarchies of structured deformations was developed by Deseri and Owen. In this work we extend the variational model of structured deformations treated by Choksi and Fonseca to hierarchies of structured deformations.

AGGREGATES OF SILICON CRYSTALS: ANALYTICAL ESTIMATES OF ELASTIC PROPERTIES

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The effective elastic properties of silicon crystal aggregates is illustrated by means of zeroth-, first-, and second-order bounds of the strain energy density as well as different unique estimates. For such single-phase, brittle material a linear elastic material law is reasonable. The silicon grains have a cubic symmetry with a not negligible amount of anisotropy, whereas the aggregate is approximately isotropic. The latter is supported by experimental findings which are used to draw conclusions about the approximation quality of the different approaches. The results are as follows: i) The use of the geometric mean of the crystal stiffnesses is sufficient for estimating the effective elastic properties of the silicon aggregate. ii) To a large extent, experimental investigations at silicon aggregates are carried out on thin layers whose findings have to be transformed from plane state to bulk state. In summary, the results imply that the elastic properties of silicon crystal aggregates can be determined with high accurcy using analytical solutions of effective medium theories.

DIFFUSION-REACTION DRUG RELEASE MODEL IN NON-HOMOGENEOUS MICRO-CAPSULES

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Spherical drug carriers are among the most common formulations for a controlled release system. Microcapsules are small spherical particles that consist of a drug-filled core or internal phase surrounded by a continuous polymeric coating. Analysis of the diffusion-controlled system are confined to homogeneous spheres where an analytical solution is available [1], and various mathematical models have been proposed over the years to describe the drug release from this system, including layer-by-layer models [2].

By today's micro-engineering potential, it is possible to fabricate and control the material properties of the substrate to have the desired *smart* release and drug kinetics characteristics. Based on the current technology of encapsulation, the present analysis applies to functionally graded microcapsules. We develop a mechanistic model to describe drug transport within, and release from, the drug-loaded spherical capsule considering a continuously changing material along the radius, that extends the multi-layer model family.

The problem is described by a diffusion-reaction equation coupled with a boundary condition modelling a surface finite mass transfer resistance, which corresponds to the case of a coated capsule. We derive a closed-form analytical solution for the concentration in the sphere, based on an eigenfunction expansion. In particular, following the ideas in [3], a hybrid numerical-analytical solution for the formulated diffusion-reaction model with space-dependent coefficients is obtained, combining the formal analytical integral transform solutions with the hybrid solution of general Sturm-Liouville problems. Radial concentration profiles in the sphere and drug release curves are shown and the dependency and sensitivity of the solution on the parametric functions are analyzed.

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HOMOGENIZATION OF FOKKER–PLANCK DIFFUSION WITH DEGENERATION

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We consider a diffusion equation of Fokker-Planck type [1]

$$\frac{\partial u_\varepsilon}{\partial t} - \Delta\left(b_\varepsilon u_\varepsilon\right) = f\,.$$

In this case the material is inhomogeneous, since its diffusion coefficient b_ε oscillates rapidly with respect to the space variable x. We assume that the material contains a periodic array of holes of period ε. The size of the holes has instead order of $\eta\varepsilon$.

Moreover, we introduce the parameter δ which controls the magnitude of the coefficient b_ε inside the holes.

We investigate the onset of upscaled equations in the homogenization limit $\varepsilon \to 0$, when $\delta \to 0$ as well, namely when mass diffusion inside the holes becomes negligible.

In the framework of the standard Fick diffusion equation this problem is a rather classical one, we refer, for instance, to [2] and references therein.

Here we consider the Fokker–Planck diffusion equation, instead of the classical Fick one, performing a thorough study of all the possible cases obtained by tuning the relative rapidity at which δ, ε, $\eta\varepsilon$ tend to zero. Besides the mathematical interest of the issue, from a physical point of view we remark that we find different macroscopic equations when we assume different scalings for the parameters above.

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HOMOGENIZATION WITHIN THE CONTEXT OF STRUCTURED DEFORMATIONS

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A classical problem in a not-so-classical theory. Structured deformations aim at providing a multiscale geometry for variational problems in mechanics by collecting macroscopic and microscopic changes in a material in a single object. An initial energy featuring a bulk and a surface contribution is relaxed in order to define the energy of a structured deformation. Within this novel setting, we aim at studying periodic homogenisation and to derive effective energies by combining the information on the microstructure with the non-trivial interaction of the bulk and surface energy terms.

JUNCTION PROBLEMS FOR LANDAU-LIFSHITZ EQUATION IN FERROMAGNETIC MULTI-STRUCTURES

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We study a quasi-stationary ferromagnetic model governed by the Laudau-Lifschitz equation coupled with Maxwell equations in a structure consisting of two joined wires. For reasons of simplicity and economy, especially by a numerical point of view, one tries to reshape the problem in such a $3D$ multi-structure with a new problem in a multi-structure composed by two $1D$ components. We shall do that via an asymptotic process based on dimensional reductions. Let $x = (x_1, x_2, x_3)$ be the generic point of $\mathbb{R}^3$ and $\{h_n\}_{n\in\mathbb{N}} \subset]0,1[$ be a vanishing sequence of positive numbers and let $\Omega_n = \left(]-h_n, 0[^2 \times]0,1[\right) \cup \left(]-h_n, 1[\times]-h_n, 0[^2\right), \quad n \in \mathbb{N}$, be a $3D$ ferromagnetic multi-structure consisting of two orthogonal joined wires. When the body is isotropic and has constant temperature lower than Curie temperature, the quasi-stationary ferromagnetic model is governed by Landau-Lifshitz equation coupled to static Maxwell equation. More precisely,

$$\begin{cases} \partial_t M_n + M_n \wedge \partial_t M_n = 2M_n \wedge (\Delta M_n - DU_{M_n}) & \text{in } \Omega_n \times]0,T[, \\ M_n(0,x) = M_{0_n}(x) & \text{in } \Omega_n, \end{cases} \tag{1}$$

where $|M_{0_n}(x)| = 1$ in Ω_n and, for every t, the scalar potential $U_{M_n}(t,x)$ and the magnetic fiel $M_n(t,x)$ are linked by: $\nabla \wedge DU_{M_n} = 0$, $div\left(-DU_{M_n} + \overline{M_n}\right) = 0$ ($\wedge$ denotes the cross product in $\mathbb{R}^3$). After reformulating the problem on fixed domain $\Omega = \left(]-1, 0[^2 \times]0,1[\right) \cup \left(]-1, 1[\times]-1, 0[^2\right)$ through appropriate rescalings, we derive the limit problem when the thickness h_n vanishes, so we attempt to simulate the behaviour of two joined wires. We obtain two $1D$ limit problems coupled by a junction condition on the magnetization. The limit problem remains non-convex, but now it becomes completely local.

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Posters

MS-14 - *Automatic construction of stents in patient-specific coronary arteries with disease*
S.I.S. Pinto, M.J. Barbosa, C.F. Castro, C.C. António, L.C. Sousa

MS-17 - *Effect of crack-parallel normal stress on the strength and failure mode of concrete*
M. Ould Ouali, A. Misrab, L. Placidic, P. Poorsolhjouy

MS-18 - *Constitutive modeling of the dynamic strain aging in C45 steel*
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MS-19 - *Strength analysis of fiber reinforced polymeric gears made by additive manufacturing*
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MS-25 - *Exploring mechanical wave propagation in multi-metamaterial structures via the relaxed micromorphic model*
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MS-27 - *Nonlinear Flexural Characteristics of Nanobeams*
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AUTOMATIC CONSTRUCTION OF STENTS IN PATIENT-SPECIFIC CORONARY ARTERIES WITH DISEASE

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Cardiovascular diseases have been one of the main causes of death in advanced countries. The clinical practice indicates that specific locations in the human circulatory system, such as curvatures and arterial bifurcations, are sensitive to the appearance of cardiovascular diseases such as atherosclerosis, caused by stenosis – accumulation of fat substances, calcium, and others – in the arterial wall. Thus, the stenosis blocks the normal circulation of blood flow. Therefore, in clinical practice, a stent is introduced in the stenotic region of the artery in order to enlarge it, for that blood flow occurs in the best way. A stent is an endoprosthesis consisting of a perforated metal tube in the form of a mesh.

The hemodynamic simulation is an auxiliary and important tool for the prevention, diagnosis, and treatment of cardiovascular diseases (atherosclerosis). Thus, to simulate blood flow in patient-specific coronary arteries with stenosis and inserted stent, it is necessary to define an automatic method of stent construction in order to save time. As far as we know, there are no works in the literature that use numerical code to construct the stent in Visual Basic® software. Visual Basic® was used due to the wide possibility of commands by the Solidworks® library. There are two different stents in the created database: a metallic one “Palmaz-Schatz” (primordial stent) and a polymeric one “Endeavor”. Figure 1a is the interface of the created software. The user can choose the artery diameter, the stenosis length, the stent type and the option to create the stent (only) or the patient artery with the stent. In Figure 1b, it can be visualized the created Endover stent (only) and in Figure 1c the created patient artery with the Endover stent.

A primordial stent and a recent one were used, as references, in the present work. However, many different types of stents, the more recent ones, should be added to the interface in a near future, in order to satisfy the need of the hospital.

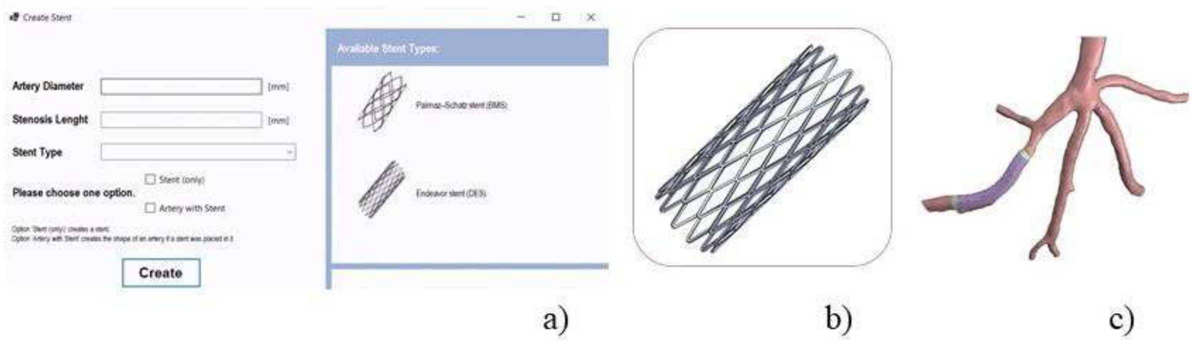

Figure 1: a) Interface of the created software in Visual Basic®, b) Endover stent created through the software, c) patient-specific coronary artery with Endover stent created through the software.

EFFECT OF CRACK-PARALLEL NORMAL STRESS ON THE STRENGTH AND FAILURE MODE OF CONCRETE

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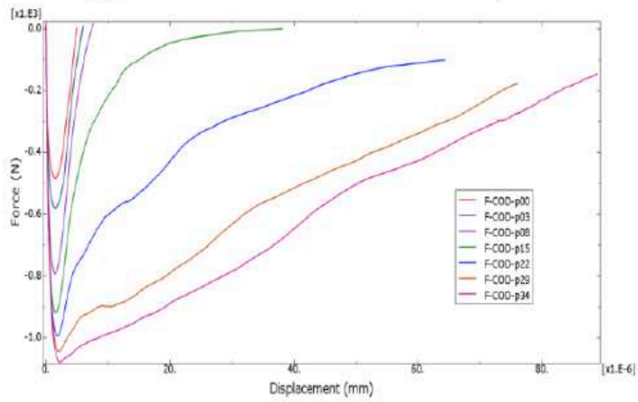
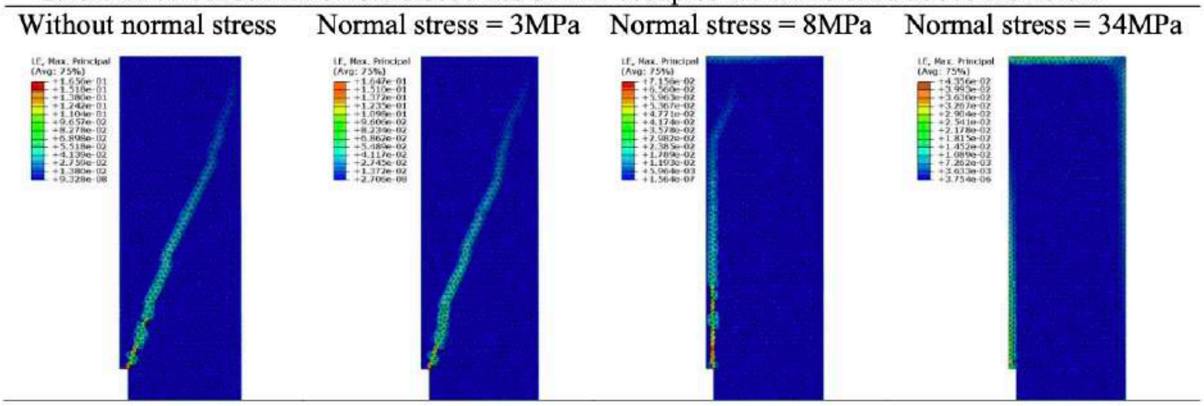
This work is dedicated to highlighting the effect of crack-parallel normal stress on the resistance and failure mode of a notched concrete specimen subjected to 3-point bending. This test formulated by Bazant and co-workers is called the "Gap test" [1]. To do this we use the GM (Granular micromechanics) model behavior model, implemented in the Abaqus/Explicit code using the VUMAT user subroutine [2-3]. The figure giving the evolution of the force according to the crack opening shows that the application of normal stress multiplies the maximum force, up to 3 times. We also confirm this trend concerning the Mode I (opening) fracture energy, as reported by Bazant and co-workers [1]. We show in the figure below the failure mode is strongly influenced by the applied normal stress. Indeed, the propagation of the crack takes place at about 45° for a standard 3-point bending test. When normal stress of 3 MPa is applied, the crack propagates at around 60°. For normal stress of 8 MPa, the propagation is parallel to the crack (90°). The more the normal stress applied increases, the wider the deformation concentration band becomes until it occupies the entire band above the notch.





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CONSTITUTIVE MODELING OF THE DYNAMIC STRAIN AGING IN C45 STEEL

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Dynamic Strain Aging (DSA) is a sudden increase in material strength within a certain range of temperatures and strain rates. The activation of DSA was experimentally reported in C45 steel at different strain rates in the range of 0.0015 s^{-1} to 0.15 s^{-1} and over temperatures in the range of 298 K to 923 K. Despite the phenomenon being observed by several studies both in C45 steel and other materials, the literature still lacks a specific constitutive model that physically captures the activation of DSA. In fact, the available constitutive models are not designed to account for such phenomenon because it involves a very specific form of interaction between dislocations and solute atoms which pin significant amount of mobile dislocations requiring higher applied stresses to overcome such pinning barriers. Such interactions between dislocations and solute atoms need to be physically captured by independent terms within any constitutive model because those interactions cannot be captured by the available formulations that consider dislocation-dislocation or dislocation-grain boundaries interactions. However, those newly proposed simple formulations and modifications can maintain the overall form of the previously formulated models, but with slight adjustment to consider the dislocation-solute atoms interactions. Therefore, the current work focuses on modifying an existing physical based constitutive model (The VA model) in order to introduce a higher order temperature and strain rate dependent terms within the model parameters themselves to capture the effect of dynamic strain aging in C45 steel. Those terms are only to capture the DSA activation and they vanish and go to zero when DSA is absent. In other words, the higher order and strain rate sensitivity modifications will ultimately converge to zero for all materials that do not experience DSA as it will be shown by the results of this proposed work. Such description without altering or changing the physical basis of the model or random performance of regression analysis can significantly help the modeling of such materials.

STRENGTH ANALYSIS OF FIBER REINFORCED POLYMERIC GEARS MADE BY ADDITIVE MANUFACTURING

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Polymeric gears have interesting properties such as lightweight, cheapness, but they have a great point of weakness consisting in the poor mechanical properties of polymers respect to metals. Polymeric gears can be also easily produced by additive manufacturing technique. The last developments of polymer 3D printers, allow to add fibers to locally reinforce the component to be produced. In this work this kind of production method has been used to manufacture a fiber reinforced gear, to keep the lightness of the polymer, but increasing its mechanical strength. In particular, the reinforcement fiber has been added on the external shape of the teeth, where the bending stress is higher, as shown in Figure 1.

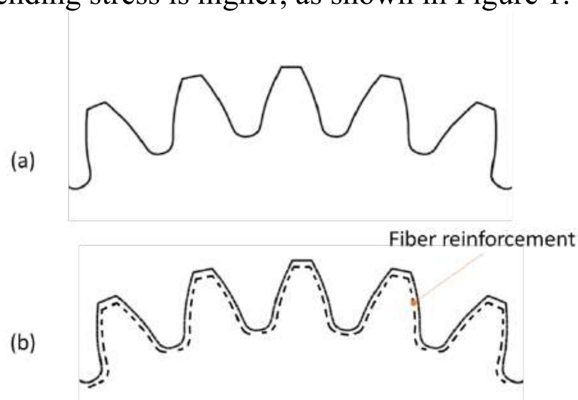

Figure 1: standard gear (a), fiber reinforced gear (b)

The aim of this work is therefore to compare mechanical strength of a standard polymeric gear, against a reinforced one made by the same base material.
The base material used to produce the gears used in this work is composite nylon know with the commercial name of Onyx, the reinforce gear was added wit continuous carbon fiber. Both gears have been made by a Markforged 3D printer.
Mechanical performance of standard and reinforced gear has been evaluated by means of single tooth bending tests with static load and dynamic (fatigue load).
Main results show that fiber reinforced gear has better mechanical performance respect to standard gear. The position of fiber reinforcement is very important, this aspect must be investigated in future work in order to optimize the reinforced gear design and to better exploit potentialities to 3D printing with fused filament fabrication, continuous fiber reinforcement process.

EXPLORING MECHANICAL WAVE PROPAGATION IN MULTI-METAMATERIAL STRUCTURES VIA THE RELAXED MICROMORPHIC MODEL

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Metamaterials have opened the door to the design of materials whose behavior does not naturally occur in continuum media. In the fields of acoustic metamaterials [3] and structural metamaterials [2], tailoring the geometry of the underlying microstructure can result in negative constitutive parameters and unexpected frequency responses. The prospect of tunable properties is of special interest for the case of metamaterials that exhibit band gaps, i.e. frequency ranges for which the wave propagation is inhibited. These dispersive properties are not captured by traditional Cauchy continuum theories and require higher order theories or continuum models with enriched kinematics. The relaxed micromorphic model has been shown to reproduce band gaps [1].

$$\begin{aligned} J\left(\dot{u}, \nabla \dot{u}, \dot{P}\right) = {} & \frac{1}{2}\rho\left\langle \dot{u}, \dot{u}\right\rangle + \frac{1}{2}\langle \mathbb{J}_{\mathrm{m}}\, \mathrm{sym}\,\dot{P}, \mathrm{sym}\,\dot{P}\rangle + \frac{1}{2}\langle \mathbb{J}_{\mathrm{c}}\, \mathrm{skew}\,\dot{P}, \mathrm{skew}\,\dot{P}\rangle \\ & + \frac{1}{2}\langle \mathbb{T}_{\mathrm{e}}\, \mathrm{sym}\nabla\dot{u}, \mathrm{sym}\nabla\dot{u}\rangle + \frac{1}{2}\langle \mathbb{T}_{\mathrm{c}}\, \mathrm{skew}\nabla\dot{u}, \mathrm{skew}\nabla\dot{u}\rangle \\ & + \frac{1}{2}\langle \mathbb{M}\, \mathrm{Curl}\,\dot{P}, \mathrm{Curl}\,\dot{P}\rangle, \end{aligned} \tag{1}$$

$$\begin{aligned} W\left(\nabla u, P, \mathrm{Curl}\,P\right) = {} & \frac{1}{2}\langle \mathbb{C}_{\mathrm{e}}\, \mathrm{sym}\left(\nabla u - P\right), \mathrm{sym}\left(\nabla u - P\right)\rangle + \frac{1}{2}\langle \mathbb{C}_{\mathrm{m}}\, \mathrm{sym}\,P, \mathrm{sym}\,P\rangle \\ & + \frac{1}{2}\langle \mathbb{C}_{\mathrm{c}}\, \mathrm{skew}\left(\nabla u - P\right), \mathrm{skew}\left(\nabla u - P\right)\rangle + \frac{1}{2}\langle \mathbb{L}\, \mathrm{Curl}\,P, \mathrm{Curl}\,P\rangle\,, \end{aligned} \tag{2}$$

In this work, the relaxed micromorphic model is used to predict the mechanical response of multi-metamaterial structures, i.e. structures combining different metamaterials in view of elastic wave control. The relaxed micromorphic model successfully captures the complex dynamical response of these multi-metamaterial structures, and these results extend the body of knowledge for which the relaxed micromorphic model yields positive outcomes.

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NONLINEAR FLEXURAL CHARACTERISTICS OF NANOBEAMS

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Advanced nano-scaled systems can be subjected to large applied forces yielding in significant nonlinear structural features. In the present study, kinematics of the beam is assumed to be consistent with the classical beam model wherein the von Kármán nonlinear strain component is considered as the source of the geometrical nonlinearity. For nanoscopic study of the nonlinear flexure of nanobeams, the mixture unified gradient elasticity is invoked. A stationary variational framework, integrating all of the governing equations into a solitary functional, is conceived. The corresponding boundary-value problem of equilibrium is determined and enriched with consistent form of non-standard boundary conditions. The size-effect phenomena associated with the nonlinear flexure mechanics of nanobeams can be efficiently realized since the stress gradient theory, the strain gradient theory, and the classical elasticity theory are consistently unified.

An efficient numerical approach is established by making recourse to the stationary variational functional wherein independent series solution of the kinematic and kinetic field variables are proposed. Suitable forms of the coordinate functions are introduced to fulfill a set of classical and non-standard boundary conditions in the flexure of elastic nanobeams with fully-clamped constraint. A comprehensive numerical study is performed to illustrate the nonlinear flexural characteristics of a nanobeam wherein the nanoscopic effects corresponding to the length-scale parameters are thoroughly examined and discussed. For small enough values of the non-dimensional load parameter, the nonlinear flexural response of the nano-beam exhibits an asymptotic behavior to the linear transverse deflection. The obtained nonlinear flexural characteristics and ensuing numerical results, therefore, detect original benchmarks for numerical analyses, and accordingly, can be efficiently implemented in structural analysis of nano-sized beam elements of pioneering nano-engineering systems.

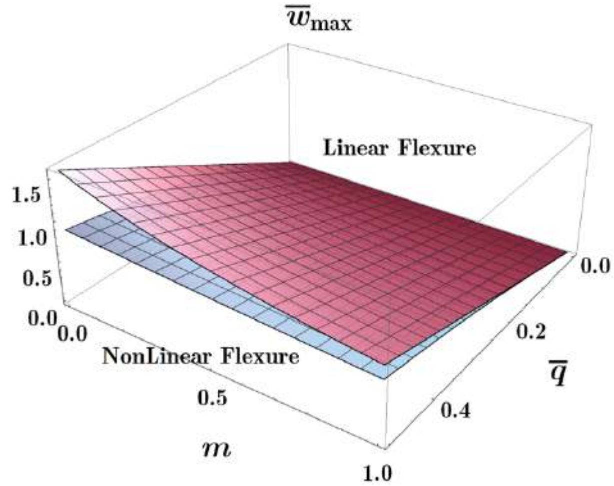

Figure 1. Nonlinear and linear flexural response of the nano-beam

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