[Proceedings of the] Joint "NewFrac Workshop 3 Reaching Out" and "TC 16 Workshop III"

JOINT WORKSHOP

"Reaching Out"

NewFrac Workshop 3 *Reaching Out*

New strategies for multifield fracture problems across scales in heterogeneous systems for energy, health and transport

TC 16 Workshop III

European Structural Integrity Society
Technical Committee 16
Finite Fracture Mechanics

17-20 January 2023

Politecnico di Torino

Preface

These proceedings collect the program and the abstracts of the talks that will take place at the joint workshop "Reaching out" organized by the NewFrac Training Network and by the ESIS Technical Committee 16 at the Politecnico di Torino, from January 17 to January 20, 2023. The workshop is part of the research and training activities of the Marie Skłodowska-Curie project "New strategies for multifield fracture problems across scales in heterogeneous systems for energy, health and transport" NewFrac (Grant Agreement n. 861061, https://www.newfrac.eu/), supported by the European Commission which is gratefully acknowledged. This workshop is the third organized by the NewFrac Training Network, following the previous ones organized at the University of Seville in the period October 1-8 (2021) and in Lucca, in the period May 9-12 (2022), respectively.

The workshop is organized in one session over 4 days. It features 40 talks: 5 plenary lectures of invited speakers (one hour long), 11 talks by senior lecturers (half an hour) and 24 talks (20 minute) including the ones delivered by the 13 Early-Stage Researchers of the NewFrac Training Network. Social activities include a visit to the Torino Mauto (car museum) and the social dinner on Thursday afternoon and evening. On Friday the open meeting of the committees of the NewFrac project close the workshop.

The Organizing Committee would like to thank Ms. María Nocete, scientific secretary of the event and of the NewFrac project, and the administrative staff of the Politecnico di Torino: Roberta Greco, Silvio D'Elicio, Cristina Vastapane, Federica Voci and Laura Ottonello. They did help us in organizing this "homemade" event in an effective and pleasant way. We wish to thank also PhD Giulia De Lucia for her availability to guide a visiting tour to Torino city center for participants remaining in Torino in the weekend after the workshop.

The organizers wish you all an interesting and enjoyable meeting. Most of presentations deal with Finite Fracture Mechanics and Phase Field modeling of fracture, but some others explore different solid and fracture mechanics modelling issues. We do hope the meeting will provide a fruitful exchange of ideas, leading to further successful researches.

Torino, 17/1/2023

The Organizing Committee

Pietro Cornetti

Mauro Corrado

Alberto Sapora

Vladislav Mantič (NewFrac Coordinator)

NewFrac & TC16 - JOINT WORKSHOP

VENUE: Energy Center, Politecnico di Torino, Via Paolo Borsellino 38

	Tuesday, 17	Wednesday, 18	Thursday, 19	Friday, 20
9:00-10:30		Rosendahl Lenarda Molnár	Invited lecture: Weinberg Kotousov	Invited lecture: Schneider Paggi
10:30-11:00		Coffee break	Coffee Break	Coffee break
11:00-13:00		Doitrand Rheinschmidt Guzmán Bushpalli Girard	Arteiro Papšik Schulz Mirzaei Chen Duminy	Mantič Levy Chao Correas Sangaletti Infante-García
13:00-14:30	13:30 Registration 14:00 Opening	Lunch	Lunch	Lunch
14:30-15:30	Invited lecture: Campagnolo	Invited lecture: Spagnoli		García Baldassari/Ferrian
15:30-16:00	Kotousov	Tsokanas		Coffee break
16:00-16:30	Coffee break	Coffee break		NewFrac Meeting
16:30-18:10	Fajardo Lacave Jiménez-Alfaro Ambikakumari Vicentini Zolesi	Macías Liu Mitrou Montanari Chang	Social programme: CAR MUSEUM - Mauto	
19:30			Social Dinner	

Duration
50'+10'
25'+5'
15'+5'

Conference venue: Energy Center

https://goo.gl/maps/MrmuEK3PH1Tt2gDVA

Lunch location: OGR-Snodo

https://goo.gl/maps/HYWu2Fpn8zobSHDR6

Guided tour: Mauto (car museum)

https://goo.gl/maps/CkpQo7uoQZEMfPNX9

Social dinner: “Al Gufo Bianco”

https://goo.gl/maps/R33JdL8BsiT61die8

Invited Lectures

Alberto Campagnolo

Advanced local approaches and automated 3D FE analyses for fatigue lifetime assessment of welded structures

Tuesday 14:30-15:30

Andrea Spagnoli

Tearing, Cutting and Puncturing in Soft Elastic Solids

Wednesday 14:30-15:30

Kerstin Weinberg

Computational fracture models for linearized and finite strains

Thursday 9:00-10:00

Jens Schneider

From brittle fracture to fail-safe. Glass structures and their engineering challenges

Friday 9:00-10:00

Program

Tuesday, 17/1

14:30-15:30 **Campagnolo A** *(University of Padova)*: "Advanced local approaches and automated 3D FE analyses for fatigue lifetime assessment of welded structures"

15:30-16:00 **Kotousov A** *(The University of Adelaide)*: "Crack closure and fatigue life evaluation for an aircraft load spectrum"

16:00-16:30 *Coffee Break*

16:30-16:50 **Fajardo Lacave AM** *(Robert Bosch GmbH)*: "A phase-field model for the multiscale analysis of fracture in short glass fiber reinforced polymers"

16:50-17:10 **Jimenez-Alfaro S** *(Sorbonne Université)*: "Modelling of glass matrix composites by the Coupled Criterion and the Matched Asymptotics approach. The role of residual stresses"

17:10-17:30 **Ambikakumari K** *(Universidad de Sevilla)***:** "Finite Element implementation of the Coupled Criterion based on the Principle of Minimum Total Energy subjected to a Stress Condition to predict crack onset and growth"

17:30-18:10 **Vicentini S** *(ETH Zurich)***, Zolesi C** *(Sorbonne Université)*: "Multi-axial loadings in phase field model of fracture: review and benchmarks"

Wednesday, 18/1

09:00-09:30 **Rosendahl P** *(Technical University of Darmstadt)*: "Fracture phenomena in the release of slab avalanches"

09:30-10:00 **Lenarda P** *(IMT Lucca)*: "A comprehensive characterization of fracture in unit cell open foams generated from Triply Periodic Minimal Surfaces"

10:00-10:30 **Molnár G** *(Université Lyon)*: "A detailed comparison between the coupled criterion and the phase-field method for fracture simulation"

10:30-11:00 *Coffee Break*

11:00-11:30 **Doitrand A** *(Université Lyon)*: "Phase field implementation of the coupled criterion"

11:30-11:50 **Rheinschmidt F** *(Technical University of Darmstadt)*: "Variational approach on the release of snow slab avalanches"

11:50-12:10 **Guzmán JL** *(Universidad de Sevilla)*: "Prediction of multiple delaminations in ILTS specimens by an Abaqus implementation of the Coupled Criterion based on the minimization of the total energy subjected to a stress condition"

12:10-12:30 **Bushpalli S** *(Fidamc)***:** "A simple phase-field method for modeling transverse damage in fiber reinforced laminas"

12:30-12:50 **Girard H** *(Université Lyon)*: "Influence of adjacent fibers on crack initiation prediction using the coupled criterion"

13:10-14.30 *Lunch*

14:30-15:30 **Spagnoli A** *(University of Parma)*: "Tearing, Cutting and Puncturing in Soft Elastic Solids"

15:30-16:00 **Tsokanas P** *(University of Patras)*: "Mode decoupling versus mode partitioning to determine pure-mode fractures in unconventional specimens"

16:00-16:30 *Coffee Break*

16:30-16:50 **Macías JM** (*Universidade do Porto*): "Micro-mechanical analysis of composite materials using Phase-Field models of brittle fracture"

16:50-17:10 **Liu Z** *(IMT Lucca)*: "A continuum large-deformation theory for the coupled modeling of polymer-solvent system with application to PV recycling"

17:10-17:30 **Mitrou A** (*Universidade do Porto*): "Capturing the off-axis behavior of notched multidirectional thin-ply laminates"

17:30-17:50 **Montanari M** *(University of Parma)***:** "Mitigating Defect Sensitivity in the Mechanical Response of Multiphase Lattice Metamaterials"

17:50-18:10 **Chang H-J** *(Safran Group)*: "Brief introduction and applications of CMC material and its modelling"

Thursday, 19/1

09:00-10:00 **Weinberg K** *(University of Siegen)*: “Computational fracture models for linearized and finite strains”

10:00-10:30 **Kotousov A** *(The University of Adelaide)*: “Non-Destructive Evaluation of Fatigue Damage with Non-linear guided Waves: Fundamentals and Applications”

10:30-11:00 *Coffee Break*

11:00-11:30 **Arteiro A** (*Universidade do Porto*): “Fast virtual calculation of B-value allowables for composite laminates with a coupled stress and energy Finite Fracture Mechanics criterion”

11:30-11:50 **Papšik R** *(University of Mining Leoben)*: “Prediction of crack initiation during hertzian indentation with the coupled criterion”

11:50-12:10 **Schulz I** *(Technical University of Darmstadt)*: “An attempt of understanding the fracture behaviour of glass in construction using the Coupled Criterion (CC)”

12:10-12:30 **Mirzaei A** *(Politecnico di Torino)*: “A novel model to estimate fatigue life of notched components based on Finite Fracture Mechanics”

12:30-12:50 **Chen X** *(Université Lyon)*: “Dynamic crack initiation in circular hole PMMA plates considering nonlinear elastic material behavior”

12:50-13:10 **Duminy T** *(Université Lyon)*: “Influence of elastic and fracture anisotropy on architectured material”

13:10-14.30 *Lunch*

16:30-18:30 **Social programme:** Visit to Museo dell’Auto, “Mauto” (Car Museum)

19:30-22:30 **Social dinner.** Ristorante “Al Gufo Bianco”, Corso Dante 129, Torino

Friday, 20/1

09:00-10:00 **Schneider J** *(Technical University of Darmstadt)*: “From brittle fracture to fail-safe. Glass structures and their engineering challenges”

10:00-10:30 **Paggi M** *(IMT Lucca)*: “A multi-phase field approach to tensile fracture and compressive crushing and applications to concrete”

10:30-11:00 *Coffee Break*

11:00-11:30 **Mantič V** *(Universidad de Sevilla)*: “Application of the coupled criterion to the propagation of interface cracks with frictional sliding contact”

11:30-11:50 **Levy M** *(Tel-Aviv University)*: “Crack nucleation in 1D heterogeneous bar – h- and p-FE approximation of a phase field model”

11:50-12:10 **Chao Correas A** *(Politecnico di Torino)*: “Crack onset from circular holes: biaxial loadings and arrayed cavity interaction”

12:10-12:30 **Sangaletti S** *(Universidad de Sevilla)***:** “Analysis-driven improvement of 3D printed composite materials: application of anisotropic Phase Field modelling”

12:30-12:50 **Infante-García D** *(Universitat Politècnica de València)*: “Error estimation of phase-field approach in Westergaard’s problem under mode I-II loading”

13:00-14.30 *Lunch*

14:30-15:00 **García I** *(Universidad de Sevilla)*: “Crack initiation at the fiber-matrix interface in LFRC under transverse tension: A 3D analysis”

15:00-15:20 **Baldassari M** *(Politecnico di Torino)*: “Size effect on concrete-like material flexural strength and fracture toughness: a Finite Fracture Mechanics approach

15:20-15:40 **Ferrian F** *(Politecnico di Torino)*: “Finite Fracture Mechanics: Size effects on spheroidal voids and corrosion pits”

15:40-16:00 *Coffee break*

16:00-17:30 **NewFrac Meeting**

Abstracts

(by alphabetical order of the presenter's surname)

Finite Element implementation of the Coupled Criterion based on the Principle of Minimum Total Energy subjected to a Stress Condition to predict crack onset and growth

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Keywords: *Finite Fracture Mechanics, Stress and Energy Criterion, PMTE-SC*

Abstract: A numerical procedure predicting crack onset and growth in brittle materials is developed using the Coupled Criterion of Finite Fracture Mechanics (CCFFM) [1] which assumes crack advances by finite steps and requires both stress and energy conditions are fulfilled. Crack advances are bridged by a continuous distribution of springs, similarly to the Linear Elastic-(perfectly) Brittle Interface Model (LEBIM) [2] combined with CCFFM [3]. The Principle of Minimum Total Energy subjected to a Stress Condition (PMTE-SC) [4,5] is implemented by a load stepping algorithm, minimizing the total energy change due to a crack advance allowed by the stress criterion. The PMTE-SC is more versatile than the classical formulation of CCFFM using stress and energy criterion curves, providing a tool to solve complex problems of industrial relevance.

A simple implementation of PMTE-SC in FEM code Abaqus considers cracks geometrically modelled as topological discontinuities in the finite element mesh, with cracks introduced explicitly during the discretization of the domain, the crack faces coinciding with the element edges. Several numerical examples are solved, showing that accurate predictions are obtained for short cracks, holes, and notches.

References:

[1] D. Leguillon, 2002. Strength or toughness? A criterion for crack onset at a notch. European Journal of Mechanics A/Solids, 21, 61–72.

[2] V. Mantič, L. Távara, A. Blázquez, E. Graciani, F. París, 2015. A linear elastic-brittle interface model: application for the onset and propagation of a fibre-matrix interface crack under biaxial transverse loads. International Journal of Fracture 195, 15-38.

[3] M. Muñoz-Reja, L. Távara, V. Mantič, P. Cornetti, 2016. Crack onset and propagation at fibre-matrix elastic interfaces under biaxial loading using finite fracture mechanics. Composites Part A, 82, 267–278.

[4] V. Mantič, 2014. Prediction of initiation and growth of cracks in composites. Coupled stress and energy criterion of the finite fracture mechanics (Keynote Lecture). In: Proceedings of the 16th European Conference on Composite Materials (ECCM16), F. París (Ed.), http://www.escm.eu.org/eccm16/assets/1252.pdf.

[5] M. Muñoz-Reja, V. Mantič, L. Távara, 2022. Comparative analytical study of the coupled criterion and the principle of minimum total energy with stress condition applied to linear elastic interfaces. Theoretical and Applied Fracture Mechanics, 103274.

Fast virtual calculation of B-value allowables for composite laminates with a coupled stress and energy Finite Fracture Mechanics criterion

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Keywords: *Polymer Matrix Composites (PMCs); Finite Fracture Mechanics; Design Allowables*.

Abstract: Structural components are typically designed considering the effects of stress concentrations resulting from geometrical discontinuities or in-service damage [1]. The replacement of metallic materials by polymer composites is dependent on the capability to predict the strength of composite laminates accurately and quickly. Moreover, analysis models should not rely on empirical parameters that need to be determined every time lay-up changes. To meet these requirements, this work will present a method that takes the laminate layers as the basic building blocks and uses the orthotropic material properties related to the directions of the fibers to obtain accurate and fast predictions of open-hole composite plates subjected to uniaxial tension or uniaxial compression loads [2]. This method is based on a coupled Finite Fracture Mechanics (FFMs) model for the strength prediction of open-hole laminates, by solving the system of equations that imposes the simultaneous fulfilment of the average stress criterion and of the FFMs criterion. Only three ingredients are required to solve this system of equations: the elastic properties of the laminate, the laminate unnotched strength and the laminate fracture toughness. To determine the laminate elastic properties, Tsai's modulus and the Tsai-normalized plane stress stiffness components are used, requiring knowledge of just one stiffness property of the transversely isotropic lamina. The laminate unnotched strengths are determined using last-ply failure analyses based on omni strain failure envelopes, which requires knowledge of the tensile and compressive strengths of the lamina in the fiber direction. Finally, the laminate fracture toughness is obtained from the intralaminar fracture toughness of the 0° plies using an energy balance and neglecting the contribution of the 90° plies (whose intralaminar fracture toughness is at least 2 orders of magnitude lower) [3]. The proposed method is validated based on experimental data for legacy laminates composed of 0°, 90° and ±45° plies, with relative errors usually within 10% in tension and in compression. For laminates with thin plies, which exhibit quasi-brittle translaminar fracture behavior, the predictions for the open-hole tensile strength differ from the experimental results by only 3% or less. Further, the proposed method is applied to new-generation composite laminates based on double angle-ply (or Double-Double) laminates [4,5]. Finally, it is demonstrated how this method can be used for fast virtual calculation of B-value allowables, incl. sensitivity analyses and uncertainty quantification and management [6].

References:

[1] Composite Materials Handbook – 17 (CMH-17). VOLUME 3. POLYMER MATRIX COMPOSITES MATERIALS USAGE, DESIGN, AND ANALYSIS. SAE International, 2012.

[2] Furtado C, Arteiro A, Bessa MA, Wardle BL, Camanho PP. Prediction of size effects in open-hole laminates using only the Young's modulus, the strength, and the R-curve of the 0°ply. Compos Part A-Appl S 2017;101:306-317.

[3] Camanho PP, Catalanotti G. On the relation between the mode I fracture toughness of a composite laminate and that of a 0° ply: analytical model and experimental validation. Eng Fract Mech 2011;78:2535-2546.

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[6] Vallmajó O, Cózar IR, Furtado C, Tavares R, Arteiro A, Turon A, Camanho PP. Virtual calculation of the B-value allowables of notched composite laminates. Compos Struct 2019;212:11-21.

Size effect on concrete-like material flexural strength and fracture toughness: a Finite Fracture Mechanics approach

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Keywords: *Size effect, Finite Fracture Mechanics, Three Point Bending, Semi-Circular Bending, Concrete-like materials.*

Abstract: The decrease of the apparent flexural strength is an ongoing key research topic, especially regarding concrete and concrete-like materials due to the huge difference from laboratory to actual structural sizes.
In recent years, Finite Fracture Mechanics has demonstrated to be an effective approach to estimate the size effect in quasi-brittle materials, allowing fast predictions suitable for crack initiation. The aim of the present work is to deepen and to extend the use of Finite Fracture Mechanics on the evaluation of the flexural strength of plain and notched specimens under bending loads. To this end, an analytical solution for the determination of the strength for plain specimens under pure bending is provided, together with the expression of the small and large size asymptotes. In addition, a master curve is illustrated, in order to easily evaluate the material tensile strength from tests like four-point bending on specimens of different sizes. Moreover, special attention is paid on the Three Point Bending and Semi-Circular Bending test geometries. For each test configuration, theoretical formulations able to assess the scaling of the nominal flexural strength (or of the nominal fracture toughness) are given. Finally, theoretical predictions are examined and compared against several experimental data from the literature, related to both concrete and rock specimens. The excellent agreement with the experimental data demonstrates the soundness of the Finite Fracture Mechanics approach, even more significant because of its simplicity.

A simple phase-field method for modeling transverse damage in fiber reinforced laminas

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Keywords: *Phase-field, transverse cracks, composites*.

Abstract: Complex failure mechanisms like intralaminar damage, interlaminar delamination and their interactions are the most common failure mechanisms in fiber reinforced composites. In the current work, we illustrate a straightforward method to solve problems involving transverse damage in fiber reinforced laminas. Due to the trending success of Phase- field in offering solutions to problems involving matrix cracks, in this work, we propose a simple phase-field model and provide an insight into the Abaqus implementation of the said approach using only a user material subroutine to study transverse damage in CFRP composites. To this end, the capability of the formulated approach considering both elastic and fracture behavior, to represent transverse cracks in transversely isotropic materials, is presented. The implementation of the proposed model has been validated by performing tests on benchmark problems and comparing their results with the analytical solutions.

References:

[1] Y. Navidtehrani, C. Betegón, E. Martínez-Pañeda. 2021. A Unified Abaqus Implementation of the Phase Field Fracture Method Using Only a User Material Subroutine. Materials, 14(8):1913.

[2] Zhang, P., Hu, X., Bui, T. Q., & Yao, W. (2019). Phase field modeling of fracture in fiber reinforced composite laminate. International Journal of Mechanical Sciences, 161, 105008.

Advanced local approaches and automated 3D FE analyses for fatigue lifetime assessment of welded structures

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Keywords: *Fatigue, Notch Stress Intensity Factors (NSIFs), Strain energy density (SED), Peak stress method (PSM), Industrial applications*.

Abstract:

In fatigue design of welded joints, the local approach based on the notch stress intensity factor (NSIF) assumes that the weld toe profile is a sharp V-notch having a tip radius equal to zero, while the root side is a pre-crack in the structure. The Peak Stress Method (PSM) [1] is an engineering, FE-oriented application of the NSIF approach to fatigue design of welded joints, which takes advantage of the singular, linear elastic, opening, in-plane shear and out-of-plane shear peak stresses calculated at the weld toe and the weld root by using coarse FE meshes. The free mesh pattern is generated by keeping constant the element type and by choosing arbitrarily the average element size within a given range. The meshes required for the PSM application are rather coarse if compared to those necessary to evaluate the NSIFs from the local stress distributions. Two-dimensional as well as three-dimensional FE analyses can be adopted to apply the method. By using the averaged Strain Energy Density (SED, which can be expressed as a function of the relevant NSIFs) as a fatigue strength criterion, a so-called equivalent peak stress is defined, which can be combined with properly calibrated PSM-based design curves to estimate the fatigue lifetime of welded structures made of either aluminum alloys or structural steels subjected to constant amplitude (CA) loadings. Originally, the PSM was validated for CA pure axial or bending loadings and CA pure torsion loadings; afterwards, the PSM has been extended to deal also with CA in-phase as well as out-of-phase multiaxial fatigue loadings. However, in service, real engineering welded structures are generally subjected to complex multiaxial variable amplitude (VA) loads. Accordingly, the PSM has recently been extended to estimate the lifetime of welded joints under such loading conditions [2]. By combining the averaged SED fatigue criterion with the Palmgren-Miner's Linear Damage Rule (LDR), the equivalent peak stress has been re-formulated in order to assess the fatigue strength of welded structures subjected to multiaxial VA loads. Moreover, to support the FE analyst in the fatigue design of complex welded structures, an interactive analysis tool [3] has recently been developed in Ansys® Mechanical, taking advantage of Ansys® Customization Toolkit (ACT), a programming interface that allows to integrate user-defined analysis workflows with Ansys® FE environment.

Because of the relatively coarse FE analyses required and simplicity of post-processing the calculated peak stresses, the PSM might be useful in the everyday design practice. To prove that, the fatigue strength of welded steel details taken from industrial case studies is analyzed according to the PSM [4]. The case studies involve a roundabout-type carrousel, a scotch-yoke valve actuator, a suspension for cableway vehicles and a sluice gate.

References:

[1] G. Meneghetti, A. Campagnolo. 2020. State-of-the-art review of peak stress method for fatigue strength assessment of welded joints. Int J Fatigue, 139:105705.

[2] A. Campagnolo, L. Vecchiato, G. Meneghetti. 2022. Multiaxial variable amplitude fatigue strength assessment of steel welded joints using the peak stress method. Int J Fatigue, 163:107089.

[3] A. Visentin, A. Campagnolo, V. Babini, G. Meneghetti. 2022. Automated implementation of the Peak Stress Method for the fatigue assessment of complex welded structures. Forces Mech:100072.

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Brief introduction and applications of CMC material and its modelling

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Keywords: *Ceramic matrix composite (CMC), Fracture, Toughness, Numerical modeling*

Abstract:
In this presentation we will briefly give an overview of the Ceramic matrix composite (CMC) material and its applications and related modelling activities at the Safran Group. First general information about the CMC material and its related applications will be briefly introduced. Indeed, the CMC material allows very high strength even at very high temperature over 1000°C, which is enough to replace some metallic components in a turbojet engine. Then the needs for the modeling of the material and related activities of Safran group will be presented. In general, the CMC is reinforced by the textured fibers or short fibers. In this presentation, we will focus on the short fiber reinforced CMC material due to fact it is likely to be used in the NewFrac project by Sara J during here secondment at Safran because it has properties that match the intended application of the model she is developing.

Crack onset from circular holes: biaxial loadings and arrayed cavity interaction

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Keywords: *Finite Fracture Mechanics, Cohesive Zone Model, Phase Field, Safety domains, Energy decompositions, Circular hole arrays*

Abstract: The phenomenon of crack onset stemming from a circular hole in a biaxially loaded infinite plate is herein investigated. Thorough analyses reveal that this setup leads to a wide range of conditions upon failure in terms of the pre-cracking stress distribution and release of fracture energy, thus rendering it an exhaustive case study towards assessing different failure criteria. Subsequently, three different approaches are used to determine the biaxial safety domains: Finite Fracture Mechanics, Cohesive Zone Model and Phase Field model of fracture. The former two provide backbone results, for that they are well-established failure initiation criteria, while the latter, much more versatile for complex fracture scenarios and well-established only for crack propagation, is herein assessed for use also for crack nucleation in a variety of conditions. To that end, special attention was paid to the choice of the energy decomposition, being herein implemented two options: No-Decomposition and No-Tension decomposition (see [1]). In particular, the latter showcased reasonable agreement with Finite Fracture Mechanics and Cohesive Zone Model, thus rendering it a solid contender for its use in complex failure scenarios with combined tension-compression stress fields. Finally, the Phase Field model of fracture with the NoTension decomposition is used to study failure onset in different arrays of holes, showing the effect on failure of the spacing.

References:

[1] L. De Lorenzis, C. Maurini. 2021. Nucleation under multi-axial loading in variational phase-field models of brittle fracture. International Journal of Fracture. https://doi.org/10.1007/s10704-021-00555-6

Dynamic crack initiation in circular hole PMMA plates considering nonlinear elastic material behavior

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Keywords: *Coupled Criterion, Nonlinearity, Dynamic, Crack initiation.*

Abstract: The coupled criterion (CC) of finite fracture mechanics (FFM) is extended to assess dynamic crack initiation in PMMA specimens with holes under quasi-static loading considering nonlinear elastic (NLE) material model. If dynamic aspects are disregarded, the failure stress predicted using the CC for either linear elastic (LE) material model or NLE material model is underestimated compared to the one measured experimentally [1]. Thus, the kinetic energy is considered in the energy criterion. The fracture stresses of PMMA specimens with holes are calculated using dynamic CC approach considering LE material model and NLE material model. In this dynamic approach, the crack length jumps from 0 to the initiation crack length $\ell_c$in a given time following a certain velocity profile $v_{crack}(t) = d\ell(t)/dt$. Besides, the PMMA tensile stress-strain curve is fitted by the hyperelastic Marlow model to represent PMMA nonlinear elasticity. Firstly, a better representation of the failure stress variation as a function of the hole size is obtained considering constant crack velocity profiles and velocities in the range [550-900] m/s (LE material model) or [400-600] m/s (NLE material model) (Fig. 1). Then, the following description of the velocity profile as a function of time is used to describe a possible increasing crack velocity during initiation: $v_{crack}(t) = \alpha v_0 \left(\frac{t}{t_1}\right)^{\alpha-1}$ $(1 \leq \alpha \leq 2)$. $t_c^1 = \ell_c^1/v_0$, and ℓ_c^1 is obtained for a constant crack velocity v_0, which guarantees that the mean velocity $\bar{v} = \frac{1}{t_c^1}\int_0^{t_c^1} v_{crack}(t)dt$ during the crack initiation ([0, t_c^1]) is v_0 for different velocity profiles. Thus, ℓ_c^1, v_0 and t_c^1 will vary for different hole diameters ϕ and different imposed displacements U. The predicted failure stresses also depend on the crack velocity profile.

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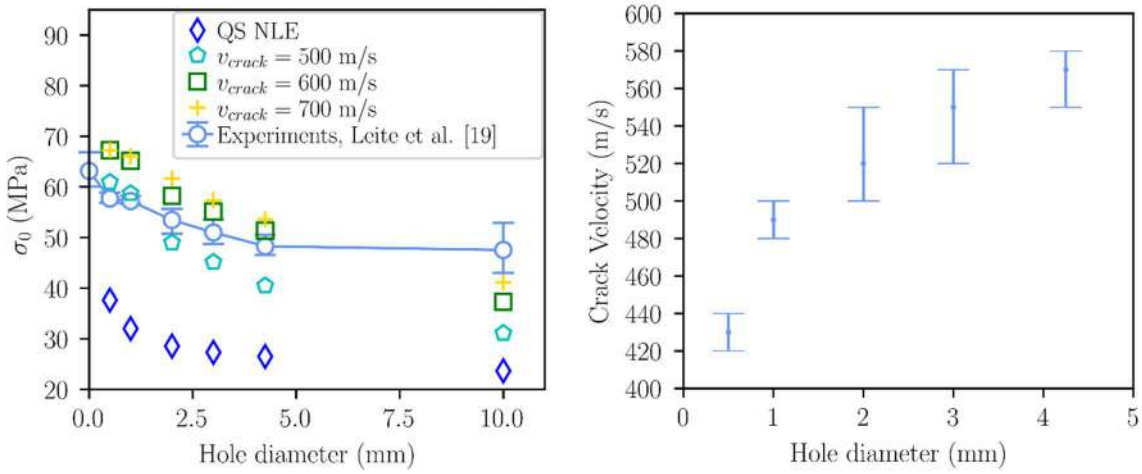

Figure 1: (a) Comparison of failure stress obtained numerically considering LE material model for different crack velocities and experimentally [1] and (b) Range of crack velocities to reproduce the experimental results using CC dynamic approach for LE case, for several hole diameters.

Phase field implementation of the coupled criterion

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Keywords: *Coupled criterion, Phase-field*.

Abstract: Phase-field (PF) approach for fracture and the coupled criterion (CC) attracted much attention in recent years due to their ability to model fracture. PF model consists in diffusing the crack surface into the volume of the solid, thus making its implementation possible through variational techniques. This diffusion is controlled by an internal length parameter, which was primarily considered to be a numerical aid without any real physical meaning. In addition to this internal length, the material critical energy release rate is required as input of the phase-field model. The latter is also an input parameter of the CC as well as the material tensile strength.

The CC was originally developed in order to overcome the limitation of Linear Elastic Fracture Mechanics to assess crack initiation [1]. PF approach also enables modeling the initiation of a crack. Therefore, the same fracture problem can be modeled with both approaches. We previously evidenced the existence of a unique correlation between the PF internal length and the material tensile strength which depends on the Poisson's ratio and local principal stress components [2].

Based on this correlation, we propose a length-free (LF) implementation of the PF approach for fracture [3]. The inputs of the LF-PF model are similar to the CC inputs, namely the critical energy release rate and tensile strength. The proposed approach is tested and compared to the CC on several benchmark examples. The proposed LF-PF approach can be considered as a PF implementation of the CC, both models may be used in a complementary manner since they share the same input parameters and provide similar results regarding crack initiation.

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Influence of elastic and fracture anisotropy on architectured material

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Keywords: *finite-fracture mechanics, matched asymptotic approach, anisotropy*

Abstract: Architected materials are composites for which the structure is configured (from the microstructure to the component scale) in such a way that it exhibits attributes not exhibited by any of the constituent alone [1][2]. They encompass a large variety of applications, *e.g.* energy storage, insulator. Some particular architectures allow materials to exhibit enhanced fracture resistance. For instance, 3D-printed-indueced polycarbonate architecture generates anisotropic toughness [3]. In nacre-like alumina, it is the alumina platelet arrangement over the length scales that induces anisotropic fracture behavior [4-5]. The fracture behavior of architectured materials is induced by a triumvirate: elastic properties, fracture properties and architecture. However, the exact contribution of each of these features remains unknown. Such knowledge would be useful for material architecture optimization. Using the matched asymptotic approach and the coupled criterion [6] on homogenized model materials, we aimed to decorrelate these features through a parametric analysis.

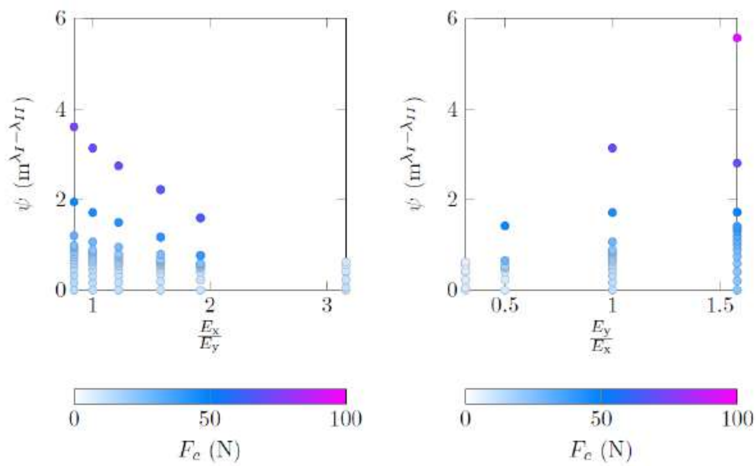

Figure 1 - Force to crack initiation as a function of the elastic anisotropy for a PMMA-based material.

For example, Figure 1 shows the evolution of the force to initiate a crack F_c (force variations depicted by color variations) as a function of both the elastic anisotropy, and the mode mixity. The isotropic material is PMMA. Anisotropy is obtained by artificially modifying the Young's moduli, while the fracture properties are isotropic and no architecture is considered. At iso-mode mixity, anisotropy can induce a difference in F_c up to a factor 5.

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A PHASE-FIELD MODEL FOR THE MULTISCALE ANALYSIS OF FRACTURE IN SHORT GLASS FIBER REINFORCED POLYMERS

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Keywords: Phase field, SFRP, anisotropy, fiber orientation

Abstract: Understanding and modeling the fracture mechanical behavior of short glass fiber reinforced polymers (SFRPs) is challenging: the strong heterogeneity induced by the manufacturing process causes a tight coupling of the material microstructure to the effective response on the component scale. Aiming to account for this microstructural complexity [1], fracture is approached using a multiscale approach. To resolve the microstructure induced anisotropy and its relationship with the macroscopic material behavior, an isotropic phase-field fracture model [2-4] is extended via the fiber orientation interpolation concept. The approach is fed by micromechanical simulations calibrated by experimental data. A validation of the proposed approach is obtained by means of numerical investigations compared to experimental findings

Hence, an innovative approach is proposed using an offline training of a database plus a fiber orientation interpolation concept [4] to consider the heterogeneity of the material. The approach is fully integrated into the seamless simulation chain for SFRPs ranging from the injection molding process to the structure mechanical fracture analysis by means of Phase Field approach. The limitations of the approach stemming from the underlying assumptions are quantified and further development needs are identified.

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Finite Fracture Mechanics: Size effects on spheroidal voids and corrosion pits

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Keywords: *Brittle failure, Spheroidal void, Size effect, Axisymmetric FEA, FFM, Fatigue limit, Corrosion pit.*

Abstract:
The present work aims at investigating the size effect of a spheroidal void in an infinite linear elastic solid under remote tension by means of the coupled Finite Fracture Mechanics (FFM) approach. The longitudinal stress field and the Stress Intensity Factor (SIF) related to an annular crack surrounding the spheroidal void -necessary for the FFM implementation- are obtained numerically through a parametric axisymmetric Finite Element Analysis (FEAs): the axis ratio *b/a* is varied between 0.1 and 10, and the Poisson's ratio between 0.1 and 0.5. Semi-analytical approximating functions providing the stress concentration factor and the SIF itself are put forward. Finally, theoretical predictions are analyzed and compared with experimental results on the fatigue limit related to corrosion pits, confirming the soundness of the present approach.

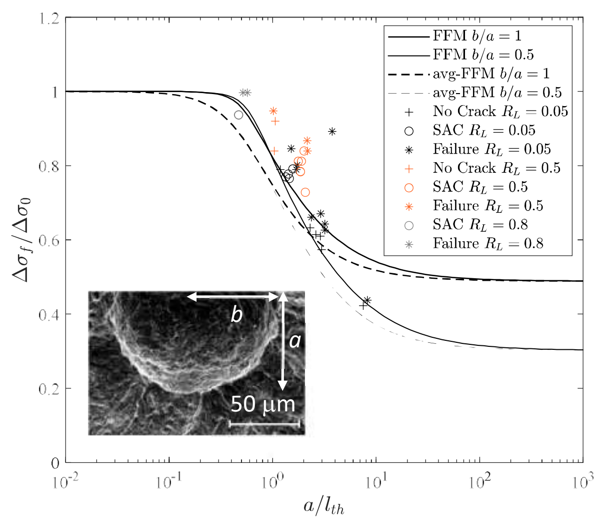

Fig. 1 Comparison between the experimental data obtained by Salzman et al. (2013) [1] and theoretical fatigue limit estimations $\Delta\sigma_f/\Delta\sigma_0$ provided by FFM (continuous line) and avg-FFM (dashed line) for *b/a* = 0.5 (thin line) and *b/a* = 1 (thick line). The subplot in Fig. 1 is re-arranged from Salzman et al. (2013) [1].

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Crack initiation at the fiber-matrix interface in LFRC under transverse tension: A 3D analysis.

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Keywords: *Composite materials, crack initiation, interface crack*

Abstract: Matrix failure, also known as inter-fiber failure, is a common failure mechanism in composite materials. It is very relevant for the material performance due to mainly two reasons: i) it is the first step of more dangerous failure mechanisms, such as interlayer delamination; and ii) it is a source of liquid and gas leakage in composite vessels. The different steps of this failure mechanism have been studied for decades using many different experimental, theoretical, and computational approaches. However, most of them are based on a plane analysis. On the one hand, experimental observations reported in the literature are mainly microscopic observations at the free edge of the composite panel, existing a relatively uncertainty about the representativity of these observations along the thickness. On the other hand, theoretical and computational approaches are typically based on assuming either plane stress or strain. Some authors claim that plane stress is the correct formulation for the study of the crack initiation of this problem because the failure starts at the free edge. In contrast, other authors use plane strain because the stress state at the free edge is far from being a plane stress state and plane strain could represent better in balance what happens in general. In this sense, this work proposes a 3D analysis of the problem, including the free edge, to evaluate the accuracy of these two formulations, highlighting the limitations of the two formulations. The computational model employs cohesive elements to simulate damage and fracture at the fiber-matrix interface and use the phase field approach for fracture for the matrix.

Finite element (FE) analyses were performed, the main results are outlined in what follows:

a. Effect of free edge is key to understand the very first step of the failure mechanism. It affects even qualitatively to the morphology of the first debond.
b. Plane stress is not an accurate assumption since the stress state at the free edge is affected by the mismatch of elastic properties of fiber and matrix along the depth. In fact, some of the stresses assumed to be zero by plane stress are at the origin of the very first debond and is basic to explain the morphology of the debond near the free edge.
c. Plane strain is a more accurate assumption to predict the overall behavior since most of the fiber-matrix system is subjected to a stress state very close to plane strain. However, plane strain is not able to capture the very first debond.
d. The geometry of the debond predicted by the computational model agrees with recent experimental observations. In addition, the sequence of failure is accurately predicted.

Influence of adjacent fibers on crack initiation prediction using the coupled criterion

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Keywords: *Fiber-matrix debonding, Finite Fracture Mechanics, adjacent fibers, composites*.

Abstract: The initiation and propagation of debonding at the fiber-matrix interface, in composite materials, have been widely studied for several decades. This type of failure is predominant and leads to the global failure of the composite. Two major numerical models have been developed to describe this phenomenon: the cohesive zone model (CZM) [1] and the coupled criterion (CC) [2]. Nevertheless, the simulation of debonding remains a challenge because it involves different phenomena, especially in the case of multiple adjacent fibers and the use of the coupled criterion.

Debonding at the fiber-matrix interface often occurs at one pole of the fiber and then propagates along two directions. The present study aims to describe the crack path of a two-fiber fiber sample with different configurations where inter-fiber distance (d) and angle (α) are varied, see Figure 1. If the inter-fiber angle is different from 90 deg., or for complex loading conditions, the initiation and propagation of debonding are no longer symmetrical [3]. To overcome this problem, one approach is to base the debonding trajectory on the stress iso-values [4]. But is this assumption reliable when the debonding initiation is driven by energy?

The influence of a second fiber on the crack trajectory is studied and the results show that the trajectory predicted by the stress iso-values is slightly different from the energy one. In the case of both stress and energy driven debonding, a new approach is employed to solve the CC.

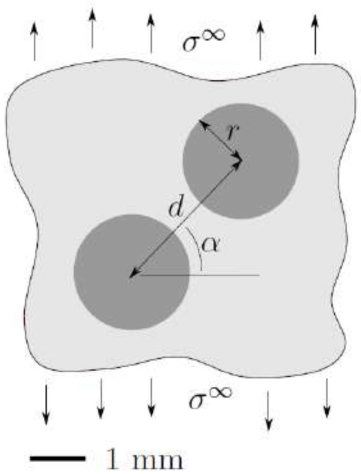

Figure 1 : Two-fiber configuration.

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Prediction of multiple delaminations in ILTS specimens by an Abaqus implementation of the Coupled Criterion based on the minimization of the total energy subjected to a stress condition

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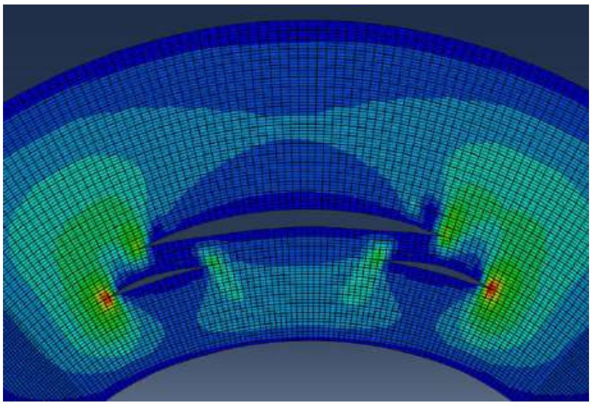
Keywords: *ILTS, LEBIM, CCFFM, PMTE-SC, AMA*

Abstract: Inter-Laminar Tensile Strength (ILTS) test uses L-shaped composite coupons with laminas having different orientations. This presentation uses the Coupled Criterion of Finite Fracture Mechanics (CCFFM) applied to the Linear Elastic-perfectly Brittle Interface Model (LEBIM) [1] based on Principle of Minimum Total Energy subjected to a Stress Condition (PMTE-SC) [2], where the energy criterion is evaluated by the change of the potential energy before and after crack onset [3]. The Total Energy minimization problem is separately solved in terms of displacement and interface-damage variable in each load step using an Alternate Minimization Algorithms (AMA) scheme [4]. This formulation is implemented in a computational procedure in Python using the commercial FEM code Abaqus®[4]. It can model multiple delaminations that occur in ILTS specimens as shown in the following figure:



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Error estimation of phase-field approach in Westergaard's problem under mode I-II loading

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Keywords: *Phase field, error estimation, mixed mode loading, Westeergaard*

Abstract: The phase field model is an attractive option over other numerical fracture models due to its relevant capabilities in the simulation of complex crack trajectories [1]. However, numerical simulations usually involve a large computational cost and finding an optimal element size h_e and length scale l_0 solution becomes critical. In this way, numerical error estimation of phase-field approach to classical Griffith's theory is mandatory. This fact has motived us to analyse the phase-field fracture approach to Westeergaard's problem in terms of crack growth initiation under isolated mode I/II and different I+II loading conditions. The so-called AT2 model is utilized without energy splits and the initial pre-crack is induced by the local history variable *H*. The problem is subjected to several loading cases: mode I, mode II and mixed mode loading with different mixed modes. Additionally, the *J*-integral is calculated along a path through exterior elements across integration points. Three different phase field length scales l_0 and four different element sizes h_e to length scale ratios are studied using structured meshes. In terms of crack path, colinear crack propagation is obtained for mode I, whereas the crack kinks for mixed mode loading. The *J*-integral value calculated after crack growth for mode I loading stabilizes to a value close to the amplified effective critical energy release rate G_c*. The results converge to maximum energy release rate criterion using Griffith's theory for mixed-mode loading conditions for the loading cases considered, but with a significantly slow rate than discrete methods. In this way, further numerical studies will be required, although the results are still promising.

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Modelling of glass matrix composites by the Coupled Criterion and the Matched Asymptotics approach. The role of residual stresses.

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Keywords: Finite Fracture mechanics – Coupled Criterion - Micro-scale – Toughening mechanisms.

Abstract: Borosilicate glass Al_2O_3 platelets composite [1] is an eco-friendly low-cost material characterized by the enhancement in fracture properties compared to glass. A first analysis of possible toughening mechanisms in this material can be found in [2]. Due to the thermal expansion mismatch between the alumina and glass, residual stresses are generated after the cooling process in the manufacture of such composites.

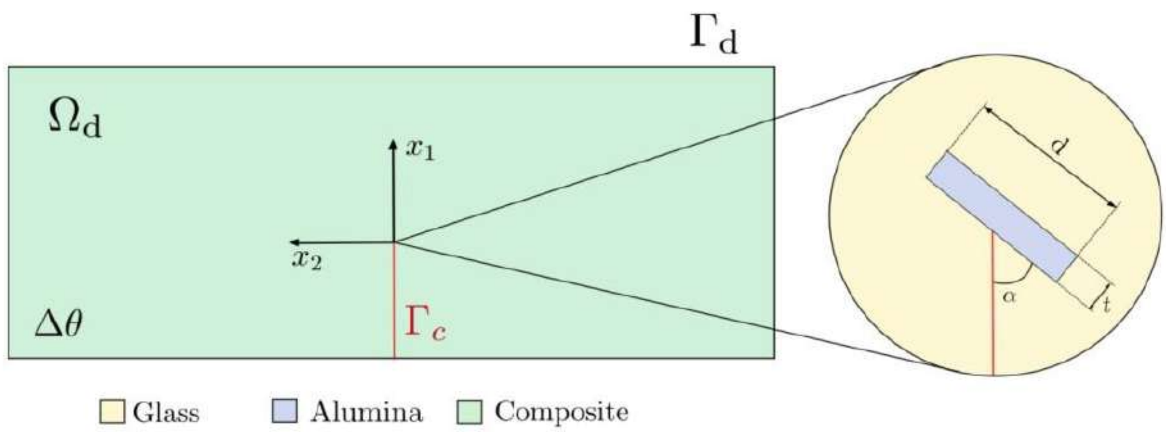

Figure 1: Schematic view of the symmetric 3-point bending test. The pre-existing crack impinges in the platelet.

In this work, the role of residual stresses in toughening mechanisms is analyzed, applying the Matched Asymptotic Expansions (MAE) and the Coupled Criterion (CC). To that aim, a symmetric 3-point bending test is solved, see Fig. 1, applying the superposition principle. On the one hand, the mechanical problem was previously presented in [2]. On the other hand, the thermoelastic problem assuming no mechanical loads and a temperature gradient is deeply studied here.

Several toughening mechanisms related to a change in a pre-existing crack path Γ_c are studied, such as a decohesion, deviation, penetration, or a crack jump. The predominant mechanism for different temperature gradient is determined, as a function of the size of the platelet. Furthermore, a value of the apparent fracture toughness in the composite is calculated.

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Crack Closure and Fatigue Life Evaluation for an Aircraft Load Spectrum

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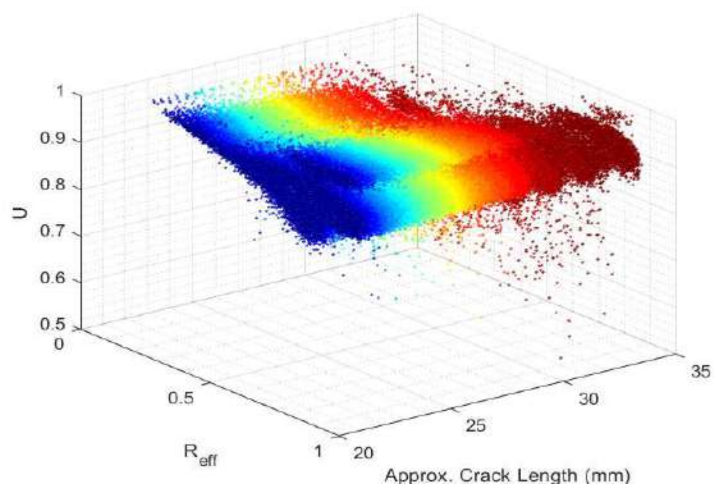
Keywords: *Crack opening loads; aircraft load spectrum; fatigue life predictions*

Abstract: Most structural failures are due to fatigue making life evaluation methods indispensable in engineering design and maintaining efficient and safe operation of high-value assets and infrastructure across many industries. Fatigue life evaluation methods under constant amplitude of loading (CAL) are well developed and normally produce quite reliable and consistent results. However, for variable amplitude of loading (VAL) theoretical predictions and experimental results could disagree by an order of magnitude, leaving a large scope for research and development. In addition, VALs are the most common loading conditions for many structures including aircraft, wind turbines and pipelines [1].

Advanced fatigue life evaluation methods under VAL are normally based on two critical components: (i) crack closure model and (ii) fatigue cycle counting algorithm. In general, it is possible to select parameters (e.g. flow stress or constraint factors) in the crack closure model or adjust the cycle counting algorithm to achieve a reasonable correlation between predictions and a certain set of experimental results. However, this approach fails if applied to a different structural component/fatigue specimen or load spectrum.

Recently we developed a cycle-by-cycle crack tip opening load measurement technique [2, 3], which can be applied to analyse crack closure for different load spectra containing millions of fatigue cycles. The figure below shows the opening load ratio, U, for a C(T) specimen as a function of crack length and R-ration for approximately 1.2 million cycles representing a typical transport aircraft load spectrum. The opening load ratios under CAL and VAL are very different and will be discussed in the presentation. In the future, the utilisation of machine learning algorithms in the analysis of cycle-by-cycle crack closure measurements will allow one to evaluate the crack opening loads based on the loading sequence rather than from theoretical modeling, which may be quite unreliable, as well as to test various cycle counting algorithms.



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Non-Destructive Evaluation of Fatigue Damage with Non-linear guided Waves: Fundamentals and Applications

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Keywords: *Fatigue; Damage; Material nonlinearities; Elastic waves; Third-order elastic constants*.

Abstract: This presentation discusses methods for the non-destructive evaluation of so-called early fatigue damage i.e., the damage accumulated before formation of a macro-crack(s). These methods are especially important for structural components working in high- and ultra-high-cycle fatigue regimes, where the crack formation stage could take up to ninety percent, or even more, of the total fatigue life [1,2].

Accumulated fatigue damage in many advanced materials and pure metals is often associated with highly localized irreversible plastic deformations. These deformations have a significant effect on material nonlinearities e.g., the third-order elastic constants. The change of the nonlinear material properties during fatigue is now widely utilized in the development of non-destructive evaluation methods of fatigue, aging, radiation and other types of dislocation-driven damage.

The effect of elastic nonlinearities on the deformation behavior of common structural materials is typically very small, thus making traditional mechanical testing techniques inapplicable to measure these nonlinearities and their changes. Therefore, new methods based on the non-linear effects associated with propagation of elastic bulk and guided waves e.g., generation of the second-order harmonics or sidebands, are currently under development. This presentation briefly discusses the fundamentals of non-linear elasticity, acoustoelasticity and ultrasonic techniques, focusing on their applications to the evaluation of early fatigue damage [1-4].

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A comprehensive characterization of fracture in unit cell open foams generated from Triply Periodic Minimal Surfaces

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Keywords: *Phase-field modelling, Triply Periodic Minimal Surfaces, Finite Element Method FEM, Open foams.*

Abstract: The main scope of the proposed study is to assess the occurrence of fracture in Triply Periodic Minimal Surfaces (TPMS) foams subjected to compressive loading. TPMS, developed by the mathematics community, may be exploited as a backbone for developing a new class of foams with open porosity for a wide range of engineering and biomedical applications [1]. Therefore, a comprehensive analysis of their fracture response is fundamental and is herein attempted. To this aim, a 3D phase field model is herein proposed and applied to TPMS foam structures under compression [2], with the goal to predict critical points for crack nucleation, potential crack paths, and the stiffness and maximum force of the unit cell, which can be related to the apparent Young's modulus and apparent strength of a macro-scale composite made of such TPMS unit cells. A careful mesh sensitivity analysis was conducted on the specimens, to provide guidelines on how to identify the optimal finite element discretization consistent with the internal length scale parameter of the phase field approach to fracture [3]. The major predicted mechanical properties for five different TPMS open foams, and for different levels of porosity, are summarized in Ashby plots. The predicted trends are in agreement with previous results on TPMS taken from the literature and show that TPMS can outperform standard Aluminium open foams.

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Crack nucleation in 1D heterogeneous bar – h- and p-FE approximation of a phase field model

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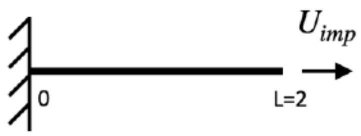
Keywords: *Phase field model, 1D heterogeneous bar, h- and p-FEA, crack nucleation*.

Abstract: In an attempt to accurately predict the crack nucleation in human bones (which are heterogeneous) and the subsequent fracture evolution, the phase field method (PFM) is being considered [1,2]. PFM was originally proposed to study fracture in homogeneous materials and applied also to several materials exhibiting structural and point-wise heterogeneity [3,4]. Most of these adopted AT2 model while ones using the AT1 model do not discuss issues related to FE approximation and verification.

For homogeneous material the discretization size should be smaller than the regularization length l_0 to ensure convergence and minimize the fracture toughness overestimation related to FE approximation, otherwise a correction factor may be applied [5]. Using the AT1 model, damage positivity and irreversibility may be ensured with different techniques such that penalization [6]. For verification of FE methods that implement PFM for heterogeneous materials, analytical solutions were derived for a 1-D bar incorporating linear, parabolic, and exponential $E(x)$ and $G_c(x)$ profiles ([7], see Fig. 1) without explicit presentation of loading history and the associated damage irreversibility constrain. In this presentation we provide explicit PFM analytical solutions for the AT1 model when applied to 1D heterogeneous bars and discuss h- and p-FE implementation: we highlight the numerical fracture toughness overestimation, a penalty technique to ensure damage positivity and numerical convergence.



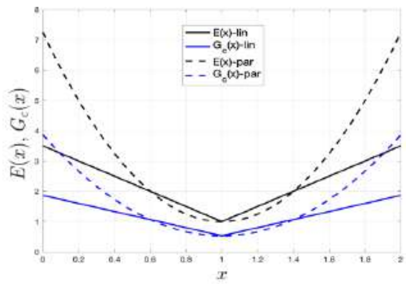


Fig. 1 – 1D benchmark problem (left) and heterogeneous Young modulus and critical energy release rate (right)

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A continuum large-deformation theory for the coupled modeling of polymer-solvent system with application to PV recycling

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Keywords: *Large-deformation, Polymer-solvent system, PV recycling, Finite element method*

Abstract: Nowadays recycling of photovoltaics (PV) using the solvent method is becoming a very hot topic as massive products deployed in the last century have approached the end of their service lifetime [1,2]. The key problem in the recycling of end-of-life PV modules is the nondestructive recovery of precious silicon wafers for the manufacturing of new products. However, the attempt to comprehensively understand the polymer-solvent system in the PV recycling process is completely lacking. In this work, a thermodynamically consistent large-deformation theory is proposed to model the coupled behaviour of this system. The development of continuum theory accounts for the solvent permeation, swelling and elastic deformation, as well as shrinking effects due to the initial crosslinking of ethylene-co-vinyl acetate (EVA). The crosslinking of EVA influences the stiffness of the polymer network, and interacts with the diffusive kinetics of solvents. Also, given the effects of mechanical constraint, the two-way coupling between the EVA deformation and solvent diffusion is established on the basis of thermodynamic arguments. The proposed modeling method is firstly applied to simulate the swelling experiments of cylindrical EVA samples in solvents Toluene, Tetrahydrofuran, and Octane, and good agreement has been achieved between the numerical prediction and available testing data. Then the second example demonstrates the capability of this modeling framework to describe the influences of initial crosslinking and mechanical constraints on the time history evolution of swelling and elastic deformation. Finally, the complete PV laminate in the 3D setting is modeled for the investigation of solvent penetration induced deformation in the silicon cell layer during the PV recycling process, and comparison has been made to showcase the spatial distribution of maximum principal stress of the silicon cell layers in solvents with different solubility parameters and molar volumes. With this computational tool at hand, it is possible to provide guidance to the design of suitable experimental procedures for the structure-intact recovery of silicon wafers in PV recycling with the solvent method.

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Micro-mechanical analysis of composite materials using Phase-Field models of brittle fracture

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Keywords: Composites, Micro-mechanics, Phase-Field

Abstract: Failure in fiber-reinforced composites is a complex phenomenon where different damage mechanisms interact and evolve through various scales. Micro-mechanical analysis using the finite element method has become an important alternative to study such failure phenomena and their interactions, by modeling explicitly the fiber, matrix, and fiber-matrix interface. In this work, the predictive capabilities of the finite element method together with the Phase-Field (PF) method for fracture has been assessed. The study compares different PF formulations, energy splits and numerical parameters, using Representative Volume Elements (RVEs) of different sizes, fiber distributions and with different boundary conditions (BCs). It is found that even though good approximations can be obtained and meso-scale failure envelopes for transverse loading generated, these are highly dependent on the modeling assumptions and PF parameters. The AT2 formulation combined with Amor's energy split provides the best predictions when compared with an analytical failure surface. The best fit is found for transverse shear-dominated loading, while larger differences are found for compressive loading, whose strength predictions are strongly affected by the PF formulations and energy splits. It is demonstrated that meso-scale strength is conditioned by interface properties as interface damage is the dominant failure initiation mechanism under tensile-dominated loading. On the other hand, PF parameters have a stronger influence on compressive-dominated loading. Finally, it is shown that assuming a perfect fiber-matrix interface has a strong effect on the expected meso-scale strength, as failure is markedly delayed. Thus, care must be taken in properly assessing all the variables involved in the modeling methodology to draw conclusions from computational micro-mechanical analyses based on the PF approach.

Application of the coupled criterion to the propagation of interface cracks with frictional sliding contact

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Keywords: *Interface crack, frictional contact, perfect bonding, coupled criterion, FFM, ERR*.

Abstract: The problem of propagation of an interface crack with frictional sliding contact zone adjacent to the crack tip is considered, assuming a perfect interface between isotropic and linear elastic adherents, i.e., equilibrium of tractions and no displacement jump across the bonded part of interface [1]. The difficulty in modeling this propagation is that the Energy Release Rate (ERR) is zero in the case of dissimilar materials, i.e., with nonzero Dundurs bimaterial parameter β, and nonzero Coulomb friction coefficient [2-5]. The zero value of ERR is a consequence of the weak singularity of stresses at the crack tip due to frictional sliding, i.e. the singularity exponent $0.5 < \lambda < 1$. An approach to deal with this difficulty, related to the Theory of Critical Distances (TCD), is considering a characteristic virtual crack increment of a small finite size [2-5]. However, the question arises as to how to determine the characteristic finite advance of frictional interface crack.

The present work proposes to apply the Coupled Criterion of Finite Fracture Mechanics (CC-FFM) [6-8] to model propagation of frictional interface cracks. A conceptually new approach is proposed for computing an incremental (or average) ERR associated to a finite advance of frictional interface crack and compared with other approaches available in the literature. If the first singular term of the asymptotic solution at the crack tip is dominant along the finite crack increment, an analytical expression is available for the incremental ERR, and an analytical solution for the critical finite crack advance and the critical value of the Generalized Stress Intensity Factor (GSIF) K_{II} can be obtained. Predictions by the CC-FFM for the limit cases given by the vanishing Dundurs parameter β or the vanishing friction coefficient, or for very high friction coefficient, are analysed and discussed. A possible application of the developed methodology to the single-fibre fragmentation test is briefly discussed.

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A novel model to estimate fatigue life of notched components based on Finite Fracture Mechanics

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Keywords: *Fatigue failure; Life prediction; Finite Fracture Mechanics; Notch; Fatigue strength*.

Abstract: This paper presents a model based on Fracture Mechanics (FFM) criterions to estimate the fatigue life of structures under uniaxial loading condition weakened by different notch geometries. By simultaneously satisfying a stress and energy condition, the FFM predicts the failure based on the critical material parameters, namely the strength and the stress intensity factor at failure. The developing idea is to catch the variation of these critical material parameters using a power law equation in the medium/high-cycle fatigue regime. Consequently, the FFM criterion is reduced to a system of two equations with two unknowns: the critical crack advance and the number of cycles to failure. Finally, the validation of the model is performed by comparing the model estimates with experimental data available in the literature for several notched samples.

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Capturing the off-axis behavior of notched multidirectional thin-ply laminates

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Keywords: *Off-axis loading, Composite laminates, Open-hole tension, Anisotropic fracture*

Abstract: The ability to simulate the response and obtain accurate strength prediction of multidirectional laminated composite components is of prominent interest in the aeronautical field, with specific interest being devoted to notched components, that often appear in aeronautical structures (e.g., bolted, riveted sheets). In this work, focus is attributed to a novel composite system, thin-ply laminates (i.e., plies of thicknesses under 0.1 mm) that have been shown to present different fracture patterns compared to *"standard"* ones (i.e., plies of thicknesses over 0.1 mm). In the former case, final failure tends to happen in the form of a single fracture plane that from a modelling perspective allows the use of novel techniques formulated for brittle fracture, such as the phase field method (PF)and Finite fracture mechanics (FFM), that seem appropriate to provide an efficient modeling basis following an equivalent single layer (ESL) representation for the composite laminated plate. The feasibility of application of these methods is qualitatively evaluated on the basis of off-axis (i.e., referring to loading on a direction that does not coincide with one of the principal axes of orthotropy of the plate) open-hole tension of a multidirectional laminate based on the experimental results of [1]. Results obtained using the anisotropic PF model of [2], which uses a 2nd order structural tensor to account for anisotropic fracture energy, reformulated as in [3] to include specific considerations of the toughness of a composite laminate, are initially presented. A successful prediction of the experimental results both with regards to fracture plane (Fig. 1) and strength, with a maximum observed error in predicted strength of 4.8%, is achieved. However, implementation does come with some limitations, namely assumptions regarding the definition of numerical parameters such as the length scale and size of the finite elements without a priori knowledge of the crack plane and resulting computational cost of the numerical implementation. Thus, these motivate the use of FFM for which the preliminary steps for its application for the specific problem of the off-axis OHT of the composite laminate of [1] are presented alongside a discussion of its main benefits and shortcomings.

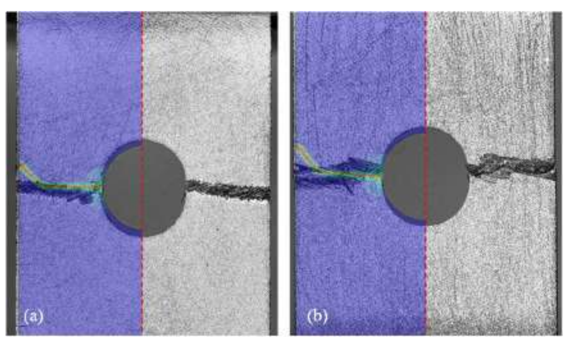

Fig.1 – Comparison of experimental and numerical crack paths for (a) 30º off-axis loading and (b) 60º off-axis loading.

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A detailed comparison between the coupled criterion and the phase-field method for fracture simulation

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Keywords: *coupled criterion, phase-field fracture,* internal length, shear fracture, tensile strength

Abstract: In the last decade phase-field models [1, 2] gain significant popularity in fracture simulation. These models regularize the sharp crack by diffusing the damage into the material. With a gradient approach, the damage variable establishes the connection between intact and broken solids. In order to achieve their goals, the approaches introduce a length scale parameter, which controls the amount of diffusion. Since their first use, it is a continuous debate whether the length scale bears any physical meaning.

In this work, we present a macroscopic approach, using the coupled energy and stress-based criterion [3], to present a relationship between tensile strength and the internal length scale. We found a robust correlation based on resistance, fracture topology, and arrest length that this connection exists. However, we argue that the correlation should be described using a failure surface rather than a single curve. The talk will present various aspects of fracture mechanics ranging from mixed mode crack initiation, intermittent cracking, and micro-metric testing on silica glass.

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Mitigating Defect Sensitivity in the Mechanical Response of Multiphase Lattice Metamaterials

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Keywords: *lattice metamaterials, defect sensitivity*.

Abstract: Nowadays "architected" materials represent an expanding galaxy of engineered materials, displaying a variety of features like tailorable stiffness and strength [1], auxetic behavior [2, 3], energy absorption [4, 5], and multifunctionality [6]. In the present work, the classical two-dimensional configuration of lattice metamaterials with triangular unit cells is considered. A combination of two dissimilar materials is designed: the "primary" material, that comprises the lattice structure elements, is made of thermoplastic polyurethane (TPU) while the "secondary" functional material, manually poured inside the lattice cells to form a regular filling pattern, kept the same for all cases, consists of an incompressible silicone elastomer (Figure 1).

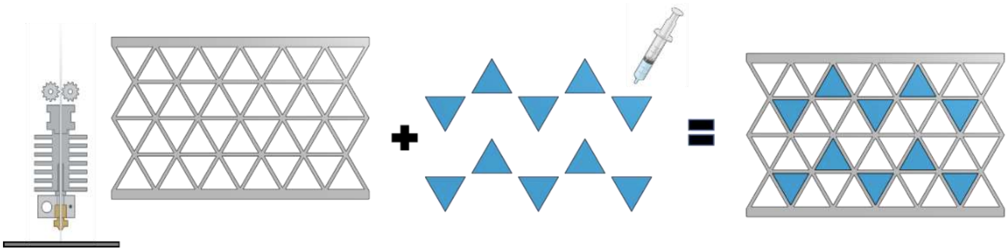

Figure 1. Schematic of a lattice 2D material with an embedded regular filling pat-tern of a second nearly incompressible highly deformable material.

Geometrical imperfections are introduced in the lattice structure to study the sensitivity of its mechanical response to the presence of intrinsic defects. In particular, three different types of geometric anomalies have been randomly introduced, namely: (i) attributed to some of the elements; (ii) reduced thickness of the beam elements; (iii) lateral shift of some nodes of the lattice.

Compressive tests are performed on 3D printed perfect and defective lattices before and after creating the filling pattern with the second incompressible material. Finally, some FE analyses are performed in order to highlight the effect of the filling pattern in improving the overall defect tolerant capability of the structure.

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A multi-phase field approach to tensile fracture and compressive crushing and applications to concrete

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Keywords: *Phase field approach to fracture, Crushing damage, Mesoscale model of concrete, Finite element method*.

Abstract: The variational approach to brittle fracture [1] is herein extended to deal with the simultaneous interplay of two failure mechanisms affecting grained heterogeneous materials in compression, namely fracture in tension and crushing in compression [2]. The problem is addressed within the context of a multi-phase field variational approach, with two independent damage variables associated to each failure mechanism. The proposed computational method implemented in the open source FEniCS finite element software [3] is applied to 2D mesoscale models of concrete specimens in compression. The predicted trends for specimens with different aspect ratios and different degree of lateral confinement are consistent with experimental results on apparent compressive strength and with typically observed failure patterns.

Acknowledgements: The authors acknowledge funding received from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 861061 – Project NEWFRAC - New strategies for multifield fracture problems across scales in heterogeneous systems for energy, health and transport.

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Prediction of crack initiation during hertzian indentation with the coupled criterion

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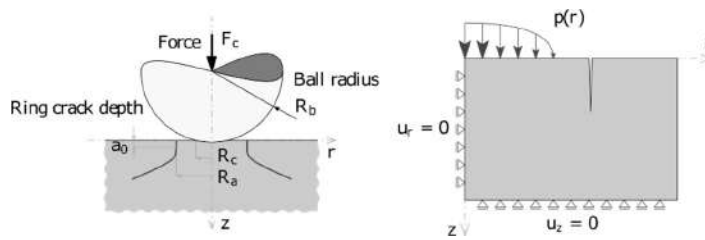
Keywords: *ball indentation, ring crack, residual stress, coupled criterion*

Abstract: When a hard spherical indenter (ball) is pushed onto a flat surface of a brittle material (glass or ceramics), a ring-shaped crack develops, which further extends into a cone crack. Two main phenomena have been empirically observed:

(1) Crack initiation force is, in some cases, linearly proportional to the ball radius. The use of simple strength criterion would imply that the strength is a function of the ball radius.
(2) Ring crack does not initiate at the radius of the contact zone, but 10-40 % farther outside, where stresses are much lower than at the contact radius.

In this work, a computational model has been developed to predict crack initiation forces and crack locations based on elastic properties, fracture toughness and strength of a brittle material without any further assumptions about the flaw distribution on the surface.



Near the contact zone, the stresses are relatively high, up to nine times the material's tensile strength. However, the energy condition may not be fulfilled. It means that fracture very close to the contact radius is possible but highly unlikely because the forces required would be much higher than at a certain distance from the contact area. At that location, the incremental energy increases and eventually fulfils the energy condition, leading to a crack offset between 10 to 40 % with respect to the contact zone radius. Consequently, the linear relation between the crack initiation force and the ball radius emerges as a natural consequence of fulfilling the coupled criterion. Compressive residual stresses induced by polishing (that can reach up to -3 GPa at the surface but vanish rapidly below the surface) must be considered in the model to reproduce the experimental observations. Hence, the coupled criterion may also be used for estimating residual stresses by comparing predictions to experiments with at least two different ball sizes. Residual stress distributions may be varied in the models until the best fit to the crack initiation forces is found.

The model's predictive ability is demonstrated by comparing calculation results with experimental data available in the literature and our own experiments.

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Variational approach on the release of snow slab avalanches

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Keywords: *Weak-interface models, avalanche mechanics, calculus of variations*

Abstract: Dry snow slab avalanches represent a severe hazard for skiers and infrastructure in alpine regions. These kinds of avalanches are triggered from the collapse of so-called weak layers that are buried in a stratified snowpack. Weak layers in snowpacks are typically made up of surface or depth hoar. Mechanically, these layers can be described as highly porous and prone to a collapse of the facetted microstructure. To describe the process of weak layer collapse, Heierli[1] proposed an anticrack model with crack surfaces moving towards one another instead of opening.

Anticracks show a similar behavior compared to classical cracks. Especially, anticrack nucleation and propagation can be tackled by the methods of finite and linear elastic fracture mechanics. Therefore, Rosendahl and Weißgraeber[2] introduced a weak interface model to the field of avalanche mechanics and implemented Finite Fracture Mechanics for the initiation of anticracks[3]. Objective of this model is the determination of weak layer stresses and energy release rate in case of collapse. Loading situations that can be regarded are gravitational loads, skiers or forced geometric changes to the structure. To improve their weak interface model, we propose a refinement of the weak layer's kinematics. Therefore, a variational approach instead of equilibrium conditions in combination with beam kinematics is pursued. It improves the rendering of stresses in weak layers substantially. In particular, the possibility to formulate boundary stress boundary conditions at the weak layers free edges itself is given. Based on this model a renewed evaluation of a set of test data on the fracture toughness and fracture envelope of weak layers is performed.

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Fracture phenomena in the release of slab avalanches

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Keywords: *mixed mode, anticrack, snow, weak layer*.

Abstract: Snow slab avalanches release when a porous weak layer buried below a cohesive snow slab collapses under external loading by, e.g., skiers, explosives, or a snowfall [1]. The collapse is known as ***anticrack*** and exhibits the characteristics of a crack whose faces move toward each other instead of apart [2]. Such anticracks are not only observed in snow but also, e.g., in the form of compaction bands in porous rocks [3], as pressure dissolution of porous seams in sedimentary rocks [4], in the failure of brittle foams [5], or as firn quakes on large glacier sheets [6].

On inclined snow-covered slopes, anticrack propagation is a mixed-mode process involving both normal (collapse, crack opening mode I) and tangential (shear, crack opening mode II) displacement of the crack faces [7]. The present work explores methods for the measurement of mixed-mode fracture proper- ties of weak snow layers and models for the prediction of anticracks from their nucleation to large-scale extension.

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Analysis-driven improvement of 3D printed composite materials: application of anisotropic Phase Field modelling

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Keywords: *additive manufacturing, anisotropy, carbon fibre, phase field*.

Abstract: In recent years, additive manufacturing has captured more and more interest among both industrial and academic players due to the incredible opportunities that this technology provides. In this field, the continuous carbon fibre deposition in particular is extremely promising from a design point of view. The ability to depose continuous Carbon Fibre alongside a polymeric material allows the designer to give particular attention to regions of the component that lead to stress concentrations, e.g., notches, discontinuities, joints etc.. Deposing the Carbon Fibre in such a way as to reinforce these regions, i.e. to reduce the stress concentration, could lead to improved resistance to fracture. In this work a combination of optimal fibre deposition and the Phase Field method for fracture is proposed to model such geometries. The optimal fibre deposition path is found for the analysed geometry and then the strength of the specimen is assessed through Phase Field modelling. Two tests of structural interest, Double Edge Notch Tension and Open Hole Tension, are simulated. In both the cases the strength obtained is compared to that of a unidirectional reinforcement. It is found that the optimal deposition path leads to a sizable increase in strength and displacement at failure of all the configurations analysed. In addition, when looking at the influence on the size effect, for the Open Hole Tension it is seen that in the case of optimized fibre deposition the plateau in the stress at failure vs hole size plot is reached earlier then for a unidirectional reinforcement. These observations become rather interesting and further emphasize the potential benefits attainable when such design techniques are to be used.

An attempt of understanding the fracture behaviour of glass in construction using the Coupled Criterion (CC)

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Abstract: Glass is an extremely brittle material that behaves almost perfectly linear elastic until it fractures. This is why, the linear fracture mechanics approach well described by Griffith's energy criterion is typically used to explain phenomena related to glass failure. For simple cases it has been shown that criterion is well suited to characterize crack growth and relate the growth to experimental parameters. Yet, in complex glass structures as present in the construction industry, where residual stress is introduced into the glass, linear-elastic fracture mechanics reaches its limits in explaining failure processes. This results in the necessity of highly complex and time-consuming FE modelling to gain a fundamental understanding of experimental phenomena. This evokes the question whether other concepts are available to facilitate and accelerate the prediction of glass fracture. One promising approach is the well-known Coupled Criterion (CC) that has already been proved to work for predicting the fracture of other brittle materials such as ceramics or laminates.
What makes it challenging with glass is that the strength necessary to apply the CC is not a constant material property but is highly dependent on environmental conditions and existing internal or surface flaws, which are only probabilistically predictable.

The general aim of this presentation is to give an overview of the current understanding of glass strength and fracture from the linear elastic fracture perspective and show examples where the use of the latter fails to explain experimentally observed phenomena. An attempt is made to explain the fracture patterns observed in experiments on glass specimen using the Coupled Criterion. First results of a study using the CC to model the glass fracture process are presented and aim to open a discussion on whether finite fracture mechanics can be applied to facilitate the understanding of glass fracture. The effects of residual stress states in glass as well as the influence of the not generally definable material strength are to be discussed

Tearing, Cutting and Puncturing in Soft Elastic Solids

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Keywords: *soft matter, finite elasticity, hyperelastic models, flaw tolerance, tearing, cutting, puncturing*.

Abstract: The topic of fracture mechanics in soft solids is relevant for a large class of materials, such as polymers, biomacromolecules, colloids, membranes, liquid crystals, granular matter, soft interfaces, complex fluids, surfactants, gels, nanomaterials, foams, silicones, biological tissues, etc. In the present work we discuss the extraordinary tearing resistance of soft solids, attempting an interpretation of this distinguishing feature by presenting a simplified model to describe elastic crack-tip blunting [1]. Firstly, for incompressible hyperelastic solids the characteristics of crack profiles, obtained by means of detailed FE simulations, are discussed in relation to the material strain hardening. Then, the proposed model is employed to derive an analytical description of the progressive non-linear decrease of the crack tip curvature under loading, assuming a finite deformation of the solid surrounding the crack. Some experimental tests on silicone cracked specimens demonstrate the validity of the analytical model in predicting the flaw tolerance in the material. Fracture is a key behavioral feature when dealing with the mechanical problem of a foreign object penetrating into a soft material, due to the inevitable laceration of the target solid involved. In this work, we discuss the resistance to penetration of a rigid cutting blade [2-4] as well as of a rigid puncturing needle [5]. A theoretical model validated by FE simulations and proof-of-concept experiments is presented. The challenging simulation of the penetration of a flexible needle is also discussed [6,7].

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Mode decoupling versus mode partitioning to determine pure-mode fractures in unconventional specimens

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Keywords: *interfacial fracture, delamination, unconventional test coupon, fracture mode decoupling, fracture mode partitioning, pure-mode fracture*.

Abstract: There is a growing research and industrial interest in determining the interfacial fracture toughness of non-traditional material systems such as dissimilar adhesive joints, asymmetrically stacked composite laminates (possibly with an elastically coupled behavior), fiber metal laminates, and thin laminates with adhesively bonded backing beams. To determine the interfacial toughness of such material systems, laboratory coupons are extracted that inherently feature a material asymmetry w.r.t. the crack plane. Because of this asymmetry, which introduces mode mixity even if the specimen is loaded in pure mode, we here call those specimens *unconventional*.

To characterize the pure-mode fracture toughnesses of unconventional specimens, researchers attempt to decouple fracture modes I and II (and III, if present) through an appropriate design of the specimens. Emphasis has been given to the case of a bi-material adhesive joint under pure-mode I loading, where two decoupling conditions have been proposed in the literature: (a) mode decoupling is achieved when the differential equation of the mode I (mode II) fracture is only governed by the interfacial normal (shear) stress and relative transverse (axial) displacement [1]; (b) mode decoupling is achieved when the bending rigidities of the two adherents are equal [2]. Those two conditions are translated into the design formulae $E_1h_1^2 = E_2h_2^2$ and $E_1h_1^3 = E_2h_2^3$, respectively, where E_i and h_i are the Young's modulus and thickness of adherent i, $i \in \{1,2\}$, respectively. Our presentation will review the existing decoupling conditions and discuss their correctness.

Mode decoupling is impossible for a coupon with pre-defined material properties and thicknesses that cannot be tailored using the above design formulae. In addition, in the presence of residual thermal stresses, common for layered material systems, decoupling conditions are not available in the literature. An appropriate mode partitioning scheme can be selected in such cases to determine the modal contributions to the energy release rate. During the last three decades, several mode partitioning methods have been proposed, which could be classified into four families [3]: methods based on a rigid interface and the beam theory; methods based on linear elastic fracture mechanics; elastic-interface methods; and miscellaneous methods. In our presentation, we will review those methods and emphasize two models we have proposed [4,5] that can consider the effects of bending–extension coupling and residual hygrothermal stresses.

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Multi-axial loadings in phase field model of fracture: review and benchmarks

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Keywords: *fracture, phase field, review, benchmark*.

Abstract: Phase field modeling of fracture is gaining popularity in the fracture mechanics community, particularly for its ability to generate cracks with arbitrarily complex geometries and topologies in two and three dimensions without the need for ad hoc criteria. The model first introduced in [1] has a clear connection with Griffith's propagation criterion via Gamma convergence tools and recent results [2] have shown that, in addition to propagation, it can quantitatively predict crack nucleation for mode-I loading. However, the initial model cannot reproduce with flexibility the experimentally measured strengths under multiaxial loads. Moreover, a modification is necessary to avoid the interpenetration of crack surfaces in compression and reflect the physical asymmetry of fracture behavior between tension and compression [3].

There are hundreds of publications proposing new models for multiaxial loads validated through different case studies making their comparison not immediate and limitations not obvious. Among these contributions, some preserve the variational nature of the phase field model [3-6] while others seek flexibility by stepping outside the variational framework [7]. The most popular variational solutions [3, 4] are based on elastic energy decompositions. This idea is adopted in [5, 6], justified through structured deformation theory.

A study that sorts the wealth of literature based on specific criteria is still lacking. In this contribution, we define these criteria as the ability to flexibly reproduce multiaxial strength and avoid interpenetration of crack faces, and so we perform a systematic review of some available models. As a result, we propose numerical benchmarks to evaluate the behavior of solutions in present and future literature. In particular, the proposed tests provide an assessment of a phase field model for both nucleation and propagation.

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Computational fracture models for linearized and finite strains

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Keywords: Crack driving force, dynamic fracture, phase-field fracture, peridynamics

Abstract: While cracks are actually sharp two-dimensional hypersurfaces the phase-field fracture approach regularizes the sharp material discontinuities with smooth transitions between broken and unbroken regions. The evolution of the phase-field follows an evolution equation where the driving forces of crack growth are derived from an energy minimization principle, typically based on an Ambrosio-Tortorelli type functional. Modifications allow accounting for the no-healing irreversibility constraint of crack evolution and, especially important, for the asymmetry of fracture, i.e., the fact that cracks only grow under tensile loadings but not under compression [1,2]. Further modifications consider the evolution problem at finite strains using energy densities, which are polyconvex functions of the deformation.

Fig.: Wave induced fracture in a 2D bar computed with peridynamics (left) and phase-field fracture (right)

In this contribution, different phase-field fracture approaches with variational and ad-hoc formulations for the crack driving forces will be presented, and dynamic finite element simulations of brittle fracture will be compared [3]. As an alternative approach to computational fracture mechanics, peridynamics will be discussed. We study the relations of critical fracture parameters in the two methods and show that our damage model [4] for the continuum-kinematics-based peridynamics manages crack propagation under dynamic loading conditions as effectively as phase-field fracture.

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