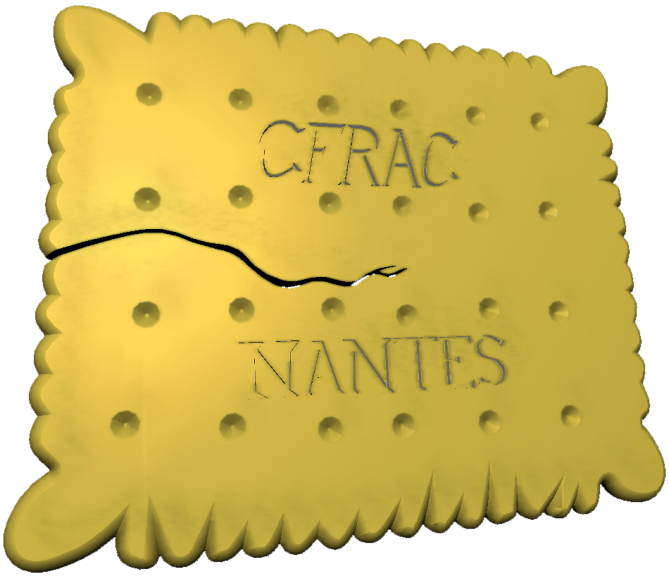
CFRAC 2017

International Conference on Computational Fracture and Failure of Materials and Structures

BOOK OF ABSTRACTS



14-16 June 2017 – Nantes (France)

Ecole Centrale de Nantes

Foreword

The increasing power of computers and the advent of numerical methods and simulation-based sciences have brought enormous changes in many scientific fields. Moreover, various modern experimental techniques provide access to a detailed characterization of the internal structure and processes taking place in materials at small scales, paving the way to new routes for model validation. Well-established paradigms in engineering sciences, based on analytical or experimental methods, are increasingly being replaced by computational methodologies that, by the means of intensive numerical simulations, supply detailed information and rapid answers to engineering problems, much beyond the dreams of the past decades.

Fracture mechanics is not being alien to this process and the emerging field of Computational Material Fracture is attracting increasing attention of researchers, both from traditional areas of fracture mechanics and from the computational mechanics community, who envisage, in that discipline, an appealing and challenging scientific field. New industrial applications of fracture mechanics also appear in this context, and they often require the development of innovative computational material failure methods. Such methods can then be applied at the structural scales in civil, mechanical, aerospace and naval industries, among others, giving responses to problems which were considered as out of reach only few years ago. One of the objectives of current research is to help designers of engineering structures who have to develop solutions responding to the ever increasing requests on performance in terms of safety, reliability, durability, low cost and low energy consumption. As new materials and new applications arise, traditional design rules and conventional testing methods become insufficient or inapplicable, which strengthens the role of computational methods in the design process (ie virtual fracture testing). Also important is the design of computational tools needed for the validation of fracture/failure models based on experiments (experiment-modeling dialog).

We hope that, in the spirit of the previous CFRAC conferences (Nantes 2007, Barcelona 2011, Prague 2013, Cachan 2015), CFRAC 2017 will facilitate the exchange of ideas in topics of mutual interest and serve as a platform for establishing links among research groups in Europe and worldwide in the fascinating area of fracture and failure. Finally we would like to express our gratitude to all the mini-symposium organizers who are in fact co-organizers of the conference and who have been able to prepare an exciting program of technical sessions.

N. Moës, X. Oliver, M. Jirásek and O. Allix
Chairmen of the Conference

Supporting institutions/organizations

- ECCOMAS European Community on Computational Methods in Applied Sciences
- CSMA French Computational Structural Mechanics Association
- ECN Ecole Centrale de Nantes
- GeM Research Institute for Mechanics and Civil Engineering (ECN/Univ. Nantes/CNRS).
- Nantes Métropole
- Région des Pays de la Loire
- CNRS Centre national de la recherche scientifique
- UPC Technical University of Catalonia
- CIMNE International Center for Numerical Methods in Engineering
- Czech Technical University, Prague.
- ENS Paris - Saclay
- LMT-Cachan Laboratoire de Mécanique et Technologie
- Université Paris-Saclay

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Mini Symposia

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  Anna Pandolfi & Michael Ortiz
- **MS2: Regularized failure models**
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  Pierre-Olivier Bouchard, José César de Sá & Ron Peerlings
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- **MS11: Fracture and damage of composites and laminates**
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Plenary Lectures

Multi-scale modelling of quasi-brittle fracture processes

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In this presentation different multi-scale modelling techniques for the description of quasi-brittle fracture processes will be discussed.

A number of relevant issues will be treated in more detail, such as the non-standard computational homogenization for localization phenomena, the extension of multi-scale modelling techniques to dynamic fracture problems and the introduction of multi-physics aspects.

Enhanced computational homogenization schemes have been developed for modelling heterogeneous quasi-brittle materials. They are characterized by the introduction of cohesive cracks at the coarse scale which are derived from propagating localisation bands at the fine scale. The schemes are objective with respect to the coarse scale discretisation and the fine scale modelling size and discretisation.

There are limitations to the well-known multi-scale schemes in cases where the separation of scales is relatively small. Direct coupling can be used then through coupled-volume or domain decomposition techniques. Furthermore, small-scale effects that are normally averaged out through computational homogenization can not always be ignored. For instance, dispersive effects may become relevant in dynamic multi-scale analyses when dominant wave lengths in the macroscopic response are of the same order as the size of a representative volume element. A dispersion tensor can then be derived in order to enhance the multi-scale scheme. The issue of multiple interacting and non-interacting length and time scales (e.g. for fatigue fracture problems) will be discussed. The use of failure models which are regularized by the introduction of a length scale parameter further complicates this issue.

Examples of multi-scale analyses of quasi-brittle fracture processes in various engineering materials will be demonstrated. Furthermore, efficiency of the computational multi-scale modelling schemes will be discussed.

Phase-field and variational models of fracture: twenty years and counting

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Since their inception in the mid-90's as regularization of Francfort and Marigo's variational model of brittle fracture, phase-field models of fracture have steadily gained popularity.

Part of this success is undoubtedly due to the relative ease of their three dimensional implementation, as well as to their postulated then demonstrated ability to capture complex fracture behavior.

In this talk, I will start by recalling the link between phase-field and variational models of fracture. Then, I will describe more recent effort to derive variational phase field models as specific examples of gradient damage models. I will illustrate both approaches using various quantitative validation and verification numerical simulations and highlight their differences and similarities. I will then present recent extensions, and will conclude with open problems and proposed extensions for the years to come.

The role of numerical tools on the development of a new generation of polymer composite materials

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The stringent guidelines on emissions combined with the strong competition between aerospace companies motivate the development of a new generation of polymer composite materials. New requirements, ranging from lightness, multi-functionality, recyclability, structural health monitoring, and faster manufacturing processes are imposed by the market. However, the time frame from material development to implementation is currently too high (up to 20 years) [1], and product innovation based on new materials is particularly fraught with risk and uncertainty. The use of computational mechanics mitigates these risks and uncertainties: not only the development of new materials is faster due to the reduced number of physical tests, but also increased knowledge on the material performance is obtained at early stages of material development. This work addresses the role of Computational Fracture Mechanics on the development of a new generation of non-conventional polymer composite materials based on ultra-thin plies [2], fibre hybridisation [3], and carbon-nanotubes [4]. The analysis models that support the development of the non-conventional polymer composite materials are based on computational micro-mechanics, cohesive zone models, and continuum damage mechanics. The models developed represent the mechanics of non-linear deformation and fracture of the new material systems proposed. Furthermore, the models are able to explain the reasons why the new materials have an improved performance over conventional materials with respect to the main failure mechanisms of polymer composite laminates, such as delamination, matrix cracking, and fibre fracture. The work presented corresponds to one of the building-blocks required for the effective optimisation of the micro-structure of composite materials with respect to a set of design drivers.

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A new finite element framework for the modeling of ductile fracture mechanisms in heterogeneous microstructures

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Ductile fracture has been studied for many years and has given rise to number of damage theories and failure criteria. However, predicting ductile fracture under complex loading path remains challenging, in particular for advanced heterogeneous materials for which failure mechanisms depend on microstructural properties such as particle characteristics (nature, shape and distribution), grains, and texture. Modeling failure at a mesoscale would help in the understanding of the role of these microstructural properties on ductile fracture mechanisms. Such a modeling requires an accurate numerical framework accounting for heterogeneous microstructure definition and meshing capabilities under large plastic strain as well as numerical methods for the modeling of failure events such as void nucleation –by interface debonding or particles failure –and coalescence. In this work, a micromechanical approach is developed in order to conduct realistic full field finite element (FE) simulations of ductile fracture at the microscale. Meshing and remeshing methods relying on the use of Level-Set functions are proposed to discretize the microstructure and its behavior under large plastic strain [1, 2]. These numerical methods are extended to account for cracks and model the microstructure failure mechanisms: void nucleation, growth and coalescence. This new FE approach is used to study the influence of multiaxial and non-monotonic loading on ductile failure mechanisms. It is shown that different loading paths leading to the same final macroscopic strain activate different nucleation mechanisms and consequently different final void volume fraction. These full field FE simulations can also be used to calibrate nucleation or coalescence failure criteria. This is done here thanks to the combination of Synchrotron Radiation Computed Laminography (SRCL) experiments and observations [3], Digital Volume Correlation (DVC) [4] and FE simulations[1, 2]. Thanks to SRCL images at the initial state, are presentative volume element (RVE) representing the exact microstructure is meshed using the body-fitted immersed method presented in [2]. The DVC also uses SRCL images at different stages of the mechanical test in order to extract the exact boundary conditions that need to be applied on the RVE. These boundary conditions play an important role on void growth as detailed in [5]. The FE framework enables the modeling of void nucleation growth and coalescence with criteria parameters that can be identified by comparison with SRCL images. The whole methodology ([6]) is carried out on nodular cast iron and comparisons with experimental observations are discussed.

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Recent research results on phase-field modeling and computation of brittle fracture

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The talk discusses recent research results obtained in the group of the speaker in the framework of the phase-field approach to fracture, based on the regularization of Francfort and Marigo's variational formulation of brittle fracture. After a general overview on recently completed and ongoing work, the focus is placed on two main topics: i. a phase-field modeling framework for fracture in partially saturated porous media, applied to the study of desiccation phenomena in soils and shrinkage in cementitious materials; ii. a computational approach to combine the phase-field approach to brittle fracture with the Kirchhoff-Love shell kinematics, while accounting for the different material behavior in tension and compression.

MS1: Theory of fracture, crack propagation criteria, and crack tracking algorithm

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In brittle or quasi-brittle materials under complex loading conditionthe nucleation and propagation of cracks is still under an extensive investigation.The key issue is givenby the difficulty to predict the crack path, in particular when multiple loads are acting and the crack is expected to manifest unstable behaviors. Theory of fracture tries to describe mathematically the complex physics of the process, characterized by the change of topology due to the formation of new surfaces with unknown location and orientation. Theoretical formulations can be taken as the basis of numerical algorithms where the accuracy of the solution can be monitored or controlled. Propagation of cracks satisfy physical criteria expressing the local attainment of the ultimate strength of the material. Recent formulations based on energetic reasoning opened an interesting avenue for the definition of new algorithms. Popular numerical techniques are based on finite element discretization, where fracture is described explicitly by reproducing newly created surfaces. Surfaces are inserted between solid elements, or cross solid elements. Phase-field approaches are attracting attention for the easiness of the implementation. Boundary element techniques have been also used with satisfactory results. Recent approaches disregard the presence of a classical mesh, avoiding the complication of disconnecting volume elements. Advanced numerical models of fracture are based on multi-scale descriptions and in some cases integrate different numerical techniques.

In this mini-symposium we would like to bring together researchers and scientist that are working on new theoretical approaches and advanced numerical algorithms to explore possible future developments of numerical methods for crack nucleation and crack tracking. New algorithms and new approaches are welcome, as well as improvement and applications of well settled formulations.

Dynamic Fracture in Quasi-brittle Materials with Random Defects

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The fracture response of quasi-brittle materials is highly sensitive to the presence and distribution of microstructural defects. We study two approaches to model these inhomogeneities. In the first, we model the defects as explicit, crack-like features in the description of the analysis domain with random distributions of size, location, and orientation. In a second method, we use a probabilistic nucleation technique based on the Weibull model to spontaneously generate seed cracks during the course of an analysis. Either approach can model media with preferred directions for crack nucleation and propagation.

We combine an asynchronous Spacetime Discontinuous Galerkin (aSDG) method [1] with a novel, rate-dependent interfacial damage model to study crack nucleation and propagation. The method's powerful adaptive meshing capabilities ensure accurate resolution of crack-tip fields and eliminate mesh dependency during crack nucleation and propagation. Thus, the aSDG method models dynamic fracture in problems where crack-path oscillation, microcracking, and crack bifurcation make computational modeling particularly challenging. We introduce a new rate-dependent interfacial damage model in which the damage rate depends on both the traction acting on the interface and the opening/slip velocity across the interface. The former factor controls the onset of damage, while the latter models later, inertia-driven stages of the fracture process.

Numerical examples illustrate the influence of material inhomogeneities on fracture patterns and demonstrate the ability of the aSDG scheme to capture complex fracture topologies. We also describe a parallel–adaptive, and synchronization-barrier-free implementation of the aSDG method in which adaptive spacetime meshing and finite element solution share a common fine-scale granularity.

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An Adaptive Mesh-Free Approach for Dynamic Failure Analysis

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Recently a new theory of continuum mechanics, so called Peridynamics [1] has been proposed to overcome the problems related to the need to have a continuum definition field for the displacement variables. Peridynamic formulation is valid even in the presence of discontinuities in the displacement field; moreover, crack nucleation, branching and propagation can be simulated conveniently. The method does not need additional external criteria to initiate or propagate cracks since the material failure is invoked through the material response in the theory. However, simulation of fully nonlocal Peridynamic models is still inevitably costly and challenging in comparison with local continuum models. Therefore, in this paper, taking the full advantages of the both models, the Peridynamic model is coupled with a simple meshless finite point method (FPM). FPM is one of the most prominent meshless methods. Since no integration is involved in this approach, it is categorized as *a truly meshless* method; moreover, it offers many advantages in terms of computational cost and simplicity over many other meshless methods.

In this paper a novel mesh-free method by a simple coupling between the finite point method (FPM) and a mesh-free Peridynamic method is introduced. In this method, the solution domain is mainly discretized by FPM points at the beginning of the analysis; FPM produces results with lower computational cost compared to a Peridynamic-only model. Then as the analysis progresses in time, FPM points can change to Peridynamic points in the parts where there is a possibility of crack nucleation or propagation. In this way, the approach benefits from the full advantages of both methods by using an adaptive partitioning of the solution domain, and it restricts the Peridynamic solution only to necessary parts. Our investigation shows that the present approach is capable to reproduce the solution of a Peridynamic-only model with a lower computational cost.

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Dynamic Crack Propagation Analysis based on Particule Discretization Scheme Finite Element Method (DPS-FEM)

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Abstract

Dynamic propagation of cracks has been one of the most important and challenging research topics in the field of solid continuum mechanics. Although a wide variety of experimental observations on dynamic propagation of cracks have been achieved, these experimental results have not been completely explained by numerical analysis. The major difficulties in dynamic crack propagation analysis are i) treatment of discontinuities in displacement field, ii) re-distribution of residual nodal force, and iii) determination of crack velocity.
A numerical analysis method PDS-FEM (Particle Discretization Scheme Finite Element Method) is proposed in this presentation and application of PDS-FEM for analysis of dynamic crack propagation will be discussed. In this analysis, dynamic crack propagation is simulated without introducing rate dependent material parameters. PDS is a discretization scheme using characteristic functions defined on a set of conjugate geometries; Voronoi and Delaunay tessellations. Displacement field is discretized by a set of non-overlapping shape functions with embedded discontinuities. As a result, there is no need for changing discretization of displacement field for fracture. Once the displacement field is discretized by PDS, the displacement field can be regarded as rigid body motion of each Voronoi cells. Thus, Hamiltonian framework for dynamics of particles can be applied for the problem of deformation and fracture of solid continuum. Re-distribution of residual nodal force is automatically taken care of by Hamiltonian dynamics. For the determination of the crack velocity, energy balance between surface energy required for creating new crack surface and change in the total Hamiltonian in the analysis domain before and after fracture is considered.

At this moment, preliminary results such as i) autonomous acceleration and deceleration of crack propagation, ii) asymptotic convergence of the crack velocity in a linearly elastic plate under static loading to the Rayleigh wave velocity, and iii) different morphology of the cracks depending on the loading conditions have been obtained.

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Keywords: dynamic crack propagation, PDSFEM

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A Continuum Description of Failure Waves

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Shattering of a brittle material such as glass occurs dynamically through a propagating failure wave, which however, can not be assigned to any of the classical waves of the elasto-plastic theories of materials. Such failure waves have been a topic of research for decades. In this paper, we build a thermodynamically consistent theory based on the idea that a failure wave is analogous to a deflagration wave, a point of view presented by R. Feng. Two fundamental thermodynamic functions (the free energy and the entropy production rate) form the basis of our theory. Such a two-function approach allows the construction of a new variational principle and a new Lagrangian formulation that produce the equations of motion. Finally, a linearization of this theory is examined to gain insight into the coupling between the diffusive and elastic wave phenomena.

Our analysis subsumes and extends a prior model proposed by Feng for brittle fracture, and we recover Clifton's model in the dissipationless limit. Furthermore, the paper reveals the importance of the coefficient of lateral diffusion in determining both the shard size and the transition from failure waves to isolated cracks. Our results are compared to experiment.

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On the stability of straight crack paths in brittle heterogeneous solids under mode I loading

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The classical fracture mechanics approach describes only partially the fracture process in heterogeneous brittle materials-such as rocks, ceramics or concrete for example. The study of crack growth in weakly heterogeneous solids where fracture behaviors can be seen as a perturbation from the response of homogeneous media is a fruitful approach that provides rich insights on the role of heterogeneities on crack propagation.
In this work, we focus on the path followed by cracks, and study whether a crack previously disturbed by some heterogeneities recovers a straight trajectory or instead departs from it. To address this question, we build on the work of Cotterell and Rice [1] enriched by the one of Movchan et al. [2] to derive a path equation for a slightly perturbed crack under macroscopic mode I loading. This path equation is then used to investigate the stability of straight crack trajectories. Three regimes corresponding to different loading conditions that can be parametrized through two length scales emerging from the geometry of the fracturing sample and the loading conditions can be evidenced: (i) a stable regime where path perturbations rapidly decay (ii) an unstable regime with an exponential growth of the geometrical crack perturbations (iii) a marginally stable regime that displays oscillatory crack solutions. These predictions are compared with experimental fracture tests in various geometries where crack path disturbances are manually introduced. We find that our approach accounts for the stability of straight trajectory as observed experimentally. The conditions required to observe oscillatory crack paths are finally discussed.

Keywords: Fracture,mechanics, crack path, stability analysis

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FEM-simulation of anisotropic crack growth in a nickel-base alloy under thermomechanical fatigue

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Nickel-base superalloys like ALLVAC®718Plus play an essential role for jet engines. Their ability to withstand simultaneously high temperatures and mechanical loads makes them ideally suited for turbine disks. In practical use however, these materials show specific exceptional fracture mechanical properties. In particular, the fracture toughness and the crack growth behavior depend on material orientation, load cycle design and operation temperature. This must be considered properly in the design stage to take advantage of the alloy and guarantee safe service life of turbine disks.

In this contribution, appropriate anisotropic fracture criteria and crack propagation laws have been developed to realistically predict the velocity and direction of crack growth. The underlying thermo-mechanical fatigue law consists of a cyclic mechanical part and a time-dependent thermal part due to creep and oxidation during dwell time, see [1]. These laws have been implemented into the Finite-Element-Code ProCrack [2], an in-house software, using Abaqus as solution kernel. ProCrack allows to perform crack propagation simulations under arbitrary mixed-mode thermomechanical loading conditions for three-dimensional structures. The temperature and orientation dependent parameters of the above crack propagation laws are identified by means of thermomechanical fatigue experiments on CT-specimens. In the end, a numerical simulation tool is provided to analyse cracks in turbine disks or sub-components made from ALLVAC® 718Plus. The feasibility is demonstrated by some examples. Further details are given in [3].

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Improvements in the accuracy of the method θ for the calculation of the stress intensity factors in 3D

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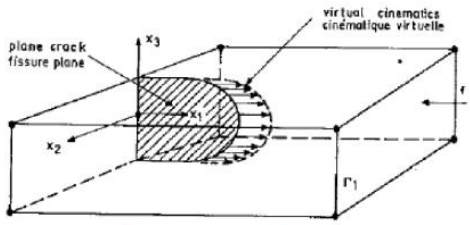
The G-theta method was proposed by Destuynder et al. [1, 2] to compute the energy release rate and stress intensity factors. This method is based on domain integrals and Lagrangian derivation of the potential energy with respect to a virtual crack extension velocity field (θ field). Currently, the method allows obtaining very good results in 2D but has several drawbacks for three-dimensional cracks that will be addressed. To better understand the problems encountered, we propose to study two 3D cases:

- a 3D case that is a simple extrusion of a 2D case so that the solution is the same for the 2D case and the 3D case ($\nu = 0$) along the extrusion direction.
- a Penny-shaped crack which has also an analytical solution [2].

In each case, the results of the calculation for G will be obtained with the extended finite element method [3] and the finite element method in order to compare both.



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A Mixed Finite Element Formulation for Strain-Gradient Isotropic Materials

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For many engineering materials experimental evidences at the micro-scale revealed that the fracture process is characterized by strain localisation, micro-cracking and void nucleation, see for example [2]. To model such size-effects and to properly describe the fracture process zone constitutive models which are not indifferent to variation of scale are required. To this aim, strain gradient elasticity has been proved to be effective; indeed, by simply assuming the stored elastic energy to be a quadratic functional of the strain and the strain gradient a process zone can be detected and an estimate of its characteristic length can be provided, see [4, 5, 10]. Recently, [11] explicitly found closed-form asymptotic solutions of the three classical crack opening problems of fracture mechanics for the *most general* isotropic strain gradient material. This allowed them to provide an analytic extimation of the process zone length and a closed-form expression for the $J-$integral; moreover, in order to select the optimal microstructure arrangements, they investigated how the ratios among the material lengths affect the energy release rate and the micro-structural strengthening effect.

In this contribution, we numerically solve the 'full' problem for the same three classical fracture modes. We prove the accuracy of the asymptotic solution in predicting the crack opening displacements near the crack tip and the limit length of the process zone. We avoid the use of C^1-elements by employing a Mixed Finite Element formulation (see for details [1]). For strain gradient elasticity some mixed formulations have been proposed and numerically tested [3, 8, 9]. Here, we chose as primary variables: displacements, displacement gradients and higher order stresses; the latters play the role of lagrangian multipliers. The Finite Element implementation has been carried out within the open source project FEniCS, [6], `https://fenicsproject.org`, which provides a computer platform for the automated solution of partial differential equations by the Finite Element method.

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Unified criteria for fatigue endurance modelling under combined loading

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Titanium compressors in an aero-engine suffer from very complex loading regimes in service. Rupture of any part in this thermo-mechanical system is life threatening and requires stringent fatigue endurance prediction methodologies. A conservative local approach is currently used in industries to justify the integrity of engine parts under combined static and dynamic loadings and it is deemed to be too limited to describe the progress of microcracks in a continuum [1].

The reasons that any local stress invariant based fatigue criteria are limited are diverse, whether probabilistic or not. Among, is the utter obliteration of stress gradient effects which arise independently from geometrical effects substantiated by quasi uniform gradient and vibratory localised stresses with high stress gradients. The current study appeals to provide a methodology to consider these effects around a "hot-spot", devised as the crack initiation site using a novel methodology based on the superposition of independent analytical and/or basic numerical stress domain functions and a multiplicative factor fitting the complex loading. Time/Space variables will be split using the Karhunen-Loève decomposition.

This method will ease post-processing of complex stress fields so as to extract rupture mechanics parameters using criteria such as in [2], from coarsely meshed domains directly from the *a priori* known sets of analytical fields, otherwise computationally very expensive. The first phase of the project consists of acquiring a tool to examine a spatio-temporal stress field in a structure. A test-case consisting of a dissymmetric notched geometry is currently being examined under the effect of combined tension and torsion. Subsequent steps will be to post-process the local "hot-spot" zone and trial the current methodology.

N.B *This thesis started in October 2016 and hopefully interesting results will be presented for the conference in June.*

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A 3D meso-scale approach to concrete fracture based on DEM and X-ray μCT images

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Fracture is a fundamental phenomenon in concretes. It is an extremely complex process since it consists of main cracks with various branches, complementary cracks and micro-cracks. It strongly depends upon a heterogeneous structure of materials changing from few nanometres (hydrated cement) to the millimetres (aggregate). The understanding of fracture at the aggregate level is major importance to ensure the safety of the macroscopic structure.

The discrete element method (DEM) was used to describe concrete fracture under bending at the meso-level. This approach allowed us to directly simulate concrete micro-structure and to comprehensively study local mechanisms of the initiation, growth and formation of cracks which affected the macroscopic concrete behaviour. The concrete was described as a random heterogeneous 4-phase material composed of aggregate, cement matrix, macro-voids and interfacial transitional zones [1]. The aggregate was simulated as 3D clusters of spheres with the same geometry as in the experiment. The 3D open source code YADE was used which was developed at Grenoble University. A linear contact model under compression was used. The contact normal and tangential forces satisfied the cohesive-frictional Mohr-Coulomb equation using the inter-particle friction angle. The internal structure of the concrete specimen was directly taken from 3D x-ray images using the micro-tomography SkyScan 117 [2]. A satisfactory agreement between calculations and experiments was achieved with respect to the main crack ‘s shape and force-deflection diagram.

In addition, the calculations were carried out with vortex-structures which turned out to be a good precursor of cracks. In order to detect vortex-structures, the Helmholtz-Hodge decomposition of a vector field from DEM calculations has been used which is one of the fundamental theorems in fluid dynamics. It describes a vector displacement increment field in terms of its curl-free and divergence-free components based on potential functions. This approach enabled us to distinguish both incompressibility and vorticity in the particle displacement field.

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3D simulations of crack growth in concrete with cohesive elements at mesoscale level

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Concrete fracture is very complex due to the occurrence of phenomena such as: branching, coalescence, kinking, tortuousness and interlocking of cracks. Concrete can be described at several levels of observation. At the macro-scale all material properties are averaged and the attention is paid to cracking. More detailed simulations take the internal structure of concrete into account. When describing concrete at the meso-level: aggregates, cement matrix, macro-voids and a thin layer between them, called the interfacial transition zone (ITZ) may be distinguished. All phases have different elastic and strength properties which influence the overall behaviour of concrete specimens.

The mesoscopic approach presented here includes interface cohesive elements to simulate cracks and takes into account 4 the most important concrete phases: aggregate, cement matrix, macro-voids and ITZs [1]. Between bulk (solid) finite elements, interface elements were placed. Cracks could be created inside the cement matrix and in ITZs but no cracks were allowed inside aggregates. Different strengths and softening characteristics were assigned to the cement matrix and ITZ. The concrete meso-structure was directly taken from experimental images obtained by means of the 3D computer micro-tomography [2]. A three-point concrete bending test was carefully studied under 3D conditions. Crack patterns and force-displacement curves were directly compared with experimental outcomes. Good agreement was obtained. The influence of model parameters (e.g. ITZ/cement matrix strength ratio, aggregate shape, aggregate diameter with ITZs) on obtained results was examined. A special attention was focused on the dependence of cracks trajectories on assumed aggregate parameters.

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Geometrical and numerical aspect of the Thick Level Set (TLS) Damage and fracture model

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In the TLS model for damage and fracture, first presented in [1], the spatial evolution of the damage is regularized by limiting the gradient of d (the damage parameter). This limiting is done by computing d as a function of another field variable ϕ for which the constraint $||\nabla\phi|| \leq 1$ must be fulfilled everywhere. The material domain Ω is therefore divided into two sub-domains, one for which $||\nabla\phi|| < 1$ and one for which $||\nabla\phi|| = 1$. In the first zone the damage is diffuse and is said to be local: its evolution depends only on the local stress or strain fields. In the second sub-domain the damage is regularized by limiting the spatial variation of ϕ and therefore avoiding spurious localization of the damage. This second sub-domain is said to be non local, and the damage evolution on this zone is driven by a non-local law which can be computed by enforcing the constraint on ϕ on the local evolution law. This approach has several advantages : (i) The non local computation can be done only on the relevant part of the domain. (i) The damage evolution in the non local zone is completely driven by the motion of the boundary Γ between the local and non local sub-domains.

The function that link d to ϕ is defined as a monotonous function of ϕ, which saturate to 1, where the material is fully damaged, beyond a certain value of ϕ, corresponding to an internal length scale l_c. This mean that the fully damaged zone is bounded by an iso-value of ϕ. This fully damaged zone is interpreted as being the crack. The model permits to describe a full failure scenario : starting from diffuse damage, using classical local damage model. When damage start to localize, the constraint on ϕ impose a non local behavior, introducing a length scale in the problem. When damage reach 1 somewhere, a crack is automatically defined and can continue to evolve. It is geometrically described by the iso-l_c surface of ϕ. With this model we were able to cover different interesting failure scenario, including damage initiation, crack apparition, crack coalescence and crack bifurcation [2], [5]. Nice features of the model include a natural link with Griffith theory for fully developed cracks as well as an equivalence with cohesive cracks [3]. The model was also recently compared with phase-field approach [4], for the brittle and quasi-brittle cases.

In this presentation we will set the focus on the implementation of some geometrical aspects of the TLS. We will in particular show how the fast marching method can be used to enforce $||\nabla\phi|| = 1$ in the non local zone, to construct the discrete space on top of the finite element mesh, that is used to compute the damage evolution, and to construct a good approximation of the skeleton of the non-local zone, where the damage gradient is not continuous. In particular this skeleton extraction can enhance a lot the precision of the TLS Method by giving a better way to extract the iso-l_c. It also permits to improve the discretization of the fields, since the skeleton is also the locus of discontinuities of the gradient of d.

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On performances of the Thick Level Set method in 3D quasi-static fracture simulation of quasi-brittle material

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Abstract

The Thick Level Set model, introduced in [1, 2], is a non-local damage model embedding displacement discontinuity.

By the way non-locality is treated in this model, high mesh density is only needed in the region surrounding the limited zone where damage evolves. In 2D, if we succeed to adapt the mesh around crack tips, this leads to acceptable problem size, even in serial computation context. In 3D, since cracks are surfaces, the refined zone still lead to a large problem that becomes difficult to solve by direct methods. In this contribution,we will first illustrate this problem with simulation examples. Then, we will present computational strategies investigated so far that address this issue.

Among many possible solutions, the two scale or GFEMgl computational framework applied to crack simulation [3] is a promising solution for the TLS method in 3D. This framework uses two interdependent problems to solve discontinuous problems repre- sented by TLS model. The coarse level problem, addressing global behavior of the part, is enriched by discontinuous functions in the vicinity of the damaged zone to take into ac- count local behavior of the cracks. This local behavior is captured by the fine level scale which corresponds to a set of independent problem resolution. Each of them is related to each enriched node support (i.e. set of elements over which the approximation function associated with the node is non-zero.) and is constructed by adapting element size to TLS requirement. Their boundary conditions are coming from coarse level displacement solution which are imposed loosely by penalization. By construction, refined element are embedded in original macro element support which permits this transfer from coarse level to fine level problems. After resolution, those local problem displacement solution fields are used, with some manipulation, as enrichment function at coarse level.

More in detail, in quasi-static TLS problems, the enriched coarse solution of previous time step is used as boundary conditions for the fine scale resolution at current time step. To get reasonable computational times, the resolution of fine scale problems are done in parallel. A MPI framework have been settled to dispatch fine scale meshing, assembly and resolution tasks. At global level, mesh, assembly and resolution are also dispatched among process. This work shows first results of this parallel framework.

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Mapped Finite Element Methods: higher order methods for simulating curvilinear crack propagation

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High order finite element solutions of crack (and re-entrant corner problems) in elasticity are notoriously challenging to attain. The slow convergence rates for these classes of problems are tied to the low degree of regularity possessed by the solution. The need for high order solutions is motivated by long running simulations of crack propagation. In fact, as the error in the crack path grows non-linearly, it is of uttermost importance to accurately resolve the elasticity fields at each time step. The above ensures that the final computed crack paths are within reasonable tolerance of the exact one without excessive computational expenditures.

To this extent, we develop higher order finite element methods for crack (and re-entrant corner) problems in elasticity. The method [1] exploits the a priori knowledge of the singular behavior of the fields to construct an alternate regular solution. Solving for the alternate problem yields optimal rates of convergence and high order of accuracy. Namely, standard finite element error estimates in the L^2 and H^1 norm are proved to hold, both for the alternate solution and the composed alternate solution. The salient feature of the method is the lack of additional degrees of freedom in comparison with standard Galerkin finite element formulation. Effectively, for the same computational cost we obtain a higher order of accuracy. Furthermore, unlike other state of the art tools, the method preserves the well conditioned nature of the system of equations and does not require the knowledge of the exact asymptotic behavior, hence the method can be readily applied to singular problems for which we are not endowed with an explicit asymptotic solution, such as cracks in graded materials. The method is verified with respect several analytical solutions in two- and three-dimensions accounting for the possible curvilinear (non-planar) geometry of cracks as well as material inhomogeneities.

We further motivate the need for higher order solutions by showcasing the rapidly convergent computation of the stress intensity factors through the use of interaction integrals [2] with the computed approximation of the elasticity fields.

The application of the method are showcased for complex fracturing problems, in particular for simulations of oscillatory fracture instabilities in thermoelastic materials subjected to large temperature gradients.

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How to equip the Finite Element Method with the capability to simulate realistic crack patterns

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Abstract

The unavoidable presence of cracks in many structures still represents a daunting challenge for the analyst who wants to simulate the full structural life cycle. Cracks do not satisfy the basic hypothesis of Classical Continuum Mechanics (CCM) i.e. the continuity of the domain where the problem is defined. Many scientists have tried to equip CCM based methods, in particular the Finite Element Method (FEM), with the capability to simulate crack propagation: interface-elements with CZM [1], X-Fem [2], element erosion [3], phase field theory [4] are probably the most popular approaches, but all of them present some drawbacks [5]. On the other hand Peridynamics (PD) based methods can easily deal with discontinuities, since the underlying theory does not assume continuous displacements, but they are not computationally efficient, due to the non-local nature of PD. Therefore, it would be very convenient to couple peridynamic grids to FEM meshes in a way to obtain a numerical method that possesses the advantages of both computational techniques and avoids their pitfalls [6-10]. Usually a small part of the model, where cracks are likely to develop or propagate, would be discretized with a PD grid, whereas the remaining part would be modelled with the more efficient FEM. In particular FEM would be used at the boundaries to avoid the soft boundary effect typical of PD. Such an approach requires an effective coupling, between the two parts of the model, that should not introduce inaccuracies. The present work introduces a new coupling technique which constitutes a significant step forward with respect to that presented in [11]. In reference [11] the PD grid and the FEM mesh had to be characterised by the same spacing and therefore they had the same density. The present approach overcomes such a restriction so that it makes possible to couple a fine PD grid with a coarser FEM mesh and in this way improves considerably the computational efficiency. The new computational method is applied to static and dynamic problems in 1, 2 and 3-D with any type of crack pattern. In this way a new computational technique is produced which equips standard FEM with the capability to effectively and efficiently describe 3D problems with crack propagation problems.

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Keywords: Peridynamics, Coupling, Crack propagation, Finite Element Method

Mixed FE solution of the layerwise model M4-5n with emphasis on embedded discontinuities

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A general solving method for the plate-type model called M4-5n, relying on mixed finite elements is presented hereafter. In particular, we explain how embedded discontinuities in a multilayer pavement structure can be easily taken into account using the numerical approach developed.

M4-5n stands for Multi-Particle Model for Multilayer Materials (M4) considering 5 equilibrium equations per layer (*n* being the total number of layers) [1]. This model can be viewed as a piling of linear elastic plates whose equilibrium equations per layer bear on the bending moments, the torques and the shear resultants of the tridimensional stresses. The load transfer between two layers is ensured by interface normal and shear stresses. This model is derived from the Hellinger-Reissner variational principle considering a polynomial representation of the stress field (3D) in the direction orthogonal to the layers [2]. This model allows us to diminish by one dimension the modeling of the actual problem, which in particular facilitates the geometrical description of embedded discontinuities (cracks or debonding). Another advantage of M4-5n is that it leads to finite values of the generalized stress fields at the location of discontinuities. In the case of cracks, propagation criteria can thus rely straightly on the values of the generalized interface stress fields or on other quantities such as the individual strain energy release rates which can be computed from these values [1][3-4]. M4-5n is quite well adapted to the study of the bending of elastic pavement structures incorporating cracks or interlayer debonding.

Recently, we extended previous research related to M4-5n to the systematic solving of the model equations by means of the mixed finite element method. The approach developed relies on the complementary energy theorem applied to M4-5n, the condition of statically admissible stress being taken into account using Lagrange multipliers which can be identified to components of the generalized displacement fields. The resulting functional, L, is proved to be equivalent to that of Hellinger-Reissner expressed in terms of the generalized fields [5]. The solution of the M4-5n problem is a saddle point for L with regards to the generalized stress and displacement fields. The solution of the mixed formulation ($dL=0$) is approximated using FEM paying a specific attention to the functional spaces of interpolation to avoid ill-conditioned systems of algebraic equations after discretization. The numerical procedure was implemented using the FreeFem++ environment [6] and then validated.

This approach makes it possible to incorporate in a simple way different types of

discontinuity in a structure. These are vertical cracks (or joints) and debonding at an interface between layers. Incorporating the first type of discontinuity for instance consists in splitting a cracked layer into two sub-layers of similar mechanical properties one of which is used to fit the crack shape and the other to represent the healthy part of the layer. In terms of FE modeling, the vertical plane the crack belongs to is represented by its contour projected on the 2D-mesh along which nodes are doubled. Then, penalty terms are added to L to ensure the traction free boundary condition applying for the cracked sub-layer and continuity of the other layers on this doubled-node (curved line) segment. A crack growing vertically can thus be handled without remeshing just by making the variable thickness of the cracked sub-layer evolve according to some fracture mechanics criteria. This type of treatment with some adaptations can be considered also to introduce debonding between layers of a structure or be generalized to take into account cracks lying in non-vertical planes still taking advantage of the 2D discretization.

As an illustration, the approach developed is used to simulate the mechanical response of a pavement structure with cracks on which a full-scale accelerated fatigue test was performed.

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Prediction of failure of a V-notched unidirectional composite using the coupled criterion

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Abstract

The coupled stress-energy criterion proved to be one of the most successful in the past 15 years in predicting crack nucleation in brittle and quasi-brittle materials. Its starting point dates back to 2002 [1]. Since then, it has been used worldwide and applied to various materials and a large number of structural cases.

In the case of unidirectional (UD) composites, special care must be taken because of the anisotropy of the elastic as well as fracture properties. Indeed, the predominant rupture mode occurs by the growth of a crack parallel to the fibers and according to the loading mode this crack often develops in mixed mode I+II. Perpendicularly, rupture is almost in- hibited.

Tensile and shear tests were carried out on V-notched UD specimens made of pultruded carbon T700 fibers [2] so called either '00' or '90' ('00' means that the fibers are vertical and aligned with the applied tension in case of a tensile test and '90' means that the fibers are orthogonal to this direction). The notch opening angle is 90 deg.

We focus on two particular tests. The first is a shear test on '90' specimens. Using the singularity theory and the coupled criterion, it is shown that the failure does not start from the notch root but from the middle of the specimen. The notch root no longer plays the role of a stress riser. As a consequence, this test allows an accurate determination of the longitu- dinal shear strength tc, which otherwise by the current ASTM D7078 standard, cannot be determined

*Speaker

The second test is also a shear test but on '00' specimens. In this case a vertical (i.e. parallel to the fibers) split starting from the notch root is observed. The failure is in mode I+II and the onset prediction requires an extended version of the coupled criterion [3] involving the shear strength as above and in addition the transverse tensile strength sc as well as the two toughness values GIc and GIIc. However, the toughness values are extremely difficult to be determined and additional tensile tests on '90' specimens would provide a relationship between GIc and sc again with the help of the coupled criterion.

The present analysis is in progress. It must be pointed out that: (i) the total critical energy release rate is derived from the Hutchinson and Suo rule [4], a comparison could be carried out using the semi-empirical rule of Benzeggagh and Kenane [5]; (ii) the stress condition uses a power law and the exponent is an adjustable parameter.

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Keywords: UD composites, v, notched specimens, coupled criterion

Variational interface zone model for brittle fracture

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A novel variational approach to model brittle fracture propagation is presented. As was previously promoted in [1], the total energy of the sructure is composed by the bulk potential and fracture surface energy. In contrast to the phase-field approach, the fracture surface is approximated directly along the edges of the finite elements in terms of the interface zero-thickness finite elements. With an introduction of the damage field as a new degree of freedom restricted to the interfaces between elements, the solution is found by the minimization of the total potential energy with respect to the displacement and damage fields. This approach avoids using an additional length scale parameter l_0, as is required e.g. in phase-field approaches, since damage is not interpreted as a continuous, volume related variable but is assumed to be distributed along discrete interface zones.

An elastic interface constitutive law with separate normal and tangential displacement opening formulations is adopted in the pre-fracture regime. In the presentation, a crack is assumed to open and to propagate in mode-I according to Griffith's criterion of brittle fracture. However, also other criteria, such as critical stress or critical displacement opening criteria, can be adopted. The solution of the discretized coupled system of equations is performed in staggered scheme, solving first the displacement related problem and then searching for the solution for the updated damage variable.

A number of numerical benchmark tests, which include comparisons with experimental results, analytical solutions, and results from phase-field models, are presented to demonstrate the performance of the proposed fracture model.

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Variational fracture mechanics: fracture energy and internal length scale

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The variational model of quasi-static crack evolution are based on the minimization of an energy functional composed of a bulk term, i.e., the strain of the sound material, and a surface energy term à la Griffith, and by adding proper irreversibility conditions for crack opening [1]. Sequentially [2], the free-discontinuity problem has been approximated with a regularized elliptic two-field functional, where one field is representative of the macroscopic displacement in the body, whereas the other phase field is similar to a damage parameter because it varies between 0 and 1 and takes the null value in a cracked (damaged) zone and 1 away from it. This latter formulation leads to a pseudo spatial-dependent theory since it allows for spatial gradients of the phase field to affect the value of the stored energy functional. The regularized functional is also characterized by an internal auxiliary parameter having the dimension of a length.

The free-discontinuity problem of [1] represents a discrete crack model since the deformation field undergoes a sharp discontinuity at the crack surface. On the other hand, the regularized formulation can be classified in the category of smeared crack models because minimizers of the new functional are characterized by bands, smooth representation of the cracks, having a thickness of the order of internal auxiliary parameter, where the gradients of the displacement field concentrate.

Alternatively, the regularized problem cannot be seen just as an useful approximation, but an independent model per se in the class of phase field models, with its own physical autonomy being able to reproduce the phenomenon of fracture for those materials usually referred to as quasi-brittle. In quasi-brittle materials microcracks appear first from the sound material in small-width bands usually referred to as the process zone, and eventually coalesce into a main crack, independently of the existence of pre-existing flaws. The regularized model can reproduce such phenomenon and embraces material parameters that are lost in the limit free-discontinuity functional. In particular, the internal parameter disappears in the discrete crack model of [1], but this represents an information about the material microstructure because it plays the physical role of the material intrinsic length-scale, that characterizes the width of the process-zone bands.

The purpose here is to investigate within the context of variational formulation the proper evaluation and correlation with the internal length scale parameter of the fracture energy that has to be dissipated to create rupture within a solid. In particular, the attention will be focused on the evaluation of the fracture energy term of the

regularized functional. Firstly, numerical convergence tests will be conducted in order to assess the numerical procedure. Successively, with the use of simple examples the physical interpretation of the internal parameter will be investigated. In particular, the different fracture topological cases will the considered in order to show the effect of damage diffusion within the solid.

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Comparative analysis of three numerical methods for fracture modeling

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Over the past 20 years, various numerical methods have been developed to improve fracture modeling of materials. The objective of this paper is to compare and confront three approaches, namely : Cohesive Zones Model [1, 2], Thick Level Set [3, 4] and Eigen-Erosion [5, 6]. The obtained numerical results were compared to experimental data in the case of crack propagation of concrete under mixed loading [7]. All the numerical tests were carried out on the same geometry and the same mesh (triangular). First advantages, disadvantages are discussed and second linkage between each methods will be presented in details.

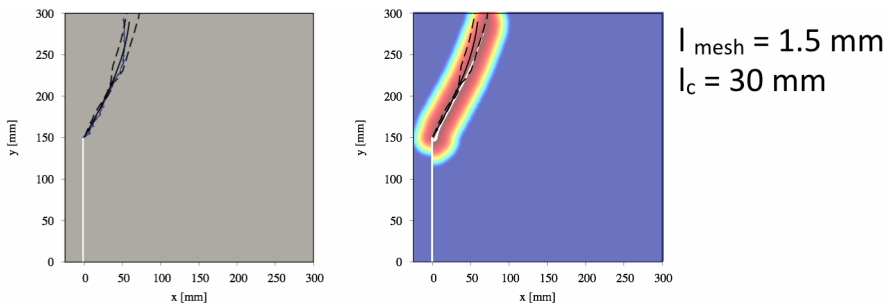

FIGURE 1 – Comparison of crack path with experimental data (in black) of the eigenerosion methods (left) and TLS for chosen parameters.

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An approach to hydraulic fracture by a phase-field model

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Abstract

Phase-field methods for brittle fracture employ a variational framework and have proven to predict complex fracture patterns in two and three dimensional examples. This contribution
focuses on a phase-field approach for a coupled field model to brittle and
pneumatic fracture in the context of both, finite and linearized strains. Two different challenges are tackled in this talk: First, we have to deal pressure-driven processes within the proposed phase-field ansatz, second, we have to consider the numerical effort of the simulations.
Our phase-field formulation is based on elasticity and a suitable operator split to
take only the tensile parts into account. Furthermore, a prescribed pressure is coupled with the phase-field parameter to consider crack propagation induced by pneumatic pressure. We use a semigeometric multigrid method as solution technique for threedimensional
problems to reduce computational complexity. The accuracy and the robustness of the solution
method will be demonstrated with a series of numerical examples.

*Speaker

A Phase-Field Crack Approximation Approach based on Crack Kinematics

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The phase-field method is a continuous approach to model the evolution of cracks within a finite element framework. Based on a energetic evaluation of the strain energy density, the initiation, propagation and arrest of cracks in a solid can be modelled. The choice of the specific parts of the strain energy density, that contribute to the evolution of the cracks, has a significant impact on the crack path. So far, there are two approaches available. For the first one, presented in [1], the strain tensor is decomposed into volumetric and deviatoric components. Both the deviatoric part as well as the expansive part of the volumetric component are assumed to contribute to the crack driving force. The second one, published in [2], exploits the principal directions of the strain tensor and the crack evolution is driven by tensile principal strains. Both approaches achieve impressive results for the simulation of crack initiation and overcome typical limitations of explicit crack approximation approaches by the use of the non-local evaluation of an energetic crack description. Furthermore, the pysically limited crack propagation velocity as well as the phenomenon of crack branching can be obtained by the phase-field method [3].

Nevertheless, both approaches show deficiencies in the correct approximation of basic crack kinematics. In a ideal plane crack with frictionless crack surfaces, there are three basic features to be obtained. First of all, the non-linear relation between deformation and force in normal direction of the crack surface, i.e. the transmission of compressive forces normal to the crack by means of contact and the traction free separation of the crack surfaces under tensile loading, need to be modelled. Furthermore, there is no transmission of shear forces over a such a crack. While the volumetric-deviatoric split fails to model the first two characteristics unless specific boundary conditions are applied, the spectral decomposition treats shear unrealistically in general. In the presentation, a new approach is presented, which couples a meaningful decomposition of the strain energy density into persistent and crack driving contributions with a kinematically motivated stress strain relation in order to model the characteristic crack kinematics. The approach is analyzed and compared to the existing approaches by the application of numerical examples.

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A model of poromechanical damaging material

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Abstract

Deterioration of mechanical and hydraulic properties of rock masses and subsequent prob- lems are closely related to changes in the stress state, formation of new cracks, and increase of permeability in porous media saturated with freely moving fluids inducing a modification of the coupling between mechanical and hydraulic behaviours. In the present talk, we describe a coupled approach to model damage induced by hydro-mechanical processes in low perme- ability solids. We describe the solid as an anisotropic brittle continuum where the damage is characterized by the formation of nested microstructures in the form of equidistant parallel faults [1], characterized by distinct orientation **N**k and spacing Lk. Faults bound otherwise elastic matrix material. We refer to this mode of deformation as recursive faulting, and the resulting microstructures as recursive faults. The assumption of faulting separates the req- uisite constitutive relations into two independent components: the behaviour of the matrix, assumed to be elastic for simplicity; and the behaviour of the faults, governed by a cohesive relation in the fault initiation stage, and by Coulomb friction and contact henceforth. The faulting construction can be applied recursively in order to generate complex fault patterns. Classic methods can be applied to describe the porous-mechanical behaviour of the solid to estimate the flow of fluids across the medium according to the presence of a fluid pressure gradient [2, 3]. The coupled approach can be used for a wide range of engineering problems, ranging from the prevention of water or gas outburst into underground mines to the prediction of the integrity of reservoirs for underground CO2 sequestration or hazardous waste storage, to the simulation of fracking processes.

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Keywords: Porous material, hydraulic fracturing, multiscale material

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MS2: Regularized failure models

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Physically sound and mathematically well-posed description of the complete process of mechanical failure must properly account for the energy dissipated by the loss of material integrity. Fracture models deal with fully localized failure patterns and attribute the dissipated energy to crack surfaces, considered as displacement discontinuities. On the other hand, continuum damage models as well as plasticity models retain continuity of the displacement field and describe the failure processes by stress-strain laws with softening, which lead to a certain dissipation density per unit volume. Objectivity of such an approach is preserved only if the width of localized damage or plastic zones is controlled by an appropriate regularization technique that acts as a localization limiter and prevents localization into zones of zero volume.The purpose of this minisymposium is to stimulate an exchange of ideas among researchers working on various types of regularization methods and non-conventional fracture models including, among others, the following approaches:

- Regularizations and approximations of crack discontinuities
- Phase-field approaches to brittle and ductile fracture
- Variational approaches to fracture
- Thick level set approaches to fracture
- Nonlocal models with variable length scale
- Regularized kill-element type approaches
- Scale bridging techniques and homogenization methods
- Diffusive fracture approaches in complex multifield environments

Special attention shall be devoted to techniques that combine continuous and discontinuous models and provide a realistic description of the entire failure process from the initial diffuse stage to fully localized rupture.

Combining cohesive and diffuse modeling of crack growth with the thick level set approach to fracture

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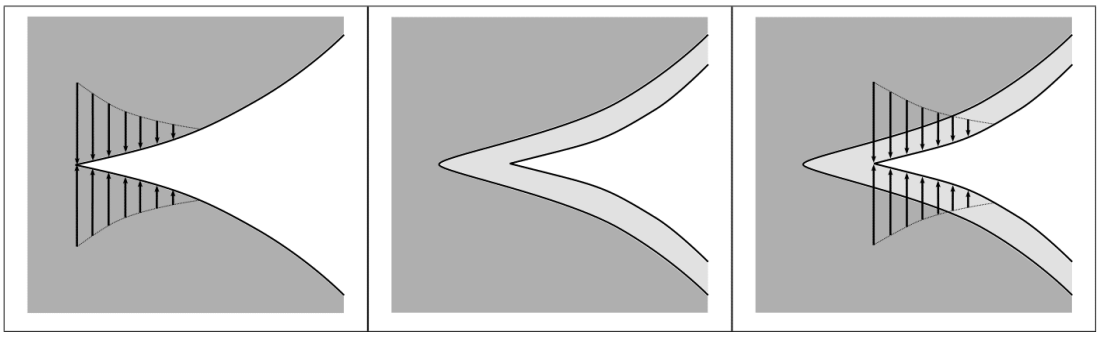
When a material model exhibits softening, spurious strain localization is likely to happen. A length scale needs to be introduced to avoid zero thickness dissipation localization process. The Thick Level Set model is a model acting as a localization limiter, it was introduced in [1]. The TLS differs from damage gradient approach and a comparison may be found in [2]. As damage proceeds, a crack is introduced in the model allowing for displacement discontinuity. In previous use of the TLS approach, the crack was introduced when the material was fully damaged (and was thus a traction-free crack). In this paper, we consider the possibility to introduce a cohesive crack prior to the material being fully damaged. The obtained TLS model is thus able to drive simultaneously both the diffuse and cohesive zone of the model.

Diffuse capabilities means that initiation, branching and coalescence are taken care of easily. See paper [3] for the latest results in 3D. Strong discontinuity (cohesive) capabilities means that the TLS automatically inserts a displacement discontinuity in the diffuse damage zone allowing mesh coarsening away from the crack tip and avoiding infinite strain close to the tip (and avoiding excessive mesh distorsion in large deformation formulations).

Figure 1 depicts the three types of models at stake : the cohesive model (a), the classical TLS model used so far (b) and the enhanced TLS model dicussed in this paper coupling diffuse damage and cohesive capabilities (c).



(a) Cohesive (b) TLS classical (c) TLS enhanced

The enhanced TLS allows to couple the advantages of the cohesive and diffuse approaches.

Advantages of the cohesive model are well known. It is an easy way to introduce size effect in a code able to handle fracture (displacement discontinuities). The mesh size needs to resolve the process zone length but not it's thickness. Simulation may thus be carried out with a reasonable mesh. Drawbacks of the cohesive model are also well known. The model does not incorporate a crack growth direction criteria. Stresses parallel to the crack faces are not taken into account (even though more evolved cohesive models try to remedy this) and so, for instance, splitting crack phenomenon cannot be modeled. Another drawback is that branching and coalescence are cumbersome to handle (either from the theoretical or computational point of views). These drawbacks are in fact the advantages of the diffuse approach.

The advantage of placing a cohesive zone within a diffuse zone is that the strain will be bounded, most likely, reducing the computational effort. Also, cohesive model do naturally introduce an anisotropic behavior (separation of normal and shear behavior) which is complicate to mimic in a diffuse manner.

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Analysis of the failure at notches and cavities in quasi-brittle media using the TLS damage model and comparison with the coupled criterion

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Predicting the maximum load that a (quasi-)brittle specimen can sustain is an important scientific and practical issue. A natural approach is to search for a criterion. Strength and toughness criteria are well suited for simple specimen having either no defect or an existing crack. When notches, or cavities, are present, the criterion is more complex to set up. We consider in this work the coupled criterion introduced by [1]. It could be qualified as semi-analytical since it starts from analytical consideration finalized by (simple) numerical treatment.

Another approach to determine maximum loads is to perform a full numerical quasi-static analysis of the specimen with an increasing loading. The failure load is defined as the maximum load above which no quasi-static solution may be found (and the specimen goes into dynamics). Since we are discussing quasi-brittle failure, we use a damage model. It is well known that regularization is needed when addressing failure with such a model, otherwise failure may be reached for infinitely small loading. Here we consider the TLS (Thick Level Set) approach of graded damage modeling. A material length scale is introduced explicitly and the model is closely connected to the cohesive zone model (CZM) [2].

Note that the coupled criterion contains a length scale since it is written in terms of toughness, strength and Young modulus from which a characteristic length may be extracted. In this work, predicted the failure load through the coupled criterion (CC) or the full damage approach (TLS) are compared. It was found that failure loads predicted by the coupled criterion are closer to those given by the full damage approach (TLS) when the coupled criterion hypothesis are verified (notch or cavity size are far larger than the material characteristic length ...). Noting that notch and cavity size affects significantly the failure load, it makes sense to analyse the role played by length ratio (notch or cavity size over characteristic length) on the predicted failure load in each model.

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Micromechnics-based non-local damage theory: Application to the prediction of localization and precursor statistics

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Abstract

Under compressive or shear loading conditions, quasi-brittle materials like concrete, rocks or ceramics fail through the emergence of a localization band that results from the collective response of a large number of microscopic dissipative events like e.g. microcracking. Originally, this problem was first tackled through the study of the response of a single repre- sentative volume element. However, it fails to capture the complex behavior of quasi-brittle solids as it predicts damage localization on domains of the order of the finite element size resulting in strong mesh sensitivity. To circumvent this difficulty, so called non-local or gra- dient damage models have then been proposed. They rely on the introduction ad hoc of a regularization length that smears out damage and delay localization. It somehow fixes the computational issues as it constrains damage to spread over domains of finite size. However, it introduces artificial interactions between neighboring material elements that turn out to control the model prediction.

In this work, we propose a micromechanics-based non-local model directly derived from the physics governing the interactions between material elements during damage spreading. The central idea is to take into account the mechanism of load redistribution following damage event that may impact damage growth in an extended region of the loaded specimen. Indeed in disordered solids, loading redistribution promotes interactions within the loaded specimen as damage growing in some overloaded region of the material can trigger damage growth in its vicinity. As recently illustrated in a simplified 1D version of our model [1], this mechanism can be embedded into a non- local continuum description where the non-local interaction function can be calculated explicitly in the limit of weakly heterogeneous damage fields.

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The predictions of our approach are compared with experimental observations made during the compression of a 2D model material made of soft hollow cylinders where damage evolution can be resolved both in space and time. We show that our approach captures not only the critical load at localization, but also the statistics of precursory damage events taking place as the material is driven towards localization.

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Keywords: Damage mechanics, localization, non, local models, precursors

Nonlocal Models with Damage-Dependent Interaction Distance: Role of Permanent Strains

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Integral-type nonlocal formulations of material models with strain softening are usually based on weighted spatial averaging with a fixed weight function that depends on the standard geometric distance between interacting material points. Such formulations act as efficient localization limiters and provide an objective description of strain localization, leading to mesh-insensitive numerical solutions. However, they also suffer by certain deficiencies.

One problematic feature is that material points on opposite sides of a stress-free crack should not interact even if their geometric distance is small. This natural requirement can be taken into account for a pre-existing crack (or notch), e.g., by defining the interaction distance based on the shortest path that does not cross the crack. However, such adjustment captures only pre-existing cracks and does not reflect the effects of a growing process zone that eventually develops into a new stress-free segment. Another deficiency of the standard averaging techniques is that, when applied to models with damage driven by nonlocal equivalent strain, they lead to a spurious expansion of the damage profile at late stages of the failure process.

The objective of this paper is to systematically compare and evaluate the performance of a new type of nonlocal averaging, initially motivated by the idea of internal time that reflects the reduction of the elastic wave speed in a damaged material [1]. Instead of internal time, one can equivalently consider a modified spatial metric leading to a damage-dependent interaction distance locally defined as the standard geometric distance divided by the square root of integrity. Preliminary studies indicated that this approach leads to shrinking of the active part of damage zone, which naturally describes the transition to a fully localized crack. However, the resulting load-displacement diagrams exhibit dramatic snapbacks and excessively brittle behavior in the final stages of failure [2].

In the present contribution, the concept of damage-dependent interaction distances is extended from pure damage models to damage-plastic models and damage models with permanent strain. It is shown that, for formulations that consider a part of the strain as irreversible, the overall response becomes more realistic for quasi-brittle materials such as concrete (Fig. 1a). Furthermore, if the damage evolution laws are properly adjusted, reasonable shapes of load-displacement diagrams with a long tail can be obtained for the damage-plastic model as well, and for pure damage models the snapback behavior

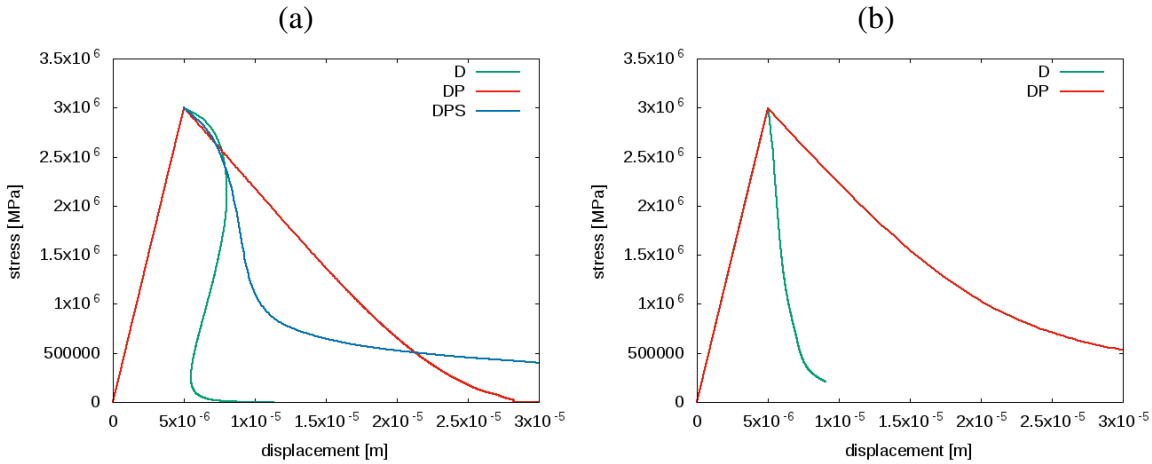

Figure 1: Stress-displacement diagrams for nonlocal models with damage-dependent nonlocal interactions and with (a) exponential (local) softening, (b) power-exponential or double-exponential softening; D = damage model, DP = damage=plastic model, DPS = damage model with permanent strains

can be eliminated (Fig. 1b). A systematic comparison of the basic properties of various formulations in the one-dimensional setting provides guidelines for extensions to multiple dimensions, which are addressed in an ongoing research.

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Nonlocal damage formulation with evolving internal length: the Eikonal nonlocal approach

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Integral non-local (INL) formulations [1] are often used to regularize continuum damage models in the presence of strain softening laws. In numerical computations the introduction of an internal length allows for avoiding pathological mesh sensitivities. Some questions concerning the identification of the internal length, its possible evolution during damage process and the need for special treatments of non-locality operators near boundaries (e.g. edges, cracks) are however still open. A physical request is that material points separated by a crack or a highly damaged zone should not interact (despite what is done in standard non-local integral theories). This can be obtained by allowing non-local interactions to evolve depending on mechanical fields (e.g. damage [2], stress [3], etc.).

Different formulations where proposed in the literature for this purpose. In particular, based on the analogy between wave and information propagation within an elastic damaged medium, Desmorat et al. [4] proposed to reformulate the classic non-local averaging procedure in terms of the ratio of the time needed for an elastic wave to propagate between two material points and the corresponding time in undamaged conditions. Using such an approach in two- and three-dimensional contexts may however reveal complex. As no general analytical solutions for the wave propagation equation through the heterogeneous medium are available, time-consuming numerical solution procedures are indeed needed.

Based on the Wentzel-Kramers-Brillouin (WKB) approximation for high-frequency wave propagation in a damaged medium, the Eikonal non-local (ENL) formulation provides a novel interpretation of damage dependent non-local interactions both in isotropic and anisotropic contexts. From a mathematical point of view, interaction distances are now computed as the viscosity solution of a time-independent Eikonal equation with a damage dependent isotropic/anisotropic Riemannian metric. From a differential geometry viewpoint, this leads to consider that damage induces a curvature of the Riemannian space in which interaction distances are computed. Geodesic interaction distances determined in the curved space are used to compute non-local variables driving damage evolution, thus preserving the general theoretical framework of INL theories. This allows modeling non-local interactions that gradually vanish in damaged zones, leading to a progressive transition from diffuse damage to fracture.

In this contribution, the numerical properties of the ENL regularization technique are investigated. Non-local interactions in 2D damaged domains are illustrated by some ex-

amples first. Attention is focused on "artificially" damaged domains, in order to put into evidence some key features of the Eikonal Non-Local formulation. A non-intrusive (or less intrusive as possible) numerical formulation [6] for modeling damage dependent non-local interactions within mechanical computations is presented then. It is obtained by coupling Fast-Marching [5] algorithms for computing interaction distances and a standard Finite Element (FE) procedure for solving the quasi-static equilibrium equations. Geodesic distances computed between Gauss points define the kernel of weighting function considered in integral non-local regularization method. Several numerical results of quasi-static simulations involving the failure of quasi-brittle materials in isotropic media are presented. This allows for showing the capabilities of the ENL formulation in properly modeling a progressive transition from damage to fracture (i.e., strain localization) and the regularization capabilities of the proposed approach. The problem of how adapt/enhance the numerical ENL framework for properly treating nonlocal interactions near free-boundaries is addressed then. Finally, a method for estimating discrete quantities (i.e. cracking) from continuous field is exposed. This technic, based on the post-treatment of the strain field, allows to investigate the capacity of ENL formulation to describe the strain localization at failure.

It should be noted that, although the method is illustrated with a simple isotropic damage model, the formulation proposed is however general. The extension to anisotropic contexts is also possible without major modifications. In this latter case, the only difference will concern the use of a Fast-Marching algorithm that now should be capable of dealing with anisotropic Riemannian metric fields.

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Variational gradient damage models: how to deal with realistic damage surfaces and stiffness recovery effects

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In many circumstances, predicting the lifespan of concrete structures submitted to mechanical loading responds to safety and/or economical needs. For this purpose, advanced models have been proposed: the local degradation of concrete is described by a damage field, the evolution of which is governed by some constitutive laws. When considering a modelling scale representing each single crack, the local damage description may remain isotropic (scalar damage variable), the anisotropy of cracking thus emerging from the crack pattern. With such models, damage results in stiffness reduction and elastic domain decrease in stress-space (i.e. strain softening). The latter is the cause of the spatial concentration of damage in (crack-like) bands the thickness of which is controlled by nonlocal damage interactions, involving for instance the gradient of the damage field [1]. In that case, the evolution of damage is provided by a variational formulation. This is similar to phase-field models where true cracks are regularised by means of a scalar variable reflecting the local degree of degradation [2]. A nonlocal length scale tunes the degree of regularisation: when vanishing, the damage distribution converges toward cracks. According to how damage, stiffness and strength interact with each other, the asymptotic crack may be of Griffith-type or cohesive-type [3].

The afore-mentioned variational formulation relies on an energy function which involves in particular the elastic energy density. The latter depends on the current strain and damage states. Of course, it implicitly defines the current stiffness reduction (optimality of the energy with respect to the strain). More precisely, it enables to distinguish which part of the (tensorial) stiffness is actually reduced and which part is not. In particular, this has straightforward consequences on the totally damaged material. We will show that there is a mathematical relation between the strain states for which the residual stiffness is zero and the sustainable stress states (in 1D, think of tensile strain states and compressive stress states). Reasonable constitutive assumptions enable to define the residual elastic energy density; some numerical applications will show the corresponding implications.

Besides, the elastic energy density also defines indirectly the shape of the elastic domain, since the damage driving force involves the derivative of the elastic energy

with respect to damage (optimality of the energy with respect to damage). In that way, the driving force depends on the strain state direction: this enables to represent damage surface which are distorted in the strain-space, as observed with concrete the strength of which is notoriously contrasted in tension, shear and compression. The analysis of a three-point bending beam will show the high sensitivity of the peak force with respect to these contrasts, which therefore cannot be neglected. A single energy function may appear too much restrictive to describe the phenomenology of both phenomena, residual stiffness and damage surface distortion. In that case, it is possible to relax the variational principle by introducing a second potential instead of the elastic energy in order to define the elastic domain (non-associated flow rule), while nevertheless preserving some of the features of the variational formulation.

In conclusion, it appears that an isotropic gradient damage model (or phase-field model) may describe a partial stiffness reduction, leading to ultimate residual stiffness or stiffness recovery, and a distortion of the damage surface, at least to some extent. Even though some constraints limit the range of application, this may prove sufficient in some cases and avoids the additional complexity of anisotropic damage models.

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Gradient damage models in large deformation

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Since 1998 [1], gradient damage models have been thoroughly developed (see [2]), yet they stayed in the framework of small deformation and rate-independent material. Our aim is now to extend these models to viscoelastic material and to study there relevance in a finite strain framework.

To take into account large deformation, an adequate hyperelastic potential ψ has to be chosen. Starting from a 3D Ciarlet-Geymonat potential, we write it in 1D so that it is convex, and its approximations for small or large strain are quadratic. This gives

$$\psi(F) = \frac{A}{2}\left(E - \frac{1}{2}\ln(1+2E)\right) \tag{1}$$

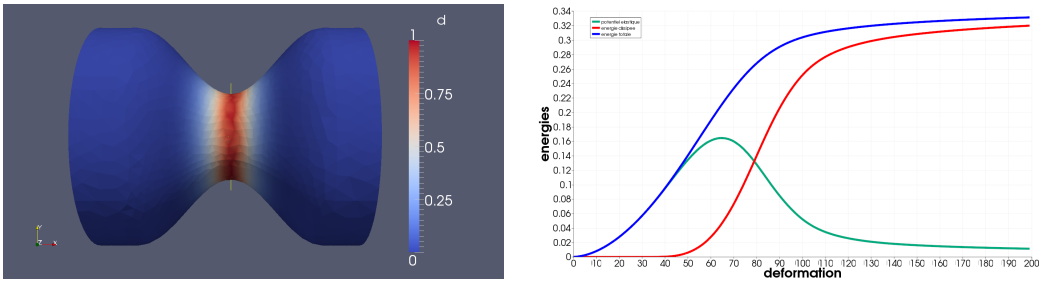
where E is the Green-Lagrange deformation, F is the deformation gradient tensor, and A matches the Young's modulus in small strain. We study a 1D damaging hyper-viscoelastic bar during a quasi-static traction test. One end of the bar is blocked while the opposite is submitted to a growing displacement. Using the multiplicative decomposition of the deformation gradient tensor $F = F^e F^v$, the total energy $\mathcal{E}_\ell$ of the bar is the integral over the domain Ω (here Ω stands for the bar) of the elastic potential previously defined by (1), the dissipated energy and the discretized viscous energy. We have

$$\begin{aligned}\mathcal{E}_\ell(u,E^v,\alpha) = \int_\Omega \Bigg[&\frac{A(\alpha)}{2}\left(E^e - \frac{1}{2}\ln(1+2E^e)\right) + w(\alpha) + \frac{1}{2}w_1\ell^2(\alpha')^2 \\ &+2\eta\frac{\Delta t}{2}\left(\frac{E^v - E^v_{i-1}}{\Delta t(1+2E^v_{i-1})}\right)^2\Bigg]\,\mathrm{d}x\end{aligned} \tag{2}$$

where the Young's modulus follow the law $A(\alpha) = A_0(1-\alpha)^2$, α being the damage variable, and the dissipated energy during an homogeneous process takes the form $w(\alpha) = w_1\alpha$. u is the displacement, ℓ is the characteristic length, and η the coefficient of viscosity. The variational formulation of the evolution problem leads to the expression of the damage criterion and the governing differential equation of the viscoelastic variable. We can then set the equations that describe the homogeneous damage evolution, and the damage localization over the bar.

Once the analytical results established, they are compared with the ones obtained through numerical simulations using the FEnicCS library and it appears that they match perfectly. The implementation is done in 1D for both hyperelastic material and hyper-viscoelastic material. The numerical problem consists of finding the displacement, the viscoelastic variable and the damage such that the potential energy of the system is minimized at each time step. In that purpose, a strategy of alternate minimization is chosen to use the fact that the energy is convex with respect to each variable: at a given time step, each one of the three unknowns is found successively while the other two are fixed, and this operation is repeated until the damage variable reaches convergence. The three problems are non linear and require the use of non linear variational solvers. Furthermore, the irreversibility of the damage evolution has to be taken into account, and to ensure that the damage of a given time step is never lower than the damage at the previous time step, a bound constrained solver is used. With such an implementation, it is possible to reach 800% of deformation.

Both analytical and numerical study being validated in 1D, the last step of this work is to extend the study to higher dimensions. To this end, damage gradient models for hyperelastic material are implemented in a finite element academic code [3]. Different 2D or 3D simulations are performed, including a cylinder or a hourglass-shaped sample under traction. The case of the cylinder shows a brutal onset of damage, while the hourglass-shaped specimen breaks progressively. Figure 1 illustrates the fracture of a hourglass-



(a) Damage localization in the constricted part of the sample.

(b) Elastic (green), dissipated (red) and total (blue) energies.

Figure 1: 3D simulation - Rupture of a hourglass-shaped specimen submitted to traction

shaped specimen submitted to a traction test. The damage occurs in the constricted portion of the sample and starts around 40% of deformation, and grows progressively until it reaches the value 1 for which it is broken.

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A two-stage algorithm for solving quasi-brittle fracture problems

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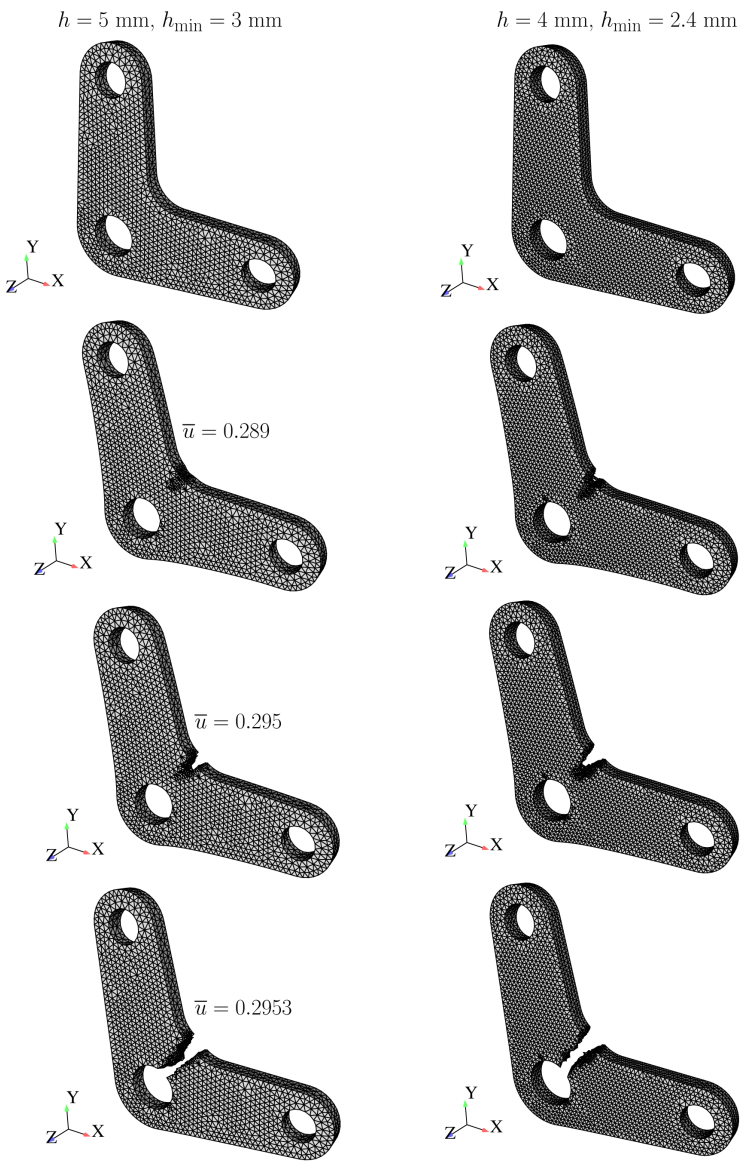
In this work a two-stage algorithm for solving quasi-brittle fracture problems, which includes an adaptive mesh refinement and a regularized continuum using a modified screened Poisson equation, is presented. A crack path criterion is not a prerequisite, as mesh refinement ultimately provides the crack path and the regularized continuum, within a smeared model, avoids the need of any type of cohesive law. Two solution parameters are included: a non-local length, appearing both in the screened-Poisson equation and the smeared model, and a mesh refinement length controlling the subdivision of elements. Initially a local approach to fracture is performed together with local remeshing and global node repositioning in order to establish the appropriate mesh for the regularized problem to be solved subsequently. This staggered approach is assessed through various quasi-brittle experiments. Both classical 2D benchmarks and 3D crack propagation examples, which predict slanting in plane stress, see the following Figure, are detailed.



(10× magnified displacement)

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On some approaches of graded damage modelling

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To prevent problem of spurious localization in damage mechanics, the introduction of a quadratic terms of the damage gradient has been used to govern the amplitude of the spatial gradient of damage. In more recent papers based on definition of Thick-Level-Set [1], the damage is function of a level-set, then the damage gradient is bounded in a domain where the level-set becomes a signed distance function. The body is decomposed in three domains : the undamaged body, the transition zone, where damage growths continuously from 0 to 1, and the totally broken material. Here we consider classical damage modelling with introduction of internal constrain on the spatial gradient of damage. This point of view produces a new model without introduction of level-set and signed distance. The local behaviour is defined by the classical free energy function of the strain and damage $w(\varepsilon, d)$. The damage d satisfies two internal constrains $g_1(d) = d(d-1) \leq 0$ and $g_2(\nabla d, d) = ||\nabla d|| - f(d) \leq 0$. These constrains are convex functions of d and ∇d if f is concave. Introducing Lagrangian multipliers and convex analysis we have

$$\lambda_i \geq 0, \quad g_i \leq 0, \quad \lambda_i g_i = 0.$$

The variations of the total potential energy exhibits the thermodynamical force Y associated to d, continuities conditions between domains and boundary conditions for the transition layer The paper proposes a complete discussion on the properties of the solution and illustration on particular cases in comparison with the model proposed in [1] . The support of ERC Advanced Grant XLS no 291102 is greatfully acknowledged.

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A Strain Gradient Approach for Modeling of Quasi-Brittle Damage Responses

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An efficient damage model for quasi-brittle materials implemented into the two dimensional C^1 continuity triangular finite element formulation [1] employing the nonlocal continuum theory is proposed. In this way, a nonlocal material behaviour is introduced in the model, enabling the preservation of the positive definiteness of the stiffness matrices, as well as the ellipticity of the damage related field equations in the softening regime. The isotropic damage law is introduced into the higher-order stress-strain constitutive relations, which enable the analysis of both homogeneous and heterogeneous materials. Such softening formulation also ensures a decrease of the nonlocality associated with the damage growth, which is necessary for the correct description of the narrow localized deformation [2]. Because the linear elastic material behaviour is considered, the constitutive tensors can be calculated only once, prior to the softening analysis by applying the second-order homogenization procedure at the appropriate microstructural representative volume element, as described in [1]. All algorithms derived are implemented into the FE software ABAQUS in order to achieve higher computational efficiency. The robustness and accuracy of the computational algorithms derived are shown in numerical examples. The numerical results are compared with the solutions obtained by other available nonlocal formulations [2,3].

Acknowledgement
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Lattice and nonlocal approaches for Discrete Damage Mechanics structural problems

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This paper investigates the link between Discrete Damage Mechanics (DDM) and Continuum Damage Mechanics (CDM). The theoretical behavior of an axial damage chain with non-uniform material properties is studied with a lattice approach and with an equivalent nonlocal continuous model. The structural system consists in associating multiple elastic-damage springs linked to form a microstructured chain, whose behaviour is modelled through DDM. The nonlinear elastic-damage springs present both stress hardening and stress softening. Some non-uniform strength properties are introduced to enforce the uniqueness response of the lattice system in the softening stage, for uniaxial tensile loading. The goal here is to develop a non-local CDM model that will mimic the behaviour of the DDM structural system. This is achieved via a continualisation procedure applied to the finite difference formulation of the local Continuous Damage Mechanics formulation. The continualization of the local DDM model leads to a non-local model for the damage propagation process along the chain. It is shown that the boundary conditions of the continualized model require a careful consideration to obtain satisfactory results of the continuous system as compared to the lattice system, over the whole loading range. The effectiveness of the coupled non-local Continuous Damage Mechanics continualized model to capture the localization phenomena in heterogeneous quasi-brittle materials is highlighted from a comparison with the reference lattice models.

Recent outcomes on fracture propagation in brittle materials as a standard dissipative process.

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Abstract

The present work frames the problem of three-dimensional quasi-static crack propagation in brittle materials into the theory of standard dissipative processes.Variational formulations are stated. They characterize the three dimensional crack front quasi-static velocity as minimizer of constrained quadratic functionals. An implicit in time crack tracking algorithm that computationally handles the constraint via the penalty method algorithm is introduced and proof of concept is provided. Novel outcomes arising from a visco-plastic regularization will also be presented.

Keywords: Stable crack growth, brittle fracture, three, dimensional fracture propagation algorithms

*Speaker

An attempt to use bounded rate damage models for mesh independent simulation of quasi static failure in explicit dynamics by using scaling techniques

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Today, realistic simulations of complex industrial problems including all their technological complexity requires using legacy codes. In the case of the simulation of failure, two main difficulties arise. The first one concerns only quasi-static or slow dynamic problems. In this case, implicit schemes are the dominant approaches. The numerous instabilities associated with damage and cracking make the convergence problematic and sometimes impossible. Here, path following techniques are mandatory and are often used in combination with viscosity. In order to ensure convergence and robustness, explicit algorithms can be used. In this case, mass and time scaling techniques are commonly allowing for quasi-static simulation. It is unclear though how the use of these techniques affects the prediction of failure.

The second difficulty is the occurrence of spurious mesh dependence in the failure prediction. The most widespread technique to obtain mesh independent results is the one of non-local models [1]. The implementation of such models in industrial software is cumbersome and the identification of these models remains an issue. An easier possibility is the development of a bounded rate version of the model [2]. This approach requires only classical, local, modifications of the constitutive law. Nevertheless, it has been much less studied and in any case have to be performed in combination with dynamic analyses.

Considering these two issues, the proposed path is the combination of explicit simulations and a bounded rate model using scaling techniques to be able to perform quasi-static simulations. This presentations explores such an approach on examples relevant for turbomachinery disks.

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A viscous regularized damage growth model representing ductile fracture

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We present a viscous regularized damage model representing ductile fracture in the context of the well established visco-plastic Johnson-Cook (JC) model combined with the JC-criterion for onset of the fracture. A major drawback is that the JC-model exhibits mesh size dependence when is it associated with the pure element deletion method. In this context many researchers have proposed remedies of various type, we mention: [1], [2] using the concepts of a damage phase field, [3] using special element enhancement of the FE-kinematics, and [4] using the standard local damage model extended with the concepts of a damage phase field. The presently proposed model is an extension of the one proposed in [4], where instabilities in the captured solutions has been encountered both for the dynamic and the quasi-static damage evolution cases. In order to overcome these difficulties, we propose to extend the fracture area development with a damage rate control of the fracture energy dissipation that is active for finite mesh sizes. When the mesh size tend to zero the viscous stabilization reduces to zero. In this context, combined with concepts of a damage phase field, without gradient enhancement but with a damage rate control, we develop a novel progressive damage evolution model. A central point in the modeling concerns the handling of the maximum energy dissipation rate principle for scalar damage evolution involving the total fracture dissipation.

The damage model yields mesh objective fracture dissipation. Two examples are included. The first example verifies mesh objectivity in the damage evolution at different deformation rates for a pearlitic plate in the zone of shear fracture. Highly FE-resolved shear zones are considered. In the second example, the perforation of a Weldox 460 E steel plate impacted by a blunt-nosed projectile was considered. Our investigations show that the mesh objective viscous damage enhancement is of high relevance also for a rate dependent thermo-visco-plastic case at adiabatic conditions. This is of great importance for e.g. machining simulations, where the handling of very high cutting speeds combined with rate dependent material behavior is a key issue to describe the material removal.

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Microbranching instability using a variational phase-field model

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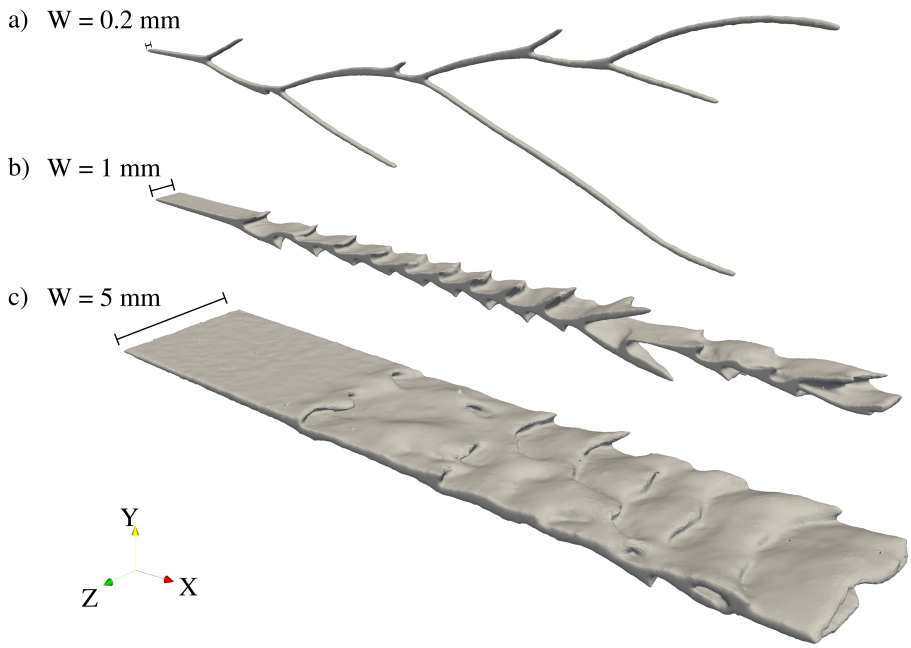

Many aspects of the microbranching instability [1] are not fully understood such as the difference of crack patterns observed in PMMA on one hand and glass or brittle gels on the other hand [2]. In this work, we simulate the microbranching instability of fast propagating cracks using a variational phase-field approach and show that three-dimensional effects are fundamental for understanding the origin of this instability.

In particular, following on a previous work regarding the branching mechanism in 2D phase-field simulations [3], we show that microbranching does not occur in 2D simulations or for very thin 3D samples and that different microbranching regimes are obtained when increasing the sample thickness, ranging from translationally invariant across the thickness and quasi-periodic patterns to localized microbranching events driven by complex 3D dynamics (cf. Figure). We further show that the transition between these different

regimes is controlled by the value of the regularization length scale inherent to the phase-field modelling of brittle fracture.

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A homogenized localizing gradient damage model with micro inertia effect

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Abstract

While the conventional nonlocal / gradient damage enhancement resolves the mesh sen- sitivity issue during strain softening at the structural level, it suffers from a spurious damage growth and free surface effect. In this contribution, a homogenized localizing gradient damage model with micro inertia effect is proposed, such that (i) a sharp damage profile is obtained during fracture; (ii) the dynamic magnification factor is captured naturally via the micro inertia effect without the need for any strain-rate dependent constitutive laws. We present a thermodynamically consistent meso-macro homogenization framework, which translates the underlying mechanics at the unit cell level onto the coarse engineering scale. The proposed model is implemented in 1D, and validated against spall experiments of concrete at different strain rates, where a good match in failure patterns and dynamic tensile strengths is obtained at low to high strain rates.

Keywords: nonlocal damage, gradient damage, micro inertia, dynamics

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Initiation, nucleation, and influence of defects in variational phase-field models of brittle fracture

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Gradient damage models can be regarded as a variational regularisation of brittle fracture and are nowadays extensively used in this context. The variational equivalence between the two models mainly relies on arguments based on *global* energy minimisation and asymptotic methods (Gamma-Convergence). However, crack (damage) evolutions obtained with a *local* minimisation criterion on the damage energy strongly depend on the internal length, and may not converge toward the evolutions obtained with (local or global) minimisation criteria on the Griffith model. These evolutions of gradient damage models introduce pertinent physical effects, as size effects and maximum allowable stresses, that are missing in the Griffith brittle fracture model. This contribution follows and extends a preliminary report on the same topic at the previous CFRAC congress in Paris. We show through carefully selected numerical experiments how the internal length may influence (or not) the evolutions based on local minimisation criteria. Moreover, we show investigate how defects can influence crack nucleation thresholds, disclosing interesting and pertinent scale effects. The numerical results will be verificated against semi-analytical calculations and compared with classical crack nucleation criteria. We report a close agreement with the available experimental results on crack nucleation for several geometries.

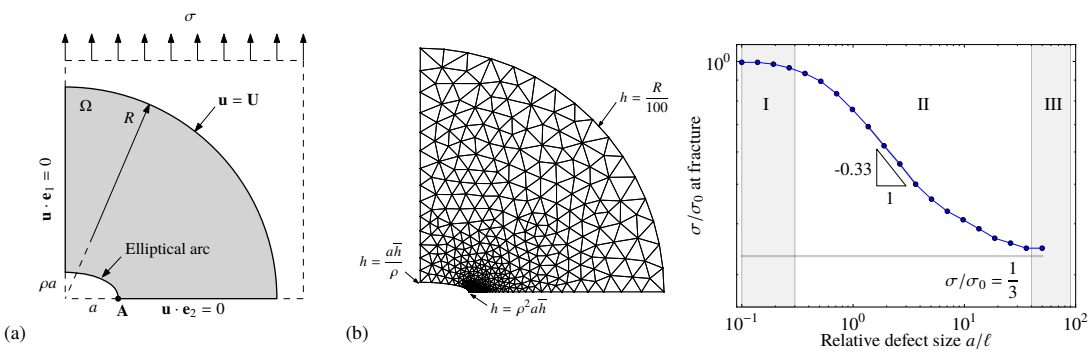

Figure 1: Remote stress at crack nucleation σ/σ_0 as a function of relative defect sizes a/ℓ for the circular hole $\rho = 1$ and an internal length ℓ.

Γ - convergence in phase-field models for brittle fracture

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The phase-field method provides a convenient way to model crack propagation without topological updates of the used discretisation as the crack is represented implicitly in terms of an order parameter field that can be interpreted as damage variable.

Miehe et al [1] analyzed the phase-field representation of a crack with the surface Γ in a two-dimensional unit square plate regarding the accuracy of Γ/Γ_{ℓ_0}, where Γ_{ℓ_0} is the diffuse phase-field approximation of the crack characterized by the internal length scale ℓ_0. In their elementary study they found that a reasonable approximation of $\Gamma_{\ell_0} \approx \Gamma$ requires a minimum size of finite elements.

A numerical convergence study of Γ_{ℓ_0} regarding ℓ_0 was carried out by May et al [2] for a one-dimensional structure. They applied a tensile load to an elastic bar with a reduced cross section in the centre part. May et al [2] found a minimum of the error $\Gamma_E = |\Gamma_{\ell_0} - \Gamma| / \Gamma$ at a certain length scale ℓ_0. The same minimum was calculated for different fine discretizations independently of the element size h. A further decrease of the ratio ℓ_0/h resulted in an increased error Γ_E. Thus, May et al [2] concluded that Γ-convergence is not necessarily attained, because their numerically obtained final crack surface Γ_{ℓ_0} fails to converge, i.e.

$$\Gamma_{\ell_0}\Big|_{\ell_0 \to 0} \neq \Gamma.$$

In our contribution, we give explanations for the minimum found in [2], we show that Γ-Convergence can be achieved and we critically discuss the assumptions that are necessary to apply the phase-field approach to brittle fracture.

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Newton methods and adaptivity for the fully monolithic solution of phase-field fracture

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In this presentation, the purpose is on the development of a fully monolithic solution algorithm for quasi-static phase-field fracture propagation. Phase-field fracture is a variational approach to fracture [1] and consists of two coupled partial differential equations and it is well known that the underlying energy functional is non-convex and sophisticated algorithms are required; see [2, 4, 5] for recent results. The incremental, spatially-discretized problem is treated with adaptive finite elements and predictor-corrector mesh adaptivity [3] that allows for a very small regularization parameter in the crack region. The nonlinear problem is solved with adaptive modified Newton algorithms, which work as inner loop within an inexact augmented Lagrangian iteration for relaxing the crack irreversibility constraint [5]. Specifically, the fully monolithic approach is compared to a quasi-monolithic approach in which phase-field is approximated through extrapolation in the displacement equation. These comparisons are done in terms of certain quantities of interest and computational cost. Moreover, features such as crack nucleation, joining, branching and fracture networks are addressed. All findings are critically commented pointing to open questions and future improvements.

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Broadening of damage in gradient models and phase-field models

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Gradient damage models have been reported to produce an unrealistic broadening of the damage zones in the later stages of material degradation. We analyse here this feature for gradient damage models with constant gradient activity (i.e. a constant characteristic length, that is, a constant diffusion parameter in the regularisation equation). We show that, even with such simple models, broadening can be controlled to a large extent with an appropiate choice of material parameters and a fine enough spatial discretisation, see Figure 1.

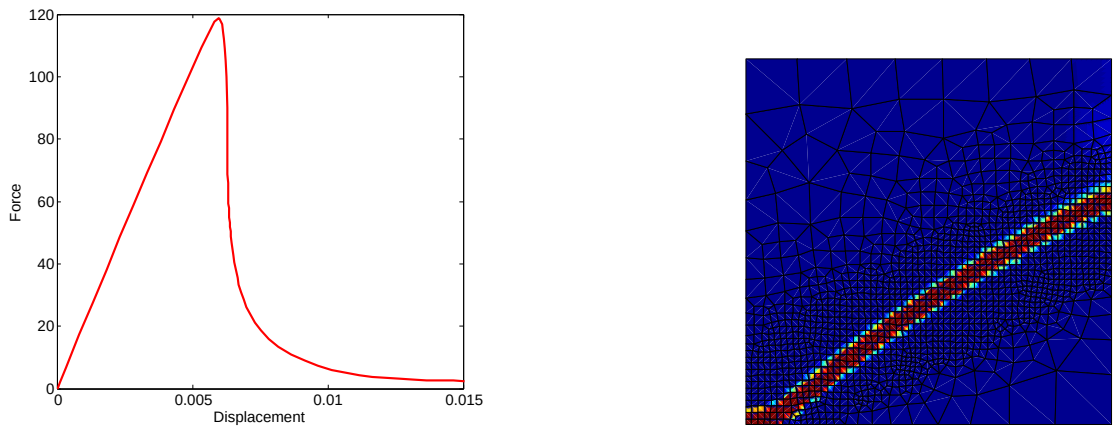

Figure 1: Brittle response and narrow damage band

In fact, damage broadens due to the "crosswind" diffusion (i.e. diffusion perpendicular to the crack path) caused by the gradient activity. If the problem setup, loading conditions and material parameters are such that crack propagation is predominant over diffusion, then little broadening is observed.

Broadening can be further avoided by using models with variable gradient activity. This refers both to gradient models with a damage-dependent, decreasing characteristic length and to phase-field approaches, which implicitly incorporate such a feature. These aspects will be discussed with some representative examples.

Analysis of Hertzian indentation fracture using a phase field method

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Fracture initiation from the defect-free surface of a brittle solid subjected to indentation loading has already been described by Heinrich Hertz more than a century ago, e.g. [1]. However, its theoretical prediction is still a challenging task due to the lack of reliable criteria for crack formation in classical fracture mechanics. The issue of indentation fracture initiation can be solved by the concept of finite fracture mechanics which comprises strength and toughness as two independent material parameters [2]. Both parameters are also contained in a phase field formulation of fracture which in addition bears great flexibility in tracking the evolving crack surface.

In this contribution, indentation fracture is analyzed by using a regularized description of cracks through a phase field. Phase field approaches to fracture have already proven their excellent ability to reproduce complex crack patterns, including the initiation of cracks in intact material [3] and the formation of cone cracks depending on Poisson's ratio [4], as experimentally observed [5]. Governing equations are derived from a variational framework, e.g. [6]. In this regard, since a wide variety of approaches has been proposed, we discuss essential modifications based on constitutive assumptions [7] to obtain physically reasonable results. Hence, fracture initiation and crack evolution are obtained by energy minimization techniques. Numerical results are discussed for various indentation loading conditions and the method's capabilities are illustrated by comparison with other numerical methods [8] and experimental results[1].

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Simulation of the ductile rupture of a low carbon construction steel using a regularized locking–free GTN model

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Micromechanically based constitutive models for ductile rupture have been developed since the 70's. These models explicitly take into account the different damage stages including both nucleation and growth mechanisms but also microstructural features such as void shape change, void rotation, coalescence by internal necking... (see reviews in [1, 2]). The physical basis of this class of models makes them very attractive to simulate the degradation of industrial structures. These models are designed so as to lead to material full failure so that they exhibit strong softening. Consequently, their use in finite element codes leads to severe numerical problems including strain and damage localization, dependency of the simulation results (energy dissipation, crack path) on mesh size and mesh type. Solving these problems is essential in order to fully benefit from advanced descriptions of damage processes to predict failure of structures. In addition, ductile fracture of metals is usually accompanied by very large strains ; this may lead to volumetric locking and to a poor estimation of stresses (in particular pressure) and consequently to a poor description of damage development.

In this work, a "non-local" model is used to avoid mesh dependency as it allows introducing a material internal length independent of the finite element discretization [3, 4]. The GTN model is used [5] and the cumulated plastic strain is chosen as the "'non-local" regularized variable. This allows dealing with both damage by void growth and strain controlled damage nucleation. A logarithmic finite strain formulation is used [6]. A specific finite element is proposed which uses a quadratic interpolation for displacements and a linear interpolation for additional degrees of freedom (cumulated plastic strain ad corresponding Lagrange multiplier). A corresponding adaption of the GTN model is also developed. The proposed element still suffers from volumetric locking at high strain levels. This problem is often neglected in the literature except when linear 4-node (2D) or 8-node (3D) elements, for which the B–bar method can be applied, are used. In this work, the proposed element is enriched using a mixed (pressure/volume variation) formulation [7, 8] so as to be able to control volumetric locking together with damage localization.

The model is applied to simulate ductile fracture of a low carbon construction steel which was experimentally characterized. Axisymmetric notched bars as well as CT and

SENT specimens are simulated. A parametric study is carried out in order to study the role of the internal length.

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Gradient-damage / plasticity variational models for cohesive and ductile fracture

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It is now well established that gradient damage models are very efficient to account for the behavior of brittle and quasi-brittle materials [2], [3]. However such models cannot describe the nucleation of cohesive cracks, *i.e.* the existence of surfaces of discontinuity of the displacement field with a non vanishing interfacial stress. Moreover, these models do not account for residual strains, typically observed during ductile fracture. A way to include such effects is to introduce a plastic strain variable, and, to couple its evolution with that of the damage variable. In [1], we implemented such a model, leveraging the variational nature of gradient damage and perfect plasticity.

For ductile fracture the problem consists in choosing stable state variable trajectory such as, the displacement (u), the plastic strain (p) and the damage (α) which conserve the energy. Equivalently, finding the triplet (u_t, p_t, α_t) at the loading time t minimizing the total energy (1).

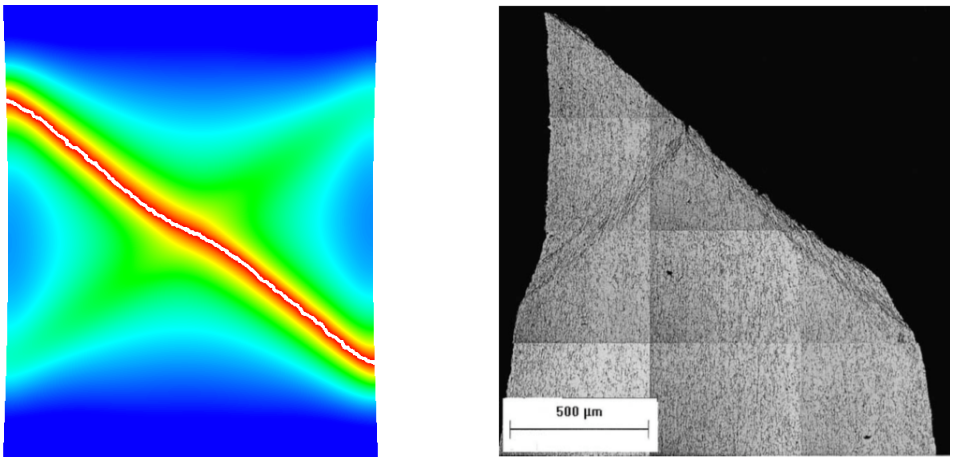
$$\mathcal{E}(u,p,\alpha) = \int_\Omega \Big[\frac{1}{2}a(\alpha)\mathtt{A}(e(u)-p):(e(u)-p) + \frac{G_c}{4c_w}\Big(\frac{w(\alpha)}{\ell} + \ell|\nabla\alpha|^2\Big) + b(\alpha)\int_0^t \sup_{\varsigma\in K}\{\varsigma : \dot{p}\}\mathrm{d}\tau\Big]\mathrm{d}x, \quad (1)$$

where $\mathtt{A}$ is the Young's tensor, ℓ being the internal length, $a(\alpha) = (1-\alpha)^2$ is the softening function, $w(\alpha) = \alpha$ is associated to the damage dissipation function, the energy release rate denoted G_c and c_w is a normalization constant. Those are the main ingredients of gradient damage models. For the perfect plasticity model, $K := \{\varsigma \in \mathbb{M}_s^{n\times n}\ s.t.\ f(\varsigma) \leq 0\}$ is the admissible stress domain and $f : \mathbb{M}_s^{n\times n} \to \mathbb{R}^+$ is the yield surface function. The plastic energy dissipation is coupled with the damage by the function $b(\alpha) = (1-\alpha)^2$.

All constitutive equations except the damage irreversibility ($\dot{\alpha} \geq 0$) can be deduced from the stability condition, which is the first order optimality conditions of the minimization problem. The total energy is separately convex with respect to the triplet (u, p, α),

thus, an alternate minimization algorithm is proposed and it always converges to a critical point.

The ability of the model to recover ductile fracture has been assessed numerically using a parametric analysis on a traction test in both one- and multi-dimensional settings. Numerical results show that cracks can propagate along plastic slip concentration (Figure 1a), experimentally a slant fracture is observed for ductile material when it is subjected to a traction loading (Figure 1b). Also the typical cup-cones fracture in a round notched bar has been recovered.



(a) Damage in the reference configuration (red is damaged, blue is undamaged and white is broken)

(b) Shear bands and fracture in notched plane-strain specimens made of AA 5754 Al–Mg alloy [4]

Figure 1: Fracture path comparison between experiments and numerics

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A micromorphic damage-plasticity model and its application in mesh-objective finite element simulations

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In the present study, a gradient-extended damage-plasticity material model is investigated and evaluated which is based on the micromorphic approach according to Forest, see e. g. references [1, 2]. A 'two-surface' formulation is utilized in which damage and plasticity are treated as separate dissipative mechanisms that may mutually influence each other owing to further constitutive assumptions present in the model. The latter property is especially convenient in the sense that it makes the model applicable to various situations in which the material's behavior is either ductile, brittle or possibly ductile-brittle. From an algorithmic point of view, a careful handling of the existing two different sets of loading / unloading conditions for damage and plasticity becomes necessary which is thoroughly explained. To illustrate the model's properties and ability to achieve mesh-objective results in finite element simulations involving material softening, several structural benchmark tests are performed and discussed in detail.

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Towards a mesh-objective description of anisotropic damage with crack-closure by means of a micromorphic formulation

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The overall goal of our work is the development of an anisotropic damage model including crack-closure, guaranteeing 'strictly increasing damage' and mesh objectivity. Here 'strictly increasing damage' is understood in such a way that additional damage does not lead to stiffening in any direction (for a more detailed explanation see Wulfinghoff et al. (2017) [1]).
Starting point of the modeling is an isotropic damage model accounting for crack-closure-effects and irreversible strains by means of an initial strain tensor (cf. e.g. Chaboche et al. (1995) [2]). For this model several parameter studies on Gauss point level are presented including the variation of the crack-closure parameter and the initial strain tensor.
Mesh objectivity is achieved by utilizing a micromorphic approach according to the work of Forest (2009) [3]. In the simple case of isotropic damage (scalar damage variable D), one micromorphic damage variable D_χ is defined which carries the gradient effects and acts as an additional degree-of-freedom on the global level. Various numerical examples are presented in which the features of the model are illustrated.

In the end we show the extension of the isotropic to the anisotropic damage model and discuss associated issues and difficulties.

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A continuous-discontinuous model to simulate crack branching and crack fluid pressure

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Continuous-discontinuous models are capable of reproducing the whole failure process in quasi-brittle materials. In [1], damage inception and evolution are described by a non-local continuous model, which regularises softening and controls strain localisation. Once the damage field reaches a critical damage value, the discontinuous model is activated and a crack is introduced by means of the eXtended Finite Element Method (X-FEM). The crack path is determined by means of the medial axis of the damage field. Then the non-local continuous model is coupled with the discontinuous model to capture damage evolution and crack propagation.

A particular phenomenon that arises when a crack propagates is its bifurcation in two or more new cracks, i.e. crack branching. In civil engineering, crack branching may appear in many problems. Cracks in quasi-brittle solids –such as concrete or rocks– tend to branch out due to instabilities, like fracture of rock faults after an earthquake. Crack branching may arise as well in concrete structures like floor slabs, hydraulic fracture of rocks, high velocity impacts or corrosion-assisted cracking.

There are several processes where a fluid interacts with some materials and produces cracking. The simulation of the fluid pressure effect inside a crack can be of interest for many industrial applications such as hydraulic fracturing or carbon sequestration. This phenomenon can be coupled to crack branching in order to reproduce a more realistic failure process.

To introduce the discontinuity, the finite element enrichment proposed for a finite element containing two cracks consists on defining two discontinuity functions, ψ_p and ψ_s, associated to each one of the two discontinuities Γ_p (principal crack) and Γ_s (secondary crack), see Figure 1. Thus, the displacement field can be decomposed as

$$\boldsymbol{u}(\boldsymbol{x}) = \boldsymbol{u}_c(\boldsymbol{x}) + \psi_p(\boldsymbol{x})\boldsymbol{u}_p(\boldsymbol{x}) + \psi_s(\boldsymbol{x})\boldsymbol{u}_s(\boldsymbol{x})$$

where $\boldsymbol{u}_c$, $\boldsymbol{u}_p$ and $\boldsymbol{u}_s$ are continuous fields and the sign functions ψ_p, ψ_s are centred at discontinuities Γ_p and Γ_s, respectively.

When branching is developed, the bifurcation of the damage field produces a bifurcation on the medial axis. This indicates that the medial axis tool is able to capture branching, see Figure 2.

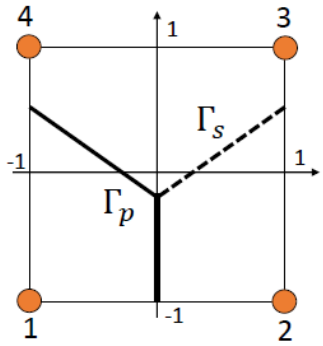
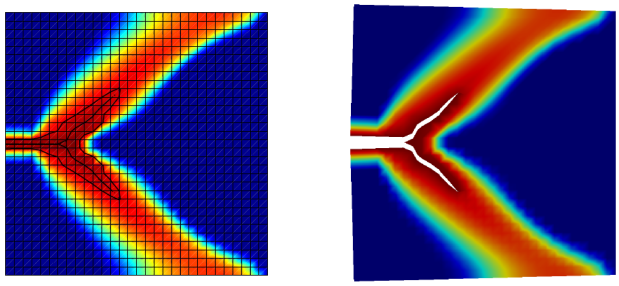


Figure 1: Principal and secondary cracks in a cracked element.



(a) (b)

Figure 2: (a) The crack path is computed by means of the medial axis, which captures branching, and (b) the branched crack opens in the following step. Amplification factor of 5000 in displacements.

Moreover, the proposed X-FEM enrichment for one bifurcated crack can be generalized to account for successive branching. The recursive application of the enrichment to each bifurcation allows to simulate tree branching-structures.

Regarding fluid pressure, the discontinuous approach is used to propose a technique to introduce its effect inside a crack. Fluid pressure is modelled as nodal forces in the cracked elements. To carry this out, it is not required to have nodes along the crack.

In this work, these techniques are used to carry out a coupled simulation where crack branching is produced and the action of fluid pressure generates crack opening and propagation.

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Regularized XFEM for the failure analysis of FRP-reinforced concrete beams under bending

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Strengthening techniques based on the use of external reinforcements made of FRP are widespread in civil engineering, especially in post-seismic structural rehabilitation. Experiments such as shear and bending tests on FRP-reinforced concrete specimens have shown that FRP-reinforced structures typically fail after the detachment of a layer comprehensive of the FRP plate and a concrete cover a few millimeters thick. Moreover, detachment is a three-dimensional mechanism involving both opening and shearing displacements along the detachment surface. Most Finite Element simulations exploit interfacial laws built-in commercial codes requiring the a priori definition of the interfacial parameters while neglecting three-dimensional effects. The regularized extended Finite Element Model (XFEM) is suitable for the effective simulation of detachment processes [1, 2], and imperfect interfaces [3]. The cornerstones of the proposed procedure are: i) the adoption of a regularized kinematics; ii) a suitable variational formulation, iii) an effective continuous-discontinuous transition procedure, iv) and the definition of the level set of the detachment-surface based on the detachment mode experimentally observed in experiments. The proposed regularized XFEM is able to capture the real crack pattern and detachment process in concrete beams strengthened with FRP plates subjected to bending tests.

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Phase-Field Modelling of Interface Failure

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Different from discrete approaches, phase-field models of crack propagation avoid the cumbersome topological updates of the analysis mesh to track the crack path. The smeared phase-field approach allows for the proper modelling of crack initiation and propagation by solving an additional scalar field problem for the evolution of the crack phase which is coupled to the mechanical boundary value problem. The width of the crack phase is governed by a characteristic length scale l. This length scale is not free of choice and is considered to be a material parameter, because it affects the critical failure load. A further crucial parameter is the critical energy release rate G_C, which can be understand as the material specific resistance against cracking.

In this contribution we consider the phase-field modelling of interface failure. The applicability of fracture phase-field models to heterogeneous materials, i.e. specimens with spatially varying material parameters, has been recently studied [1, 2]. It has been shown that the phase-field model is able to reproduce complex cracking phenomena as crack deflection, crack arrest and repeated crack initiation.

Here, we model interface failure between two materials by a local reduction of the critical fracture energy G_C in the vicinity l_I of the given interface. Due to the use of a smeared crack model, many parameters interact and influence the failure behaviour of the interface. In particular the following issues are examined:

- the interaction between the characteristic length scale l and the interface width l_I,
- the influence of the spatial distribution of G_C on the physical interface behaviour,
- the influence of the finite interface on the structural behaviour.

Several numerical examples are used to investigate the applicability and the properties of the phase-field model for interface failure. Eventually, comparisons with cohesive zone models will be presented.

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Phase Field study of the instabilities of crack front under mixed mode loading and plane stress.

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Abstract

The instabilities of an initially tilted crack front under mode I loading in a finite size sample under plane stress condition is studied using a phase field model. Simulations show, that below a critical initial tilt angle the crack front relaxes smoothly toward a mid-sample crack front as was observed in recent experiments in gels and the agreement between experiments and simulations on the relaxation is quantitative. Nevertheless, there is a strong discrepancy between the experimental value of the critical angle above which the crack front is no longer stable and the one computed nmerically. The possible reasons for this are discussed using numerical experiments.

*Speaker

Phase Field Modeling of Fatigue Failure

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Abstract

The understanding of damage evolution, fatigue and fracture is of great interest in many engineering applications. The phase field method provides a powerful tool for the modeling and finite element simulation of fracture. This is due to the facts that the method provides a holistic description of the entire evolution of fracture and that numerical difficulties in dealing with sharp crack descriptions are avoided by the regularized modeling of fractures. Thus, in recent years, phase field models of fracture have been extensively used to study quasi-static and dynamic fracture problems. In contrast, research on applications of the methodology to fatigue scenarios is rather scarce so far. Fatigue crack growth results from progressive material degradation due to statically subcritical cyclic loading. In this work we propose an extension of a phase field fracture model which is able to account for such effects by means of an accumulation term in the evolution equation of the fracture field, which creates an additional driving force for crack propagation. In a first step, the evolution equation is formulated in the time domain as it is standard in phase field formulations. Concerning the discretization in time this means that each cycle must be discretized by several simulation steps in order to properly resolve the changing loading conditions within the cycles. However, this approach is no longer feasible when fracture occurs only after a very large number of cycles as in high cycle fatigue. Therefore, the evolution equation is reformulated and implemented in the cycle domain in order to enable efficient simulations.

Keywords: phase field method, fracture, fatigue, cyclic loading

*Speaker

A novel variational phase-field model for the description of fatigue phenomena

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Fatigue is a key phenomenon in mechanics, and is responsible for more than 75% of structural failures. Nevertheless, the development of reliable fatigue models is still an open issue and involves a significant portion of the undergoing research in the field of mechanics of materials. Most existing fatigue design rules are not based on mathematical models, but rather on empirical laws deduced from extensive and costly experiments.

In this work, we propose a new variational fatigue phase-field model, which relies on the introduction of a suitable strain history variable. As the history variable increases, the material fracture toughness is reduced. As a consequence, fracture is favoured where the highest strain variations have occurred. In this first step of a longer term project, the analysis is limited to the simplest possible setting, namely: linear elasticity, brittle material behavior, symmetric response in tension and compression. Nevertheless, in this variational framework, the extension of phase-field models [1, 2] to include additional material phenomena, as fatigue, is straightforward.

We show the results of numerical simulations based on a numerical solution strategy devised from the variational approach. Despite being based on the simplest constitutive assumptions and on few material parameters, the present model is capable to describe the typical $\sigma - N$ (Wöhler) curves and the occurrence of fatigue failure under variable amplitude cyclic loading. We also highlight the capability of the model to describe the three typical fatigue fracture regimes, namely the elastic stage, the stable fatigue crack propagation phase and the final abrupt fracture.

This work is part of a joint project within the *MIUR-DAAD Joint Mobility Program* among the institutions.

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A variational model for fracture with anisotropic surface energy

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Most theoretical and computational studies in anisotropy materials have assumed implicitly that the energy per unit area required to creating new surface by fracture is independent of the crack extension orientation. For anisotropic materials, even some elastically isotropic materials such is not the case and the value of surface energy vary with the orientation of the fracture plane [1, 2]. Furthermore, the anisotropy of the fracture toughness influences more strongly the crack propagation of a wide variety of materials, such as carbon steel piping [3], single crystals [1], extruded polymers [4, 5], ferroelectric ceramics [6] and shale [7].

When the surface energy is anisotropic, all the crack path selection criteria are not relevant. Some pioneering works (theoretical and experimental) have investigated the problem of crack path selection in materials with anisotropic surface energy. The maximum energy release rate criterion had been generalised to materials with orientation dependent surface energy $G_c(\boldsymbol{n})$. However, the recent experiments [4] on tearing of thin anisotropic films have interrogated our fundamental understanding of the principles of crack path selection. The great success of the variational approach to fracture suggests that the variational model for fracture could provide a unifying and general framework capable of addressing fracture with anisotropic surface energy. Though a very recent work [8] within the framework of variational approach to fracture had reproduced all the features of strongly anisotropic fracture and strikingly well recent experimental observations [4], there are still a lot of fundamental questions that are open and need to be addressed. This contribution is trying to deal with fracture with anisotropic surface energy particularly strongly anisotropy resulting in nonconvex variational problems, which have to resort to either adding higher-order regularization terms as in [8] or replacing the original variational problem by its quasiconvexification relaxation.

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Modeling inter/ trans granular failure using an anisotropic phase field approach

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A new multi-phase-field method is developed for modeling the fracture of polycrystals at the microstructural level. Inter and transgranular cracking, as well as anisotropic effects of both elasticity and preferential cleavage directions within each randomly oriented crystal are taken into account. For this purpose, the proposed phase field formulation includes: (a) a smeared description of grain boundaries as cohesive zones [1], avoiding defining an additional phase for grains; (b) an anisotropic phase field model [2]; (c) a multi-phase field formulation where each preferential cleavage direction is associated with a damage (phase field) variable. The obtained framework allows modeling interactions and competition between grains and grain boundary cracks, as well as their effects on the effective response of the material. The proposed model is illustrated through several numerical examples involving a full description of complex crack initiation and propagation within 2D and 3D models of polycrystals.

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MS3: Ductile fracture, modeling of shear bands and necking

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An increased interest in ductile fracture understanding and modeling for complex loading paths has been observed in the scientific community during the last decade. This increased interest is partly due to the fact that conventional ductile damage models and ductile fracture criteria fail to accurately predict ductile failure for complex loading paths and for novel advanced materials.

The purpose of this minisymposiumis to discuss these models and criteria, to identify their limitations and to come up with new ideas and solutions regarding ductile fracture. This symposium will also be the place for discussions regarding the physical mechanisms of ductile damage under complex loading paths and to discuss the computational challenges associated to ductile damage, both at the micro-scale and at the macro-scale.

A diverse variety of topics will be addressed, including:

- ductile fracture at multiple scales, including micromechanical analyses accounting for materials' microstructural heterogeneities;
- complex loading conditions: large plastic strain, multiaxial and non-proportional loadings, effect of strain rate;
- ductile failure under shear loading and modeling of shear bands;
- competition between damage growth and localization phenomena;
- new mathematical formulations and numerical solution strategies dedicated to efficient modelling of continuum ductile damage and its transition to discontinuous fracture;
- theoretical and numerical aspects related to advanced fully coupled constitutive equations including time and space discretization, mesh dependence, meshless methods, solution strategies, etc.;
- experimental observations or quantitative characterization of ductile failure mechanisms in support of computational modelling or giving guidance to the development of new computational models;
- methodologies for proper damage model calibration.

Theoretical, computational and materials studies related to ductile fracture, shear bands and necking are welcome to the minisymposium.

On the Competition between Shear Bands and Failure by Void Coalescence

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Analyses of ductile failure by shear banding versus cumulative damage growth by void growth to coalescence are carried out using a coupled plasticity and damage formulation. The constitutive porous metal plasticity relations account for void shape effects, void rotation, plastic anisotropy and void coalescence. The latter is modelled using a separate effective yield function with associated evolution equations of the internal parameters. The resulting model is a hybrid two-surface pressure-sensitive and dilatant plasticity model. The same model is employed to study (i) the effect of plastic anisotropy on crack initiation in round notched bars; (ii) the conditions under which failure occurs subsequent to shear band formation as opposed to void-coalescence induced crack initiation; and (iii) failure by void coalescence under shear-dominated loadings. In particular, an important distinction is made between shear failure and failure in shear.

Modelling of Intermittent Shear Bands and Ductile Fracture of a Thin Aluminium CT Specimen

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Abstract

In recent experimental studies it has been shown that in an AA2XXX alloy strain localization in slant bands preceded the onset of damage, originating slant fracture ahead of a notch. The multiple and intermittent crossing bands observed in synchrotron images investigated with digital volume correlation (DVC) could be related to dynamic strain aging (DSA). The transition from flat to slant fracture in a thin aluminium CT specimen do not show the dimples related to void damage and a distinct transgranular fracture mechanism is involved.

In FE analyses of the CT specimen, it is necessary to combine several models:

- a DSA model *at the slip system scale*,

- porous plasticity for void damage,

- the Coulomb model *at the slip system scale* for transgranular fracture.

The backbone of this combination is a mean field polycrystalline model. Multiple crossing strain bands are obtained, similar to the ones observed in tomography. Crack propagation occurs during strain rate bursts. The strong relation between DSA and the transition from flat to slant ductile fracture is emphasized.

Some numerical problems have been accounted for in a pragmatic way:

- CPU time and convergence accuracy in relation with the waiting time of the DSA model and the automatic stepping time algorithm,
- mesh dependence of crack propagation, in particular mesh size and the Cartesian mesh orientation for slant fracture.

Keywords: Aluminum alloy, Dynamic strain aging, Finite elements, Fracture mechanisms, Polycrystalline model, Synchrotron laminography

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Deformation and fracture of lath martensite: brittle or ductile?

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Advanced high-strength steels are generally multi-phase steels, in which lath martensite is one of the key constituents. The generally brittle martensitic phase clearly improves the strength but it is also known for its detrimental effect on the ductility. In spite of these established views, recent literature reveals that lath martensite may deform and fracture in a ductile manner. This contribution focuses on the intrinsic physical reason behind the ductility mechanism, using a combination of small scale experiments and computation analyses of the presumed deformation mechanisms leading to deformation and failure.

The strongly anisotropic plastic behaviour of lath martensite originates from localized plasticity at lath boundaries [1], where thin, nanometer scale films of FCC austenite are retained. The physical origin of the localized boundary plasticity of lath martensite is presumed to be related to these films, which may favour dislocation mediated plasticity and/or phase transformation induced plasticity. To investigate this effect, crystal plasticity simulations have been carried out [2]. The presumed mechanism of interfacial plasticity perfectly captures the global stress-strain behaviour of both specimens, as well as the local plastic activity. Plasticity parallel to lath boundaries can occur also in absence of any dislocations in the austenite films, via phase transformation mediated by interface migration. This mechanism can be described with a crystal-plasticity type flow rule and can accommodate local strains up to 90%.

Using micro-scale tensile test, it was shown that sliding occurs for all types of investigated boundaries, e.g. lath boundary, sub-block boundary and block boundary [1]. These boundaries trigger a glide mechanism that is of key importance for the ductility and fracture behaviour of the martensite. The mechanism has been demonstrated experimentally, and incorporated in a micromechanical model that accounts for slip parallel to the interfaces. The potential role of embedded thin retained austenite films is thereby elucidated.

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Application of a Modified GTN Model to Predict Large Deformation Failure of Pressure Vessels

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Abstract

The purpose of this research is to predict failure of a largely deformed pressure vessel. The employed Gurson-Tvergaard-Needleman (GTN) model enables a failure prediction through its in-built damage evolution law. A critical damage threshold defines the limit state of the evolution. Here, crack initiation is seen as the limit. Unfortunately, the GTN model does not capture void volume growth under shear stress and shows thermodynamic inconsistencies under pressure. To overcome these drawbacks and to make the model applicable to a wide range of complex stress states, a user-defined subroutine of the GTN model with an extension of its damage evolution law [1] has been developed. The routine also accounts for large deformation which is advantageous for ductile vessel materials. The wall of a pressurised vessel is subjected to multi-axial stress states. Features, such as flanges and valves, lead to even more complex stress states. The subroutine is used to determine the burst pressure and the location of failure. This research compares the results of the conventional and the modified GTN model with results of experimentally conducted burst tests. The conclusion of this research is that there is a clear improvement in failure prediction by using the modified GTN model. [1] K. Nahshon, J.W. Hutchinson, Modification of the Gurson model for shear failure, European Journal of Mechanics – A/Solids 27 (2008) 1-17.

Keywords: GTN model, shear softening, large deformation, failure, pressure vessel, multi, axial stress

*Speaker

Fracture in multi-phase materials: why some microstructures are more critical than others

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Although multi-phase materials are widely used, the micro-mechanisms dominating fracture are only partially understood. This paper systematically investigates this topic using computational models. An idealized microstructure is employed wherein a brittle hard phase and a ductile soft phase are randomly distributed. The idealization facilitates transparent analyses with well controlled variations. Three topics are considered:

1. the competition between fracture initiation in either of the phases [1],
2. the effect of the local phase distribution on fracture initiation [2, 3],
3. the effects of the local phase distribution as well as of early nucleated voids on fracture propagation [4].

The results indicate that, depending on the macroscopic stress state, one of the phases dominates the fracture initiation. The local phase distribution determines where fracture initiates. These 'initiation hot-spots' are composed of regions of hard phase in the tensile direction intersected by bands of the soft phase in the shear directions. These features are consistently observed for both damage mechanisms.

The final localization through void coalescence is controlled on a longer length scale. It is observed that voids link-up through the soft phase, whereby the macroscopically observed ductility is predetermined by the microstructure. When several 'initiation hot-spots' are closely separated and aligned in the directions of shear, the ductility is much lower than for the case that these 'initiation hot-spots' occur more scattered. The macroscopically observed ductility is furthermore strongly influenced by the amount of hard phase and the phase contrast.

For the regime in which void nucleation dominates, the average phase distribution around voids is identified also in the real microstructure – both using a microscopic analysis [5], as well as using simulations on microscopic images [6]. To enable the latter, improvements have been made to the FFT-based micromechanical solver [7]. This analysis confirms the observations made using the strongly idealized microstructures.

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Phase Field Modeling of Ductile Fracture in Soil Mechanics

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This work outlines a rigorous framework for the ductile failure of frictional materials in elastic-plastic soil mechanics undergoing large strains.

Describing soil crack formation can be achieved in a convenient way by recently developed continuum phase field approaches to fracture, which are based on the regularization of sharp crack discontinuities [1]. This avoids the use of complex discretization methods for crack discontinuities, and can account for complex crack patterns. For frictional materials, a *non–associative* Drucker–Prager–type elastic-plastic constitutive model suitable for a wide range of applications in soil mechanics is developed [2], and linked to a failure criterion in terms of the elastic-plastic work density that drives the fracture phase field. On the algorithmic side, we develop a general return mapping scheme of the non–associative elastoplasticity in the spectral space of logarithmic principal strains and dual stresses.

We demonstrate the modeling capabilities and algorithmic performance of the proposed formulation by representative simulations that describe soil crack formation using elastic-plastic fracture mechanics.

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Phase field and gradient damage models in ductile failure

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Phase field modelling of ductile damage is the main concern of the present work. In recent studies, it has been shown that the use of the phase field diffusive equation within the structure of the mathematical brittle failure model is closely related to nonlocal gradient-enhanced damage model approach [1] and it is suggested that it may some have advantages by avoiding the "broadening" of the damaged zone in the vicinity of the crack tip [2]. Also when it comes to fracture analyses, brittle fracture phase field approaches [3-4] are able to deal with rather complex crack patterns while it keeps the well-posedness of the partial differential equations by eliminating or alleviating spatial discretization dependence.

The extension of phase field modelling to ductile failure has been attempted in recent years [5-6]. Nevertheless, it is still not fully established in this area and research is still needed to assess its performance on plastic-damageable continua, whether from the theoretical point of view as well as from practical point of view.

The aim of this study is to develop a damage model based on the phase field approach and compare it with traditional gradient models in ductile damage.

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A phase-field model for hydrogen-assisted fracture in elastic-plastic solids

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This paper deals with the formulation and numerical implementation of a coupled continuum theory for the interaction of elastoplastic deformation, hydrogen diffusion and fracture in solids. The theory is developed within the framework of continuum mechanics and relies on recently developed strategies for incorporating an additional phase field to embody fracture ([1]).

A specialization of the theory is presented to model hydrogen-enhanced decohesion in metals and the corresponding numerical implementation based on the finite-element method for spatial discretization and an implicit Euler scheme for time-stepping.

To illustrate its potential utility, we apply the model to investigate the problem of environmentally-assisted crack propagation in a center-cracked panel under tensile loading. The results are compared with the ones obtained in [2]. It is shown that the model is capable of reproducing some distinctive experimental facts of this problem published in the literature.

Keywords: hydrogen induced cracking; stress-assisted diffusion; phase field model; solute diffusion

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Development of modified-Rousselier model for creep damage problems in eXtended finite element method (XFEM) approach

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Abstract

This paper contributes to the knowledge about creep by investigating creep damage behaviour by means of a modified Rousselier model using continuum damage mechanics (CDM) without need to re-mesh discontinuous elements. A modified damage model in creep using a Rousselier model will be introduced using a commercial software via a user-subroutine based on ABAQUS/ Standard module (UMAT). In addition, an extension analysis using eXtended Finite Element Method (XFEM) is required to enhance the capability of the creep damage analysis due to crack growth and propagation. Following this, the developed subroutine were being tested and validated with the analytical and other benchmark problems. As a result, good agreements were achieved in the developed model, in which indicates the capability of this model to give an accurate and precise estimation of the creep damage behaviour of material. New creep parameters have been proposed and introduced in the model of modified-Rousselier solution, in order to solve the creep damage problems. Therefore, a new constitutive creep damage model based on the modified-Rousselier model was successfully developed in which to solve the creep damage problem and to allow crack growth to take place without any remeshing.

Keypoints: Modified-Rousselier model; creep damage; XFEM; UMAT-subroutine; creep crack growth

Application of uncoupled damage models to predict ductile fracture in sheet metal blanking

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Abstract

The increasing demand of high-quality products over the years has promoted the development of several models to predict damage accumulation and fracture during their manufacturing process. Due to their simplicity and overall accuracy, the uncoupled damage models (fracture criteria) have been the preferred choice to simulate ductile failure, especially in engineering applications. Nevertheless, the predictive capabilities of these type of models were classically limited by the complexity of the loading paths encountered in several form- ing processes, making them not suitable for all cases. This drawback is attributed to the use of stress triaxiality as the only variable introducing the influence of the stress state into their formulations, contrasting with several recent studies where it has been demonstrated that the Lode angle (related to the second and third deviatoric stress invariants) also plays a crucial role in damage accumulation [1]. Consequently, some advanced models have been recently formulated in the space of equivalent plastic strain, stress triaxiality and Lode angle, with successful results in a wide range of loading conditions. In this work, a comparative study of different uncoupled damage models for the numerical prediction of ductile fracture in the blanking process is performed. The selected phenomenological models were recently implemented in a fully implicit homemade Finite Element code [2], which considers large strains, frictional contact and crack propagation (i.e. element deletion method). All the models considered here account for damage sensitivity to both the stress triaxiality and the Lode angle. The material characterization is performed thanks to different mechanical tests under different stress states and a full inverse analysis, taking into account the entire loading paths to fracture. Finally, the numerical predictions obtained for different process parameters are compared with experimental results, where especial attention is given to the final shape of the sheared edge.

Keywords: Blanking process. Ductile fracture. Fracture prediction. Finite Element method.

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Numerical investigation of ductile damage in flexible forming process of aluminium sheet metals

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Flexible forming process is widely used in the aircraft and automobile industry. It is employed in many operations like deep drawing, bending and stamping. It consists of using an elastomeric material between the punch and the sheet or between the sheet and the die. Several researchers studied analytically, experimentally and numerically the forming process with flexible tools [1,2]. Despite of the big interest in this technology, scarce information are available on parameters influencing forming capability (friction, rubber shore..) and many important aspects have not been deepened yet; particularly the occurrence of anisotropy, damage and fracture mechanisms.

In this work, a finite element simulation of flexible forming process of aluminum sheet metal is carried out. Two process are simulated: on one hand, the effect of rubber pad on forming capability is studied by comparing flexible bulge to hydroforming. On the other hand, a stamping of aluminum sheet metal with soft punch is performed[3]. Based on the theory of Continuum Damage Mechanics (CDM), a local approach with fully coupling between ductile damage and an elasto-plastic model with mixed non linear kinematic/isotropic hardening is introduced [4]. The model is implemented into a user-defined material (VUMAT) subroutine for the commercial finite element code ABAQUS/Standard. A Mooney-Rivlin theory is adopted for rubber material behavior. Comparisons in terms of damage occurrence, thickness variation and sheet formability are made.

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New biaxial specimens for the characterization of damage and failure in ductile sheet metals

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The presentation deals with the development of specimen geometries for biaxial loading taken from thin metal sheets. The new pre-notched specimens are tested under different biaxial loading conditions covering a wide range of stress triaxialities to analyze stress-state-dependent damage and failure mechanisms, [1, 2]. Corresponding numerical simulations indicate a homogeneous distribution of stress triaxiality and Lode parameter within the critical region. For the Z- and H-specimen (Fig. $1_{(a,c)}$) shear loading can be directly superimposed by tension or compression while for the X02-specimen (Fig. $1_{(b)}$) tension/compression loading leads to shear stresses within the notched region. Strain fields in critical regions of the specimens are analyzed by digital image correlation (DIC). The experimental results are used to validate damage and failure criteria and corresponding evolution laws of the phenomenological continuum damage approach.

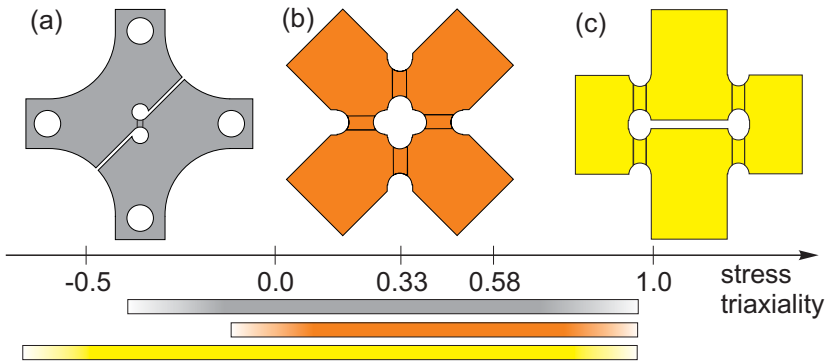

Figure 1: New specimen geometries: (a) Z-, (b) X02- and (c) H-specimen

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Simulation of ductile damage failure of butterfly specimen

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Abstract

Strenuous efforts based on micromechanics approches have been made over the past decades in order to achieve understanding of ductile fracture of metals. The first micromechanical model introducing a strong coupling between deformation and damage is the Gurson-Tvergaad-Needleman (GTN) model. To put it in a nutshell, the material is assumed to be composed of a dense matrix sprinkle with evenly distributed spherical microvoids. When the stress triaxiality (the ratio of the first to second stress invariants) is high enough, the voids remain near spherical, and in such cases the ductile fracture process is rather well described by the GTN model. However, if void nucleation is disregarded, this model cannot describe ductile failure evolution for shear stress close to zero.

An extension of the GTN's plastic potential Φ_{GT} was proposed in [3] where the authors focused their study on the determination of yield surfaces for porous materials using a huge number of finite element simulations. Three arrangements of spherical voids over a wide range of *vvf* f were considered. The obtained yield points was fitted by a new yield function Φ which turned out to be similar to Φ_{GT} for f ranging between a very small value to the percolation threshold. As a novelty, the yield function Φ was found to explicitly depend upon the third stress invariant. In this investigation, in order to examine the effect of stress triaxiality and shearing upon material failure, a constitutive GTN-like model based on the plastic potential Φ, once described, is numerically implemented in a finite element program.

The proposed constitutive model is then used to analyze the behavior of a three-dimensional butterfly specimen subjected to a combination of shear and traction loading conditions. This specimen has been optimized by Dunand and Mohr [2]. Two loading paths have been considered: shear-dominated and tension-dominated deformation resulting in low and high stress triaxialities in the middle section of the specimen,respectively. The calculations have been car-

ried out in Abaqus Explicit and similar values for the damage parameters (nucleation and coalescence) have been used for both the proposed model and the GTN one in order to compare their ability to predict void growth to coalescence and the corresponding failure mechanism. The obtained numerical results may be briefly summarized as follows: i) at high stress triaxialities, the proposed constitutive model gives similar predictions as the GTN model. Indeed, up to the failure initiation of the specimen, the predictions incorporating the present model are in a close agreement with those provided by the GTN model, confirming the potential of the former constitutive model to fulfill to the requirement of transferability between different loading conditions; ii) At and beyond failure points of specimen, noticeable disagreement has been observed between predictions of both models.

Material parameters, geometry of the specimen [1], and used FE mesh

Material parameters:	$\bar{\sigma}(\bar{\varepsilon}^p) = \sigma_o\left(1 + A\,\bar{\varepsilon}^p\right)^N$
	$\sigma_o = 1\,\mathrm{MPa}$, $\mathrm{A} = 300\,\mathrm{MPa}$, $\mathrm{N} = 0.10$, $\rho = 7830\,\mathrm{kg/m^3}$
	$q_1 = 1.5$, $q_1 = 1.0$, $q_1 = 2.25$, $f_c = 0.067$, $f_f = 0.20$
Simulation constants:	$\mathrm{H} = 12.6\,\mathrm{mm}$, $\mathrm{L} = 62.1\,\mathrm{mm}$, $\mathrm{h} = 2.0\,\mathrm{mm}$, $\mathrm{t} = 0.4\,\mathrm{mm}$
	$5 \times 10^{-3} \leq \text{Time period} \leq 6 \times 10^{-3}$

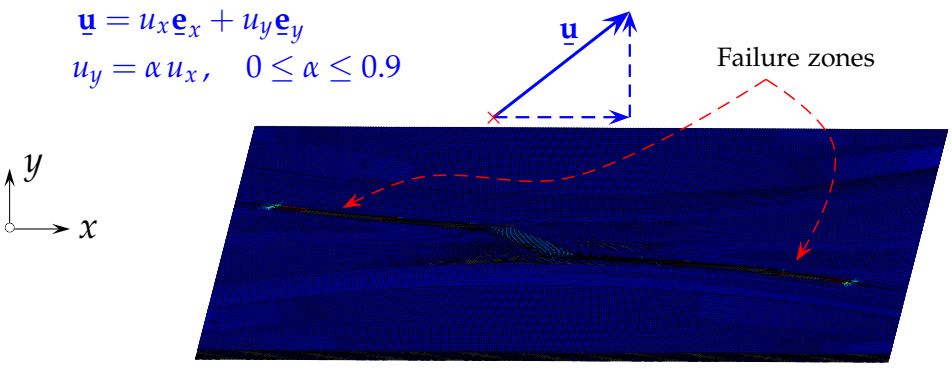

Figure 1: Void volume fraction contour corresponding to the almost total failure of the butterfly specimen under shear-dominated deformation ($\alpha = 0.1$).

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Cohesive Band Model: a triaxiality-dependent cohesive model inside an implicit non-local damage to crack transition framework

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Abstract

Accurate numerical prediction of the whole ductile failure process is still a challenge. The adequate numerical scheme has to concord with the physical reality composed of an initial diffuse damage step followed by ultimate localised crack initiation and propagation. Currently, two main modelling philosophies exist. On the one hand, continuous approaches, described by damage models, are suited for diffuse damage, but are unable to represent physical discontinuities. On the other hand, discontinuous approaches are suitable to describe crack propagation behaviour and other localised processes, but fail in diffuse damage prediction of ductile materials. Moreover, they do not usually capture triaxiality effects or in other words, in-plane stretch effects, which are mandatory for accurate ductile failure simulations. To describe the ductile failure process, the numerical scheme proposed here combines both approaches and by this way, their respective advantages: an implicit non-local damage model combined with an extrinsic cohesive law in a discontinuous Galerkin finite element framework [1]. An application example of this scheme is shown on the attached figure with a comparison of the experimental force-displacement curve [2]. An implicit non-local model [3] is involved to model the initial diffuse damage stage. Upon damage to crack transition, a cohesive band [4] is used as cohesive law in order to introduce in-plane stretch effects during the crack propagation. This model is based on the assumption that all the damaging process occurs inside a band of small but finite thickness ahead of the crack surface. The strains inside this band is obtained from the neighbouring strains and from the cohesive jump. Then, the stress-state inside the band and the cohesive traction forces on the crack lips are deduced from the underlying continuum damage model. The band thickness is not a new material parameter but it is computed to ensure the energetic consistency of the numerical scheme [5].

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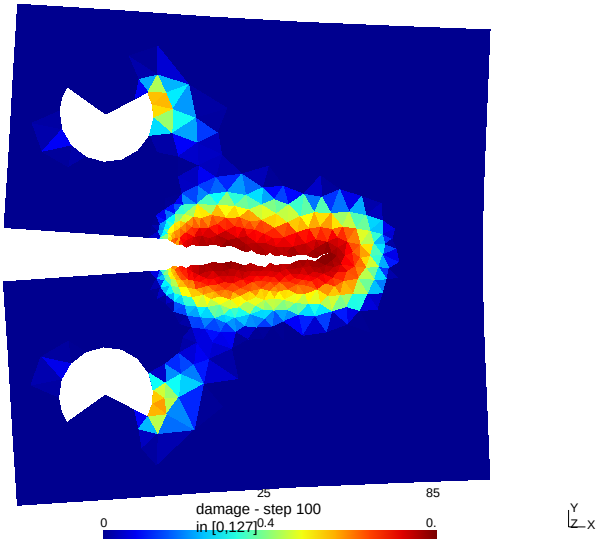

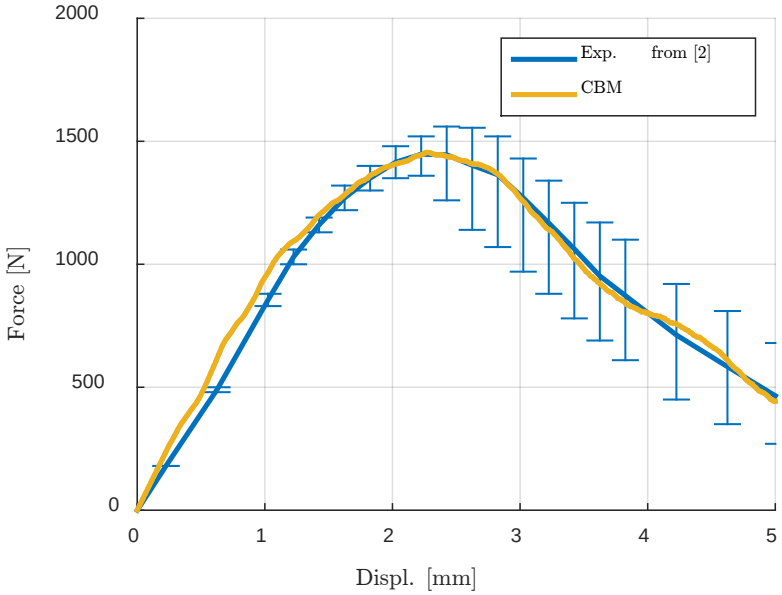

Keywords: Cohesive band model, Discontinuous Galerkin, Damage to crack transition, Cohesive zone, Implicit nonlocal damage

Application of the Configurational Force Concept in Modelling of Ductile Fracture and Materials Design

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Configurational forces are thermodynamic driving forces that describe the behaviour of defects in materials, e.g. [1]. It is demonstrated in this presentation that the configurational force concept is a highly efficient tool for modelling the behaviour of cracks. In recent papers, we have shown that it enables us to

(1) evaluate the crack driving force in materials, independent of their constitutive relations,
(2) evaluate the crack driving force in any type of inhomogeneous material,
(3) evaluate shielding and anti-shielding effects of macro to nanoscale material inhomogeneities,
(4) estimate the crack growth direction using the criterion of maximum dissipation,
(5) evaluate the influences of eigenstrains and residual stresses on crack driving force and crack path,
(6) evaluate the shielding and anti-shielding effects of near-tip and remote plasticity.

One example for the successful application of the configurational force concept is the physically correct quantification of the crack driving force in elastic-plastic materials. The procedure is applicable even to cyclically loaded structures and/or for growing cracks [2,3].

Another example is the development of design concepts for new materials with highly increased fracture resistance and/or damage tolerance. The idea is to distribute inhomogeneities in the materials so that the crack driving force is locally strongly reduced, which leads to cracks arrest. Procedures for generating the architectural parameters for such a new generation of fracture resistant material have been recently developed [4,5]. The findings have been confirmed by experiments.

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MS4: Advances in the Experiment-Modeling Dialog

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Huge progress has been made in recent years in numerical methods dedicated to simulation of failure and crack propagation. Validation of such methods calls for quantitative comparisonbetween the numerical modelling and experiments that reveal the complex, heterogeneous phenomena at play. Advances in 2D and 3D imaging technology plus in full-field measurements have provided mature techniques that enable the analysis of fracture at various scales, which could be used in quantitative validation of numerical simulation methods. However, the dialog between modelling and experiment is an area of development and still requires the key links to be established that can provide the best out of both domains. Examples include (but are not limited to):

- Providing a metric for comparison of results from simulation and full-field measurements, allowing for a quantitative and critical analysis of their consistency;
- Revisiting modelling parameters (geometry, loading, constitutive law, ...) based on experimental observations;
- Identifying parameters that may be difficult to access otherwise (e.g. fine description of a cohesive zone model);
- Delineating the limitations of simplified modelling (e.g. continuum damage vs. micro-cracks);
- Designing optimized experiments with appropriate discriminating/robustness compromise
- Controlling an experiment on difficult-to-measure quantities (e.g. stress intensity factors or modal mixity);
- Incorporating additional experimental observations, such as acoustic emissions or ultrasonic velocity measurements
- Including coupled phenomena, e.g., hydro-mechanical effects (both in terms of best measurement practices and simulation).

Attendees are encouraged to present their strategy and recent results in the field of fracture and failure tackled through dedicated, coupled experiments and computational modelling, for materials or structures.

A crack path tracking algorithm for digital image correlation results

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Aerospace structure design requires accurate models for complex loading paths or advanced materials. However, the identification of the models' parameter is challenging, especially when a crack is involved.

For ductile materials, crack initiation and propagation can follow quite rapidly damage onset and the presence of a crack must be taken into account to properly calibrate the damage model. This is for example the case for the nickel base superalloy inconel 625: Large plastic strains are observed before the onset of damage, which is immediately followed by crack initiation. Identifying the damage parameters thanks to methods such as the Finite Element Model Update then implies that, in the computation, a true discontinuity must be inserted. The transition from a continuous damage distribution to a discrete crack is done thanks to a crack path tracking algorithm such as the marching ridges algorithm proposed in [1]. This algorithm does only rely on a scalar field associated to material degradation (e.g. damage or porosity) to predict where a crack should be inserted (see Figure 1). However, validation of this numerical tool requires quantitative comparison between the computed crack path and the observed one.

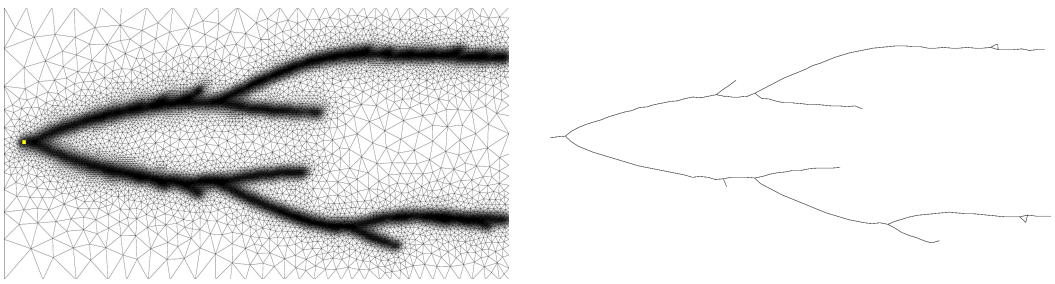

Figure 1: Left: Damage distribution (adapted from [2]). Right: Associated crack path obtained with the marching ridges algorithm.

For quasi-brittle materials, the crack path must be known to allow identification of the fracture parameters [3, 4]. However, the presence of confined non-linearities in the

vicinity of the crack tip makes it difficult to project the observed fields onto a basis of theoretical functions known to be solutions within the framework of linear elasticity. Besides, the determination of the crack orientation is in itself a challenge in the case of non-straight paths [5].

This contribution presents a new application of the marching ridges algorithm to track crack paths based on experimental results. The advantages of this method include the ability to track complex crack paths and the absence of any assumptions on the constitutive model. As the displacement field is the only one directly accessible thanks to digital image correlation, two main key points must be considered: The choice of the most appropriate correlation algorithm in the presence of a crack; and the choice of an adequate norm to build the scalar field needed for the crack path tracking algorithm (see Figure 2). Consequent adjustments of the algorithm will be discussed.

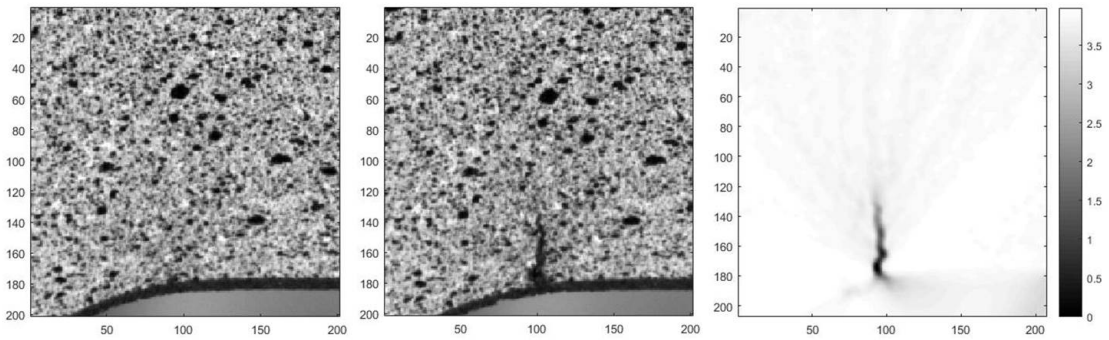

Figure 2: Experimental images of an inconel 625 specimen and a scalar field used for crack path tracking.

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Identification of adhesive layers cohesive properties using a Timoshenko beam model with contact coupled with a CZM

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Integrity of assembled structures relies to a large extent on that of their adhesives and/or interfaces. Our work concerns the study of this integrity using cohesive zone model (CZM) to analyze fracture. These models have the advantage of incorporating a characteristic length in the description of fracture initiation and propagation, which can lead to size effects studies.
One common test to characterize mode I fracture is the Double Cantilever Beam Test (DCB). Many authors used Euler-Bernouilli beam theory to study the deflection of the two beams and cohesive zone model for the interface [1, 2, 3]. Nevertheless, the process zone length where the debonding mechanism occurs, resulting from the equilibrium is often of the order of the beam's thickness. Important errors can arise from neglecting shear stress along the interface.

To reduce the error when modeling the DCB Test, Timoshenko beam theory seems more appropriate. This theory is often used when the beam's length is comparable or smaller than it's thickness. To this purpose, we propose a new model (See Fig.1) composed of three regions. The first region represents the free cohesive zone beam subjected to punctual load P or displacement U at it's free edge. The region 2 represents the bounded region where a cohesive zone model is inserted between the two beams and finally the region 3 a contact region where the shear stress decays to become zero. t_x is the cohesive stress distribution along the process zone L_{cz}. The analytical solution obtained has been compared to numerical solution using finite element modeling (Abaqus). Our results show that the displacement field obtained with our model is quite different from those obtained with Euler-Bernoulli model in the literature. A further quantitative study will be presented to show the advantage and the limit of each of these two theories.

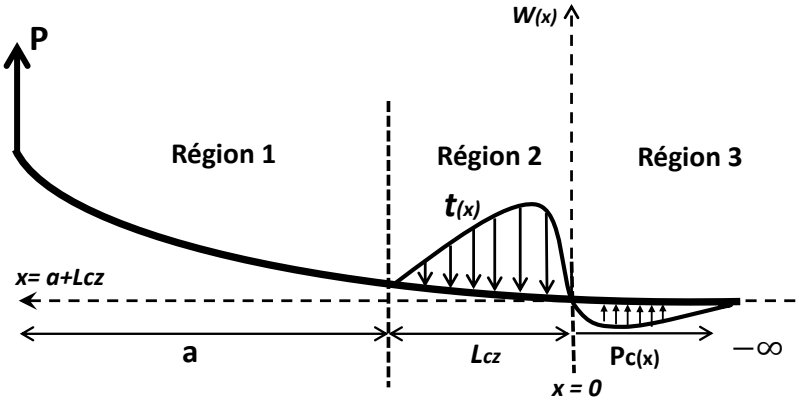

Figure 1: Schematic representation of a DCB fracture test: Region 1 represents the beam submitted to free end load P, region 2 is the fracture process zone where crack intiation and propagation occur and region 3 which can be represented by a beam on elastic foundation (displacement $\neq 0$) or a rigid contact(displacement $= 0$)

The analytical displacement fields explicitly depend on the cohesive zone parameters (T_{max} and δ_{max} and thus G_c). We have used this information to try extracting these cohesive parameters from a numerical experiment and from an actual experiment, using a least square optimization method. First, the numerical experiment of a DCB test allowed to asses the effects of various cohesive law profiles and cohesive parameters on the identification process, and the identification was successful. Once our approach validated on numerical data, our next step was to try it on a real laboratory Wedge test in our case. Two samples of polycarbonate bounded with a commercial adhesive were tested in order to extract the cohesive parameters of the adhesive. The experimental displacement field was computed using Digital Image Correlation and the deflection along the model was extracted afterward. The most difficult step was to differentiate the damage from the crack propagation. A methodology combining Digital Image Correlation and local identification approach [4] was used to identify the onset of debonding and crack propagation. Then, the displacement field along the beam's sample was computed to extract the cohesive parameters of the adhesive.

Finally, our work shows the limit of global identification methods which use global displacement field to extract local cohesive parameters. Even if the traction along the interface T_{max} and the critical opening δ_{max} of the adhesive can be obtained, they may still be influenced by the traction separation law presumption of our analytic model. We will finally present a comparison between using a rectangular or triangular traction separation law and it is impact on the identifications results.

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On the Authority of Experiment Versus Model in Full-Field Damage Identification

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Identification using full-field inverse methods such as FEMU or Integrated-DIC identify a set of unknown parameters (e.g. material parameters) by minimizing the gap between the measured and simulated quantities such as displacements, forces and/or temperatures [1, 2]. For many identification cases these methods have proven fruitful. However, often when identifying complex nonlinear behavior such as damage parameters, additional challenges arise. An example is shown in Figure 1 where a notched aluminum specimen is pulled to failure while observing the front and back surfaces with cameras. The developing damage zone, which ultimately evolves into a ductile crack, curves downward on the front face while curving upward on the back face indicating flat-to-slant crack front orientation.

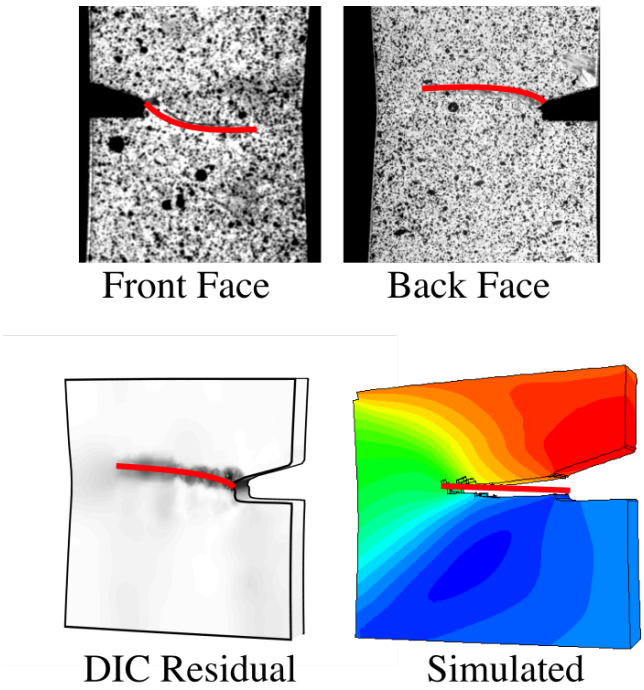

Figure 1: The *Front Face* and *Back Face* of a notched aluminum tensile specimen as imaged just before complete failure, with the corresponding *DIC Residual* and the *Simulated* displacement field using the identified parameter set (fully damaged elements are deleted). The crack is indicated with a red line in each figure.

It is often challenging to predict the flat-to-slant behavior because this behavior is often triggered by minute variations such as specimen geometry or experimental mounting, which are tedious to model. However, experimentally the full behavior is know (at least on the surface) and this knowledge can be added to aid the model in following the same path as the experiment. The subject of this paper is to optimally balance the authority between the experiment and simulation both in space and time to reduce the experimental-numerical gap and thereby improve the identification quality.

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Dynamic brittle fracture by XFEM and gradient-enhanced damage

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Abstract

A combined continuous-discontinuous approach to fracture is used to model crack prop- agation under asymmetric dynamic loadings. A gradient-enhanced damage model is utilized to evaluate degradation of the material in the process zone. This type of model avoids mesh dependency and pathological effects of the local damage models. A damage-based criteria is utilized for crack propagation. In this framework, crack propagation occurs as a result of material softening and degradation in the process zone in front of the crack. As damage reaches its critical value, by using the extended finite element method (XFEM) a discon- tinuous crack is introduced within the damage band. An operator-split approach is used to solve the problem. Finally a brittle fracture case is modeled to show the capabilities and robustness of the employed approach.

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Keywords: extended finite element method, gradient enhanced daamage, crack propagation, dynamic loading

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Half-minute lab tomography of an *in situ* fracture test

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4D mechanical test in a lab-tomograph is performed using a recently developed Projection-based Digital Volume Correlation (P-DVC) method [1, 2] in no more than 35s acquisition time per loading state. It consists in an *in-situ* DCDC crack propagation test for an elastic-brittle gypsum specimen. The procedure exploits an initial full reconstruction of the sample obtained by classical means followed by only two orthogonal radiographs at each of the 13 loading step.

The higly regularized kinematic analysis is performed based on a reduced finite element modeling for which the appropriate boundary conditions and crack propagation stage are identified from the radiographs and force measurements. This completely integrated model-based analysis of the entire test provides a full space and time identification (4D) of the kinematics, including the crack position and the determination of two material parameters, the Young modulus and toughness.

The mechanical model used to regularize is to be validated resorting to the residual fields (i.e. the remaining diference between the radiographs and the deformed projected volume at convergence). What has not been taken into account by the kinematic corrections informs on the limitations of the regularized model.

With 2 radiographs rather than full 3D volumes, the proposed procedure achieves a drastic reduction in acquisition time as compared to classical Digital Volume Correlation analysis. In the considered example, acquisition time is cut down by a factor of 350.

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Computational modeling of mixed-mode fracture of cement mortar with full-field displacement boundary conditions: A phase-field approach

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The aim of this work is to provide a qualitative and quantitative comparison between interactive mixed-mode fracture test results in cement mortar and numerical simulations carried out with the phase-field approach. Phase-field modeling is an elegant approach to simulate complicated fracture processes, including crack initiation, propagation, merging and branching in a unified framework without the need for ad-hoc criteria and on a fixed mesh [1]. As opposed to conventional mixed-mode fracture tests with predefined loading, interactive tests with multiaxial loading which are controlled during the propagation of the cracks can create more complex and stable crack propagation patterns [2]. Moreover, the development of measurement techniques such as digital image correlation (DIC) provides the possibility to quantitatively characterize the full-field kinematics during the tests. In this work, full-field displacements measured by DIC during interactive mixed-mode fracture tests on cement mortar specimens are adopted as boundary conditions for phase-field numerical simulations.

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Experimental failure surfaces and their theoretical predictions for plastic donded explosive and its simulant

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Abstract

In this work, the failure of two quasi-brittle aggregate materials is studied, an energetic material and its simulant.

The energetic material is a plastic-bonded explosive (PBX) composed of 95% wt of HMX crystals. It presents the following characteristics: nonlinear quasi-brittle behaviour with asymmetry between tension and compression, strain rate sensitivity, temperature and pres- sure dependencies. It also contains residual strains [1]. The simulant material of PBX is an aggregate composite processed by moulding under hot hydrostatic pressure. It consists of 94.5%wt of crystals mixed with 5.5%wt of a polymeric binder. The solid fraction of crystal is composed of 29.3%wt of barium meal (BaSO4) and 65.2%wt of melamine. The binder is of about 5.5%wt. It is made of an epoxy resin and a blue pigment. The resulting material has a mean density of 1.73 with a high residual porosity of 28% [2].

A recent study by Picart and Pompom [3] presented a comparative study between experimental failure surface of a PBX and the predictions of the theoretical criteria developed in the literature. Unfortunately, some points of compression-compression quadrant still unavailable.

When dealing with the simulant material, only quasi-static tensile and compressive tests were already achieved [2].

In this study, a large experimental campaign was carried out on simulant material, lead- ing to a presentation of a whole experimental failure surface. Then, failure surfaces of PBX and simulant materials are compared. Existing failure criteria developed originally for concrete are applied for both materials and the results are discussed.

It appeared that the failure surfaces of both materials present almost the same global trends and the applied theoretical criteria successfully fit experimental points.

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Keywords: aggregate material, experimental failure surface, failure criteria

Experimental investigations about the origins of the anisotropic behavior in mechanical loading of extruded AA2017 aluminium alloy

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Abstract

The present work presents experimental investigations of the origins of the anisotropic behavior in cyclic loading. In a first step, the study is conducted using the quantification of fatigue damage evolution in AA2017 aluminum alloy, subjected to proportional cyclic loading in two directions, axial and shear cyclic stress controlled loadings. The aim is to confirm the anisotropic behavior in cyclic loading which is already revealed in recent studies. To this end, we have used several models of fatigue damage quantification, such as those of continuum damage mechanics (CDM) and those using the evolution of the strain energy. Then, we have completed a comparative study of damage evolution obtained by CDM models with those obtained using models based on the evolution of the strain energy. The obtained results confirm the anisotropic nature of our material and show that the evolution of the fatigue damage in aluminum alloys are more consistent with the criteria based on the strain energy. In a second step, microstructural investigations are performed in order to understand the origins of the anisotropic behavior. Indeed, we have used a Scanning Electron Microscopy (SEM) to analyze the main phases and precipitates in the principal sections of the samples used in cyclic loading, the transversal and the longitudinal one. It is shown that the struc- ture and morphology of these phases and the precipitates are responsible of the anisotropic behavior of the current aluminum alloy. Moreover, the results obtained using the Kikushi diagrams, the poles figure and the inverse poles figures confirm these conclusions. Indeed, these results show a great difference in the texture of the two directions of a cyclic loading.

Keywords: Anisotropic behavior, extruded aluminum alloy, fatigue damage, microstructures and EBSD analyzes, pole figures and Kikushi diagrams.

*Speaker

Effect of Lode Angle and Stress Triaxiality on Steel Behavior: Experimental and Numerical Investigations

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Abstract

A series of experimental tests under different load scenarios have been performed on steel specimens, which generate different stress tensor invariants.
In the different loading scenarios, the Lode angle parameter is changing from 0 degrees, which corresponds to uniaxial tension condition and goes up to 30 degrees, which is the pure shear condition. The yield condition is also evaluated in between uniaxial tension and pure shear condition, which mobilize Lode angles of 10 and 20 degrees respectively.

The load is applied to solid round bars in form of combinations of uniaxial tension and torsion which will result in combined tensile and shear stresses that maintain a constant ratio throughout the experiment. For different Lode angles, the ratio of uniaxial tension to shear will change from infinity (which will result in uniaxial tension) to zero (pure torsion). These results can show how the third invariant of stress deviator affects the behavior of steel material.

To look at the compressive behavior, and capture the possible difference between compressive and tensile behavior, further experiments are being conducted to extend the Lode angle beyond 30 degrees up to 60 degrees which represent the uniaxial compression case. Since we cannot capture the difference between compression and tension only considering second and third invariants, we to introduce stress triaxiality measure to capture the difference in behavior of steel and aluminum under tension and compression.

Digital Image Correlation (DIC) have been used as a full-field measurement method for displacement field and calculation of the strain distribution of the steel specimens under the above-mentioned loading scenarios. Using this method, plastic flow rule is obtained by integration of the plastic strain rate through the physical domain of the specimen and it can be expressed in terms of the first invariant of stress tensor and the second and third invariant of stress deviator. The results can be used to investigate the crack growth based on the local and global strain distribution.
3D numerical analysis has been carried out and has been discussed the need to move from a von Mises elastoplastic constitutive model with an associated flow rule to an elastoplastic one that takes into consideration also the first invariant of the stress tensor and the third invariant of the deviatoric one.

Keywords: Lode angle, stress triaxiallity, steel, digital image correlation, hardening

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Experimental and theoretical investigation on the influence of ageing materials on functional fatigue of Shape-Memory ESTANE

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Thermally-induced Shape-Memory Polymers can react, according to their properties, to an external stimulus and come back to their permanent shape. This effect is called Shape-Memory Effect (SME) and is due to the particular physical properties of the polymer structure. Programming of SMPs is performed in a so called Shape-Memory Creation Cycle, where the sample is heated above its transition temperature (T_{sw}) and deformed to the desired form. Consequently, it is cooled down blow Tsw and the shape is memorized. Here for SM creation, the polymer chemistry and polymer morphology in combination with the programming of the material are required. The present work focuses on the importance of ageing materials and programming parameters upon the functional fatigue of a commercial polyetherurethane of type ESTANE which is associated with repeating up to 10 programming cycles has been examined. The repeated Shape-Memory Cycle results in an increase of irreversible strain associated with a corresponding decrease of recovery ratio at the beginning of a thermo-mechanical cycling. The experimental results are compared with a 3-Dim finite viscoelastic material model based on the multiplicative decomposition of the deformation gradient and a fully implicit time-integration scheme.

Experimental and Computational Analysis of Pressure Reducer Failure

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Abstract

Flaw appearance, possible crack occurrence and propagation along with the final failure are of serious concern when designing any engineering structure, but especially when dealing with pressure equipment. Defining the cause of failure can help in improving design of future products. Usually, research of failed pressure equipment is aimed at investigation of the root causes of pressure vessel wall cracking [1], compressor's impeller blade [2] or crankshaft failures [3], but there are also failures of auxiliary pressure equipment [4]. They all can cause considerable time and financial losses in industrial plants.

One of such failures is investigated in this paper. Using experimental and computational analysis, failure analysis of a cracked pressure reducer on an air compressor was performed. Series of such failures were recorded and an attempt was made to determine the cause of failures. Besides visual examination that revealed location of the fracture, several other experimental techniques were used: optical microscopy revealed basic microstructure of the fractured surface along with possible inclusions while detailed scanning electron microscopy (SEM) examination at suitable magnifications was employed to characterize the fine microstructure of the fractured surface and reveal flaws that served as crack initiation points. Optical emission spectrometer with glow discharge source (GDS) sample stimulation was used to determine chemical composition of material. Additionally, hardness test was performed and maximum tensile strength of the material was derived from it.

Further, stress intensity factor was determined computationally by finite element analysis for different crack configurations and loading options. This data was used to perform estimation of failure probability on the basis of failure assessment diagram [5]. Finally, given all performed investigation, possible causes of crack occurrence are outlined. Obtained results can be used in improving further design of such pressure reducers and for predicting their fracture behavior.

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Keywords: pressure reducer, failure analysis, experiment, finite element analysis

Temperature control of dumbbell specimens exposed to cyclic loading - experimental foundation of the investigation of the dissipated energy as an end-of-life predictor

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Wöhler curve databases are applied to check the applicability of end-of-life predictors within Wöhler's concept [1]. The method is to determine the level of superposition of the different Wöhler curves. In case of superimposed Wöhler curves the investigated criterion is considered as applicable. In most cases the values of the investigated criteria are calculated by simulating the experiments with the finite element method (FEM). Unwanted shifts, which lead to inaccuracies in the assessment of the criterion, occur if the FE analysis does not include parameters that influence the durability in reality.
Charrier et al. measured a significant influence of the temperature on the durability behavior on a carbon black filled NR. The temperature of the specimen depends on the testing frequency and on the loading. The load levels are considered as a given parameter. To perform the durability tests for the required Wöhler curve database a reasonable testing frequency is needed. Self-heating of the specimen occurs. In the present study, this parameter is not implemented in the used material model such that the investigated criterion depends on the temperature.
Hence, the aim is to attain similar specimen temperatures independent of the testing frequency and loading. Forced convection is examined as a tool to achieve that aim. It can be experimentally shown that this method is able to lower the skin temperature for all chosen test conditions close to ambient temperature. The inner temperature of the specimens is measured with a so-called *cutting test*. The drop of the skin temperature, thanks to forced convection, is equal to the drop of the inner temperature. Finally, a simple analytical model of a cylinder is applied to describe these observations.

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MS5: Dynamic fracture, fragmentation and impact

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Dynamic fracture is an important issue in safety assessment of structures under extreme loading. This mini symposium is aimed towards providing fruitful discussions and exchange of ideas and concepts among different approaches used by researches in the fields of experiments, modeling and simulations. The contributions are welcome in order to discuss different views forthe same problems.

In the framework of the workshop a number of not yet well understood fundamental questions should be discussed, for example: Do the dynamic local inertial terms influence the crack birth and how? How do stress waves influence crack propagation paths? How does the strain rate influence material properties, strength and fracture energy? What is the reason behind phenomena of crack branching and change of the failure mode? What is the role of inertia? What is the maximum crack velocity in different materials? What are the limits of fragmentation simulations in terms of fragment size and residual velocities? Does the fracture occur due to plastic exhaustion (tearing) of the material or is the damage the leading term in the fracture of ductile materials?

Furthermore, some technical aspects, experimental and numerical, are of great importance to improve our understanding of different phenomena. For instance: What are the most efficient loading systems for measuring dynamic crack propagation in experiments? How do one measure a dynamically progressing crack? Can one observe the initiation of dynamically loaded crack? What arethe problems related to the objective evaluation of experimentally measured data? What are reliable numerical models and approaches used for simulation of materials and structures under dynamic loading: cohesive crack models, X-FEM, EFG or SPH, deletion of finite elements? Are multi-scale modeling approaches reasonable to be used for modeling of dynamic crack propagations?

All contributions fromthe field of experimental, numerical and theoretical fields of research are welcome. Moreover, presentations on industrial real life applications are also of great interestand are welcome.

Failure analysis of quasi-periodic lattices

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Quasi-periodic structures have been widely studied, notably in the atomic vibration domain, due to the fact that they appear spontaneously in some atomic structure. A lot of mathematical works have been devoted to analyze their unusual topology and to develop efficient algorithms to their construction. They are also manufactured, at the atomic level, in order to better understand their unusual mechanic and electronic behaviors. The recent progresses in the additive manufacturing open new possibilities for using quasi-periodic structures at macroscopic scale by allowing the printing of complex meta materials, in a consistent manner.

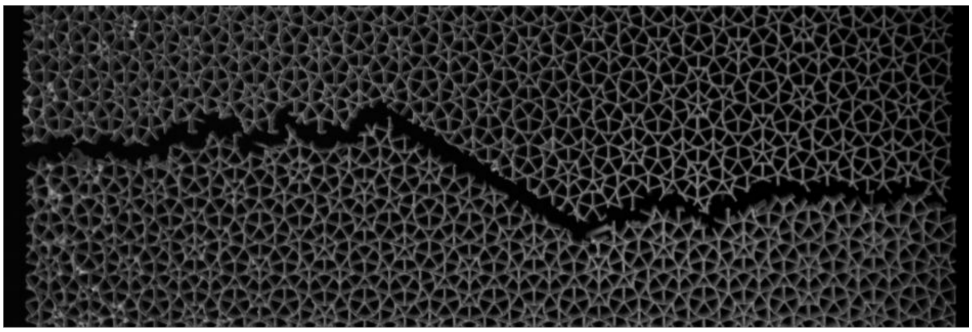

Figure 1: Failure of an quasi-periodic Penrose beam lattice..

The aim of this study is to create a discrete beam model with brittle fracture criterion able to model propagation of failure in quasi-periodic meta-materials. It is shown that strong interactions between the crack and the material structure occur. These interactions can be triggered by the geometry of the beam, namely the ratio between the beams' length and their width. This ratio controls the respective contribution of bending and tension modes what strongly influence the way the crack propagates through the lattice. The behaviours of different quasi-periodic lattices are compared to the behaviour of their periodic counterparts. In the case of transient loadings, the influence of the quasi-periodic structure is even more pronounced due to its unique vibration response. It have been shown in previous work that quasi-periodic beam structures can exhibit localization of vibration at low and high frequencies, notably in their optical branches, leading to localized stationary waves which influence crack propagation.

Quantifying Macro-Descriptors of Dynamic Fragmentation with Thick Level-Set Method Approach

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The Thick Level-Set (TLS) method is a non-local damage model with application to quasistatic and dynamic fracture simulation. Defining the damage field by a level-set function, complex fracture evolution such as crack branching and coalescence is handled naturally. Strain localization is prevented by limiting the damage gradient around cracks, forcing damage to diffuse to a finite characteristic length. We apply the TLS approach to model dynamic fragmentation of a brittle rod in one dimension. While using a constitutive model including a softening function that replicates a linear traction-separation law from the cohesive zone model, we find that the TLS model favorably predicts macro-descriptors of the fragmentation process, mean fragment size and dissipated fracture energy, over a variety of dynamic strain rates. The simulation results compare well to analytical estimates, numerical results from finite-element simulations using the cohesive element approach, and physical experiments.

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Dynamic Fracture of CT Concrete Specimens Exposed to High Temperature: Numerical and Experimental Study

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Recent experiments and numerical studies performed on plain concrete specimens at ambient temperature showed very interesting and complex fracture behaviour of concrete under high loading rates. The simulations and experimental tests performed on compact tension (CT) specimen [1] highlighted the phenomenon of crack branching at high loading speeds. However, the behaviour of concrete exposed to high temperature is different than the behaviour of concrete at ambient temperature. Due to high temperature there is temperature induced damage of concrete, free thermal strains and load induced thermal strains, which can significantly change concrete properties and the response of concrete under high loading rates.

In the present contribution the experimental tests and numerical simulations of compact tension specimens exposed to temperature up to 400°C and subsequently loaded under high loading rates are presented discussed. In the experiments the CT specimens were first heated, under low temperature gradients, up to certain temperature level, cooled down to the ambient temperature and subsequently loaded under high loading rate. The 3D FE analysis is performed using temperature dependent microplane model for concrete.

The results of the study show that with increasing temperature the failure mode is similar as for the specimen under ambient temperature. However, the dynamic increase factor (DIF) for resistance is decreasing with increasing temperature level, i.e. the specimen at high temperature becomes less sensitive to the strain rate at high temperature. The results of numerical simulations support the experimental evidence.

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Modelling Mixed Mode Fracture of Concrete under Dynamic Loading

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Abstract

In the present work the classical tests on double edge notched specimen performed by Nooru-Mohamed [1] were numerically investigated employing 3D FE software MASA, developed at the University of Stuttgart. The constitutive law used for concrete is the microplane model with relaxed kinematic constraint [2]. The rate sensitivity is directly incorporated in the constitutive law, while the structural inertia is accounted for through explicit dynamic analysis.

First the numerical model was verified against the experimental results for one selected load path under static loading. The validated model was then used to study the effect of high loading rate on the fracture behaviour of concrete under the investigated loading condition. The investigated loading rates ranged from moderate to high.

The numerical results clearly demonstrated the effect of loading rate on load-displacement behaviour in case of mixed-mode fracture. It is found that high loading rates can lead to a change in crack orientation and propagation. Upon reaching the maximum crack propagation velocity crack branching takes place. The obtained numerical results are consistent with previously performed experimental and numerical study on compact tension specimen [3].

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Keywords: concrete, double edge notched specimen, dynamic fracture, high loading rate, crack propagation, microplane model

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Mesoscale modeling of dynamic fracture in quartzite and sandstone and homegenization to macroscale

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Abstract

The proposed presentation is part of the MEMIN (Multidisciplinary Experimental and Modeling Impact Research Network) project, which is devoted to the experimental and numerical investigation of the effects of meteorite impact on geological materials from laboratory scale to natural scale.

In general, high velocity impacts on rock material cause fractures in the target that may lead to spallation of material near surfaces. Since scaling laws are intended to provide relationships between natural and laboratory craters, spallation effects, which are of great importance in laboratory craters, need to be properly quantified. This challenging task can be addressed with numerical methods if appropriate material models exist.

For this purpose, we investigate dynamic fracture in quartzite and sandstone. We present a new methodology to derive three-dimensional macroscale material data from one-dimensional dynamic fracture experiments, namely Hopkinson-Bar experiments in spallation configura- tion, using a new mesoscale simulation model. Intergranular fracture is modeled by a specific cohesive zone formulation. Mesoscale failure parameters are identified from a parameter study such that simulated macroscopic failure quantities conform to experimentally measured data.

The calibrated mesoscale model is then subjected to a set of multiaxial load cases in order to derive macroscopic yield and failure parameters using averaging techniques. The results can be directly used to calibrate macroscale material models for dynamic fracture and will support the predictability of laboratory craters and, in particular, of spallation effects.

Keywords: mesoscale, dynamic fracture, cohesive zone, rock, homogenization

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High-velocity crack speed in wood fibre composites: an experimental and numerical study

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How fast does a mode I crack propagate? Here, the question is addressed by a series of experiments, using a high-speed camera to track the crack propagation. A strip specimen geometry was chosen for the experiments, since it provides fairly easy interpretation of the results [1]. Two different materials were studied: one wood fibre composite, consisting of a PLA matrix and natural wood fibres, and one homogenous plastic, consisting of the PLA matrix material without fibres. Experiments were performed under different humidity conditions, and for different initial crack lengths.

The experimental results are compared to numerical results. In the numerical analysis, a dynamic phase field model is used to simulate crack propagation. In a phase field model, a crack is represented by a phase field d, which is defined over the entire body Ω, and has values 1 in the proximity of the crack and 0 elsewhere. The method is based on the principle of energy minimisation, and the governing equations are obtained from variation of the Lagrangian,

$$L = \int_{\Omega} \psi_k \, d\Omega - \int_{\Omega} \{[(1-d)^2]\psi_e^+ + \psi_e^-\} \, d\Omega - \int_{\Omega} G_c \left(\frac{d^2}{2l} + \frac{l}{2} \nabla d \cdot \nabla d \right) d\Omega.$$

Here ψ_k is the kinetic energy density, G_c the fracture toughness and ψ_e the elastic energy. The elastic energy is split into ψ_e^+ and ψ_e^-, and only ψ_e^+ is degraded by the crack phase field d. The use of a phase field extends the crack evolution to all possible crack states in the body, and thus the model is capable of capturing e.g. branching phenomena without additional criteria.

It is observed that crack branching is more common in the PLA specimens than in the fibre composites, for both wet and dry specimens. This implies that there are other energy consuming mechanisms present in the composites, such as fibre fracture and fibre pull-out. The experiments also support previous results, in that the crack propagation velocity increases for shorter initial crack lengths and that the energy required to cause fracture increases as the initial crack length decreases [1]. In sum, the observations indicate that while the composites qualitatively behave according to prevailing theories, for complex and fibrous materials such as wood and fibre composites, microstructural effects need to be taken into account.

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Computational study for dynamic crack propagation in pressure vessel wall with hydrogen leakage using particle and Euler method

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Astract

This computational study provides useful information for predicting dynamic crack propa- gation accompany with hydrogen leakage in pressure vessels as an important part of assessing hydrogen as an energy vector . The present study was conducted by using a hybrid of the coupled particle and Euler methods.

The computational analysis procedures consisted of two main parts. The first part was crack propagation analysis of a thin square plate, which simulated the wall of a high-pressure vessel by using a particle method. The plate was stainless steel, which is widely used for hydrogen vessels. Initially, it was assumed that the plate contained a defect, and then tension was applied to three sides of the plane uniformly, inducing crack propagation. These phenomena were simulated by using peridynamics theory, which is a particle method.

After crack propagation analysis, the particle coordinate values of the partition wall were converted to Euler mesh data. The data were fitted to Euler numerical space, which was used for simulating high-pressure hydrogen leakage into air at atmospheric pressure.

The second part of the analysis procedures was high-pressure hydrogen leakage through cracks in the barrier wall. Two-phase compressible flow calculated by the volume of fluid (VOF) method was considered. VOF is an advection scheme that allows the programmer to track the shape and position of the leaked hydrogen interface from the generated crack in pressure vessel wall. Hence, the Navier-Stokes equations with the VOF algorithm, a conti- nuity equation, and an energy equation were solved simultaneously in the study.

*Speaker

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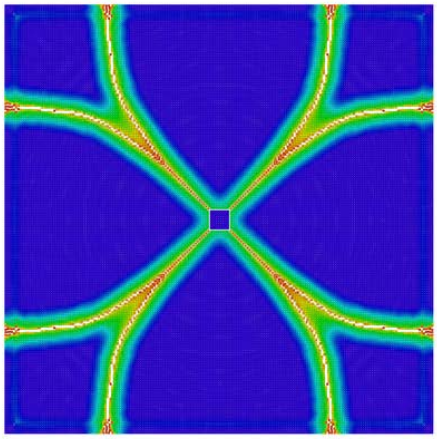
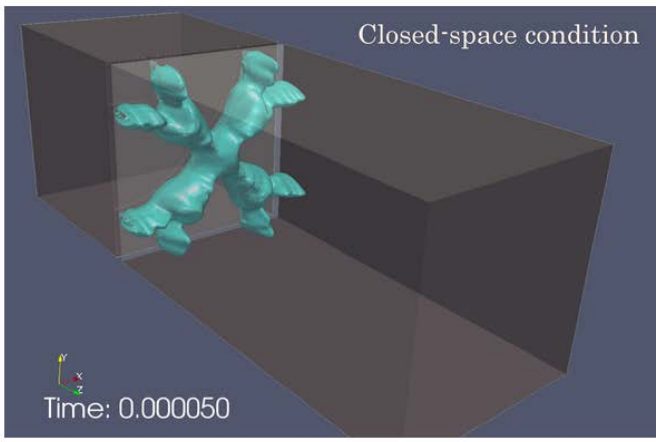
Finally, the hydrogen concentration in outer space was numerically predicted with different boundary conditions and crack propagation shapes in the high-pressure tank wall. Two types of boundary conditions were applied to investigate the differences in time variation of the hydrogen concentration, temperature, velocity, and pressure after crack propagation (Fig. 1).



Crack propagation by particle method



Iso-surface profile of hydrogen volume fraction in leakage process by Euler method

Keywords: Coupled particle and Euler method, Peridynamics, MPS, VOF, Hydrogen leakage, Pressure vessel

The Discrete Element Method for the estimation of the critical dynamic energy release rate: application on spherical structures

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An original numerical procedure for estimating the critical dynamic energy release rate (G_{ID_C}) is proposed. The Discrete Element Method (DEM) [1] is used to simulate the dynamic fracture by implementing the node release technique [2]. It is shown that for a linear relaxation scheme and a fracture process zone length equal to the mean radius of elements in the DEM model results comparable to finite element or analytical methods are obtained in plate structure [3]. This procedure is then applied on spherical structures where the rapid crack propagation (RCP) is experimentally observed. Composite hollow spheres ($\phi = 30$ mm) subjected to RCP in mode I are uni-axially pre-stressed until failure. Crack tip position as a function of time is recorded with the help of a high speed camera (75000 fps).

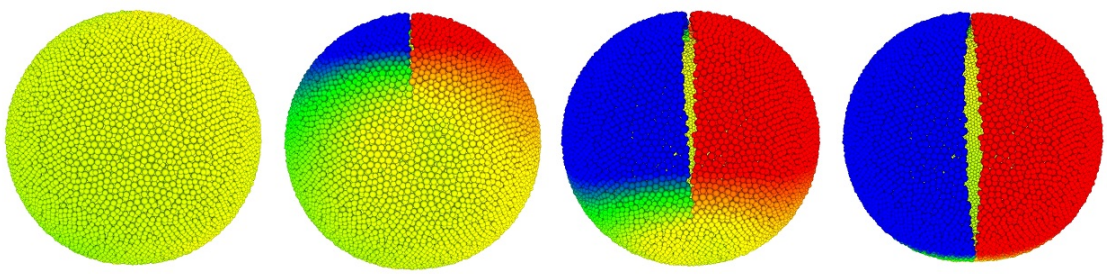

Figure 1: Discrete Element crack growth modelling of a pre-stressed hollow sphere

In spherical structure, see Fig. 1, the numerical results reveal a high proportion of energy dissipated through inertial effect as well as a dependence of the thickness of the hollow sphere over the range of 0.04 mm to 1.2 mm. At a crack tip velocity of $0.6c_r$ (with c_r the Rayleigh wave speed of the material) the dynamic correction factor (G_{ID_C}/G_{I0}) decreases from 0.4 for the plate [4] to less than 0.05 for the hollow sphere. Similar results have been shown for the longitudinal dynamic fracture of polymer pipes [5]. The quantitative results of G_{ID_C} are in good agreement with the literature and the present model offers an alternative to the finite element method to simulate the rapid crack propagation.

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Numerical Modelling of Structural Degradation under Adiabatic Shear Banding and Micro-voiding

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Adiabatic shear banding (ASB) is a strain localization phenomenon occurring in high strength materials like titanium and aluminium alloys subjected to dynamic loading involving quasi adiabaticity and low stress triaxiality conditions. Since it acts as a precursor to catastrophic failure, see e.g. Longère and Dragon [1], it is thus crucial to numerically model its formation and consequences when dealing with structures submitted to high loading rates.
A large scale postulate is used herein to obtain a global insight into the structural material response. The adiabatic shear band cluster is indeed contained/embedded within the representative volume element (RVE), and not the opposite as usually considered. The effects of ASB initiation and evolution on the RVE (material point) response are double: kinematic, namely a progressive deviation of the plastic flow in the band plane, and material, namely a progressive anisotropic degradation of the elastic and plastic moduli. A physics-motivated, unified constitutive model has been initially developed in order to describe both aforementioned ASB effects, see Longère et al. [2], and then recently completed to reproduce the consequences of microvoiding in the band wake, see Longère and Dragon [3].
The enlarged model has been implemented as user material into the engineering finite element (FE) computation code LS-DYNA in the context of standard FE kinematic formulation. The performances of the numerical model are assessed regarding initial-boundary value problems with increasing complexity.

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Dynamic fracture simulations through strain injection techniques

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A methodology for the simulation of dynamic crack propagation based on Finite Elements with Embedded discontinuities (E-FEM) is presented . Both strain and displacement discontinuities are injected within the finite element through a kinematic enrichment considering discontinuous strain and displacement modes. The technology has been already utilized in a wide number of quasi-static tests in [1, 2] and recently adopted for the study of dynamic fracture propagation in [3]. The strain injection technology is complemented with the crack path field tracking algorithm which computes the trace of the strong discontinuity and provides an extra robustness to the crack modeling approach. Due to the intra-elemental character of the kinematic enrichment, the overall computational cost turns to be remarkably lower (up to three orders of magnitude lower in terms of FE discretization) than other existing techniques based on supra-elemental crack modeling, e.g. phase-field or gradient damage approaches.

Upon increasing loading rates, crack propagation instabilities, such as crack curving and branching, have been observed and their impact in terms of the resulting crack pattern, i.e. crack surface, and dissipated energy is studied. Results turn to be reasonably insensitive to spatial and temporal discretizations provided that they suffice to model the underlying physics and a convergent behavior, in terms of the dissipated energy, is observed upon refinement of the FE mesh and adopted number of time steps. An interesting correlation is found between the maximum experimental crack speed and the maximum dissipation of a single crack at the onset of branching considering that the energy is instantaneously released which can be used to estimate the crack speed upon branching based on the overall dissipation which is a remarkably less fluctuating field.

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A numerical study on crack branching in quasi-brittle materials

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Experimental and theoretical research show that crack branching may occur for a relatively wide range of cracks speeds, depending on the material characteristics, load history, geometry and boundary conditions of the problem. The dynamics of crack propagation is investigated numerically in this study with a recently developed *effective rate-dependent* damage model enhanced by a stress-based nonlocal regularization scheme. This phenomenological model reproduces the major phenomena associated with crack propagation and branching in quasi-brittle materials. This approach solves mesh dependency and avoids the use of ad hoc criteria to control crack branching.

It is established that branching does not occur at a specific crack speed. It is shown that when a cracked body is loaded under tension, the stress field at the crack tip tends to evolve from mode-I to a mixed-mode state while the crack speed increases. Beyond a certain crack speed, the stress distribution around the crack tip reaches a critical state which favors the widening of the fracture process zone parallel to the forward cracking direction. A single crack is no longer stable. When this condition is met, crack branching occurs whenever the stress field at the crack tip is destabilized by either a physical discontinuity or an interfering stress wave reflected at the specimen boundaries (see fig. 1).

It is discussed and demonstrated that a rate dependent model enhanced with a length and a time scale leads to realistic representations of crack dynamics in quasi-brittle materials. The time scale introduced by the new *effective rate* concept proves to be necessary to account for the inherent micro and meso-scale structural inertia effects associated with cracking.

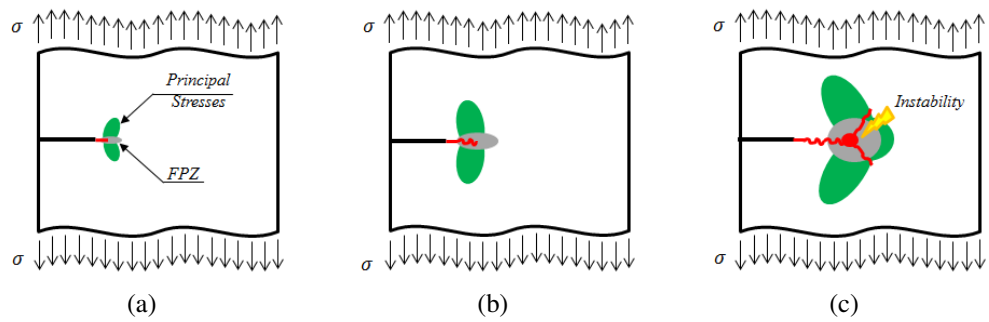

Figure 1: Evolution of stress field and FPZ at the crack tip.

Dynamic fracture and fragmentation of Ice: an SPH modeling

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This presentation is first devoted to the presentation of experimental results on ice fracture at slow and fast strain rates (strain rates from 10^{-3} up to 10^{3}). The traction strength is between 6 and 12 times smaller than the compression one. This material has a mechanical behaviour which is similar to concrete. For that reason a Mazar type of material behaviour is chosen for the material modelling. This model is then extended to fast transient behaviour. The model is implemented in SPH formulation and coded in LS-DYNA explicit code. The computations will present the application of the models to 3 types of experiments: Brazilian test which clearly show the limits of the first Mazars model, and on which the model is improved. Hopkinson dynamic fracture tests, and impacts of ice spheres sent at velocities up to 700m/s onto a circular clamped AU4G plate. The ice is modelled with SPH whereas the metallic parts are represented by finite elements.

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MS6: Fracture of Polymers

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In this proposed mini-symposium, we invite all researchers involved in fracture of polymer materials. An increased interest in understanding and modeling both fracture and fatigue of these materials has been observed in the scientific community during the last decade. Materials concerned are engineering polymers such as thermoplastics, thermosets, elastomers and blends,but also biopolymers. A large variety of topics can be addressed including:

- new computational methods,
- fracture of polymers at different scales, including micromechanical approaches,
- large strain fracture and fatigue for complex loading conditions,
- influence of time, relaxation and creep, dynamic fracture of viscoelastic and viscoplastic materials,
- theoretical and numerical strategies developed for complex constitutive equations of polymers,
- experimental techniques and observations in support of computational modeling,
- coupling with environment: degradation, ageing, thermal damage, ...

Although numerical methods are the main topic of the conference, both theoretical and experimental studies are welcome and encouraged.

Fracture Analysis of Polymers by Phase-Field Method

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Abstract

Polymers are a common material and widely used in industrial application. As indicated by experiments, most polymers exhibit both elastic and viscous behaviour simultaneously, which yields a time dependent response. However, these properties can be simulated successfully by continuum mechanical approaches from the numerical point of view. In this work, the Bergstr´om-Boyce model is taken into consideration for fracture analysis, see [1]. The complexity of this model is the nonlinearity of the viscous evolution law and the mechanical response on both equilibrium and the non-equilibrium branch. With respect to fracture aspects, a phase-field method is proposed for the crack approximation, which provides the advantage that it does not require the numerical tracing of the displacement singularity, as shown in [2]. The phase of fracture or unfracture can be indicated by a continuous scalar valued phase-field quantity. The driving force for crack propagation is derived from the elastic energy density function. Therefore, the elastic energy from both the equilibrium and the non-equilibrium response is necessary to be taken into account for the crack evolution.
Furthermore, due to the procedure of manufacturing or post-processing, polymers are possibly characterised as anisotropic properties. These anisotropies for both mechanical and fracture features can be resolved numerically. On the one hand, the anisotropic mechanical property can be obtained as a result of applying fibres or reinforcement elements directionally. On the other hand, anisotropic fracture properties can be achieved by reformulating the energetic function for the fracture surface, as indicated in [3]. The gradient of the phase-field in the fracture surface energy function is defined as a direction dependent term. Thus, the fracture toughness is varying directionally and the crack is supposed to propagate along the weak direction. Moreover, the elastic energy degradation due to fracture is specifically identified, since cracks are sensitive to tensile loading. Then volumetric energy is considered to contribute to fracture only if the element is undergoing tension. Besides, by solving the whole equation system, an enhanced staggered algorithm is proposed. The mechanical and the phase-field equilibrium equations are solved alternately and cyclically up to both of them reach a state fully converged. Consequently, representative numerical examples are performed. The crack patterns of isotropic and anisotropic formulations are investigated and compared.

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Keywords: phase field method, finite strain, nonlinear viscosity

Multiscale modeling of fracture in thermoplastic PC/ABS blends

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The macroscopic deformation and failure behavior of rubber-toughened thermoplastic PC/ABS blends is governed by various microscale damage mechanisms. Crazing and void growth from cavitated rubber particles prevail in the ABS phase while PC typically fails by ductile rupture at large strains [1]. In order to gain a better understanding of the micro-macro relationship in PC/ABS blends undergoing failure, different approaches are utilized and discussed in this contribution.

In a micromechanical RVE approach the two constituents are represented as distinct phases. To capture the deformation behavior of each phase different plasticity models are employed. Within the PC phase the standard glassy polymer model by Boyce [2] is utilized. To capture the deformation behavior of ABS in a homogenized sense two different approaches relying on either the mechanism of distributed crazing [3] or void growth [4] are studied. Individual local failure criteria are employed in each phase. Numerical simulations looking at the effect of the blend composition on the overall response are compared with experimental findings.

Complementarily, purely macroscopic material models accounting for the pronounced plastic dilatancy of the material are analyzed. Different models capturing this overall plastic dilatancy are compared with respect to their capability to match experimental data for PC/ABS blends. This study comprises finite element simulations of fracture experiments and the comparison with experimental results.

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Unified Modelling Concept for Incrasing or Non-Monotonic Fracture Energy vs. Crack Speed Relationships: Physical Basis and Computational Solution

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Abstract

Fracture rate dependence in polymeric materials manifests itself in qualitatively different ways. While often the fracture energy vs crack speed (Gc-v) relationship is increasing, cases are known when the opposite is valid, even for materials of great engineering interest [1,2]. The possibility of a non-monotonic Gc-v law exists as well [3, 4].
These qualitative features are not only interesting in itself, but can also have important structural consequences, as decreasing Gc-v curve branches can induce fracture instabilities, e.g. stick-slip crack propagation [5, 6, 7, 8], or catastrophic failure.

Motivated by a recently formulated thermodynamic derivation [9] for the fractional cohesive-zone model developed in Ref. [10, 11], we present an improved cohesive-modelling scheme based on micromechanics-based physical arguments, which can result in either monotonic or non-monotonic Gc-v curves within a unified conceptual and modelling framework. Although alternative modelling approaches predicting non-monotonic curves exist, to the authors' knowledge they all resort to structural arguments, such as crack blunting/branching [12] or test specimen finiteness [4]: on the other hand our model is fully local and can exhibit non-monotonicity even for a single material point.

Postulating the existence of a rate-independent rupture energy, associated with the rupture of bonds, a damage variable is introduced, which is assumed to evolve as a rate-independent function of part of the elastic energy. The overall rate-dependent response is retrieved by introducing additional internal variables associated with viscous dissipation.

With our proposed approach, the choice of different evolution laws for the damage variable results either in a sigmoidal shape of the Gc-v curve, typical of certain elastomeric interfaces (as in Ref. [11]), or in a non-monotonic bell shape of the Gc-v curve, which can be associated with the behaviour of some polymers below their glass-transition temperature. This proposed unified model can thus capture the significant differences found in the type of rate dependence of fracture in elastomers and glassy polymers, supported by a physical explanation of these differences.

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Keywords: rate dependence, fracture energy vs crack speed, fractional viscoelasticity, cohesive, zone.

Non-equilibrium diffusion and chemically induced crack propagation in polymers

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Diffusion processes can interact strongly with the mechanical behavior of polymers and other materials. Atoms or molecules of a diffusing chemical species will typically create (reversible) swelling, but can also disrupt the atomic organisation of the host material, causing permanent (plastic) strains, which will add-up to those originating from mechanical loading. Example of such phenomena can be found in diffusion of water in polymers (plastification/aging), wooden materials (mecanosorption), or of Li-ions in batteries' electrodes.

Brassart and Suo [1] recently proposed a modeling approach of this kind of phenomena, through the introduction of non-equilibrium diffusion equations. When coupled to plasticity, it allows to reproduce experimentally observed behaviors, e.g. in Li-ion batteries' electrodes, with coupling effects between Li-ion flow and development of plastic strains. We have reformulated this model in a variational framework, allowing to formulate boundary value problems of diffusion coupled to mechanics as optimization problems, with nice mathematical and algorithmic properties.

This numerical modeling framework has then been applied to study the behavior of a cracked specimen, subjected to cyclic chemical loading. The model then predicts that, even under moderate mechanical loading, which by itself would not generate development of plastic strains, this cyclic chemical loading leads to creep behavior and crack development. Such mechanism could thus contribute to crack propagation under chemical/environmental loading.

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A micro-macro approach to strain-crystallizing rubber-like materials

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Strain-induced crystallization (SIC) is a process in which small crystalline regions appear inside the amorphous rubber material when undergoing large amounts of stretch. Formation of these polymer crystals around crack tips is often attributed to the superior fatigue and fracture properties of rubber-like materials [1]. The micromechanical properties of the cross-linked polymer chains undergoing reorientation, large deformation, and SIC [2, 3] are linked to the macroscopic deformation through a maximal advance path based homogenization approach [4]. Experimental results show that the majority of polymer crystals are orientated along the stretch direction [5], thereby inducing an anisotropic material response. In the proposed model, a macroscopic crystallinity parameter is defined which describes the magnitude and orientation of the individual polymer crystals. The degree of crystallinity of any polymer chain is assumed to depend on this macro-scale crystallinity parameter as well as on the chain's orientation with respect to the direction of the crystal. Numerical simulations include uniaxial tension tests and complex 3D simulation of SIC around a cracked region. The simulation data show good agreement with experimental results [1, 5] even in tcomplex stress situations around a crack.

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Physically-based constitutive modeling of rubber-like materials

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In this contribution, we present a physically-based full network model for various types of rubber-like materials. The numerical integration over the unit sphere is avoided by using a generalized analytical network-averaging concept [1]. The free energy of polymer chains is represented on the basis of a closed form of the Rayleigh exact non-Gaussian distribution function. Thus, the inverse Langevin function is entirely bypassed. Furthermore, inelastic effects in filled natural rubbers are elucidated by four deformation-induced mechanisms of the network: damage, recovery, rearrangement and hardening. The proposed model includes very few physically motivated material constants and demonstrates good agreement with multi-dimensional experimental data of both unfilled and filled elastomers.

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Experimental characterization of crack growth in polyurethane membranes

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Abstract

The problem of crack growth in rubber-like materials has mostly been tackled through the fatigue point of view. Nevertheless, the study of dynamic crack growth under quasi-static loading is developing since the 2000s along with the observation technics [1]. Here, we aim at characterizing experimentally the crack growth speed in polyurethane under the various deformation states of a single test: planar tension.

The loading of the planar tension testpiece is followed with a high-resolution camera and the crack growth, initiated with a small cut on one edge once the desired stretch ratio is reached, is filmed with a high-speed camera. Digital image correlation is used throughout the test to measure the deformation field. Thus, we are able to follow the crack speed evolution from the initial cut to the final breakage of the sample. The test is then analyzed as the changes of the sample from a "pure shear" testpiece with a small crack [2] to a classic "pure shear" testpiece [3] and finally to a single edge notch testpiece [4]. The goal is to determine if the speed of the crack can be related to the tearing energy computed analytically on each part of the sample for various global stretch ratios.

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Keywords: Crack growth, Elastomere, Pure Shear

*Speaker

MS7: Modelling and simulation of damage and fracture induced by repeated contacts

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This minisymposium aims at bringing together experts in modelling techniques and computational methods for the physical understanding and simulation of damage and fracture phenomena in materials and components induced by repeated contacts. Perspective authors are invited to contribute on the following topics:

- Modelling and simulation of damage and fracture induced by repeated contacts;
- Numerical methods for damage mechanics in the presence of repeated loadings;
- Numerical methods for fatigue crack growth;
- Modelling and simulation of fretting fatigue damage;
- Modelling and simulation of crack closure effects;
- Modelling and simulation of fracture and contact mechanics problems at material interfaces;
- Multi-scale numerical modelling in tribologic fatigue (fretting fatigue, rolling contact fatigue, influence of the microstructure, hardness, residual stresses or heterogeneities);
- Rolling contact fatigue;
- Damage caused by oscillatory normal contact;
- Modelling of plastic and/or frictional shakedown problems;
- Fracture and contact problems in finite elasticity.

Practical Comparison of 3D and 2D Finite Element Models with Contact Loading for Crack Driving Forces

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Abstract

The growth of surface cracks under rolling contact is of interest in many applications as e.g. wheel/rail contact or roller element bearings. They are driven by normal and tan- gential contact loads and in some cases some fluid entrapment effects. Several groups have developed finite element models for calculating the driving forces for surface cracks both in 3D and 2D models. Lately, most groups focus on studying special effects like anisotropic fracture toughness [1], influence of residual stresses and crack driving force formulations for elastic-plastic material behaviour [2] in 2D plane-strain models. Models using non-linear material descriptions are computationally very time- consuming and have to assume that a 3D load case can be simplified towards a 2D case and will deliver at least qualitative results. Such 2D models assume that the contact loads are somehow equivalent to a parallel cylinder- cylinder contact with a crack through the whole length of the cylinder. Taking the maximum contact pressure and longitudinal contact length of the 3D situation in the 2D models, crack driving forces will certainly be overestimated. When studies with 2D models want to make quantitative predictions, it would be helpful to know to what extend crack driving forces are overestimated in 2D models.

In this work, four typical surface crack geometries are loaded with contact patches that quasistatically move over the surface both in a 3D model and corresponding 2D models. The contact patches assume full slip and realistic loads of a wheel/rail contact. The traction stresses are thus proportional to the contact pressure with friction coefficients of 0, 0.3 or 0.5. Stress intensity factors (SIF) of type 1 and 2 are evaluated and differences in both the evolution and the minimum and maximum values are shown. For the cracks perpendicular to the surface, the results show that normal SIF (type 1) values can be corrected with the ratio of geometry factors for through and half-penny shaped cracks as stated in [3] and shear SIF values correspond reasonably well. For inclined surface cracks, the 2D model overestimates the shear SIF values by up to 100% for the chosen crack geometry and loads. The results also show

*Speaker

that 2D models do not necessarily feature the same dependencies on e.g. crack length and friction coefficient as the 3D models. The work shows limitations and problems when using 2D models for calculating driving forces on surface cracks under contact loading and thus helps to use them for more practical predictions.

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Keywords: rolling contact fatigue, fracture mechanics, finite element modelling, contact loading

The semi-infinite Trench and its application to the solution of Complete contact Problems

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Most contact problems are solved using half-plane theory, and there are relatively few solutions for so called 'complete' (sharp-edged) contacts. Even fewer solutions are available for cases where the contact edge is near to an adjacent internal corner. If the separation between the contact edge and adjacent material is extremely small, the gap may be thought of as a crack and, further, if the contact edge is known to be in a stuck state the classical semi-infinite crack eigensolution will define the tractions along the adjacent contact interface, and hence define the minimum coefficient of friction to ensure adhesion.

Here, we will first look at the application of these ideas to the behaviour of a block sitting in a socket only just bigger than itself, so that the crack solution applies. We go on, separately, to look at the solution for a semi-infinite trench, that is, an infinite plane containing a square-bottomed slot of finite width, d. At points remote from the trench root ($r \gg d$, where r is a polar coordinate measured from the trench-bottom, loading is excited by using the classical modes *I* and *II* crack-tip singular solutions, together with a third term corresponding to the T stress. The last is very important for contact problems because a major element of loading is contact pressure adjacent and parallel to the crack (or trench) flank. A carefully graded finite element model of the semi-infinite trench is formed, and, at the corners forming the trench bottom, the eigensolution corresponding to a notch of internal angle $3\pi/2$ (a three quarter plane) is collocated in. Hence we have a nested asymptotic structure, and we can infer the potential slip behaviour near the contact corner when its separation from an adjacent body is small but not infinitesimal.

An interesting feature of these problems is that, because the two singular solutions to the crack problem are of equal strength (they are, of course, both square root singular), they have an equal relevance, and the mode mixity controls the tractions implied along the contact interface. However, when we have a wedge solution the mode *I* eignesolution is always more strongly singular and hence this will dominate behaviour very close to the corner. The coefficient of friction to maintain adhesion is hence uniquely determined by the wedge angle – for a three quarter plane it is 0.543.

The semi-infinite trench problem is also of relevance to the near-crack tip fields in the presence of blunting, of course, and, in the semi-infinite form advocated, may be applied to crack tips of any geometry, provided only that the crack tip stress intensities are known.

An insight into the adhesive wear mechanism using the phase field approach to brittle fracture

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The problem of adhesive wear is of paramount importance in tribology [1]. Pioneering investigations on this wear mechanism are dated back to the 1950s, when the Archard model was proposed to describe wear at the scale of a single asperity contact, and deduce a law holding at the macroscale, the so-called Archard's law [2]. Experimental results by Brockley and Fleming [3] on a model junction subject to severe wear shed light onto the fracture mechanism considered by Archard and taking place during the interaction of two surface asperities.

In the present study, the model junction problem analysed in [3] is reconsidered and further investigated in view of the recent progresses of the phase field model for brittle fracture [4,5]. The junction between two triangular asperities in 2D is numerically modelled by considering perfect adhesion at their common interface and a far-field shearing load. The phase field approach to brittle fracture allows to simulate the stage of crack nucleation and its propagation, reproducing the experimental results in [3]. Moreover, as a further step with respect to the results in [3], by exploiting the computational facilities of virtual testing, different junction geometries are examined. Finally, different size-scales of the asperity junction are considered, to elucidate the occurrence of size-scale effects on the crack pattern and eventually on the mode of wear, essential to understand the transition from adhesive to abrasive wear.

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MS8: Enriched finite-element formulations for fracture

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In recent years there has been a growing interest regarding the numerical modeling of fracture mechanical problems. For that purpose, several innovative approaches, using element or nodal enrichment strategies, were proposed. The aim of this minisymposium is to address all these enrichment techniques, both from a theoretical and a practical perspective. The topics to be covered include, but are not limited to:

- embedded and generalised/extended finite element formulations for cracks or heterogeneities;
- modeling of material interfaces and/or microstructure of a material;
- new techniques to overcome convergence problems in the modeling of fracture in brittle and granular materials;
- 3D and large scale problems.

Damage coupled with elastoplasticity – robustness and stability issues of a special finite element technolgy

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In the present contribution, a coupled damage-plasticity model is developed. The anisotropic variant is based on a second order damage tensor and applies two potentials, one for the plasticity and one for the damage part. The formulation includes only very few material parameters and can be easily transferred to large deformations. Example computations and comparison with experimental results show that the model yields physically reasonable results whereas it is numerically still feasible.

An important part of the talk is the study of a suitable finite element technology (see e.g. [1]). The focus is here on reduced integration with hourglass stabilization. Due to the fact that the physically relevant equations are only evaluated in the centre of the element, the element behaves extremely robustly in the way that extreme distortions of the element shape are possible. In the contribution, issues such as accuracy of the results as well as mesh dependence are in the focus. The simulations are run very far beyond the stress maximum.

A further important aspect is the stability behaviour. In this context, we investigate the consequences of loss of positive definiteness of the material tensor as well as of the acoustic tensor. The influence of a non-local extension [2] of the model is brought into play and investigated.

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Multiscale analysis and Material Sensitivity of Failure in Heterogeneous Materials Using an Interface-Enriched Generalized FEM

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Abstract

A multiscale, parallel finite element solver is developed to efficiently solve large structural problems involving materials with complex microstructures such as those encountered in particulate and fiber-reinforced composites. At the mesoscale, emphasis is placed on capturing the geometry of the material interfaces using a hierarchical, structured discretization of finite elements that do not conform to the microstructure. In the elements traversed by material interfaces, we adopt an interface enriched generalized finite element method (IGFEM) which relies on polynomial enrichment of the solution at points defined by the intersection of the material interface with the non-conforming element edges. This approach allows for the effi- cient and accurate modeling of the microstructure generated directly from micro-CT images of actual composite samples. Another key advantage of the IGFEM is its ability to simplify the complex and time-consuming mesh generation step associated with the simulation of several representative microstructures.

At the mesoscale, emphasis is placed on modeling the failure of the material interfaces using a cohesive model between the cohesive tractions acting across the interface surfaces and the corresponding displacement jumps. To that effect, a discontinuous (C-1) enrichment of the displacement solution is used in the non-conforming elements traversed by failing material interfaces. The impact of interface failure processes taking place at the mesoscale on the macroscopic constitutive response of the heterogeneous medium is captured using a homog- enization scheme.

The multiscale, nonlinear IGFEM analysis is complemented by a multiscale adjoint differentiation scheme used to extract the material sensitivity of the macroscopic constitutive response on the parameters (strength and critical displacement jump) that define the cohesive failure of the material interfaces.

Keywords: IGFEM, Sensitivity Analysis, Multiscale, cohesive

*Speaker

Phase field approach to brittle fracture for functionally graded materials

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In last few years, a considerable attention has been devoted to variational-based phase field approaches to model and simulate fracture [1]. According to this approach, fracture is described by a scalar damage variable, which affects the material properties in order to model the transition from the undamaged and the broken material. One of the major advantage of this diffusive-type formulation is that cracks in the material are represented through iso-lines of the phase-field variable equal to unity. Consequently, a crack does not need to be treated as a material boundary, thus avoiding the representation of discrete displacement discontinuities. From the computational viewpoint, this formulation can be implemented as a finite element coupled multi-field nonlinear problem.

In this study, the phase field approach to brittle fracture is generalized to address functionally graded materials (FGMs). These nonhomogenous materials, whose elastic properties and toughness are function of the position, have been characterized from the fracture mechanics point of view using asymptotic methods and linear elastic fracture mechanics, see e.g. [2,3]. However, the finite element simulation of crack growth without remeshing is still an open issue. Here, two types of grading are considered: (*i*) Young modulus and toughness linear or exponential space-dependent functions; (*ii*) angular grading of Young modulus and toughness. The derived novel computational framework is applied to FGMs in order to elucidate the role of grading on the crack path under mixed mode fracture conditions.

Acknowledgments
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A phase field approach for modeling damage using natural neighbour Galerkin method

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In this work we present a phase field approach for modeling damage using natural neighbor Galerkin method. Numerical simulations based on standard continuum damage models are often found to suffer mesh dependency. The growth of damage tends to localize in the smallest band that can not be captured by the coarse spatial discretization. As a consequence, increasingly finer discretization grids lead to faster crack initiation and growth. In the limit of infinite spatial resolution, the predicted damage band has a zero thickness and therefore the crack growth becomes instantaneous. The response is then perfectly brittle, that is no work is needed to complete the fracture process. The non-physical mesh sensitive response is normally overcome by using a regularization scheme such as the gradient theory. The recently developed phase field approach to fracture [1, 2] also serves as a means to provide nonlocal results. The non-locality is introduced by considering a diffuse interface concept. To this end, we propose in the present work a meshless natural neighbor Galerkin method outlined in [3, 4], for modeling damage using the phase field approach. The performance of the proposed formulation will be demonstrated by means of some representative numerical examples.

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An Efficient Parallel Implementation of the Enhanced Local Pressure Model for the Simulation of Hydraulic Fracturing

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Hydraulic fracturing, or fracking, is the process by which a fracture propagates due to hydraulic loading, i.e. by applying a fluid pressure inside the fracture. In geo-mechanics, this process is applied to stimulate oil and gas reservoirs by injecting a highly viscous fluid into the underground formation. Another application is the creation artificial wells with increased conductivity for Enhanced Geothermal Systems. The fracking procedure can be controlled by adjusting several parameters, such as the magnitude of the hydraulic loading and the viscosity and density of the pressurized fluid. In order to understand the effect of these parameters on the fracture process, in relation to the mechanical properties of the formation, numerical simulations can be of assistance.

Generally, the starting point for developing a numerical model to predict crack growth in geo-mechanics is a poromechanical continuum model for a fully saturated medium. Here, the fluid flow in the bulk is represented by a mass-balance equation in combination with a Darcy law. In order to correctly model crack growth due to fracking, the following three key ingredients need to be taken into account: (i) the exchange of fluid between the fracture and the rock formation (ii) the fluid flow in the fracture and (iii) the changing spatial configuration due to fracture propagation, i.e. the creation of a crack surface [1].

In the recent years, the development of models to predict crack growth in fully saturated materials has concentrated on the application of the partition of unity method [2, 3]. An extension of these models is the enhanced local pressure model by Remij *et al.* [4]. In this model, the pressure in the fracture is described by an additional set of degrees of freedom. The pressure gradient due to leakage near the fracture surface is reconstructed analytically, based on Terzaghi's consolidation solution. As a result, relatively coarse finite element meshes can be used. In addition, with this numerical formulation it is ensured that the injected fluid flow ends up completely in the existing pre-crack.

Recently, the Enhanced Local Pressure model has been extended to simulate fracking processes in three-dimensional domains and the propagation of hydraulic fractures near natural faults and other cracks [5]. In order to be able to run realistic simulations with these models, parallelization of the code is inevitable.

In this paper, we will present the parallelization of the Enhanced Local Pressure code by using a domain decomposition strategy [6]. Special attention is paid to the data man-

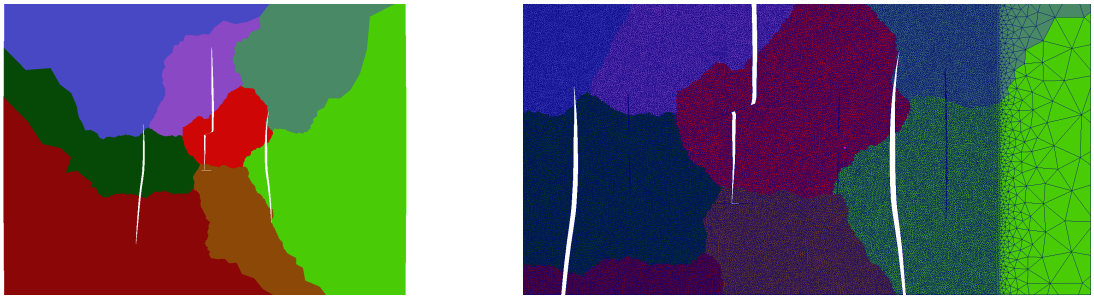

Figure 1: The parallel simulation of multiple hydraulic fractures near existing faults. Each color in the figure denotes a different domain, which is calculated by a different processor. A zoom of the figure with the dense finite element mesh is shown in the figure on the right-hand-side.

agement of the additional degrees of freedom and the calculation of the partition of unity enrichment functions. The resulting linear system of equations is solved in parallel using a GMRES algorithm in combination with a two-level preconditioner. The performance of the code is demonstrated by means of a number of realistic fracking simulations, including a case with multiple, interacting cracks.

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A simplified hydraulic fracturing model in 3D with prescibed pressure profiles

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Abstract

A simplified and robust hydraulic fracturing (HF) model is introduced where the propa- gation of an arbitrary three dimensional fracture can accurately be predicted with minimum effort. In HF, the Reynolds' equation usually poses a challenging task for numerical meth- ods, in particular in a viscosity dominated propagation regime [1] where no distinct lag between the fluid and fracture front exists due to the singularities of the fluid pressure and stresses in the host rock. That equation often requires several iterations between the fluid and solid models which can lead to a computationally expensive and unstable simulation [2]. As a simplification, we propose the use of pre-defined pressure distributions instead of the Reynolds' equation which enable a quasi crack-width-independent description of the fluid pressure. In [1], it is shown that the pressure distribution has a constant behaviour in the toughness dominated regime and an r to the power of (–1/3) behaviour in the viscosity dominated regime, wherefore, these two pressure characteristics are considered in this con- tribution. The time-dependent behaviour of the dominant regime during the propagation is considered by a combination of both distributions which is based on a time-dependent scaling function $0 \leqslant \Phi(t) \leq 1$. This function scales the influences of the toughness and viscosity regimes at a specific time by $\phi(t)$ and $(1 - \phi(t))$, respectively. It is noted that the aim of this contribution is not the formulation or definition of the scaling function, instead our interest is on a more generalised description of the pressure distribution exerted by the fracking fluid onto the surrounding host rock in the context of the XFEM [3].

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Keywords: propagation regimes, fluid model

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3D crack propagation within the polycrystalline microstructure of dual phase steels during forming processes

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Abstract

During forming processes of dual phase steels within the polycrystalline microstructure cracks might nucleate and propagate and eventually lead to the failure of the material. In addition, during the time the formed engineering part is in service, the damage development emanating from the production of the part and its use might have an influence on its life- time. Hence, it is important to know about the initiation and growth of microcracks and their effect on the macroscopic behaviour of the material and the engineering part.

In this contribution we present a method to calculate crack propagation within the poly- crystalline microstructure of steels under finite deformations. The method incorporates the XFEM in combination with level set techniques and a nonlocal modified Gurson type damage model in combination with finite deformation crystal plasticity. The nonlocal damage can be interpreted as a void volume fraction, and its value along the crack front is used to determine whether the discrete part of the crack propagates. We define the crack propagation direc- tion as the direction of fastest void volume growth. For details of this approach we refer to [1].

Due to complicated crack geometries and crack propagation the XFEM enrichments of nodes might lead to badly conditioned global system matrices due to possible near linear dependencies between standard and enriched degrees of freedom or between enriched degrees of freedom. This problem has been addressed in [2] and other publications. One way to over- come this problem is to stabilize the element stiffness matrices by adding some small artificial stiffness to those eigenmodes that should not have a nearly zero eigenvalue. This technique is presented for the case of linear elastic fracture mechanics in [2]. Here it is extended and applied to the severely nonlinear case including non-symmetric stiffness matrices and localization phenomena. [1] S. Beese, S. Loehnert and P. Wriggers: Modelling of Fracture in Polycrystalline Materials. In: Giulio Ventura and Elena Benvenuti (Editors) Advances in Discretization Methods, SEMA SIMAI Springer Series, vol 12, (2016), ISBN 978-3-319- 41245-0.

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Keywords: XFEM, ductile fracture, crack propagation, stabilisation

*Speaker

Crack propagation using XFEM coupled with Adaptative Mesh Refinement

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Abstract

The eXtended Finite Element Method (XFEM) [1] [2] has been used in Cast3m [3] to simulate static and dynamic problems of crack propagation in elastic-plastic materials. In the context of non-linear behaviour we used over-integrated elements[4]. Computation of incremental propagation implies an accurate description of physical quantities (stress, strains, internal variables ...) in a limited area around the crack front, specilly when local citeria and inelastic materials are concerned. Then apriori ignorance of the propagation path, forces us to use a really fine mesh of enriched elements in a rather large zone. Consequently the cost of this method increases drasticly for engineer-sized problems.

Thus we decided to develop an adaptative mesh refinement tool, to create a fine meshed zone that will follow the crack front during the propagation. This tool is completed whith the XFEM method and limits the calculation time with the number of small enriched elements.

The procedure used to simulate a crack propagation with the XFEM method coupled with an AMR tool in Cast3m, will be described. More particularly the presentation focuses on two important steps of this procedure :

1) the refinement algorithm for enriched elements.

2) the method used to transfer the mechanical fields from one mesh to another between two steps of propagation, and the good properties of this field transfer.

The efficency of the method is illustrated by an application case of crack propagation in elastic-plastic media in 3D.
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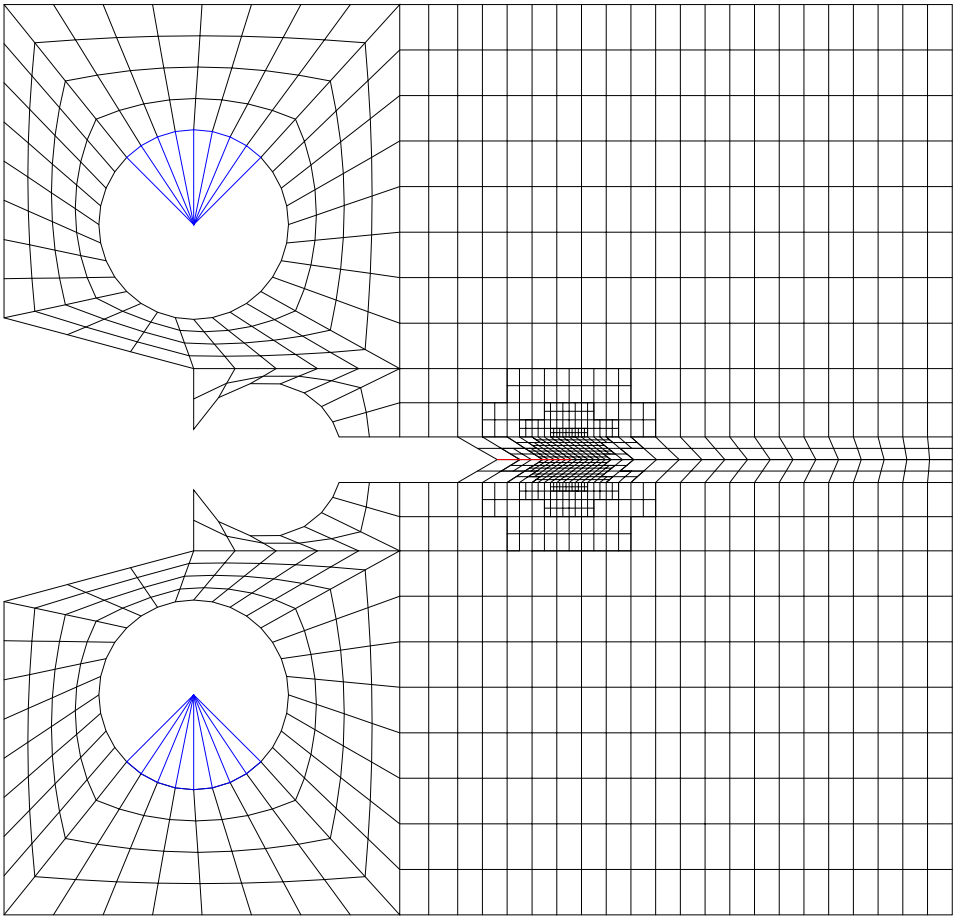
Keywords: eXtended Finite Element Method, Adaptative Mesh Refinement, crack propagation, elastic, plastic, 3D, field transfer



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Error-based mesh adaptation during crack propagation simulation with X-FEM

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Abstract

Even though the eXtended Finite Element Method offers a lot of flexibility in terms of mesh generation, control of the mesh refinement remains a critical issue for the sake of numerical accuracy. This is especially true when dealing with linear elastic fracture mechanics where stress intensity factors governing the propagation are computed in an area close to the crack front. Mesh adaptation is therefore a logical option but must be done with care in order to compromise the computational cost and the interpolation error.

The adopted error estimator is based on a global recovery technique of the strain field coher- ent with the adopted enrichment of the finite element formulation, as proposed by [Duf08]. Based on this, different mesh refinement criterion are tested and compared. These can be classified either as Equal-distribution criterion to reduce the global error and balancing the local one all over the computational domain, either as Min-Number criterion [Coo95] to min- imize the total number of elements for a given global error.

Once this is defined, several mesh adaptation strategies combining both mesh refinement and coarsening are set-up, tested and compared. This is done first on the classical Westergaard problem for which an analytical solution is available. Evolution of the local and global errors, effectivities and the total number of elements through the mesh adaptation iterations and studied. Adequacy of the applied strategies with respect to the X-FEM technique is highlighted.

Regarding crack propagation problems, best suited strategies are compared on a 3D four- points bending test. A drilled hole in the specimen attracts the crack so that mixed-mode fracture do occur. Error-based mesh adaptation is applied at each crack propagation step and the influence of the chosen strategy on the crack path is studied. By doing so, at the end of the propagation, the total number of elements is about one order of magnitude lower than a corresponding one obtained with a fixed mesh. As the computational cost of error computational and adaptation cannot be neglected, several ways of improvement are consequently proposed.

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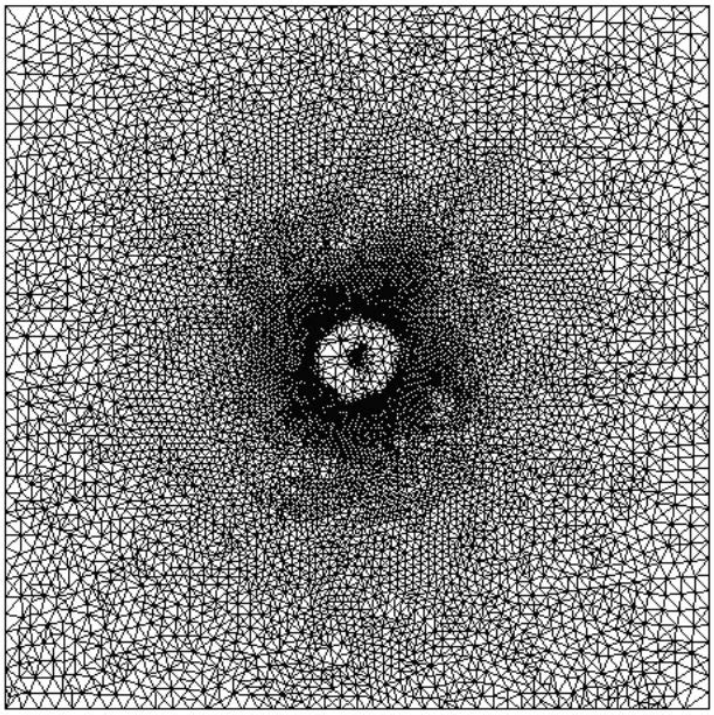

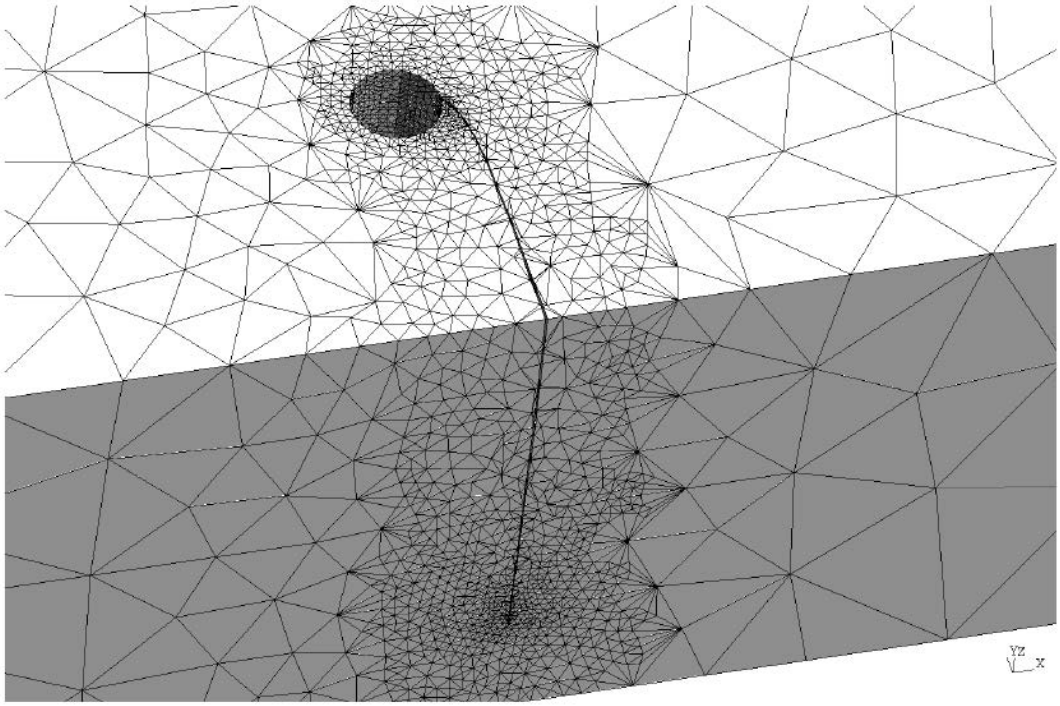

Keywords: XFEM, recovery techniques, error estimator, mesh adaptation, crack propagation

Modelling the failure of honeycomb materials with gradient-elasticity

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Honeycomb materials are used in this work as model macroscopic structure for analyzing the interactions between a crack and the surrounding material structure. As for crystals, the symmetry of the lattice can be used to define the symmetry of the physical properties of the lattice. Namely, the elastic tensor almost inherits directly the material symmetry. Concerning failure, the existence of preferential cleavage planes leads to anisotropy in the fialure behaviour. This effect is called latter on diretionality. Further, depending on the crack length compared to the size of the unit cell, size effects could be obtained.

Accounting for size effects requires that a internal length is introduced in the macroscopic continuum model. Gradient-elasticity is selected as it was shown in [1] that it allows for a transfering between the scales the meaningful kinematic variables. A failure criterion is developped in this context. It is shown that the dicrete nature of the lattice cannot be ignored at this stage. The criterion is based on the transfert of strain and strain gradient at the crack tip to a unit cell boundary. Then, using this crack tip variables to defined boundary conditions, the crack direction is determined.

An X-FEM implementation of gradient elasticity is performed using C^1 finite elements. This allows for modelling crack propagation independently of the mesh. Results on strongly anisotropic lattices show that the model is able to capture directionality and size effects.

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Dealing with many interfaces and Lagrange multipliers within the extended finite element method

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Modelling diffuse microcracking in heterogeneous materials, like rocks is important from the engineering point of view. The numerical modelling of the phenomenon requires three main ingredients: generation of representative volume elements (RVE) for the correct representation of the rock grains, discretization of the governing equations and applying a proper crack propagation model. This work concentrates on the discretization part, while keeping in mind the other two aspects.

In certain types of rocks (like granite for example), experiments show that intergranular cracking is more likely to happen than intragranular cracking. We use this assumption in the numerical simulation, i.e. all possible crack paths are supposed to be known from the beginning. In this way, discontinuities in the displacement field are present along all grain boundaries (interfaces). Until a crack really opens along an interface, this discontinuity must be suppressed. Several methods exist for the prescription of interface conditions. We apply the Lagrange multiplier method for two reasons. First, it does not introduce any numerical parameter. Second, (as the cohesive model) it represents the interfacial traction that can later be used in crack propagation.

The generation of a conforming mesh for many grains (which can be concave, elongated and of different sizes) is challenging particularly in 3D. Therefore, we use the fictitious node method [3], an element technology enabling the straightforward representation of strong discontinuities within an element (and similar to the extended finite element method [4]). The naive use of the Lagrange multiplier method on non-matching grids often leads to unstable formulations due to the failure of the LBB condition. The creation of a stable Lagrange multiplier space with one interface was performed for linear [1] and quadratic [2] triangular elements. This work provides a systematic approach for many interfaces possibly cutting each other using bilinear quadratic elements. A robust and general method is created to handle the situation when an interface is close to a node. The proposed method naturally extends to 3D.

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Extended quadratic elements for strong discontinuities

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There is no question that the quality of eXtended Finite Element (X-Fem) solutions to problems with strong discontinuities has dramatically improved in the last decade, nor can it be doubted that there is still a long way to go.

For instance, most X-Fem implementations make use of either linear triangles/quadrilaterals in 2D or linear tetrahedra/hexahedra in 3D and increasing the order of the approximation space is not sufficient to guarantee an improvement in performances and convergence properties [1].

When considering Heaviside-like enrichments, severe ill-conditioning is likely to occur for elements crossed by an interface whenever the area or volume ratio between the two parts on the opposite sides of the interface is very small. However, in practical situations there is no way to avoid the occurrence of discontinuities arbitrarily close to nodes or element sides, since by its very definition an X-Fem interface can be arbitrarily positioned within a mesh.

In this communication we present a new family of extended quadratic elements enriched with Heaviside-like functions. The proposed elements will be shown to behave fairly better compared to usual quadratic approximations in that both the size and the condition number of element matrices are considerably lower compared to classical Lagrangian elements.

Numerical results for representative test cases involving strong discontinuities will demonstrate the capabilities of the proposed approach.

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Higher Order PDS-FEM and Application for Modeling Brittle Cracks

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We present the higher order extension of Particle Discretization Scheme[1] (PDS) and its implementation in FEM framework (PDS-FEM) for simulating 3D crack propagation in large scale models. A unique property of PDS is the use of conjugate tessellations $\{\Phi^\alpha\}$ and $\{\Psi^\beta\}$ (as an example Voronoi and Delaunay pair) to approximate functions and their derivatives, respectively. In the higher order extension, functions and their derivatives are approximated as the union of local polynomial expansion about the mother points of each element of the respective tessellations. Let $\boldsymbol{x}^\alpha$ and $\boldsymbol{y}^\beta$ be mother points of each tessellation element Φ^α and Ψ^β; and $\phi(\boldsymbol{x}^\alpha)$ and $\psi(\boldsymbol{y}^\beta)$ be characteristic functions of Φ^α and Ψ^β, respectively. Higher order PDS approximates a function $f(\boldsymbol{x})$ as $f(\boldsymbol{x}) \approx f^d(\boldsymbol{x}) = \sum_{\alpha,n} f^{\alpha n} P^{\alpha n}(\boldsymbol{x})$, where $\{P^{\alpha n}\} = \{1, (\boldsymbol{x}-\boldsymbol{x}^\alpha), \ldots\}\phi^\alpha(\boldsymbol{x})$ is a set of suitable polynomial bases. The unknown coefficients, $f^{\alpha n}$, are found minimizing a certain error norm. Since the support of $P^{\alpha n}$ is restricted to each tessellation element Φ^α, the approximation $f^d(\boldsymbol{x})$ has numerous dicontinuties along the boundaries of Φ^α. It is to define bounded derivatives PDS uses the conjugate tessellation Ψ^β for approximating the derivatives. Just as the function, the drivatives are approximated as $\frac{\partial f(\boldsymbol{x})}{\partial x_i} \approx \sum_{\beta,m} g_i^{\beta m} Q^{\beta m}(\boldsymbol{x})$, where $\{Q^{\beta m}\} = \{1, (\boldsymbol{x}-\boldsymbol{x}^\beta), \ldots\}\psi^\beta(\boldsymbol{x})$. The inherent numerous discontinuties in the function approximation $f^d(\boldsymbol{x})$ can be utilized to numerically efficiently model discontinuities in boundary value problems, like crack propagation.

Higher order PDS is implemented in FEM framework to numerically efficiently simulate 3D crack propagation in elastic solids. The details of FEM implementation and modeling cracks, verification with benchmark problems including mode-I crack problems, and simulations of 3D propagating cracks are presented.

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MS9: Statistical aspects of fracture

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Stress concentration in the vicinity of crack tip enhances the role of microscale heterogeneities and defects on the macroscale failure behavior of solids. This translates into strong fluctuations during crack and damage evolution, puzzling scale free fracture patterns and large specimen-to-specimen variations of strength, which are difficult to capture through conventional continuum approaches. The past twenty years have seen the emergence of novel approaches, some of them inspired from statistical and non-linear physics, which may permit to overcome the above difficulties. The objective of this minisymposium is to discuss the recent advances in the modeling of the statistical aspects of fracture and their experimental investigation. Applications of this research to material characterization, failure analysis and structural health monitoring are also most welcome. Key topics will include:

- Predictability in brittle fracture: Statistics of failure strength, material defect characterization, crack initiation, size effects
- Statistical characterization of patterns and shapes in fracture: crack trajectory, morphology of fracture surfaces, fragmentation, crack networks
- Intermittency, crackling and universal features :acoustic emission, stick-slip dynamics of cracks, crack pinning, earthquake statistics
- Statistical approaches in damage mechanics : quasi-brittle materials, compressive and shear failure, localization
- Scale coupling and emergence of effective failure properties: Theoretical and numerical methods to address multiscale processes, homogenization techniques, stochastics approaches
- Statistical tools for engineering applications: Structural health monitoring, acoustic emission techniques, risk assessment, quantitative fractography, failure analysis

Numerical, theoretical and experimental studies are welcome and encouraged.

Dependence of Transverse Failure of Composites on Statistics of Fiber/Matrix Interface Properties

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Abstract

A key failure mode in fiber-reinforced composite laminates, transverse failure has been the focus of multiple studies, as it is often a precursor to other, more critical failure modes such as inter-ply delamination and fiber breakage. The initiation and propagation of transverse cracks are affected by a variety of random microstructural quantities including fiber place- ment, fiber radii, constitutive properties of the fibers and the matrix, and failure properties of the fiber/matrix interfaces. Since experimental observations on carbon/epoxy material have indicated that transverse failure is primarily associated with fiber/matrix interface debond- ing, this study focuses on quantifying how the statistical nature of interfacial properties affect the composite failure response. The main objective of this work consists in extracting the sensitivity of the transverse failure response of a 90-degree ply with respect to the distribu- tion characteristics (mean and standard deviation) of the fiber/matrix interface properties, which are assumed to be described by a Weibull model. The computational model of the transverse failure event combines a nonlinear Interface-enriched Generalized Finite Element Method (IGFEM) solver specially developed for this application, and a cohesive model of interface debonding. The sensitivity analysis relies on an analytic computation (using the direct method) of the sensitivities of the failure response with respect to the cohesive prop- erties of each interface. The approach is first demonstrated on a 'reference' model involving a one-dimensional domain containing N cohesive interfaces described by randomly selected cohesive failure properties. The method is then applied to the more complex problem of a composite laminate involving many fibers and whose virtual model is constructed directly from optical images of a 0/90/0 composite laminate.

Keywords: Composite, cohesive model, interface, statistics, sensitivity analysis, transverse failure

*Speaker

Out-of-plane crack propagation in heterogeneous materials under pure mode I loading

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Heterogeneous materials are all around us, be it by choice (concrete, composite, etc.) or by mistake (welding defects, quenching of a workpiece). Describing the role of those material microstructures on the behavior of cracks is a prerequisite to make reliable predictions on the resistance and lifetime of solids and insure people safety as well as environmental protection. It raises important concerns especially in a time where the emergence of new fabrication methods (e.g. 3D printing) and the appearance of social and environmental concerns (e.g. recycling plastic waste in concrete) multiply the heterogeneous materials engineers have at their disposal.

Motivated by these challenges, we computed the out-of-plane propagation of a semi-infinite plane crack under pure mode I loading in brittle heterogeneous materials through a first-order perturbation analysis. Using concepts issued from Linear Elastic Fracture Mechanics, we compute the evolution of the in-plane and out-of-plane perturbations of the crack front in an infinite medium made of a homogeneous matrix and random distributed spherical inclusions, whose toughness is greater than the one of the surrounding matrix. The perturbation analysis is conducted with the formulae extracted from the work of Gao and Rice for the in-plane situation [1] and Movchan et al. for the out-of-plane perturbation [2]. Simulation results allow us to determine the influence of the microstructural features on the macroscopic fracture behavior. We will focus on how the microscopic variations of toughness control the effective toughness of the sample and affect the fracture surface roughness as well as the intermittent crack dynamics [3, 4].

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Dynamic Fracture in Heterogeneous Material, the Influence of Elastic Wave Field and Geometry of the Sample

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We present an experimental study of the dynamics of rapid moving cracks in brittle heterogeneous amorphous polymers. We first compare some of the features of dynamic fracture in heterogeneous and homogeneous materials, including the micro branching instability. We compare the behavior of the crack front in the homogeneous and heterogeneous case to unravel the possible influence of the elastic wave field as an effective disorder. Finally we analyze the roughening properties of the crack front in correlation with a model identifying the dynamically growing front with an elastodynamic line in a random media.

1. Introduction

Dynamic fracture mechanics [1], its instabilities and associated generic aspects [2] have been the focus of many studies over the last thirty years. The singularity of the dynamic stress field at the vicinity of the crack has been experimentally measured [2] and the influence of elastic waves on the crack tip has been questioned [1-3]. Conversely the 3D aspects, the influence of the finite geometry and the retroaction of the elastic waves on the crack still remain open questions, both on theoretical and experimental sides. Besides, the presence of defects at small scales has been shown to yield giant scale-free fluctuations reminiscent of critical behavior in problems of quasi static crack propagation [4]. Here, we will extend this research to the dynamic case, investigating the influences of defects as well as the key role of elastic waves in this problem as an effective field of heterogeneities.

2. Experimental Setup

The experiment consists in driving a stable tensile crack at high velocity in a model material obtained by sintering PMMA beads. Specimens (fig 1) are parallelepipeds of dimension 140×125×15 mm^3. A rectangular notch is milled at one of the lateral faces and a thick groove is introduced. It permits to accumulate stresses until a dynamic fracture is initiated. The sample is then placed between two jaws of a loading machine. The location of the crack tip as a function of time is determined from measurement of the resistance of a network of thin metallic stripes (step 50 µm). As the crack progresses, the threads are torn apart and a jump in output voltage is observed.

Once the sample is broken, crack surfaces are visualized post-mortem using either standard microscopy or a Bruker mechanical profilometer. These postmortem analysis allow us to study the surface roughness evolution created during the dynamic fracture extension to understand how morphological fluctuations dynamically organize for this type of rapid growth of the fracture front [6].

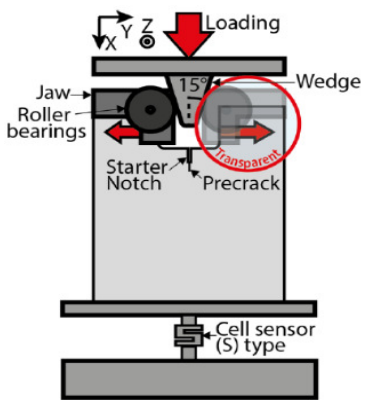
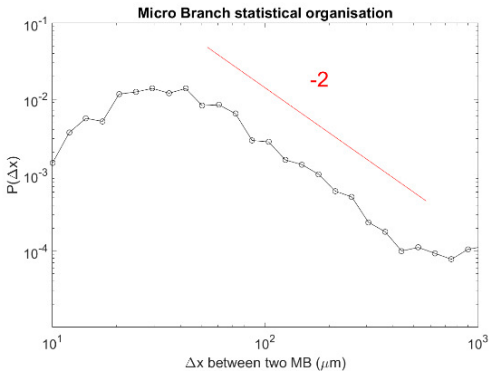


Figure 1. sketch of the experiment setup [5]

3. First Results

Micro Branching instability is a generic aspect of the dynamic, opening mode, fracture. Here, we will examine the key role of elastic waves played on the problem by systematically studying the effect of the sample geometry. A first study has revealed a power law distribution for the distances between successive micro-branches along a line which is the signature of self-organization and, as such, support the hypothesis of a wave mediated process. A second study has shown an abrupt and highly localized modification of the behavior of fracture surface's roughness in heterogeneous samples from a power law structure function for the fastest part of the propagation to a logarithmic behavior for the slowest. Same pattern emerged for the homogeneous ones. This could mean that the wave field behave like an effective disorder which affect the crack front growth.

Fracture properties in the heterogeneous samples will be addressed. Fracture energy versus velocity curves will be presented for various heterogeneity size and different sample geometries for a specific case). Besides, the postmortem statistical analysis of surface roughness will provides information on the dynamic growth of the crack line and inform us on how some characteristic intrinsic length-scales (eventually specimen size dependent) emerge in the different regimes.



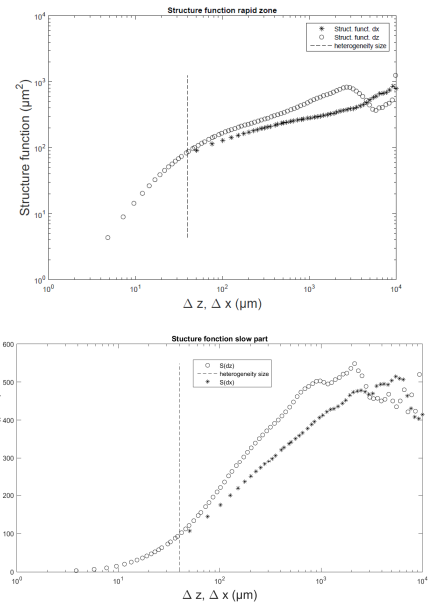


Figure 2. (a) Distribution of distances between two micro branches along a line of instabilities. A power law distribution is measured. (b) Structure function for one experiment on heterogeneous material ($d_{\text{het}} \sim 40\ \mu m$) in the fastest and the slowest regions.

4. Conclusions

The dynamic evolution of the wave front in a heterogeneous material and the key role played by elastic waves history and retroaction will be examined here via a series of experiments in homogeneous and heterogeneous materials broken at high speed.

Acknowledgements

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On the dynamic perturbation of crack front by micro-scale material heterogeneities

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Crack growth at high speed is controlled by the interplay of the moving front with micro-scale material properties [1]. Due to its associated fine time and length scales, this heterogeneous dynamic fracture problem remains a current challenge both for numerical modeling and experiments. In this work, we study the perturbation of an in-plane dynamic crack in presence of micro-scale heterogeneities with an idealized shape of weaker and tougher regions. A comparison is made with an equivalent interface made of average homogeneous fracture properties. The dynamic rupture of a planar interface is modeled following a cohesive approach. The elastodynamic response of the surrounding semi-infinite bulk is computed with a boundary integral formulation, which provides a very fine discretization of the fracture plane unattainable with more conventional methods [2, 3]. Our study starts with a classical problem of earthquake dynamics; the criterion governing the inter-sonic propagation of shear cracks. We show how an increase in toughness heterogeneity dramatically changes rupture dynamics, even when the distortion of the crack front is prevented by plane strain conditions. Heterogeneous properties lead to increasing elastic radiation caused by the successive periods of crack acceleration, which significantly eases the transition to super-shear rupture speed. Since any material presents heterogeneities at a certain scale, we further investigate how the heterogeneous interface properties (size of the heterogeneities, toughness ratio between weaker and tougher portions of the interface) control the transition from quasi-homogeneous to heterogeneous dynamics. We finally measure the size of the fracture process zone and emphasize the role of this critical length scale for heterogeneous dynamic fracture.

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Linear (in)stability analysis prediction of the fault angle in damage models

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Under the assumption that the frictional resistance impeding the development of a shear fault is the same resistance that governs the sliding friction across a fault once formed, the Mohr-Coulomb criterion predicts the critical stress and the fault angle of an homogeneous material. However, experiments have shown that it does not always capture correctly the dependence of the fault angle on the confinement applied during failure tests. We present a progressive damage model of a disordered material based on an elasto-brittle rheology that implements the Mohr-Coulomb criterion at the local scale. Using numerical simulations, we explore the dependence of the fault angle on the internal friction coefficient, the Poisson's ratio, and the confinement applied on the sample, and show that it deviates significantly from the Mohr-Coulomb prediction. A linear stability analysis of this damage model shows that there are unstable modes in the damage field, with the most unstable mode giving the fault angle. This prediction is in very good agreement with the results of the numerical simulations at weak disorder. Our approach does not limit to solids described by the Mohr-Coulomb criterion and applies to a wider class of elasto-damageable materials.

Statistical size effects on the mechanical behavior of concrete under uniaxial compression

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The size effect on strength of concrete has been studied for a long time from various approaches [1]. The weakest-link theory remains nowadays the basic tool to interpret statistical size effects on strength, i.e. how the probability of failure under a given stress depends on external size. The main shortcoming of Weibull's theory is that the activation of fracture from the weakest flaw is assumed to set the final strength, i.e. possible interactions between microcracks and defects during progressive damage are implicitly neglected [2]. The objective of this study is to determine experimentally the influence of "external" (sample) and "internal" (microstructural) sizes on compressive strength of concrete. For this purpose, about 600 uniaxial compression tests were conducted on cylindrical concrete specimens with four different diameters varying from 40mm to 160mm but a constant length-to-diameter ratio (L/D=2). These specimens were prepared from three different compositions (mean aggregate size and proportion). The associated microstructural correlation length was extracted from image analysis. Acoustic Emission (AE) signals were recorded during several tests on samples of different sizes and compositions to analyze the progressive damaging process up to failure. The relationships between compressive strength, elastic modulus, dissipated energy up to failure in one hand, and microstructural as well as specimen sizes on the other hand, were analyzed statistically. This demonstrated the failure of the weakest-link approach to describe size effects on compressive strength of concrete.

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Crack-Crack Interaction in Linear Elastic Fracture Mechanics

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Predicting the direction of a crack submitted to mixed mode loading is key in a variety of domains ranging from earth science to structure safety. In the context of Linear Elastic Fracture Mechanics (LEFM), many bifurcation criteria have been proposed overtime: the Principle of Local Symmetry (PLS) [1], the Maximum Tangential Stress (MTS) [2], the Strain Energy Density (SED) criterion [3], ... The MTS and PLS are the most widely used and give extremelly simillar results. [4]

Whether the theoretical framework of LEFM+PLS is sufficient to study propagation paths of interacting cracks is still under debate. The simplest case of crack interaction is sometimes referred in the literature as *en-passant* cracks pairs (EP-cracks): two initially straight, parallel and offset cracks which are submitted to far-field opening stress. It was observed experimentally many time that EP-cracks propagate straight ahead until their inner tips overlap, where they begin to attract one another. This behavior can be reproduced correctly assuming the PLS [5]. However, it has been observed that cracks may repel one another in some instances [6]. In this case, it seems that the PLS systematically underestimates the angle of repulsion [7].

We present a simple iterative method, based on FEM computation and SIF extensions, to compute quickly and accurately crack paths in the context of LEFM and under the assumption of PLS. Applying it to the case of EP-cracks, we were able to determine under which conditions the trajectories were repulsive or attractive. We computed full crack paths reproducing the experiments presented in [6], providing further insights into the limitations of applying the LEFM+PLS framework to the case of interacting cracks.

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Triangular fracture pattern reveal the nature of slip-stick transition in polymeric materials

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In certain polymeric materials like PMMA, cracks driven at some intermediate range of velocity display oscillatory response with a propagation speed alternating from fast to slow. This so-called stick-slip instability [1] is observed in several other systems during the peeling of a thin film or the sliding of a frictional body although emerging from different competing mechanisms.

In this work, we design a fracture test to investigate thoroughly the transition between the slip to the stick regime. Using a high-speed camera we accurately study the stick-slip dynamics of the crack during its deceleration. We observe that for different initial conditions G_{ini}, the transition from slip to stick happens at different energy release rates (G_t) [see Fig 1(a)] . Assuming a crack growth $G_c(v)$ law as proposed in Bonamy et. al.[4] for fast cracks we capture the crack front evolution equation during the slip regime until it enters in the stick regime [see Fig 1.(b)]. We also find that the different values of G_t at transition relates to different rate of change of energy release rate ($\dot{G}$) that is controlled by the initial condition G_{ini} of the crack.

To get more insights on the mechanisms governing the transition from slip to stick fracture, we analyze the fracture surface and find a unique recurring triangular pattern in the transition zone [Fig.2 (a)]. A closer look at the crack front geometry within this transition regions shows that the crack line is [See Fig. 2 b inset], reminiscent of a planar crack pinned by a tough obstacle of constant width [3]. To understand further this, we analyze

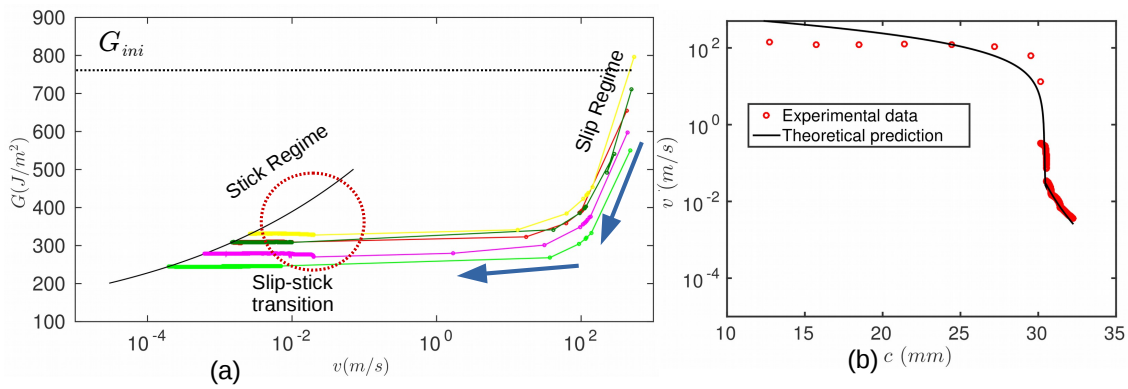

Figure 1: Crack dynamcis during the transition from slip to stick: (a) Energy release rate vs crack velocity for different G_{ini} (b) Crack velocity vs position for $G_{ini} = 800 J/m^2$

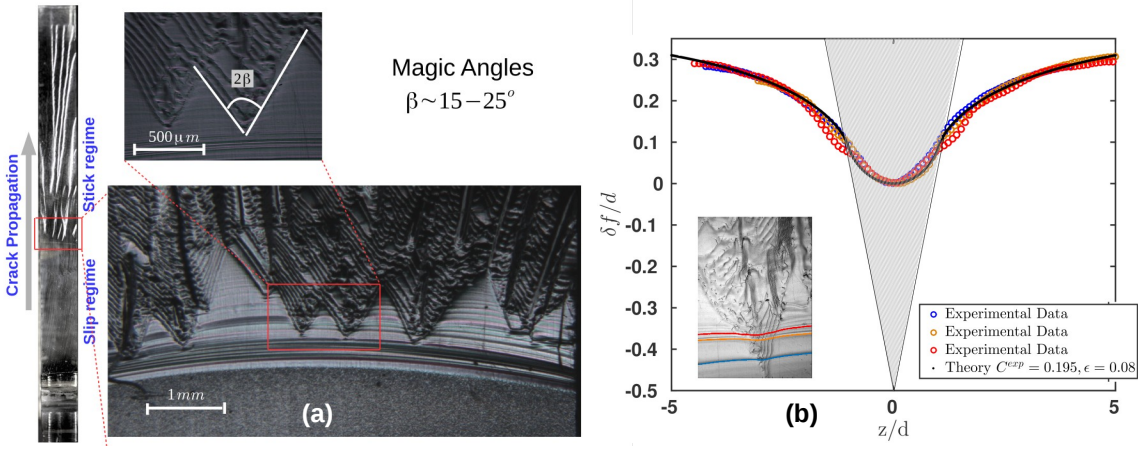

Figure 2: (a) Triangular fracture patterns observed at the slip-stick transition in PMMA (b) Experimental comparison of theoretical front shape with theory

the problem of a brittle crack front pinned by a triangular obstacle of large toughness. This problem can be solved exactly using Rice's work which provides the distribution of the elastic energy along a perturbed crack front [2]. The deformed shape not only depends on the toughness contrast (C) of the obstacle but also on the ratio ε of the growth speed of the obstacle along the crack front direction to a characteristic material velocity $v_0 = \frac{G_c(v)}{G_c'(v)}$ that emerges from the rate dependency of the fracture energy. This solution captures well the experimental front shapes observed on the fracture surfaces [See Fig 2 (b)] and interestingly provides us an estimate of the difference in fracture energies inside and outside the triangle. This is an indication that the transition from slip to stick occurs heterogeneously along the front through the nucleation of self-generating tough stick phase and their spreading along the crack front into the slip phase.The value of contrast C and velocity ratio ε selected by the material at the stick-slip transition will be finally discussed.

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Depinning dynamics crack front from a designed obstacle

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Abstract

Woods, nacre, bones or rationally designed artificial materials are all heterogeneous solids with mechanical properties far exceeding those of their constitutive components. Understanding the role of microscale heterogeneities on the macroscale fracture behavior of solids remains a query, even more pressing as the rapid development of microfabrication techniques now allows to tailor the microstructure at ever smaller scales. Recently, many progresses were made for weakly heterogeneous brittle solids where models describing a crack front as a deformed interface pinned by tough obstacles have been successfully applied. However, most natural and engineered materials have a microstructure composed of discontinuous heterogeneities which cannot be described as weak obstacles. The strong pinning regime when toughness gradients are large challenges standard homogenization approaches. In this regime, crack propagation is not quasi-static, but proceeds by intermittent and local micro- instabilities. Further, for a disordered distribution of obstacles, crack growth takes place close to the so-called depinning critical transition so that the crack front dynamics is dom- inated by avalanches spanning over a large range of length and time scales. The precise understanding of the front evolution during these rapid events is a prerequisite to predict and, further control the fracture energy of heterogeneous solids.

In this talk, I will present a combined experimental and theoretical study on the spatio-temporal dynamics of a crack front propagating at the interface between a rigid substrate and an elastomer. The instabilities are triggered by pinning the front by an isolated tough obstacle. We show that the relaxation dynamics follows a universal law which only depends on the crack speed at depinning for an obstacle of unit strength. To model this behavior, we introduce an equation of motion for the crack including a non-local line elasticity and a nonlinear rate dependency of the dissipative mechanisms taking place within the process zone. We provide an analytical solution for the depinning of a crack from a single obstacle that is shown to capture quantitatively all our experimental observations. The implications of our results on the energy dissipated during fast fracture events and the fracture behavior of materials with randomly distributed obstacles will be discussed

Keywords: Fracture, Crack dynamics, Depinning, Instability, Heterogeneity, Disordered material

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MS10: Multi-scale analysis

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This minisymposium is dedicated to discuss recent advances on fracture and failure of materials using methodologies that specifically consider mechanisms interacting across the scales. Scale transitions in space and time, involving at least 2 scales, are of interest as well as all issues related with the transfer between scales and computational efficiency. The prime focus on this topic is computational, but multi-scale approaches incorporating experimental input are also welcome. Topical points of interest for this minisymposium are:

- Two-scale modeling of microscopically based failure processes in materials
- Multi-scale methods for capturing emergent phenomena related to fracture
- Two-scale simulations of strain localization, crack initiation and propagation
- Computational homogenization based techniques enabling failure process simulations
- Numericaland experimental validation of multi-scale techniques for failure
- Numerical or analytical methods for bridging the gap between scales
- Coarse graining methods focusing on material damage and failure
- ROM, FFT,VME and other numerical procedures aiming at reducing the computational cost associated with multi-scale techniques in material failure.
- Multi-physics and coupled fields at different interacting scales

On the FE·Meshless computational homogenization for the analysis of two-dimensional heterogeneous periodic materials

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Over the last few years, substantial progresses have been made in the two-scales computational homogenization. This method is essentially based on the assessment of the macroscopic constitutive behavior of heterogeneous materials through the boundary value problem (BVP) of a statistically representative volume element, named as unit cell (UC). In this framework, the first-order method has now matured to a standard tool and several extensions have been addressed in the literature [1, 2].
In the present study, a first-order homogenization scheme based on a discontinuous-continuous approach is presented. At the mesoscopic level the formation and propagation of fracture is modeled employing a UC consisting of an elastic unit surrounded by elasto-plastic zero-thickness interfaces, characterized by a discontinuous displacement field. At the macroscopic level, instead, the model maintains the continuity of the displacement field. The inelastic effects are enclosed in a smeared way, introducing a strain localization band established on the basis of a spectral analysis of the UC acoustic tensor. Another key-point is the numerical solution of the UC BVP, which is obtained by means of a more cost-effectiveness mesh-free model. Both linear and periodic boundary conditions have been applied to the UC.

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General imperfect interface models at finite deformation and their influence on the macroscopic material response

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Abstract

Cohesive zone models are frequently applied for the numerical analysis of material failure. However, considering a geometrically exact description, fundamental principles such as balance of angular momentum [2], material frame indifference and thermodynamical consistency [1] are not trivially fulfilled in cohesive zone models – except for fully isotropic models. The assumption of a fully isotropic model – however - constrains the ability to model shear and anisotropic effects are excluded in general. Within this talk, the numerical implementation of the novel interface model [3], which is consistent with the aforementioned fundamental physical principles, is presented. The general framework enables the simulation of anisotropic hyperelasticity and anisotropic material degradation. Implementational aspects of this novel framework are discussed. Furthermore, the influence of general imperfect interfaces at the microscopic scale on the overall macroscopic response is investigated by embedding the interface model within an FE2-type homogenization scheme. Thereby the impact of anisotropic material degradation on the macroscopic material response is analyzed and several failure modes are compared.

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Keywords: cohesive zone, interface, homogenization, material degradation

*Speaker

An Enriched Quasi-Continuum Approach to Crack Propagation in Discrete Lattices

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Lattices of trusses or beams have been successfully employed for decades to model the effect of microstructure on the macroscopic response of discrete materials, such as foams or textiles, as well as of heterogeneous materials such as concrete. However, for real engineering scale applications such models suffer from a prohibitive computational cost due to the fact that the large separation between the scale of the microstructure and that of the macroscopic engineering structure necessitates an enormous number of elements (trusses or beams). In damage and fracture problems, where the mechanics of the problem is governed by the microstructural evolution of a limited part of the structure, fully resolving the microstructure may also be unnecessary.

In the present study we develop a multiscale methodology for precisely this type of problems. The method is based on the Quasi-Continuum (QC) method, a concurrent multiscale method originally designed by Tadmor *et al.* [1] for conservative atomistic systems. The method has been extended more recently to dissipative interactions, first on a heuristic basis in [2] and later more systematically on the basis of the minimization of incremental energy [3, 4].

Here we develop a strategy to adaptively refine the QC discretization to full resolution (i.e. to the lattice spacing) in those regions where the damage evolves, whereas full benefit is taken of the QC coarsening where the damage is inactive. In particular, an X-FEM enrichment is employed in the wake of the crack tip in order to allow coarsening in this region as well. This strategy ensures that the 'true' physics of the microstructural model are captured in the process zone, while nevertheless managing the computational tractability of the problem.

The performance of the method is demonstrated by a number of example problems. Figure 1 shows a preliminary result of a simulation of crack initiation and propagation in a Single Edge Notched Beam loaded in shear. The underlying lattice has an X-braced unit cell consisting of damageable trusses. The damage evolution results in the initiation of a crack at the notch tip. The crack then propagates in along the curved path which is so

characteristic for this problem. At each stage of the simulation, the process zone is fully resolved. Away from the crack tip, however, including in the wake of the crack tip, the QC discretization is substantially coarser than the lattice spacing.

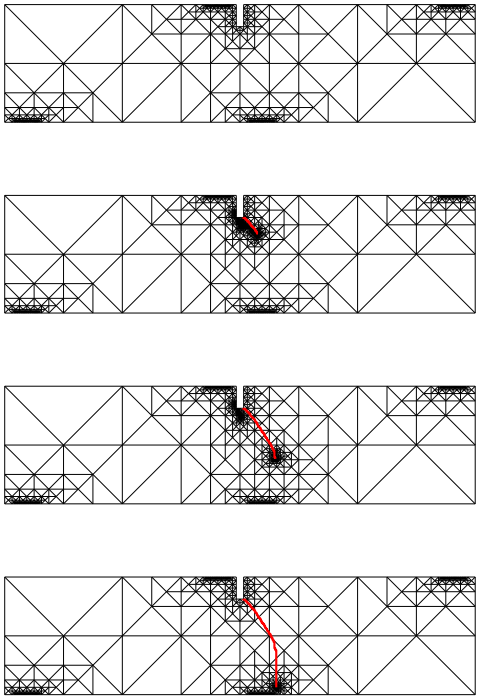

Figure 1: Application of the enriched QC methodology to a Single Edge Notched Beam under shear. Shown is the evolution of the QC triangulation as the crack (in red) grows. The underlying X-braced lattice is always fully resolved in the process zone. Note the coarsening of the discretization in the wake of the crack tip, by virtue of the enrichment.

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Quasicontinuum simulation of crack propagation in elastic-brittle disordered lattices

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Discrete particle models can effectively capture complex material responses, especially localized phenomena such as damage or plastic softening. Such models use a network of particles interacting via discrete links or connections to represent a discrete microstructure of the modeled material. They can reproduce fine details of the microstructure and the resulting material properties if the resolution of particles is sufficiently high. On the other side, particle models have two main disadvantages: Firstly, a huge number of particles needed to describe the response of large-scale physically relevant models results in an extensive system of equations, which is expensive to solve. Secondly, the process of assembling of this system is also computationally expensive because all discrete connections must be individually taken into account.

A quasicontinuum (QC) based method can remove both of these disadvantages of high-resolution particle models. The QC method can efficiently handle regular atomistic lattices by combining continuum and atomistic approaches. This method was originally proposed by Tadmor, Ortiz and Phillips in 1996 [1]. Since that time, the QC method has been widely used and extended to applications for a variety of materials represented by regular lattices [2]. An extension of the QC method to irregular lattices has recently been developed by the authors [3].

In this work, the material is represented by particles interacting via elastic-brittle links formed in a disordered lattice. Numerical simulations of crack propagation are performed for two- and three-dimensional examples. Each simulation consists of a series of elastic steps. In each step, one link that reaches the critical strain level is removed. The final crack trajectory is represented by the positions of individually cracked links. A QC method is used to simplify the fully resolved particle model. Five QC-inspired approaches with different levels of simplification presented in [3] are used to simulate the crack propagation. These approaches are based on

- interpolation,
- isotropic and anisotropic global homogenization,
- isotropic and anisotropic local homogenization.

The results obtained with these simplified approaches are compared with the fully resolved particle model. All approaches provide a significant reduction of the problem size

and achieve speed-ups by a factor of 10. At the same time, the macroscopic crack trajectory and main features of the force-displacement curves are captured very well.

The ongoing work is focused on an extension to links with nonlinear material behavior, such as plasticity or damage, based on a combination of the QC method with a continuous material model exploiting the idea of microplanes.

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A Naval Application of Crack Propagation in Residual Stress Fields

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Naval structures evolve in an environment such that they encounter severe and repeated loads. Fatigue life is the combination of initiation and propagation life. Fatigue design methods generally limit themselves to the first part and consider the second one as a margin for uncertainty. Though, propagation life determination can be beneficial when the initiation life might be insufficient, or the margins may be too low. Otherwise, it is also useful to study crack propagation at the design stage as it can improve the time to answer an issue in case of in-service flaw detection. Obviously, the whole structure cannot be totally studied with crack propagation techniques, but focus can be made on critical hot-spots. Additionally, the main manufacturing processes involved in shipbuilding are forming and welding, which may introduce high residual stress fields. Those can be considered as well in the initiation stage [1] as in the propagation stage, for their accelerating or reducing effects.

In the present paper, the authors present an original methodology, based on the eXtended Finite Element Method [2], for determining lifespan for propagating cracks into residual stress fields, supposed to represent the effect of manufacturing. State-of-the-art methods and tools are used to develop the methodology to consider multiple potential cases. The proposed methodology is validated through a detailed experimental validation on an unwelded geometry (Figure 1). The methodology is further verified on a real-like welded geometry, for which experimental data is available.

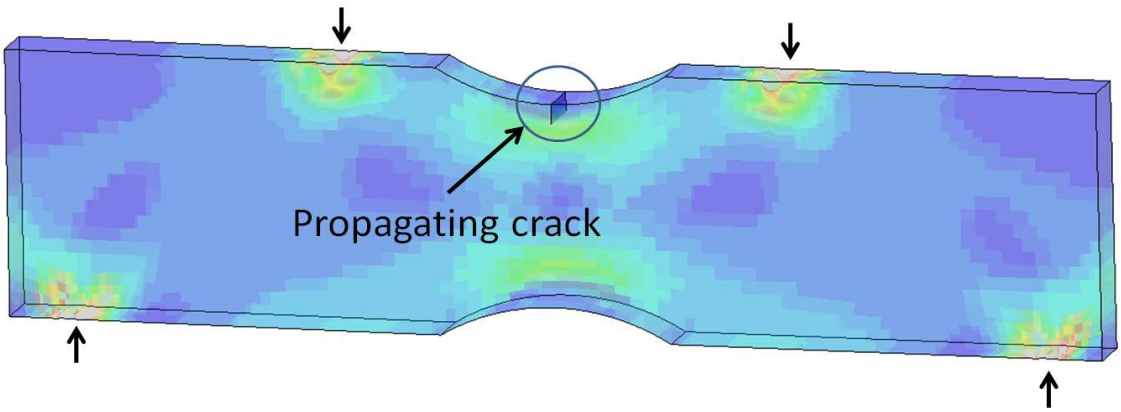

Figure 1 : Crack propagation under compression (four point bending) in a tensile residual stress field

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A multiscale analysis of fracture in Magnesium alloys

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Abstract

Magnesium alloys are often highly anisotropic materials, making their behavior difficult to characterize for general loading conditions. In order to model their plastic behavior, it is necessary to account for plastic anisotropy that results from the activation of specific slip and twinning systems. This study will investigate independent models for plastic anisotropy and for damage accumulation leading to ductile fracture. The ultimate goal is to develop a predictive model of ductile fracture that accounts for crystallographic details. Here, the plastic anisotropy of alloy AZ31 processed using severe plastic deformation is modeled using separate plastic yield functions for twinning and glide by dislocation motion. The parameters of these yield functions are determined through optimization comparing experimental tension and compression tests loaded in principal and off-axes directions with corresponding single cell finite element simulations. The results of this optimization allows the model to capture the anisotropic behavior of the material. Damage accumulation in a Mg-Y-RE alloy is modeled using a micromechanics-based continuum damage model. This model incorporates void nucleation, void growth and void coalescence to determine fracture. The material parame- ters, such as the hardening parameters and the initial values of microstructural variables, are determined through experiments and micrographs of the undeformed material. The model allows the prediction of fracture strains at various triaxiality levels. Both models (plasticity and fracture) provide insight into anisotropic deformation and fracture in magnesium alloys and constitute a first step toward more robust predictions under general loading conditions.

Keywords: Plastic anisotropy, Ductile fracture, Magnesium alloys

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High performance model order reduction techniques in computational multiscale fracture

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ABSTRACT: Multi-scale computational homogenization methods (FE2) offer a huge potential to incorporate, to macroscopic propagating fracture modeling, the complexity of the material meso/micro-structure morphology, through simple and physically realistic models. However, they presently suffer the burden of their enormous computational cost, since the computational complexity (number of the involved operations) has a multiplicative character in terms of the involved sampling points at every scale.

In this context, a powerful, and conceptually simple but efficient, multiscale computational model for fracture has been recently presented by the authors in [1] and successfully applied to a number of 2D benchmarks. In this work, two combined techniques are explored and applied to that model: 1) low-dimension-space projection of the solution (reduced order modeling, ROM) and 2) reduced optimal quadrature (ROQ). They lead to a high performance reduced order model (HPROM) of the original high fidelity (HF) multiscale fracture problem [2], which dramatically diminish the computational demand, at the cost of a very small additional error. A number of representative simulations in 2D problems show high resulting speedups and linear scalability in terms of the problem complexity, which make think of the HPROM techniques as a possible way to make computational multi-scale computational fracture available for daily-life engineering problems.

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A multiscale model for fracturing solids

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Fracturing solids can be studied by means of computational homogenization, whereby simulations are performed on Statistical Volume Elements (SVEs). However, pathological SVE size dependence and macroscale mesh size dependence of the effective simulated response are two major difficulties. These difficulties have been successfully addressed in the literature, but existing schemes generally require explicit identification and tracking of a dominating microscale localization zone. To circumvent the need to track the microscale localization zone, we propose a scheme where the macroscopic localized zone is approximated as a strong discontinuity by means of XFEM as indicated in Figure 1, and the macroscale displacement jump is applied in a smeared sense on the SVEs located on $\bar{\Gamma}_d$. In this way, we obtain the problem of finding the macroscale displacement field $\bar{\boldsymbol{u}}$ that fulfills

$$\int_{\hat{\Omega}} \bar{\boldsymbol{\sigma}}\{\bar{\boldsymbol{\epsilon}}_r\} : \delta\bar{\boldsymbol{\epsilon}}_r \,\mathrm{d}\Omega + \int_{\bar{\Gamma}_d} l_d \left(\bar{\boldsymbol{\sigma}}\{\bar{\boldsymbol{\epsilon}}_d\} - \bar{\boldsymbol{\sigma}}\{\bar{\boldsymbol{\epsilon}}_r\}\right) : \delta\bar{\boldsymbol{\epsilon}}_r \,\mathrm{d}\Gamma + \int_{\bar{\Gamma}_d} \bar{\boldsymbol{\sigma}}\{\bar{\boldsymbol{\epsilon}}_d\} : \left(\llbracket \delta\bar{\boldsymbol{u}} \rrbracket \otimes \boldsymbol{n}\right)^{sym} \mathrm{d}\Gamma = \int_{\Gamma_{ext,N}} \hat{\boldsymbol{t}} \cdot \delta\bar{\boldsymbol{u}} \,\mathrm{d}\Gamma \quad \forall \delta\bar{\boldsymbol{u}} \in \bar{\mathbb{U}}^0,$$

where $\bar{\boldsymbol{\epsilon}}_r \stackrel{\text{def}}{=} [\bar{\boldsymbol{u}} \otimes \boldsymbol{\nabla}]^{sym}$ is the standard small strain measure, $\bar{\boldsymbol{\epsilon}}_d = \bar{\boldsymbol{\epsilon}}_r + \frac{1}{l_d}\left(\llbracket \boldsymbol{u} \rrbracket \otimes \boldsymbol{n}\right)^{sym}$ is the smeared macroscopic strain in the localized zone, l_d is the width of the localized zone, and the effective macroscale stress $\bar{\boldsymbol{\sigma}}$ is obtained from the microscale solution as a standard volume average. Furthermore, we introduced the approximation $\int_{\bar{\Omega}_d} f_\square \,\mathrm{d}\Omega \approx \int_{\bar{\Gamma}_d} l_d f_\square \,\mathrm{d}\Gamma$ and defined $\hat{\Omega} \stackrel{\text{def}}{=} \bar{\Omega}_r \cup \bar{\Omega}_d \setminus \bar{\Gamma}_d$. To overcome the issue of pathological SVE size dependence of the solution upon localization, we consider $\bar{\Omega}_d$ entirely populated by SVEs through the (narrow) width l_d[1], define an *effective discontinuity* $\bar{\Gamma}_{d,\square}$ through the center of the SVE parallel to $\bar{\Gamma}_d$ and obtain the geometric relation $l_d = |\Omega_\square| \,/\, \left|\bar{\Gamma}_{d,\square}\right|$.

Regarding the microscale problem, we remark that standard choices for boundary conditions on the SVE may lead to inaccurate results when localization occurs in the SVE. In the present work, we therefore employ localization aligned weakly periodic boundary conditions [1] that allow the periodicity directions to be aligned with the dominating localization direction.

[1]In other words, we choose l_d such that it matches the size of $\Omega_\square$.

To illustrate the performance of the proposed scheme, we consider a plate with a softening region as shown in Figure 2a. The reaction force vs displacement for the lower right support is shown in Figure 2b. As can be seen, the proposed scheme shows excellent agreement with the fully resolved simulation (DNS) for different choices of the SVE size.

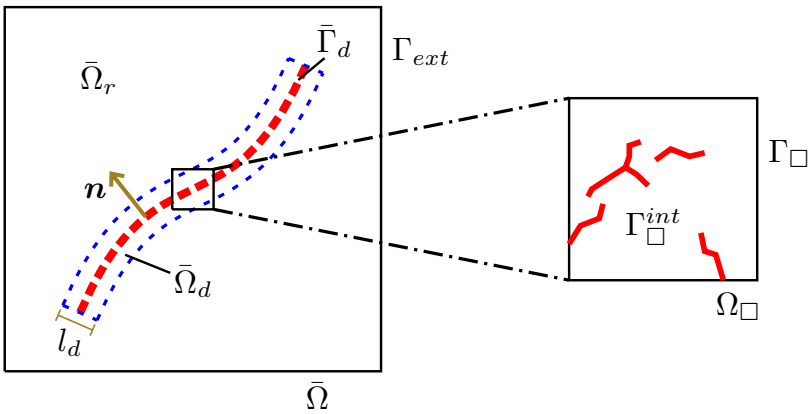
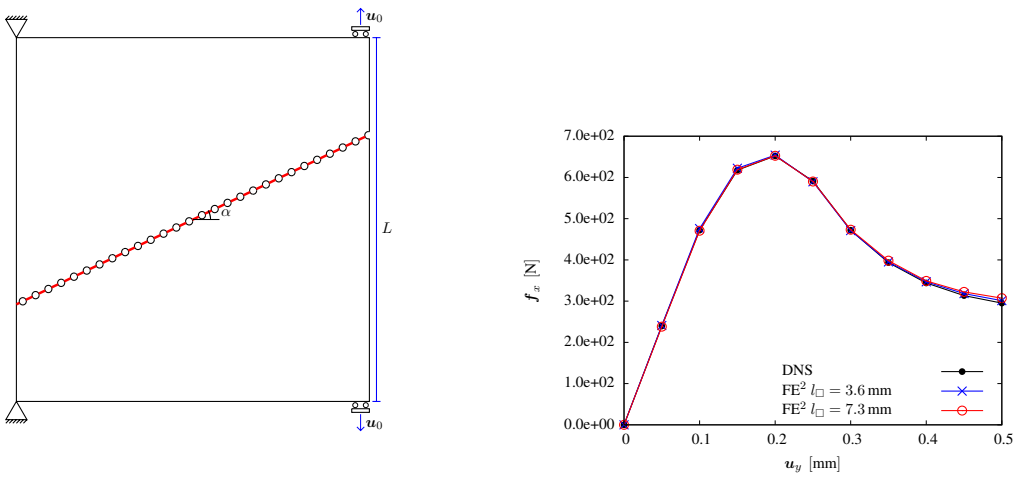


Figure 1: Macroscopic domain $\bar{\Omega}$ divided into a part $\bar{\Omega}_d$ containing an effective macroscopic discontinuity $\bar{\Gamma}_d$, and a part $\bar{\Omega}_r$ that is free from macroscopic discontinuities.



(a) Geometry. $L = 100\,\text{mm}$ and $\alpha = 25°$.

(b) Reaction force vs displacement for the lower right support.

Figure 2: Numerical example: A plate containing a softening region with a cohesive surface and holes.

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On the potential of multiscale simulations for the virtual testing of carbon composites

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Abstract

The simulation of composites at microscopic or mesoscopic scales has benefited from the improvement of finite-element methods and the continuous increase in computing power, leading to a better understanding of the local phenomena guiding the composite behaviour and failure. The improving reliability of the numerical predictions allows for a progressive substitution of experimental tests for the investigation of mechanical properties for the benefit of virtual testing.

In the present study, a unit cell of woven composite is modelled on the mesoscopic scale, following the procedure detailed in [1]. In an early numerical stage, a finite-element model of the dry-fibre textile is generated in TexGen [2] and compacted in order to increase the rovings nesting. The meshing of the matrix embedding the rovings is performed in a second stage. Finally, the mechanical properties of the weave in tension, compression and shear are predicted by a unit cell simulation with periodic boundary conditions. Through the duplication of the unit cell, larger test specimens (e.g. in tension, compression or bending) are investigated and the influence of the specimen geometry and roving architecture on the measured properties is investigated.

This paper discusses the possibility of a fully numerical investigation of carbon woven com- posites on a multiscale basis with the explicit finite-element software LS-DYNA.

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Bottom-up Multiscale Approach on Transverse Cracking of Cross-ply Laminates

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Abstract

In this work a bottom-up multiscale approach is applied on a fibre-reinforced polymer (FRP) material to simulate and capture the main features of a cross-ply laminate under longitudinal tension [1].
In the first stage, Computational Micromechanics (CMM) models are employed to characterize the equivalent properties of a lamina, namely, stiffness, strength and fracture toughness. While RVE-type models are used to characterize the stiffness and strength of the FRP, fracture properties cannot be obtained from these models as the application of periodic boundary conditions (PBC) degenerates the representation of the fracture process. Instead, a CMM embedded cell model has been developed to track the propagation of an intralaminar crack under transverse tension to estimate the transverse tension intralaminar fracture energy [2].

Once the ply level properties were obtained, a homogenized numerical 3D model of a cross-ply laminate was tested under longitudinal tension. The main features of this configuration were observed: in-situ effect on the critical load and crack density evolution. These results were compared to reference analytical solutions from the literature and a 2D CMM model previously developed [3].

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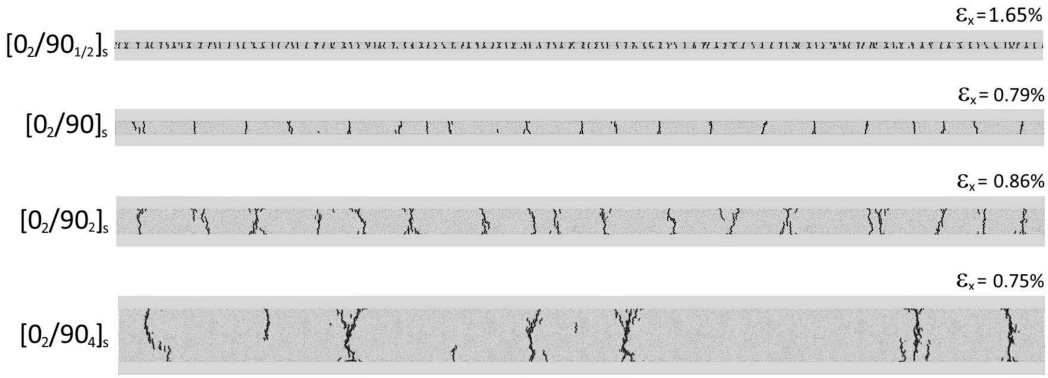
Keywords: Fibre reinforced polymer, Intralaminar toughness, Cross ply laminate, Multiscale

*Speaker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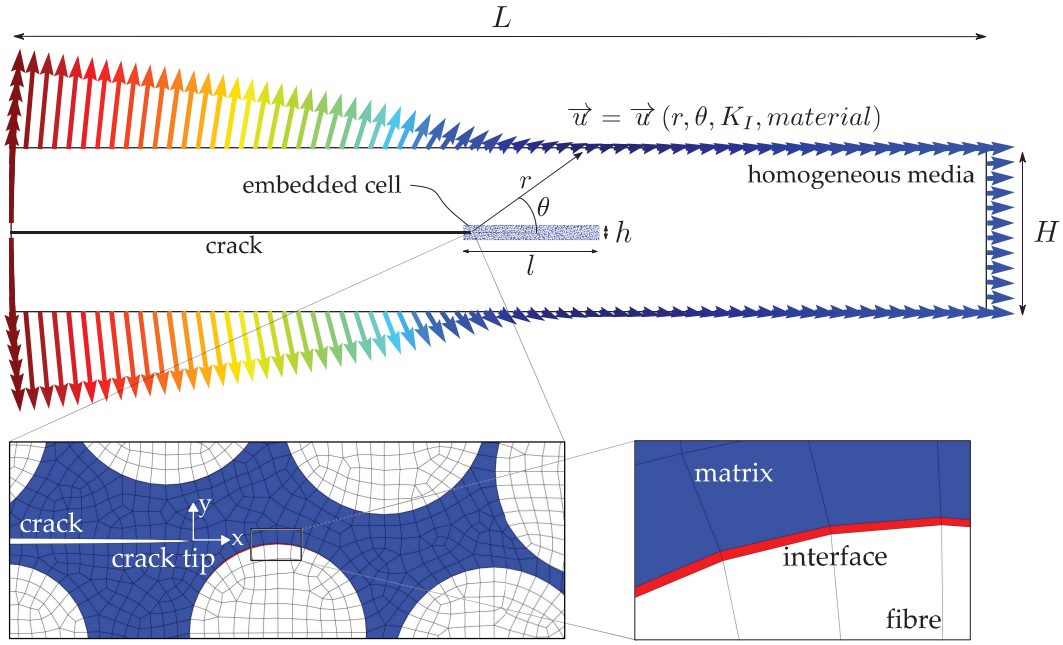
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Multispatial/Multitemporal homogenisation analysis of hygrothermal fatigue in glass/epoxy composites

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Research on the numerical simulation of extreme environmental conditions on composite materials has been on the rise. A relevant application for such simulations concerns structures such as wind turbine blades, which are subjected to cyclic environmental exposure involving extreme temperatures, moisture ingression, UV and erosion. Among such environmental influences, the combination of water diffusion and high temperatures (hygrothermal ageing) is regarded as the one capable of causing the highest impact on mechanical performance.

Upon absorption, water molecules promote microscopic degradation processes such as resin plasticization, interface weakening and differential swelling. Numerical simulation of macroscopic material degradation induced by such microscopic degradation mechanisms requires the use of multiscale techniques such as FE^2 [1]. Furthermore, since the ageing process is driven by diffusion, a multiphysics analysis must be performed. In addition to being a multiscale problem in space, simulation of cyclic environmental exposure also involves multiple time scales. A single cycle may consist of a 24 hour period, while a complete lifetime analysis may be on the order of years. Therefore, a cycle-by-cycle analysis is prohibitive, which necessitates the use of a cycle stepping technique.

This work presents a numerical framework for environmental fatigue damage prediction in unidirectional composite laminates. The material is represented by a microscopic Representative Volume Element (RVE). The resin is modelled as elasto-plastic with damage [2] and cohesive softening is considered for the fibre/matrix interfaces [3]. The macroscopic response is obtained through FE^2 from embedded micromodels. Cycle stepping is achieved with the time homogenisation procedure presented in [4]. The accumulated fatigue damage is considered to be almost periodic in time and the material state after multiple cycles is obtained by homogenising the response of a single cycle. This procedure is extended to a multiphysics framework that includes a Fickian diffusion analysis. The framework is used to predict damage in specimens subjected to multiple immersion/drying cycles.

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A two-field multiscale computational homogenization method for failure modeling of microstructured materials

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Abstract

Computational homogenization approach is one of the most accurate tools for non-linear problems with evolving microstructures. The basic idea of this approach is to extract upperscale constitutive relations at an arbitrary material point from the resolution of a lower-scale boundary value problem (BVP) defined from the underlying microstructure at that point. Our work focuses on developing a large-strain continuous-discontinuous computational multi- scale framework in order to predict the failure response of structures made of microstructured materials [1].

Under macroscopic loading conditions, the microscopic damage initiates and accumulates leading to highly localized deformation regions which results in the loss of representativeness in terms of the homogenized bulk behavior. However objectivity can be obtained in terms of the homogenized traction separation relationship based on the failure zone averaging scheme [2]. A large-strain hyperelastic formulation with non-local gradient enhanced damage model [3] is considered and the resulting homogenized cohesive law is up-scaled in an efficient way.

The macroscopic problem is solved by a two-field formulation with interface elements inserted at the beginning of the simulation. The required material behaviors at both bulk and interface integration points are obtained from the microscopic analyses. During the prefailure stage, the displacement continuity over interfaces is ensured by recourse to augmented interface terms related to an augmented field. After the onset of failure detected by the loss of ellipticity of the homogenized tangent operator, the crack path is assumed to explicitly follow the element interfaces. This assumption allows modeling the crack initialization and propagation efficiently without the need of topological changes in the mesh [4]. Compared to other computational homogenization schemes for fracture analyses, the homogenized cohesive law can be directly integrated into the macroscopic problem by enforcing not only the equality between the macroscopic displacement jump and homogenized cohesive jump but also the traction continuity over cohesive interfaces using augmented interface terms.

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Keywords: Computational homogenization, two field, failure, discontinuous

A multiscale plastic damage model with associated flow rule for brittle geomaterials

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In order to model macroscopic mechanical behaviors of quasi brittle geomaterials under compression, a new multiscale damage-friction coupling model is presented. The macroscopic constitutive equations are formulated by adapting the Mori-Tanaka homogenization scheme and within the framework of irreversible thermodynamics. The macroscopic inelastic strain of material is physically generated by frictional sliding along closed cracks and strongly coupled with damage evolution by crack growth. A Coulomb-type friction criterion serving simultaneously as the yielding function and plastic potential is established, implying associative flow of the inelastic strain which is generally not feasible in the traditional plastic theory for cohesive-frictional geomaterials. The damage evolution related to microcrack propagation, including tensile wing microcrack propagation under low confining pressure, is quantitatively described by a strain energy release rate based damage criterion. By damage-friction coupling analyses, profound description of the nonlinear strength envelope, macroscopic volume compressibility/dilation transition and strain softening behaviors are presented. For practical application, a local numerical integration with explicit return mapping algorithm and the method of calibration of the model's parameters are developed [1]. Comparisons between model predictions and experimental data for some granites under compression are performed to evaluate the performance of the proposed model, one of the simulation results being given in Figure 1.

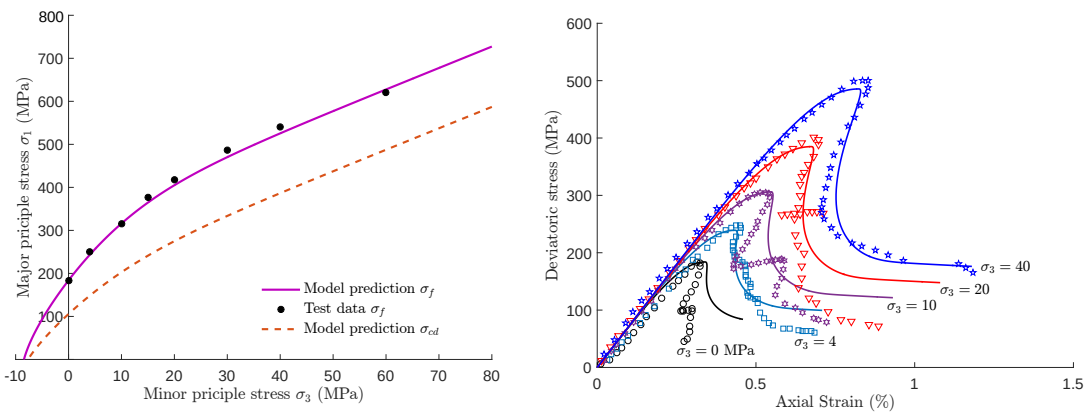

Figure 1: Comparisons between model predictions (solid lines) and experimental data for Lac du Bonnet granite (data extracted from [2])

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A Hybrid Nonlinear Multi-Scale Analysis of Reinforced Concrete Structures

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Abstract

This paper presents a numerical procedure for constructing a hybrid nonlinear multi-scale model for the analysis of reinforced concrete structures considering the occurrence and evolution of damage to mechanical failure. The formulation includes complex phenomena such as cracking in the concrete bulk and the location of reinforcement rebars and its interaction with the surrounding concrete.

The hybrid approach combines computational efficiency and results accuracy of a multi-scale coupling of two or more sub-structures. The computational model involves different scales of analysis spanning from linear-elastic to nonlinear-damage analyses. Different levels of analysis of sub-structures, parts of the complete structure, are integrated and coupled to be executed together in two or more analysis programs and/or computer systems using for one or more scales conventional structural elements with linear or nonlinear behaviour with empirical hysteretic rules and for the analysis of the remaining structures nonlinear finite elements derived from a plasticity enriched damage mechanics formulation and bar elements representing reinforcement bars with an explicit elastoplastic behaviour including a bond-slip relationship.

To illustrate the capabilities of the hybrid formulation proposed, the pushover and seismic analysis of an example reinforced concrete structure are carried out using two specialized nonlinear finite element programs, OpenSEES and FEAP, communicating by the capabilities of the hybrid simulation program, OpenFRESCO, responsible of integrating the global response of the system.

Finally the conclusions of this work, derived from the formulation of the hybrid method proposed and the analysis and validation of the results obtained, are given.

Keywords: Multi, scale, Hybrid Simulation, Reinforced Concrete, Continuum Damage

*Speaker

An adaptive concurrent multiscale model for concrete

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An adaptive concurrent multiscale model for concrete is presented. The main novelty is the use of the coupling finite elements [1] to ensure the continuity between the nonmatching meshes from macro- and mesoscales. In this approach, the macroscale stress distribution is used as an indicator to properly update the modeling of the critical regions from the macroscale to the mesoscale one. The mesoscale model is a heterogeneous material, consisting of the coarse aggregates, mortar matrix and ITZ. The mesoscale material structure is built embedding coarse aggregates into the mortar matrix randomly, according to a grading curve [2]. The fragmentation technique, based on the use of finite elements with a high aspect ratio [3], and a continuum tensile damage models [3] are used to describe the crack initiation and propagation in the mesoscale. The numerical results obtained show that the proposed model is able to reduce significantly the computational cost when compared to a full mesoscale analysis.

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Two-scale modeling of microscopically based failure processes at early stage of damage of ferritic ductile iron

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In this work, a multi-scale analysis to study the early damage mechanics of ferritic ductile iron is introduced. The methodology combines numerical analysis and exhaustive experimental observations in both macro and micro scales. The multi-scale problem is modeled using the pre-critical regime of the Failure–Oriented Multi-Scale Variational Formulation (FOMF)[1], which is implemented via a FE^2 approach. Finite element analysis in the micro-scale is customized to account for plastic deformation and matrix-nodule debonding. Experiments in the micro-scale are used for microstructural characterization of the material mechanical properties and the assessment of the micro-scale plasticity/damage mechanisms; experiments in the macro-scale provide the data to calibrate and validate the methodology. The multi-scale model is found effective for capturing the sequence of events and extent of the plasticity/damage mechanisms in the micro-scale as well as to infer, via inverse analyses, the parameters of the matrix-nodule debonding law (fracture energy and peak tensile stress), which cannot be estimated through experiments. Results allow to draw conclusions related to the applicability of the FOMF and the RVE sizing for non-linear damage analysis. Additionally, it allows to develop new insights for the better understanding of ductile iron damage micromechanisms at early stage of damage.

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A Multiscale Approach with Application to Phase-Field Modeling of Fracture

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The variational approach to fracture by Francfort and Marigo and the related regularized formulation of Bourdin et al. [1], which is also commonly referred to as a phase-field model of fracture, see e.g. the review paper [2], is a widely accepted framework for modeling and computing the fracture failure phenomena in elastic solids. The formulation is non-linear and calls for the resolution of small length scales. Its single-scale treatment is nowadays well-established and shown to be computationally demanding [3, 4]. As such, an idea of multiscale approach that enables to "send" the non-linearity to a lower (local) scale, while dealing with a purely linear problem at an upper (global) one, seems particularly appealing.

Clearly, this cannot be realized via standard homogenization techniques [5] due to a strongly localized phenomenon inherited by the model. In this contribution, we propose a multiscale approach combining the FETI-2LM method [6] and the so-called non-intrusive re-localization formulation [7].

The main novelty here is that we impose the mixed, or, more precisely, the generalized Robin-type boundary conditions [8, 9, 10] to bridge the corresponding scales. In contrast to the Dirichlet boundary conditions being used in [7], this does not lead to a stiff local response, particularly in a softening regime, thus not requiring any "extra efforts" like e.g. relaxation procedures [7]. The important ingredient these mixed conditions (also termed the Dirichlet-to-Neumann map) is an optimal augmented interfaced operator [11], whose construction is, in general, challenging and accomplished in our case using sensitivity analysis.

With numerous numerical examples, we show that the proposed two-scale procedure indeed yields results similar to the reference single-scale solution (this includes the entire failure process simulation, as well as the load-displacement curves), yet they are obtained with much superior efficiency. We note that the presented method is (algorithmically)

perfectly suitable for the parallel computing concept thus promising further reduction of computational effort.

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Multiscale Pase field modeling of brittle cracking in heterogeneous materials

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Abstract

Modeling the initiation and propagation of cracks in heterogeneous brittle materials is a challenging task in engineering. This works presents a scheme to simulate cracks in heterogeneous brittle materials avoiding to model micro-voids or inclusions which naturally exit in civil materials such as concrete or mortar. A multiple-phase field method and computational homogenization technique are combined to define effective behaviour of an equivalent homogeneous media. The case of porous media in compression is handled by a specific two- field formulation. The extensive computation times related to fully meshing micro-voids for explicitly tracking cracks be alleviated by the present multi–scale approach.

Keywords: Phase field method, multiscale modeling, damage, homogenization, crack propagation.

*Speaker

MS11: Fracture and damage of composites and laminates

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The objective of this mini-symposium is to provide a forum for the in-depth discussion of new and recent analysis methods that simulate the non-linear deformation and fracture of composite materials. Such models may address different matrices (e.g.polymer, ceramic, metal), different reinforcement materials (e.g.carbon, glass) and architecture (e.g. laminates, fabrics, spread tows). Abstracts submitted to this mini-symposium may also include models developed at different length and timescales, addressing quasi-static or dynamic loading and degradation mechanisms such as fatigue. Recent developments on the constitutive and kinematic representation of the failure mechanisms of composite materials are also within the scope of this mini-symposium. In summary, the following topics are welcome:

- Fracture of polymer, ceramic and metal-matrix composites.
- Fracture of unidirectional, non-crimp, braided and woven fabrics.
- High-strain rate failure response of composites.
- Simulation of fracture of composites under fatigue loading.
- Micro, meso, and macro-mechanical modeling of composites.
- Multi-scale modeling of inelastic deformation and fracture of composites.
- Advanced kinematic representations of discrete fracture in composites.
- Composite fracture prediction using Finite Fracture Mechanics.
- Simulation of the hygro-thermal degradation of polymer composites.
- Effect of defects and uncertainties

Analysis of Rate-Dependent Delamination Described by Delayed Damage Model with Bounded Rate

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Experimental data for composite laminates, for instance those for mode II delamination reported in [1], indicate the existence of an important rate effect at the interfacial level. Taking into account such effects is important for a correct delamination prediction in many situations, e.g., for the purpose of impact design of composite absorbers. In this context, the objective of the present study is to improve the understanding of the relation between the rate of crack propagation (delamination) and the dissipated energy per unit area, as predicted by a cohesive interface model based on the concept of delayed damage with a bounded damage rate [2].

To make a semi-analytic treatment possible, the idealized problem of delamination of an infinitely long layer from a rigid substrate is considered, and solutions corresponding to propagation of the crack tip (delamination front) at a constant velocity are constructed. The delaminating layer is modeled as an elastic Timoshenko beam connected to the substrate by an inelastic interface, which is described by a cohesive zone model. The cohesive law is postulated in a damage format, in the spirit of a delayed damage model with bounded rate.

Mathematical description of the above problem leads to a set of ordinary differential equations, which is simplified by conversion to dimensionless variables. The solution is then obtained by a specific form of the shooting method, adapted such that the solution satisfying all boundary conditions is obtained without iterations. This efficient numerical technique permits simple and fast calculations, and the dependence of the physical characteristics of the system on the choice of model parameters can be evaluated. Such calculations elucidate the role of individual parameters and facilitate identification of optimal parameter values from experimental data. They also reveal some of the fundamental features of the model, including its scaling and asymptotic properties.

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Delamination modeling at the inter-ply scale in unidirectional composite laminates

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Composite materials such as carbon/epoxy laminates made of unidirectional plies are nowadays widely used in the aeronautic industry due to their good specific mechanical properties. However, they still suffer of early delamination when subjected to low velocity impact for example. For that, toughened materials have been developed to improve the properties related to delamination. One solution among others has been to incorporate polyamide particles in the inter-ply region [1, 2]. Under macroscopic loading conditions of mode II type, this solution gives good results, while for mode I the toughening effect is not always achieved. A model developed at the inter-ply scale would be interesting to clarify the link between macroscopic loading conditions and local dissipative mechanisms and therefore develop robust toughening solutions.

Delamination consists in crack propagation between two plies. Typical delamination tests aim to achieve pure-mode macroscopic loading conditions and to quantify the energy dissipated by crack propagation. The generalization of these results to more complex loading conditions is not straightforward, as the link between the macroscopic mode and the local dissipation mechanisms is not simple (see for example [3]). The relation between matrix properties and macroscopic delamination has been studied experimentally by [4]. In mode I, the crack mainly goes out of the inter-ply zone to the weakest link which is the fiber/matrix interface. In mode II, the crack is formed from successive hackles leading to a large process zone. The simulation of such a macroscopic crack therefore needs for the micro simulation to go further than the first micro crack. Some plasticity is accompanying this mechanism. In epoxy matrices, the size of the plastic zone ahead of a crack tip can be roughly estimated to 10 microns to 20 microns which is then the optimal thickness of the inter-ply region to ensure maximum dissipation. Note that in general, this plastic zone is confined by the surrounding plies which are very stiff in the fiber's directions.

The purpose of this paper is to discuss the models available to describe and simulate properly the physics of degradation in the inter-ply region. For that, available models in Abaqus are studied and their limits discussed especially regarding localization and scale transition representativity. To overcome the difficulty to represent correctly dissipated energies during cracking, a phase-field model [5] has been developed in the framework of a thermo-mechanical coupled problem. This leads to a very simple implementation in Abaqus. Several classical representative examples are treated (DCB and CLS testing configurations) to illustrate this approach.

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Geometrically nonlinear beam finite elements for modelling the mixed-mode rate-dependent delamination in layered structures

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Layered structures appear in many engineering applications and in nature as they optimise functional and structural performance of systems. Delamination or debonding are one of the most prevalent and severe failure modes in layered structures which occurs when a crack initiates and/or propagates along the interface between two layers. In this work delamination is studied using cohesive-zone models (CZMs) where the displacement field is assumed to be discontinuous on the considered interface and a nonlinear traction-separation law between the displacement jump and the associated interface traction is defined [1].

The traditional way of determining the key parameters governing crack propagation along an interface between their layers is based on fracture mechanics and requires the determination of the fracture energy G_c (or critical energy release rate) of the interface. But G_c cannot be considered only as a material or interface property: its value certainly depends on the mode mixity, often on the loading rate, and among other factors it can also depend on the dimensions of the specimen as a result of size effects. The idea of separating out the different dissipation mechanisms occurring during fracture has been a common feature of CZMs recently proposed in [2-4].

In particular, when the interlaminar fracture process is significantly rate dependent, fracture-mechanics based approaches can only characterise the phenomenological dependence of the fracture energy on the crack speed. Instead, the rate-dependent CZMs recently co-developed in Refs. [2-4] are less phenomenological and better linked to the underlying physics.

It is well known that CZMs require the use of a very refined mesh along the potentially delaminating interface, which makes them too computationally expensive to be used in conjunction with 2D and 3D solid elements as every-day design tools in engineering practice. To bridge this gap, new computational methods based on the use of geometrically non-linear beam-type finite elements stemming from Reissner's beam theory for the layers and interface elements with a mixed-mode CZM have been developed [5-6]. Beam elements are more intuitive than solid elements and, in

geometrically linear analysis, Reissner's theory corresponds to the well-known Timoshenko theory which forms a part of every engineering education. On the other hand, in a geometrically non-linear setting, it makes the basis for the development of exceedingly robust finite elements capable of handling finite displacements and rotations. Most importantly, the beam elements make use of a smaller number of degrees of freedom, with significant reduction in the overall computational burden.

It has been recently shown that beam elements can be used with very good accuracy to model not only the widely used double-cantilever-beam test, but also the mode-II and mixed-mode delamination tests both in geometrically liner [5] and non-linear analysis [6].

In this work, building on the earlier work [2-6] briefly reviewed above, a rate-dependent mixed-mode interface element is implemented within a multi-layer beam environment consisting of two- or three-nodded beam finite elements. The presented model is verified against experimental results for mode I delamination (DCB test) and computationally more expensive models which use plane-strain 2D finite elements with significantly higher number of degrees of freedom [3]. Special attention is dedicated to the choice of optimum solution procedure for the non-linear problem and reducing the computation time. The model developed will be a framework for a novel method of determining the material properties of the interconnection of layered structures in conjunction with experimental measurements (e.g. force-displacmenet diagram for a DCB test).

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Adaptive modelling of delamination growth using isogeometric continuum shell elements

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A key to successful modelling of the complex progressive failure in layered composite materials is to have computationally efficient models and methods which can be adapted to the predominant failure mechanisms in each specific loading case. In particular, efficient approximation and solution methods for delamination modelling is crucial, since "high-fidelity" FE models with many elements through the component thickness interconnected with cohesive interface elements leads to unfeasible simulation times and memory requirements. For that purpose, several papers have been published that present alternative methods for modelling concepts which support laminate failure analyses requiring only one shell element through the thickness and where arbitrary delamination propagation is accounted for only in areas where it is needed, cf. Brouzoulis and Fagerström [1], Hosseini *et al.* [2] and McElroy [3].

The proposed new concepts however need to be further developed before they can be readily applied to solve engineering problems in which delamination cracks can initiate and propagate. For traditional finite element based shell models, such as the one presented by Brouzoulis and Fagerström (based on the eXtended Finite Element Method, XFEM), improved methods to predict the interlaminar stresses are needed for an accurate prediction of delamination initiation, since the transverse stresses predicted directly from the shell solution are of too low accuracy. This was recently done *e.g.* by Främby *et al.* [4] who complemented an XFEM shell formulation with a stress recovery approach (see *e.g.* [5]), performed over a patch of elements, thereby making the model fully adaptive. As for the alternative concept based on an isogeometric approach by Hosseini *et al.*, there is a need to handle successive introduction of new discontinuities by means of knot-insertion in an automated fashion. A first step in this direction was taken by the authors in [6], outlining strategies for how to initiate and propagate delamination cracks using this framework. As a benefit over FE based C^0 continuous shells, the necessary improvements of the interlaminar stresses for isogeometric shells can be performed element-wise since in-plane stresses are smooth over element boundaries.

In this contribution we focus on the further development of the isogeometric solid-like shell element [2,7,8] to allow for an automated insertion of discontinuities. The formulation adopts NURBS (or T-spline) basis functions for the discretisation of the

shell mid-surface, whereas a higher-order B-spline functions are used for the interpolation in the thickness direction. A discontinuity can be incorporated in this latter function by so-called knot-insertion to account for ply interfaces (weak discontinuities) and delaminations (strong discontinuities) [8,9]. In order to automatically enhance the element, various stress-based criteria using element local improved interlaminar stresses are investigated. In this way, the isogeometric continuum element can be used in an even more efficient fashion, allowing for the detailed analysis of large, thin-walled composite structures.

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A new mixed-mode cohesive delamination model with internal friction

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Delamination is a failure phenomenon typical of composite materials. The numerical simulation of the decohesion between layers is often addressed by means of a cohesive approach, making use of interface elements. In the literature, there exists a huge number of works regarding the cohesive modelling of delamination, see for instance ([1], [2], [3], [4]).

This work is devoted to the formulation of a new cohesive law, able to deal with the general case of mixed mode behaviour, typically occurring in real life delamination problems. The proposed cohesive model has been developed within a thermodynamically consistent framework and it is based on an isotropic damage formulation. In order to properly reproduce the coupling between normal and shear modes, a three-surface activation domain characterized by an internal friction angle is introduced in the plane of the cohesive stresses (Figure 1): each of the three normals to the domain defines a distinct damage mode. A decomposition of the strain energy release rate in terms of the three damage modes is achieved in a natural way by projecting the cohesive tractions onto the three normals. The mixed-mode fracture energy is the result of modes interaction, without the need to define an empirical law.

Several numerical examples are simulated in order to validate the proposed interface law in both pure mode and mixed-mode delamination problems. In particular, the comparison between the numerical results and the experimental data of Mixed-Mode Bending (MMB) tests ([5], [6]) is shown.

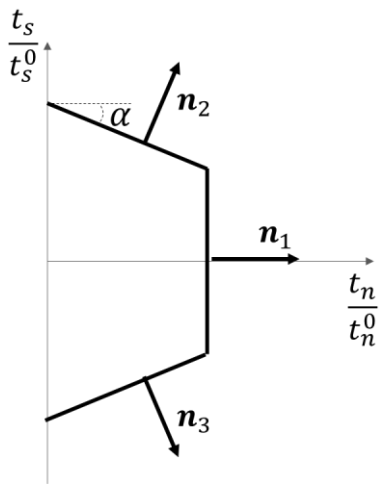

Figure 1: three-surface activation domain

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Modelling the failure mechanisms in z-pin reinforced composite laminates

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Controlling the propagation of damage due to delamination is a key requirement in the design and certification of structural components made of fibre reinforced composites [1]. Through-thickness reinforcement (TTR) in the form of Z-pinning is an effective means of achieving this for pre-preg laminates.

Here the z-pins are modelled using Finite Element Analysis (FEA) at a high-fidelity level. The bridging force brought by the presence of the pin is captured by a novel interface constitutive model, coupling cohesive and frictional behaviour. The epoxy pocket surrounding the pin is represented by a thermo-visco-plastic constitutive model [2]. A maximum stress criterion is used to capture longitudinal pin failure, and a cohesive formulation is applied for capturing splitting of the pin. A three-dimensional continuum damage model is used to model the constitutive behaviour of the fibre reinforced laminates [3].

An automated script has been created for generating the complex full 3D model and mesh (see Figure 1). The model is built with a single delamination plane located at mid-height of the laminate. The objective is to study the behaviour of the pin under different mix mode loading conditions (tension and/or shear) and to capture the phenomena which contribute to an increase in apparent toughness of a pinned composite. The analysis is then repeated for different pin lengths.

The capabilities of this high-fidelity modelling approach are evidenced by capturing the bridging force (and apparent increase in toughness) due to the presence of Z-pins in laminates with different thicknesses. The structural response of a single Z-pin is analysed under quasi-static and high-strain rate loading as well as under different mix-mode conditions. Results from the numerical model are compared with experimental data and an excellent agreement is found (see Figure 2).

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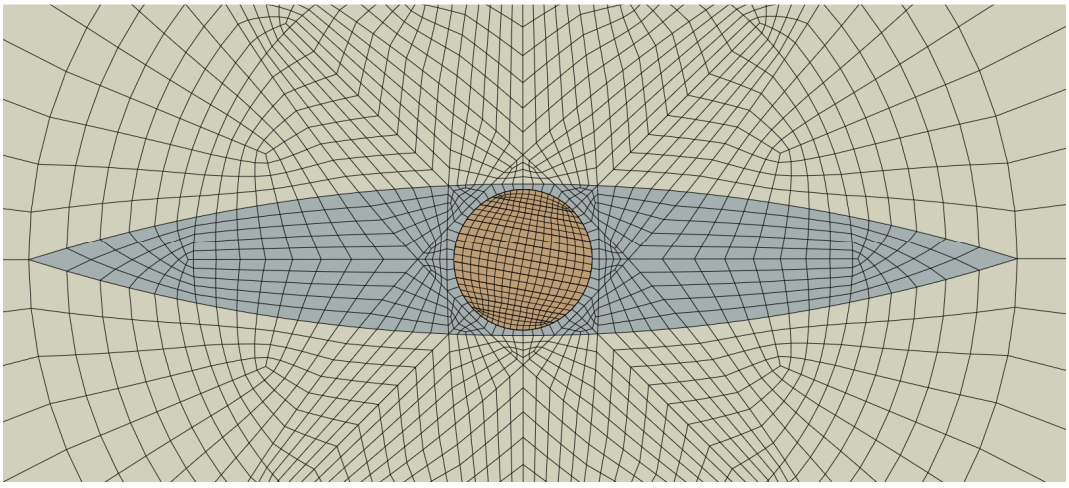

Figure 1. Cross section view of mesh used for high-fidelity modelling: laminate in grey, epoxy pocket around the pin in blue and pin in orange.

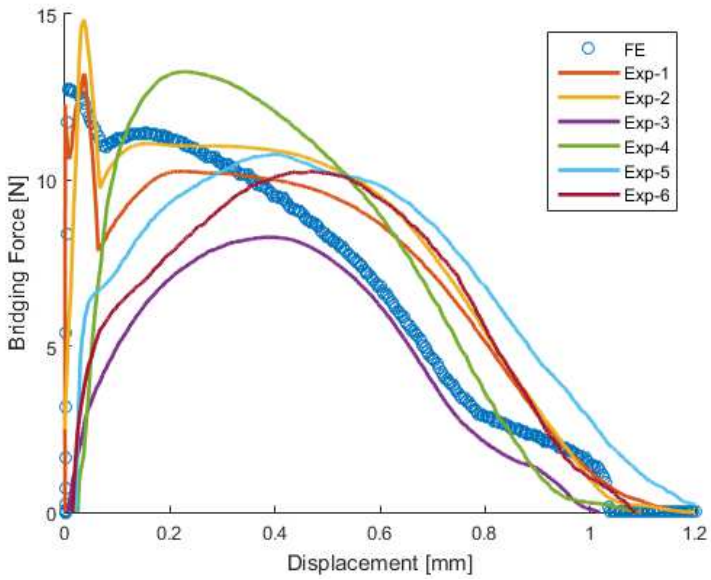

Figure 2. Single Z-pin under quasi-static mode I loading. Comparison with experimental data.

Modeling of mode I facesheet to core delamination of sandwich panels exhibiting fiber bridging by means of cohesive zone formulations

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Sandwich constructions are utilized in many applications, e.g. in the baseline design of the payload fairing for NASA's Space Launch Systems (SLS) heavy lift vehicle, since they provide a favorable ratio of stiffness and strength to weight. The SLS fairing is realized through separable petals which are comprised of carbon fiber reinforced plastic (CFRP) facesheet and aluminum honeycomb core sandwiches. During coupon testing severe fiber bridging was observed at the interface of the honeycomb core and the CFRP facesheet. The severity of the fiber bridging resulted in inadequate predictions by conventional cohesive zone formulations. The experimental results for instance exhibited a concave-convex pre-peak shape in the load-displacement curve as well as two distinct regions of high interfacial traction - one close to the crack front and one several millimeters in the wake of it. Neither of these observations could be captured with conventional cohesive formulations. Therefore, a novel cohesive zone formulation was developed which accounts for these observations by an initial interfacial stiffness and energy release rate, in conjunction with a novel cohesive component to account for the fiber bridging. Compared to conventional cohesive zone formulations the predictions by the novel formulation matched the observed experimental results significantly better in terms of load-displacement curves and apparent energy release rates as well as local strain patterns.

A continuum damage model for delamination and intralaminar damage in composite laminates

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Abstract

Carbon fiber reinforced composites have become very popular in numerous engineering applications in aerospace, automotive, and maritime industry. These composites are typically composed of reinforcing fibers – either unidirectional carbon fibers or woven or braided textiles – embedded in a polymer matrix material. They are advantageous due to their ease of manufacture, damage tolerance, and relatively low cost. However, physics-based modeling of the mechanical behavior of such composites is challenging. While in the unidirectional case all fibers are considered as perfectly aligned in one particular direction, textile composites introduce additional geometric complexities, which cause significant local stress and strain concentrations. Since these internal concentrations are primary drivers of nonlinearity, damage, and failure within textile composites, they must be taken into account in order for the models to be predictive.

For this, an orthotropic continuum damage model is presented in this paper, which enables accounting for the interaction of damage evolution in different directions by introducing six independent damage variables. Thereby, uniaxial loading states can lead to different damage progression in directions other than the loading direction. The model is thermodynamically consistent and mesh objective due to use of an energy based regularization scheme.

It is shown that the model can be successfully applied on different scales: on the microscale of unidirectional carbon fiber reinforced polymers it is applied for the matrix material in an isotropic manner, whereas on the meso-scale of textile composites the same model can be used to describe the orthotropic damage behavior of the yarns. Moreover, on the macro-scale the model allows the prediction of both intralaminar damage progression as well as delamination in layered composites.

Keywords: continuum damage model, anisotropic damage, composites

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Progressive Failure Analysis of Stiffened Composite Panels with Skin-Stringer Debonding and Intralaminar Damage using a Two-Way Loose Coupling Approach

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Abstract

Due to their excellent material properties such as high stiffness and strength to weight ratio, fibre reinforced composite structures receive particular attention today. The common application of stiffened panels in aircraft structures requires accurate and efficient nonlinear finite element analysis capability for the post-buckling regime, when exploiting the load car- rying capacity of stiffened panels beyond the first (skin) buckling. With an eye on future design scenarios in which unnecessary conservativeness is reduced [1], the analysis of the failure behaviour of the panel should include a progressive damage analysis, involving an appropriate modelling of the material degradation. In the current work, the combination of skin-stringer debonding and intralaminar damage is modelled and investigated, making use of a global-local approach for intralaminar damage.

Global-local approaches based on two-way loose coupling methods, e.g. [2, 3], are among the promising methods for post-buckling progressive failure analysis, combining the advantages of an efficient analysis at the global level on the one hand and an accurate material damage analysis at the local level on the other hand. In earlier work, a two-way loose coupling global- local finite element approach considering intralaminar failure modes such as fibre and matrix damage has been presented [3]. In the corresponding verification and validation studies, this two-way loose coupling approach was carried out for a basic, characteristic structure, a flat, one-stringer stiffened panel.

As various experimental observations have shown (e.g. [4]), skin-stringer debonding is a common damage mode of a stiffened panel, which together with intralaminar damage can result in failure of the structure. In the present work, the combination of skin-stringer debonding and intralaminar skin and stringer damage is modelled. In order to predict the initiation and progression of skin-stringer separation, the adhesive layer between skin and stringer is modelled with cohesive zone elements. The two-way loose coupling approach is used to model the fibre and matrix damage initiation and growth. Numerical studies are carried out to assess the failure behaviour of a specific, characteristic stiffened composite panel including debonding between skin and stringer. Particular attention is paid to the interaction between skin-stringer debonding and intralaminar skin and stringer damage.

*Speaker

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Keywords: Two way loose coupling method, global local analysis, progressive failure analysis, stiffened composite panels

Extension of level set model to the numerical modeling of multifront delamination problems for composite laminates

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Abstract

For numerical simulation of delamination, the approach used by the industry usually consists in using interface elements such as cohesive ones. This can be time consuming or lead to mesh size problems and currently limits the dimension of parts that can be optimized in pre-design stage of industrial projects.
To avoid that, an interesting approach was proposed by F. P. van der Meer et al. [1]. First, they use an implicit description of the delamination front that does not depend on the mesh (based on a level set field). And second they assume that the cohesive zone reduces to a line and use an explicit energy-based criterion from fracture mechanics to drive crack growth. This model showed good results in agreement with cohesive zone ones for the 2D case of a 2-ply carbon-epoxy membrane submitted to tension with a unique delamination front [1]. We will show that it can be extended to the case of multifront delamination problems (see e.g. in Figure 1). Comparisons to numerical simulations with cohesive elements will be done.

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Keywords: delamination, laminate, composite, level set

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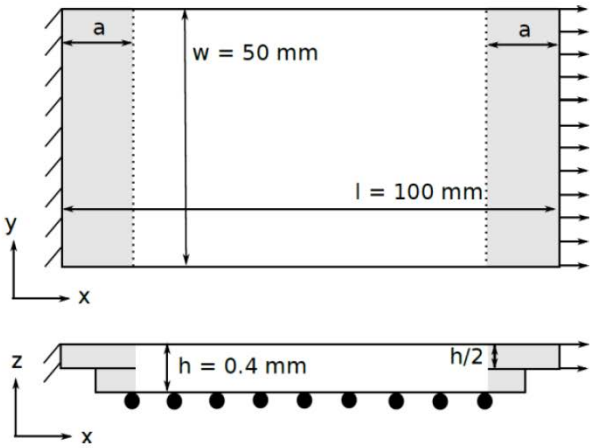
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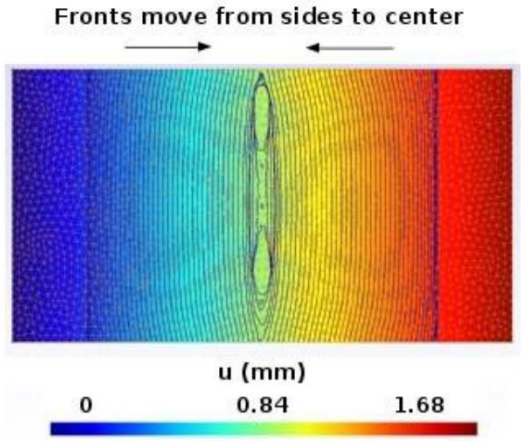
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Fibre direction tracking to solve mesh bias in continuum damage modelling of composite matrix cracks

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Continuum damage models are an attractive choice to simulate matrix cracking in composites due to their simplicity and ease of implementation. However, a well-known drawback of such formulations is their sensitivity to grow the damage in a direction dictated by the pattern of the finite element mesh [1]. While one way to solve this problem is to orient the mesh in the crack growth direction [2], this is not sufficiently general as it puts a restriction on the mesh development. Also, multidirectional laminates contain plies of different fibre orientations stacked together, and different mesh patterns have to be designed for each ply to simulate crack growth correctly. Composites often fail by complex interactions of matrix cracks and delaminations [3]. Thus, it is extremely important to capture the discrete crack paths correctly, because an incorrectly predicted crack pattern may lead to an unrealistic sequence of overall damage progression, and subsequently an incorrect global failure prediction. In the present work, a simple element tracking algorithm is used to allow matrix cracks predicted by a continuum damage model to propagate in the correct direction, independent of the underlying mesh. The algorithm works on a ply level, where crack growth direction is known a priory (being the fibre direction). Based on a predetermined set of neighbour elements of a given element, decisions are made about which neighbours would contain the next crack segment when the crack advances. A further advantage of the method is that it allows for individual cracks to be discretely modelled, with a predefined minimum crack spacing implemented. This overcomes another limitation of continuum damage models, where discrete cracks are usually only represented in a smeared sense. The failure algorithm uses a stress based initiation criterion and an energy regularised propagation criterion for accurate representation of the damage accumulation. This procedure has been implemented in Abaqus/Explicit, and shown to be able to reproduce complex crack networks in multidirectional laminates, independent of the mesh pattern. In the example shown in figure 1 an unstructured mesh has been used to show the method's ability to represent straight crack lines, regardless of the underlying mesh pattern.

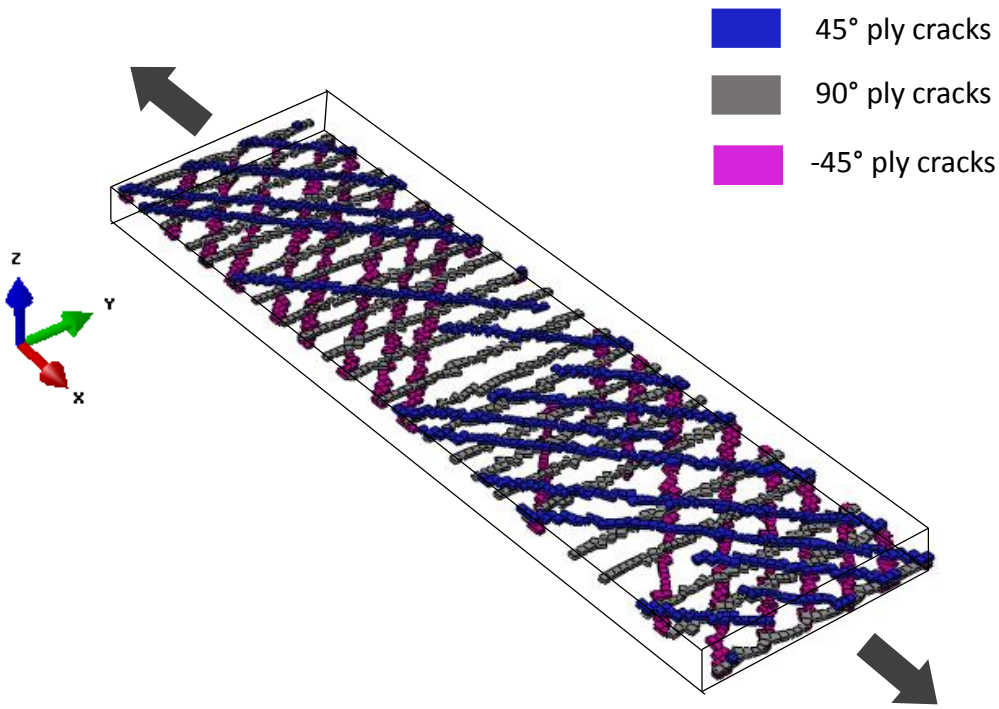

Figure 1. Matrix crack growth in a multidirectional laminate under tension.

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On matrix cracking and splits modeling in laminated composite

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The use of composite materials has considerably increased so far in mechanical design especially in the aeronautic and space industries. However, composite structure manufacturing may require numerous experimental tests from component scale to full scale which are expensive in economics. Therefore the virtual testing, whose goal is to drastically reduce the huge number of industrial tests involved in current characterization procedures, constitutes one of today's main industrial challenges. An answer to these challenges is what we call "damage mesomodel for laminated composite", developed at LMT-Cachan since the 1980s. The mesomodel is capable of describing highly complex nature of composite degradation which involves not a single but several damage mechanisms: fibre failure, fibre/matrix debonding, transverse microcracking and delamination. Nevertheless, the predictions from the such model could be much too conservative in some composite structures involving extensive splitting. From phenomenological aspects, although the transverse microcracking and splits result from the same damage mechanism that is the intraply matrix mcirocracking, the transverse microcracking is characterized by the microcrack density whereas a split appears as an extremely thin matrix microcrack relatively isolated and mainly due to shear. Here, the mesomodel has been found to manifest a shortcoming: the calculated splits are too thick. Then this paper deals with this challenge, the transverse microcracking and split modeling in the ply. As a natural approach, cohesive interfaces are appropriately used for representing extremely thin splits that are completely damaged zones in addition to delamination intefaces. Moreover, for the sake of the virtual structural answer, the problem of splitting detection is discussed and an ad hoc criterion has been proposed for avoiding to introduce a priori cohesive interfaces that is not objective. An illustration is developed so as to compare the classical mesomodel with the proposed mesomodel-based approach. Comparison with experiments is also shown.

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Crack Initiation and Propagation in Textile Composites at the Mesoscopic Scale

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A strategy to model the initiation and propagation of transverse yarn cracks at the mesoscopic scale of textile composites with the aid of Finite Fracture Mechanics (FFM) is presented. The numerical results are compared to experimental observations of the evolution of crack and decohesion density during multi-level tensile tests on composites with a multi-layer woven reinforcement. A Finite Element (FE) model of a mesoscale unit cell of the studied composite is generated taking into account the shift between the reinforcement layers and the compaction of the fabric before resin injection. This ensures strain fields close to those observed experimentally by Digital Image Correlation (DIC) [1].

The crack initiation is modeled using a coupled criterion consisting of a stress condition accounting for the material strength and an energy condition based on FFM [2]. In the studied composite, the energy criterion is dominant, i.e., it determines crack initiation rather than the local material strength. The use of a stress criterion alone would significantly underestimate the specimen strain at crack initiation. However, it provides a good estimate of the crack locations, which are close to those obtained with the energy criterion, and is therefore used to save computational costs. The crack locations agree qualitatively well with the experimental observations, with the exception of some non-repeating crack patterns due to material variability not taken into account in the model.

The cracks initiate at a finite length, determined by the maximum of the energy release rate, and extend through the whole yarn thickness. Since the stress condition is not fulfilled at the interfaces between yarns, the cracks initiate without decohesions around their tips. However, as soon as the crack is present, decohesions between yarns initiate and propagate, without further increase of the material strain, up to a finite length determined by FFM [2]. Crack and decohesion propagation with increasing strain is then modeled using FFM for small increments of the crack or decohesion surface [3]. The energy release rate for crack propagation is higher than for decohesion propagation. Thus, cracks propagate with a constant decohesion length, and decohesions only propagate further once the crack crosses the whole unit cell.

The evolution of the crack configuration in the composite unit cell is shown in Figure 1 for the four crack density levels measured experimentally. The crack density is defined as the total surface of all cracks divided by the unit cell volume. When multiple cracks are modeled, coupling between close cracks must be taken into account in the modeling of crack and decohesion initiation and propagation. It is found that coupling is negligible if the distance between cracks is larger than about half a yarn width (these cracks

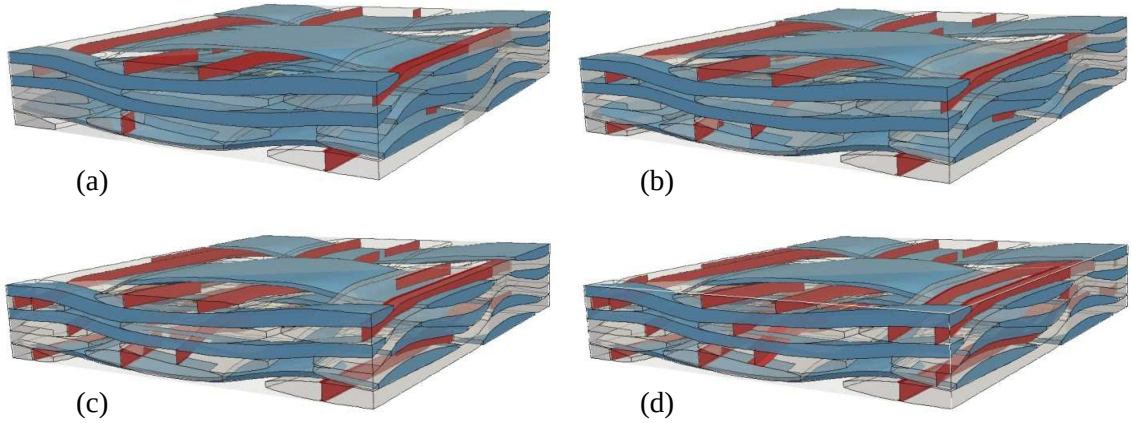

Figure 1: Damage in the unit cell predicted for the crack density levels measured experimentally: (a) $\rho_c = 0.09$ mm^{-1}, (b) $\rho_c = 0.13$ mm^{-1}, (c) $\rho_c = 0.18$ mm^{-1}, (d) $\rho_c = 0.22$ mm^{-1}.

can therefore be modeled independently), but influences significantly the initiation and propagation of closer cracks [3].

The numerically calculated evolution of the crack and the decohesion density is in good agreement with the experimental observations if a fracture energy of $G_c = 200$ J/m^2 is used for the yarns and the interfaces. The decohesion density is calculated from decohesion lengths determined with the aid of DIC on the specimen edges, as decohesions mainly open in mode II and can therefore not be directly detected on the microscope images of the edge of the damaged specimen. The evolution of the decohesion density as a function of the crack density is invariant under linear rescaling of the fracture energies of the yarns and the interfaces, and is also in good agreement with the experimental observations. Furthermore, the evolution of the homogenized elastic properties of the composite (modulus, Poisson ratio) as a function of the crack density is calculated and agrees well with the experimental data.

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A constitutive law for modeling elasto-plasto-damage mechanisms in UD-plies: Damage evolution under multiaxial strain states

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Abstract

The damage evolution during strain softening of an elasto-plasto-damage constitutive law[1,2] for fiber reinforced polymer plies is treated. The existing model, that has been implemented in ABAQUS/Standard (SIMULIA, Providence, RI, USA), predicts plastic deformation and uses continuum damage mechanics to model matrix cracking and progressive fiber failure.

After the onset of strain softening the multiaxial strain state is reduced to an equivalent strain, which is used to determine the damage evolution.

The existing formulation is based on selected strain components which has restrictions in handling certain strain states, e.g. constrained Poisson contraction.

The aim of the present work is to modify and extend the formulation of the equivalent strain to account for more general in-plane strain states which, eventually, drive the damage evolution.

The modifications to the constitutive model are demonstrated for selected test cases of the Third World Wide Failure Exercise (see e.g. [2]). Of particular interest is the third test case with a [0/90/0] laminate under uniaxial tensile loading, where the Poisson contraction of the 0° plies is constrained by the 90° ply.

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Keywords: Fiber reinforced polymers, Constitutive law, Elasto, plasto, damage model, Continuum damage mechanics, Strain softening

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Progressive Failure Analysis of Composite Structures Based on the Strain Invariant Failure Theory

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The implementation of a constitutive model for transversely isotropic damage in fiber-reinforced composites as a user-defined material model (UMAT) in Abaqus is presented. Damage initiation in the orthotropic linear elastically modelled composite material is based on the Strain Invariant Failure Theory (SIFT) [1], utilising the first and the second deviatoric strain invariant. The materials micromechanics during damage initiation are considered by amplification of the strain invariants with amplification factors determined from periodic micromechanical representative volume elements (RVEs) taking into account different fibre arrangements. The RVEs are simulated in Abaqus utilising periodic boundary conditions (PBCs).

Damage evolution is based on the Material Property Degradation Method (MPDM) [2] driven by two damage variables representing failure longitudinal and transverse to the fibre direction with linear or exponential damage evolution laws. The effective material stiffness and nominal stress in the damaged material is obtained by means of a fourth order damage tensor [3]. In order to improve convergence of the numerical simulations viscous regularisation of the damage variables is implemented.

The implemented material model is validated by comparison of the numerical results with experimental tests of multilayer carbon fibre specimens, utilising digital image correlation (DIC) to record the evolution of surface strains on the tested specimens.

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Numerical analysis of the single fiber fragmentation test

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There is a trend towards the use of microscale analysis for the understanding and prediction of the performance of fiber reinforced composites. The appeal of the microscale lies in the fact that the constituents (fiber and matrix) are more easily characterized than the composite material. Supposedly, the complexity of the composite material behavior can be completely described with a model that only receives input from simple tests on the fibers and the pure resin. However, with the definition of the two constituents, the micromodel is not yet complete. Especially when it comes to failure analysis, the fiber/matrix interface also plays an important role in the composite material behavior. Measurement of interfacial properties is still an open issue.

The single fiber fragmentation test is one of the experiments that has been proposed to get information about the fiber/matrix interface [1]. The test specimen consists of a single fiber embedded in matrix material. When the specimen is loaded in uniaxial tension, multiple fiber breaks can be observed as well as fiber/matrix debonding in the vicinity of these fiber breaks.

In this contribution, a numerical model for the single fiber fragmentation test is presented. The fiber is modeled as a 1D object inside a 2D or 3D model. Slip degrees of freedom are introduced such that the fiber can slip in longitudinal direction but not move with respect to the surrounding matrix in transverse direction. A Weibull strength distribution along the length of the fiber is introduced to represent the stochastic nature of fiber failure in the test. Brittle fiber failure is supposed, with a sub-stepping algorithm where internal forces across the broken fiber are removed in multiple increments for numerical robustness. For the matrix a pressure dependent constitutive model with damage and plasticity [2] is used and for the fiber/matrix interface a cohesive law with friction [3].

The model is used to test different hypotheses concerning which information can be obtained from the experimental observations of the sequence of multiple fiber breaks, debonding and crack saturation. Model results are compared with experimental observations for validation. Finally, the model is used to interpret measurements on specimens that have been exposed to moisture and elevated temperature in order to characterize interfacial degradation under these conditions.

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Effect of matrix ductility on failure of thermoplastic composites: a computational micromechanics study

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Abstract

In this paper, the effect of polymeric matrix ductility on the failure of thermoplastic composites is studied through a computational micromechanics framework. Two types of polymer matrices were analysed with a remarkable difference in their ductility. Firstly, optical microscopy image of random arrangement of fibres in GFPP was obtained, and the representative volume element (RVE) size is rigorously determined via geometrical two-point probability function. Secondly, 3D finite element model of the RVE was imposed with periodic boundary conditions. Two loading cases were studied: transverse tensile and in-plane shear loadings under quasi-static loading rate. Here, we also propose a modified periodic boundary condition to accurately capture the in-plane shear behaviour of [±45]s laminate. The fibre is assumed to be isotropic linear elastic, while the constitutive model of the matrix is capable of describing pressure-dependent yield strength and damage onset often found in thermoplastics. Cohesive elements are inserted into fibre-matrix interfaces to simulate debonding. In transverse loading case, which is different from shear loading case, we found that increasing matrix ductility is not an effective strategy to improve the strength and ductility of GFPP. We also performed experimental studies to study the effect of matrix ductility through quasi-static indentation and microscale three-point bending on GF/PP cross-ply laminates.

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Phase field modelling of failure in hybrid laminates

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Fibre Reinforced Polymers are increasingly used as structural materials in several engineering fields, mostly due to their extremely high resistance to weight ratio. In fact, carbon fibre/epoxy composites offer high stiffness and low density resulting in some of the highest achievable specific elastic moduli and tensile strengths among structural materials. These desirable properties make them suitable for applications such as aero-structures, spacecraft, motorsports, high specification sports equipment, where ultimate mechanical performance and lowest possible weight are crucial. Nevertheless, the brittle response at failure due to complete lack of ductility, limit the advantage of the full strength of the material since great safety coefficients are imposed by technical guidelines at the design level. Moreover, although their increasingly wider adoption, the development of a consistent theoretical framework for their modelling in all applications is still ongoing research.

A possible strategy to provide the composite with a ductile failure response is to consider novel composite architectures where fibres of different stiffness and ultimate strain values are combined (hybridisation) [1]. In a tensile test, failure occurs first in the fibres with lowest ultimate strain inducing a stress relaxation (a decrement of stress at fixed global mean strain for the hybrid composite). The remaining high elongation fibres are proportioned to sustain the total load up to failure. By optimising the quantity and type of fibres, a ductile to failure response can be achieved.

In this work we present a simplified 1D phase field formulation [2] to capture the main feature of the UD hybrid composites [3]. The brittle behaviour of the two materials is determined through the minimisation of an energy functional defined on two fields, i.e., the displacement and the phase fields, establishing an energetic competition between the elastic energy release and material damage localised in fracture surfaces. Moreover at the interface level a nonlinear cohesive interface law is assumed. Fracture mechanisms are carried out by parametric analyses of the different failure mechanisms of the laminates. The models is capable to reproduce and describe at the same time failure within the material and delamination at the interface level according to experimental observations.

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Numerical stochastic study of porosity and wrinkles defects in composite materials: influence on the mechanical behavior

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The use of composite material in the aerospace and the marine renewable energy industry is more and more widespread due to their excellent specific properties. The manufacturing processes of composite parts may lead to defects which decrease the mechanical properties of the structure [1]. Those parts are thus subjected to systematic long and costly non-destructive testing to detect any defects resulting from manufacturing processes. In case of negative results regarding conservative criteria, the composite components, such as wind turbine blades, can be considered non-compliant and can be rejected leading to non-negligible economic consequences. In this numerical study we propose to analyze the impact of two types of defect: porosity and wrinkles. Those two defects are, on the other hand, submitted to geometrical uncertainties such as porosity distribution or wrinkles size. The second aim of this work consists in taking into account these uncertainties in order to get more robust physical predictions [5].

In this paper we adopt a parametric vision of the uncertainties [2] consisting in representing the probabilistic content through a finite set of random variables. In the case of porosity, these input random parameters allow characterizing the geometry of the voids modeling the porosity and their spatial distribution. In case of wrinkles, they represent the shape and size of these defects. We thus focus on the propagation of uncertainties based on spectral stochastic methods [3] such as the L2 projection method [4] which belongs to the so-called non-intrusive techniques. These methods only require the use of deterministic solvers, such as classical finite element software, and easily allow parallel computing.

The first proposed study deals with the influence of the porosity. We first work at the micro-scale where the details of the material (reinforcements and voids modeling the porosity) are geometrically represented. The random response is analyzed with respect to the input uncertainties on the porosity rate. We then focus on building a macroscopic model using numerical homogenization techniques allowing the scale

transition. Results coming from both microscopic and macroscopic models are compared and discussed using classical mechanical quantities and damage criteria. The second part of this work is dedicated to wrinkle defects which appear at the interface of the ply. We thus work at the mesoscopic scale where ply of composite laminates are characterized by their effective elastic properties. We use a parametric representation of the ply geometry basically through its height and width which are considered as random variables. We thus propose to analyze the influence of these parameters on local mechanical quantities such as stress fields and local damage criteria.
The whole proposed study will be illustrated with several numerical examples which aim at analyzing the sensitivity of the structural response to the variability of the product / processes parameters and a possible analysis of the mechanical reliability.

This study is part of the SIMSCEF project managed by IRT Jules Verne (French Institute in Research and Technology in Advanced Manufacturing Technologies for Composite, Metallic and Hybrid Structures). The authors wish to associate the industrial and academic partners of this project; respectively ADWEN, DAHER, GeM Institute (UMRCNRS-ECN-Nantes-University 6183).

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Material, failure, and tensile test simulation model for short glass fibre reinforced polypropylene

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Nowadays short fibre reinforced polymers are often used in load carrying structural parts. On the one hand they are easier to manufacture in a mass production scale compared to continuous fibre reinforced polymers. But on the other hand their morphology is much more complex. The orientation and distribution of the fibres determine the material behaviour in terms of stiffness and strength. The characterization of the mechanical behaviour of this type of material is important for a proper component design. Simulation software is getting more and more efficient and simulations are a suitable way beside the classical experiments to investigate the material behaviour. With micromechanical software (Digimat) the stiffness of short fibre reinforced polymers can be determined in an efficient way. Because of the heterogeneous orientation of the fibres in a component or specimen the determination of the strength is a difficult but important task. The strength of short fibre reinforced polymers was determined for low-speed strain rates for specimens with different fibre orientations based on data of tensile tests. For the failure modelling the micromechanical approach "First pseudo grain failure" (FPGF) in Digimat was used [1]. The needed parameters for the material and failure description were determined with the reverse engineering method. Integrated finite element simulations were performed. The found parameters were validated with tensile tests with specimens with different fibre orientations. Therefore ISO-MPS specimens were used. A problem occurred as the simulated specimens did not reveal failure in the middle of the specimen as the conducted experiments would suggest. They show failure in the vicinity of the shoulder of the ISO-MPS specimen and therefore they fail at a lower stress than the specimens in the experiment. These inaccuracies could lead to an improper component design. Therefore, approaches are shown to find a solution for this problem. Furthermore double edge notched specimens with different notch radii were simulated and compared with the unnotched one.

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Damage evolution in composite pipes using a continuum damage mechanics formulation.

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ABSTRACT

Composite pipes are replacing conventional steel pipes in oil and gas transport applications. Their strength is determined by specific failure criteria for composite materials, however, once the damage has initiated there exists an interest in knowing how it propagates or evolves in order to determine the remaining life of a pipe. After damage initiation, mechanisms like micro cracking, fiber rupture, fiber-matrix debonding and delamination can occur [1]. Continuum damage mechanics is a phenomenological theory for taking into account these mechanisms in the effects of the mechanical material behavior [2].

Currently, it exists a variety of damage models for composites laminates [3]. Ferry et al. [4] have proposed an anisotropic damage model for pipes with good agreement with experimental data. Other models are also developed or implemented for composite pipes for example in [5]. Solution of these models are indeed not very easy and usually an implementation in a FEA (Finite Element Analysis) code is needed. A common numerical method to solve for these equations is the return mapping algorithm. In this work, we study the numerical methods available for the solution of damage evolution in composite laminates by the application of an industrial example: composite pipes.

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MS12: Quasi-brittle cracking in Concrete and Rock, including durability mechanics, coupled processes and hydraulic fracture

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Quasi-brittle materials such as concrete or rock, when subject to mechanical action (either direct or indirectly induced by environmental effects), exhibit a transition from (visco)elastic response, to distributed micro-cracking, and coalescence to localized macro-cracking. In the approximately 3 decades since the term quasi-brittle was coined, a variety of models have been proposed. Models based on the continuum approach such as elasto-plasticity, continuum damage mechanics have been extensively developed. The processof localization into macro-cracks has been tackled either via "discrete cracking" (Fictitious crack model) or "smeared cracking" and associated regularization procedures with subsequent and size effect laws. A number of numerical techniques have emerged that try to reconcile all aspects of quasi-brittle material behavior, although no magic recipe seems to have been proposed as yet. Techniques such as zero-thickness interface elements or XFEM allow to integratediscrete cracks into background continuum meshes. Each one has its advantages and disadvantages, requiring in some cases, costly algorithms for re-meshing, crack tracking, etc.

Besides direct mechanical actions, cracking of concrete and geo-materials is often caused by environmental processes or flow/diffusion/transport-induced actions. All those problems have in common the need to solve coupled problems including mechanical and flow/diffusion/transport equations, although the degree of coupling may vary substantially from one case to another. This includes for instance (but not exclusively):

- cracking of concrete-like materials due to differential volume changes due to durability-related phenomena such as drying shrinkage, sulfate attack, carbonation,alkali-silica-reaction, high temperatures.
- cracking (or opening of existing fractures) in rock masses due to fluid injections such as hydraulic fracture.

Quasi-brittle materials are heterogeneous in nature, and micro-or meso-mechanical models in which the heterogeneities are described explicitly are able to simplify considerably the constitutive description, and yet offer a much more powerful tool to represent the material behavior in simple and complex scenarios including not only complex mechanical scenarios but also combination of mechanical and diffusion-driven or coupled environmental actions.

This mini-symposium intends to gather contributions on all those and related topics, with a specific view to applications on concrete and rock.

Numerical and experimental investigation of size effect in concrete by the scaling of microstructure

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Size effect has been a major problem in the design of structures. The problem becomes more acute and complex in concrete as these materials are incapable of plastic yielding, failing due to fracture characterized by a large fracture process zone (FPZ) that undergoes distributed strain-softening in the form of microcracking and fractional slip.

Size effect has been rigorously analysed in concrete. When a concrete structure is loaded, the strain energy is absorbed in the FPZ due to toughening mechanisms. As the structure size increases, FPZ becomes negligible, whereas for small size structures, the FPZ can be of the same magnitude as the structure size. Thus the presence of FPZ is considered the main cause of the size effect. Bazant [1] considered size of FPZ as a material property and multiple of maximum aggregate size ($D_{max,agg}$). Aggregate plays a key role in the microstructure and regards as the skeleton of concrete as 60-80% of a concrete mix is occupied by aggregates. Hillergorg [2] concluded that the fracture energy increases when $D_{max,agg}$ increases from 8 to 20mm. As shown by Chen [3], when $D_{max,agg}$ is small, the fracture surface is smooth, however when $D_{max,agg}$ is large, surface becomes rough and complex. Otsuka [4] concluded that when the maximum aggregate size increases, the width of FPZ increases while the length of FPZ decreases.

Thus, it can be inferred that ratio between the structure size and the aggregate size is a fundamental factor which is causing the size effect. When the structure size increases, $D/D_{max,agg}$, ratio between the characteristic structural dimension D and the maximum aggregate size $D_{max,agg}$ increases and approaches D, the material behaviour approaches linear elastic fracture mechanics (LEFM). However, when the structure size is small i.e. at laboratory scale where D and $D_{max,agg}$ are of same magnitude, LEFM is no more applicable. In this case mesoscopic and lattice element type finite element modelling are more predictive where aggregate size and distribution is explicitly taken into account.

The objective of this study is to investigate experimentally and numerically the role of the ratio $D/D_{max,agg}$ as the cause of size effect. This can be done by three methods: *Method* 1 by scaling D, or *Method* 2 by scaling $D_{max,agg}$, or *Method* 3 by scaling both i.e. keeping $D/D_{max,agg}$ constant. In this study the three methods were investigated by using three types of concrete mix ($M1$, $M2$, and $M3$) which were designed with same aggregate to mortar volumetric ratio and same mortar properties. Only the aggregate sizes were changed. Aggregate sizes were up-scaled in $M1$, $M2$ and $M3$ concretes such that the volumetric fraction of aggregate (as $D/D_{max,agg}$) in each concrete remains same.

- In the first series $S1$, notched beam specimens were prepared using $M2$ (medium size aggregate) concrete on geometrically increasing sized specimens ($D1$, $D2$, $D3$). In this way, the ratio $D/D_{max,agg}$ was up-scaled (*Method* 1).
- In the second series $S2$, three notched beams were prepared with same dimensions (specimen height, $D2$), each with different concretes $M3$, $M2$ and $M1$ respectively. In this way, the ratio $D/D_{max,agg}$ was up-scaled in each beam (*Method* 2).
- In the third series $S3$ of concrete specimens, both aggregate size $D_{max,agg}$ and specimen height D were scaled. Beam $D1$ (small beam) was prepared with $M1$ concrete (small size aggregate), beam $D2$ was prepared with $M2$ concrete and beam $D3$ (large beam) was prepared with $M3$ concrete (large size aggregate). In this way the ratio $D/D_{max,agg}$ was kept constant in all three beams of this series (*Method* 3)

The beams were tested in three point bending and fracture process was monitored with digital image correlation (DIC), crack lengths and crack openings were measured and the role of $D/D_{max,agg}$ as the cause of size effect is analysed.

The numerical investigation has been carried out by Discrete Element Modelling (DEM). DEM simulation has advanced advantages in simulating cemented material behaviours and exploring the microscopic mechanisms which attracts increasingly researchers using it. Here the mechanical behaviour of the assemblage is dominated by the micro properties of particles and bonds between them. Nitka and Tejchman [5] successfully modelled the behaviour of concrete in uniaxial compression and tension to model the concrete fracture at aggregate level. In this study, a three-phase model is adopted in modelling concrete. Aggregates were modelled by clumping smaller particles together as clusters. Micro parameters of matrix, aggregate and interface transitional zone are determined through inverse calibration using Levenberg-Marquardt (LM) algorithm on compression and direct tension test for mortar and concrete. The crack propagation obtained by using DEM and the role of aggregate in concrete fracture processes was analysed.

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Influence of concrete meso-structure on the interaction between damage and non-elastic deformation of cement paste: 3D FE study.

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Abstract

To better understand the behavior of concrete under environmental conditions it's important to account for the material heterogeneity. The inhomogeneous structure of concrete and its interaction with (1) the load induced damage and (2) time-dependent non-elastic deformations of cement paste (e.g. basic creep, shrinkage, variation of termal strains and humidity), is most probably responsable for strong time-dependent response of concrete.

To clarify this aspect the above mentioned effects are investigated through mesoscale analysis of a concrete cylinder. In the 3D FE model concrete is treated as a bi-phase composite material, consisting of coarse aggregate and mortar matrix. A non-linear constitutive law, based on the microplane theory, is assumed for mortar, while the aggregate is linear elastic. For different levels of the applied uniaxial compressive load, the influence of the following parameters is investigated : i) basic creep of mortar, (ii) shrinkage of mortar and (iii) cyclic variation of thermal strains. Finally, to account for the interaction between these variables, the effect of their combination is also studied. In the model, the basic creep of mortar is assumed to be linear and it is based on the Maxwell chain model.

The study shows that with higher loading level, the increase with time of non-elastic deformations of concrete becomes progressive. This phenomenon is related to the interaction between the load induced damage of mortar and its non-elastic time-dependent deformations, such as : creep, shrinkage and thermal strains. It seems that the main reason for such strong interaction, governing the time-dependent behavior of concrete, is the material heterogeneity.

Keywords: Mesoscale modeling, nonelastic deformation, creep, shrinkage, fe elements, microplane model

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Statistical organization of acoustic events induced by the slow propagation of a single crack in a heterogeneous solid

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In heterogeneous materials under slowly increasing compressive loading, damaging processes are sometimes erratic, with random sudden cascades of microcracking events spanning a variety of sizes. Such so-called crackling dynamics [1] are e.g. revealed by the acoustic emission accompanying the compressive failure of porous materials or, at much larger scale the seismic activity going along with earthquakes (see [2] for review). In both cases, statistical analyses have revealed complex time-energy organization in mainshock-aftershock sequences obeying a range of robust empirical scaling laws [3] (Gutenberg-Richter and Omori-Utsu being the most well-known) that help carry out seismic hazard analysis and damage mitigation. These laws are usually conjectured to betray the collective dynamics of microcrack nucleation.
The experiments presented at CFRAC were designed to unravel to which extent such a seismic-like time energy organization for acoustic events (AE) hold in the much simpler situation of a single propagating. Such cracks were slowly driven in artificial rocks under tension [4] and the statistical organization of the so produced acoustic events was characterized. This organization shares some similarities with that observed in compressive or shear fracture and, at much larger scales, in earthquakes. Some specific features however emerges and, as will be discussed at CFRAC, constraint the seismic laws and their interrelations.

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A Consistent Multiscale Approach for Multiphysical Failure Processes in Poroplastic Materials like Concrete

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Multiphysical failure processes in concrete are due to arbitrary combinations of temperature, fluid pressure and mechanical actions. The consequences on concrete overall features and durability strongly depend on degradation mechanisms and processes that take place at different length scales, but mostly on the meso and microscales. Particularly and regarding the fluid pressure and thermal actions, most of the degradation processes are controlled by the heterogeneities of the microscopic scale, while in case of the mechanical actions both the micro and mesoscales play a relevant role. Thus, realistic and accurate numerical modeling of concrete fracture, degradation and failure processes when subjected to arbitrary multiphysical actions require multiscale analysis to account for the different mechanisms and features controlling the complex coupled thermo-hydro-mechanical response behavior of this composite. Among the different multiscale approaches for material modeling, those based on computational homogenization methods are the most popular ones due to the involved versatility and accuracy.

In this work a thermodynamically consistent semi-concurrent multiscale approach is formulated for modeling the thermo-poro-plastic failure behavior of concrete materials. Thereby, a discrete approach is considered to represent the RVE material response, while a continuous, smeared-crack approach is followed for the macroscopic scale. After formulating the fundamental equations describing the proposed homogenizations of the thermodynamical variables, the dissipation and the free energy, the attention is focused on the constitutive models for both the skeleton and porous phases. Then, numerical analyses are presented to demonstrate the predictive capabilities of the proposed thermodynamically consistent multiscale homogenization procedure for thermo-hydro-mechanical failure processes in concrete.

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Multi-scale modeling of fracture and creep behaviors of recycled aggregate concrete

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Abstract

Recycling of waste construction materials has become one of the sustainable solution to meet with the depletion of natural resources and the shortage of waste disposal land. Numer- ous studies concerning about the concrete made with recycled aggregate have been carried out. It is found that this kind of concrete generally has a higher water absorption and a relative lower strength due to the porous old attached mortar [1]. Two kinds of interfacial transition zone (ITZ) exist in recycled aggregate concrete (RAC), one between the recycled aggregate and the old residual mortar, and the other between the aggregates and the new mortar. The relatives qualities of the two ITZs can determine the mechanical behavior of concrete [2]. However, most of the researchers are only interested in determining the physical properties of those thin zones, few studies regarding the calculation of the mechanical properties of ITZ in RAC have been found, probably due to the complexity of its microstructure.

In this work, we have proposed a methodology to account for the influence of the inter- facial zones in the finite element modeling of recycled concrete. Considering the "numerical calculation cost", the thickness of ITZ is chosen to be 100μm, which is the minimal size of finite elements in this modeling [3]. For those, the three-point flexural tests for concretes with 0, 30% and 100% recycled aggregates have been firstly performed. Then, based on the experimental results, the input mechanical parameters (tensile strength and fracture energy) of the model have been calibrated. The rest of the parameters are determined according to the hydration model or taken directly from the literature. Finally, the damage model is validated by comparing the simulation result with the fracture test of 30% RAC.

With the information of the damage model, the mechanical behavior of RAC under constant loading can be simulated by coupling the creep and the damage occurred simultaneously in concrete. Firstly, the three-point bending creep tests of RAC beams were carried out. Then, by applying a multi-scale model developed by Farah et al. [4], the experimental results were used to calibrate the viscoelastic parameters of the different phases of material. The valida- tion of this coupling creep-damage model was achieved by the fact that the numerical result of concrete with 30% recycled aggregates corresponds well with the experience. By knowing the replacement percentages of natural aggregates by recycled ones, our model can predict the fracture and creep behaviors of RAC with the identified parameters.

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Keywords: multi, scale modeling, recycled aggregate concrete, fracture, creep

A micro-macro model for the damage prediction of concrete based on the hydration process

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Computational modelling of failure in mortar and concrete suffers from a dependency on a number of empirical parameters, mostly due to the lack of explicit incorporation of failure mechanisms from the micro-level. These parameters need readjustment to fit experimental data, and so will change when the microstructure changes. Previous studies [1, 2] have shown that in the case of linear elasticity, the effective elastic properties of cement paste can be determined from micro-level simulations using the intrinsic properties of cement phases.

Following this line of reasoning, and in an attempt to resolve this issue and take into account the fracture properties of cement paste, a multiscale modelling scheme is adopted. First, a hydrated cement microstructure is generated through the cement hydration program VCCTL using typical cement data and hydration parameters. As for mortar and concrete, the same mesoscopic mesh scheme is used. Cement phases are distinguished and attributed a series of fracture parameters derived from experimental testing and/or molecular simulations present in the literature. The damage model developed by Fichant et al. [3] is used through the three scales of cement paste, mortar and concrete and the effective damage properties are transmitted from one scale to another. Finally, a reverse identification analysis is used to tweak two intrinsic parameters, and the robustness of the multiscale scheme is tested by trying to reproduce earlier experimental results.

In order to validate the model, simulations are performed for failure tests on concrete at different ages from 12 hours to 28 days. The simulations are compared in good agreement with experimental measurements [4]. The next step of the study is the 3D modelling in order to check the ability to simulate large structures.

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Modelling Bond between Reinforcement and Concrete after Exposure to Fire

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Abstract

The behaviour of bond between reinforcement and concrete at high temperature is numerically investigated considering the splitting of concrete using the beam-end test specimen. A transient 3D finite element code that utilizes temperature dependent microplane model [1] as the constitutive law for concrete is employed.

In this work, first a beam end test that was performed at room temperature is simulated to validate the numerical model. It was observed in the test as well as in the analysis, that the usable bond strength is limited by concrete splitting. The same model is then used to investigate the influence of high temperature on usable bond strength. Two heating types are considered to simulate the exposure conditions in a slab and in a beam, namely one-sided and three-sided heating, both following the ISO 834 fire scenario.

The results clearly show that under realistic conditions of concrete cover, confinement and fire exposure, the concrete splitting almost always limits the bond performance. The results further indicate that the beam-end test specimen offers a suitable setup to investigate the pull-out behaviour of reinforcement under high temperatures accounting for different influencing factors. Based on these numerical results, a detailed experimental programme is being pursued at the University of Stuttgart.

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Keywords: bond degradation, fire, temperature dependent microplane model, concrete splitting, beam, end test

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Explicit modelling of cracking induced by drying shrinkage

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The prediction of the durability of a concrete structure is closely linked to the prediction of cracking at its early age. Indeed, differential drying between the surface and the core of the structure leads to a heterogeneous stress state and can induce significant micro-cracking at the surface [1, 2]. These micro-cracks will impact not only the mechanical properties but also the permeability of the structure [3].

In this study, a sequential analysis is proposed to represent the drying evolution and the corresponding cracking pattern. First, Finite Elements calculations are used to perform drying simulations and obtain drying shrinkage strains. Then, a beam-particle model is applied to obtain the deformation shape and the cracking pattern. Indeed, this Discrete Elements model is designed to describe discontinuous mediums and thus can naturally predict crack initiation as well as their propagation and closing [4]. This analysis allows us to accurately model the cracking induced by drying shrinkage.

The dried specimens can then be subjected to various numerical tests in order to analyse the impact of drying effects on concrete mechanical properties – such as the Young modulus, the tensile and compressive strength and the fracture energy. The influence of shrinkage on the cracks formation and re-closure appearing during the mechanical loading can also be investigated. These numerical studies will benefit from an experimental campaign performed in parallel.

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A multi-fiber Timoshenko beam finite element with embedded discontinuities to simulate the behaviour of reinforced concrete structures till failure

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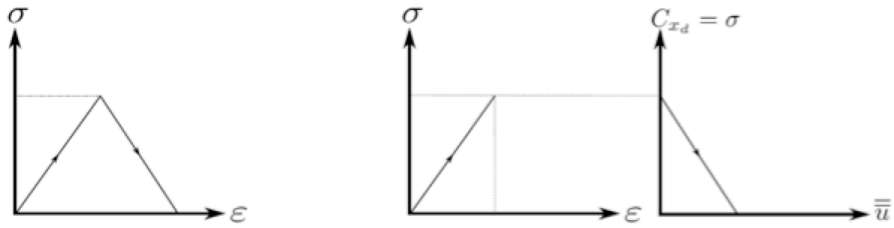
A multi-fiber beam finite element based on the Timoshenko theory is proposed to simulate failure of reinforced concrete structural elements. Its section can have an arbitrary shape and each fiber has a local constitutive law. The concrete fibers behave according to a continuous damage mechanics law and the steel fibers have an elasto-plastic behaviour.

The new displacement-based finite element (FCQ) proposed by Caillerie, Kotronis, & Cybulski, 2015 is adopted. This formulation uses shape functions of order three (3) for the transverse displacements, two (2) for the rotations and adopts an additional internal node. This results to a finite element free of shear locking. In Bitar, Grange, Kotronis, & Benkemoun, 2016, the performance of this element with respect to other Timoshenko finite element beam formulations found in the literature is presented.

In order to capture failure, we focus on strong discontinuities (Simo, Oliver, & Armero, 1993) and more specifically on the Embedded Discontinuity Approach (EDA), Wells, & Sluys, 2000. EDA represents an alternative method to the smeared and discrete crack representations avoiding some of their drawbacks as described in Lotfi & Shing, 1995. Localized failure is incorporated into the standard displacement-based finite element using additional variables. The fibers are enhanced in order to describe concrete crack openings and the development of plastic hinges for steel (Jukic, Brank, & Ibrahimbegovic, 2014). Accordingly, additional shape functions are added to interpolate the displacement jump within the enhanced finite element. A linear cohesive law, linking the axial stress and the axial displacement jump, characterizes the material behaviour at the discontinuity. The variational formulation is adopted in the context of the incompatible modes method followed by the corresponding computational procedure.

A numerical illustration of the proposed model is presented on a cantilever multi-fiber Timoshenko beam. The beam is submitted to a vertical displacement at its free end. First, the fibers are modelled considering a softening elastic model and no enhancement (figure 2 (a)) and then with enhancement figure 2 (b), considering an elastic model coupled to a cohesive one as showed in figure 1.

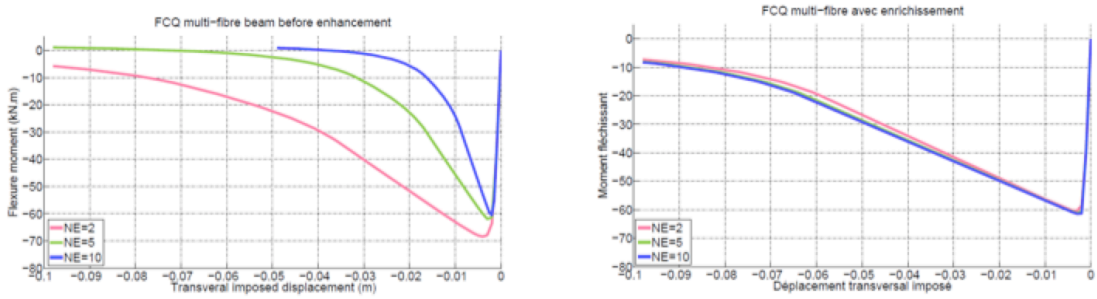


(a) Softening elastic model

(b) Elastic model coupled to a Cohesive model

Figure 1 – Material laws at the fiber level

Figure 2(b) shows that the fiber enhancement can limit the mesh dependency at the global scale.



(a) Global response before enhancement

(b) Global response after enhancement

Figure 2 – Beam global response: study of the mesh dependency

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A Thick Level Set approach for numerical Simulation of restrained shrinkage cracking in concrete structures

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Abstract

To ensure the requested service life and minimize durability risks in concretes structures, it is ideally desired to predict and control shrinkage cracking. Despite decades of research, it remains a key topic in the construction industry today. The present work is dedicated to modeling damage evolution and eventually crack propagation in concrete structures due to restrained shrinkage using the promising Thick Level Set approach (TLS).

Shrinkage, a time dependent volumetric change, is a complex material response affecting concrete in an adverse manner. When restrained by friction, shrinkage introduces a heterogeneous stress field leading to crack development when exceeding the material tensile strength (Figure 1).

When applied to damage models, the Thick Level Set (TLS) approach offers non-local treatment preventing any spurious localization problem. This approach was previously presented in [1-2] highlighting numerous advantages for damage and fracture simulation such as automatic transition from damage to fracture, crack branching and crack interaction to cite a few.

Within this method, the damage variable is directly expressed in terms of a thick level set function used to separate the undamaged from the damaged zone. A characteristic length, beyond which the material is fully damaged, is introduced and pilots the natural transition from partial damage to macroscopic cracking. The damage growth is then treated using the classical level set convection and reinitialization equations.

To better represent the complexity of the described application, several additions are required. Attention is focused herein on key features such as ***i)*** the restrained shrinkage representation, ***i i)*** the identification of the potentially fiber-reinforced concrete appropriate behavior law (e.g. parameters of the bi-linear Cohesive Zone Model [3]), ***iii)*** the introduction of the structure self-weight into the problem formulation and ***iv)*** the friction description along the interface without introducing contact detection algorithms.

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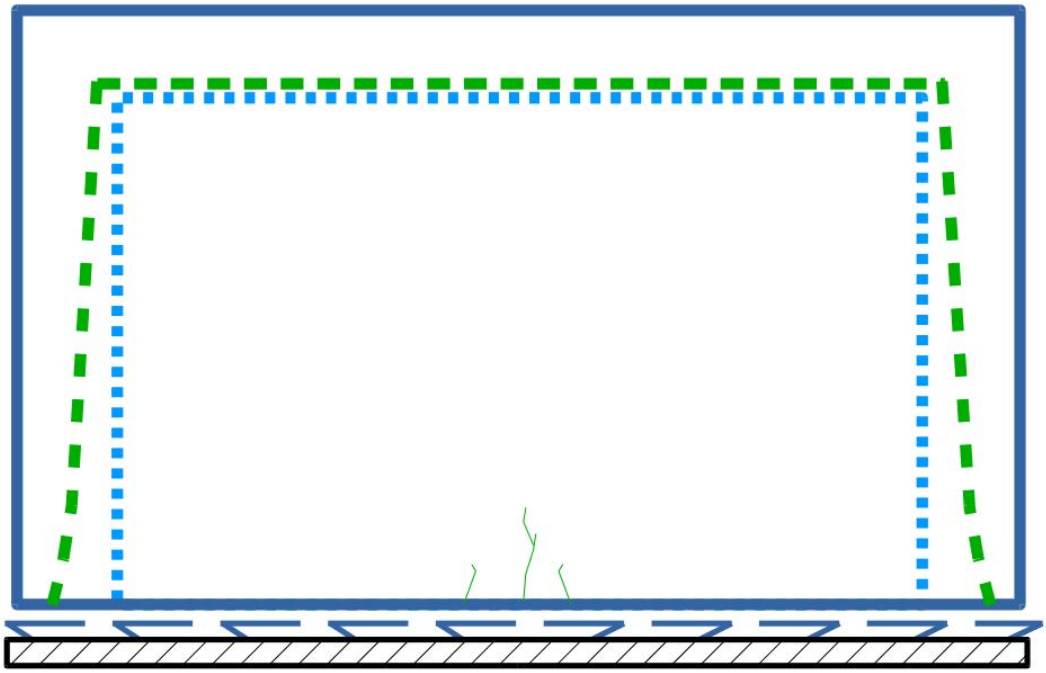

figure 1.

Keywords: Thick Level Set, Damage and fracture, restrained shrinkage

Numerical Strategy fot Developing a Probabilistic Model for Elements of Reinforced Concrete

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Abstract

This paper introduces a new approach to model cracking processes in large reinforced concrete structures, like dams or nuclear power plants. For these types of structures it is unreasonable, due to calculation time, to explicitly model rebars and steel-concrete bonds. To solve this problem, we developed, in the framework of the finite element method, a probabilis- tic macroscopic cracking model based on a multi-scale simulation strategy: the Probabilistic Model for (finite) Elements of Reinforced Concrete (PMERC). The PMERC's identification strategy is case-specific because it holds information about the local behaviour, obtained in advance via numerical experimentations.

The Numerical experimentations are performed using a validated cracking model allowing a fine description of the cracking processes.

The method used in the inverse analysis is inspired from *regression algorithms*: data on the local scale would shape the macroscopic model.

Although the identification phase can be relatively time-consuming, the structural simu- lation is as a result, very fast, leading to a sensitive reduction of the overall computational time.

A first validation of this multi-scale modeling strategy on a reinforced concrete slab-beam is proposed. Promising results in terms of global behaviour, macro-cracking information and important reduction in simulation time are obtained.

Keywords: Reinforced concrete structures, Cracking process, Finite Elements, Multi, Scale Model- ing Strategy, Probabilistic Approach

*Speaker

Fracture Behaviors of Recycled Aggregate Concrete Beams under Different Loading Rates

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Abstract

Utilization of recycled concrete as coarse aggregate to make new concrete, called recycled aggregate concrete (RAC) is an important technology for sustainable development of the construction industry. Many studies have been conducted on various properties of RAC structural members. This study was focused on the numerical modeling of the effect of high loading rate on the behavior of RAC beams. Two new material models were developed and used together with the commercial finite element software ABAQUS R . One model is a viscoelastic model that can predict the increase of stiffness (modulus of elasticity) of RAC with increasing loading rate, and the other model is a multiphase composite model that can determine the effective stiffness of RAC taking into account the special internal structure of recycled aggregate. Two different cases were considered in the numerical simulation. Case 1 is for fixed beam size under different loading rates, and Case 2 is for fixed loading rate with different beam sizes. For Case 1, the simulation results of the maximum loads under three different strain rates agreed with test data quite well. The good agreements with the test data indicated that the two new material models can characterize the effect of high loading rate on RAC beams very well. For Case 2, three beam sizes and one loading rate was studied. The post-peak Force vs. CMOD curves from the simulation follow the same trend of the test data. The stress distributions in the beams of different sizes are similar. However, the maximum loads predicted by the numerical model did not agree very well with test data. This is due to the fact that the maximum forces of RAC notched beams exhibited size effect, which was not considered in the present model. So, the size effect of RAC beams will be a future research topic.

*Speaker

3D DEM analysis of damage and failure in cohesive granular materials

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A class of rock-like materials such as sandstone and granite are cohesive granular materials. Deformation and failure process of such materials are inherently related to damage of cemented interfaces between grains. Despite significant advances in continuum mechanics models including phenomenological and micromechanical ones, the key issue remains the description of discontinuous displacements during damage of interfaces. In this paper, a discontinuous approach based on discrete element method (DEM) is proposed. Compared with many existing studies on granular materials, the emphasis is put on the failure process of cohesive interfaces. For this end, a new failure criterion of interface is developed. Both tensile and shear failure are taken into account. The tensile failure is controlled by the normal contact force on the interface. The shear failure is driven by both normal and shear contact force. In particular, the shear failure condition takes into account interface cohesion and friction. A nonlinear failure envelop is proposed in order to better describe the strong pressure dependency of failure strength of rock-like materials. After debonding, the interface strength is controlled by residual friction. The proposed model is implemented into the PFC code. A series of numerical assessments are performed for both two and three dimensional configurations. It is found that the mechanical behaviour (deformation, strength and failure patterns) is clearly influenced by the geometrical conditions. Most existing two dimensional simulations cannot correctly describe failure process in cohesive granular materials. Further, compared with experimental data obtained on sandstone, the proposed model is able to well reproduce the main features of mechanical behaviour of this class of materials, such as pressure dependency, brittle-ductile transition, and volumetric dilatancy.

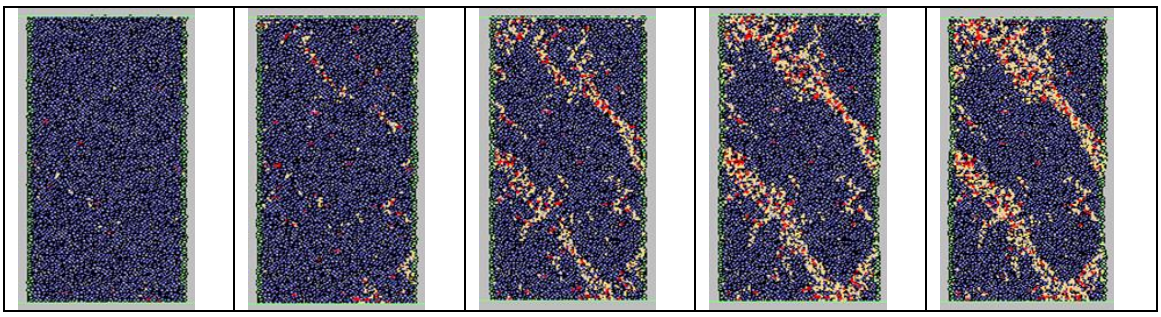

Figure 1: Cracking process in a section of cylindrical sample at different loading steps (Yellow: tensile fractures; red: shear cracks)

Lattice analysis of hydraulic fracturing in the presence of joints

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Characterizing the path of a hydraulic fracture in a heterogeneous medium is one of the challenges of current research on hydraulic fracturing. We present here a 2D lattice hydro-mechanical model for this purpose.
The mechanical model corresponds to the model proposed by P. Grassl, capable to describe consistently size effect on structural failure [1] with a consistent prediction of the fracture process [2]. The mechanical lattice is coupled to a dual hydraulic lattice that describes fluid flow. These two lattice descriptions are coupled according to the following rules : (i) the action of the fluid pressure on the skeleton is represented by using Biot's theory, (ii) the interactions of cracks on the fluid flow are represented by Poiseuille's flow. Numerical coupling is achieved with a staggered coupling scheme.
We consider first the propagation of fractures restricted to the homogeneous case. The numerical model is compared to analytical solutions. It is found that the model is consistent with LEFM in the pure mechanical case, and with analytical solutions from the literature in the case where the leak off is dominant.
Finally, the influence of a natural joint of finite length crossed by the fracture is investigated. Natural joints are represented by introducing lattice elements that form a joint with a plastic-damage behaviour. Two cases are considered, the case of a joint perpendicular to the crack and the case of an inclined joint. In the first case, the crack passes through the joint, which is damaged due to the intrusion of the fluid. In the second case, the crack follows the joint and propagation starts again from the tip.

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Simulation at the meso-scale of crack induced permeability in concrete, estimate of the non linear evolution of flow coefficient

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Abstract

The coupling between cracking and permeability of geomaterial members such as concrete and rock is of great interest for numerous problems. In most case the structure is wanted to be tight in order to prevent fluid or gas to migrate, this is as an example the case of nuclear waste disposals, nuclear plant confinement vessels, or other simple civil engineering infrastructures. In other cases, like hydraulic fracture for gas or geothermal welbores, the geomaterial is wanted to be permeable. If the material is uncracked, the overall permeability is driven by the migration into the porosity, in a case of macroc- racking the flow into the cracks governs the overall permebility. The coupling between cracking and permeability can be introduced by the way of the damage variable [1, 2], but the application of this method must be restricted to the initiation of damage in particular conditions. An other way is to use directly the value of the crack width and to compute the permeability through the so called "cubic law". The crack width could be a direct result of the computation for discrete methods, embedded crack element or X-FEM methods, or the result of a post processing for continuous damage approches [3]. In most cases the direct use of the cubic law overestimates the flow and authors use a tortuosity or flow coefficient which value ranges from 0.01 to 1. The computation of the cracking process at the mesoscopic scale allows to model the transition between difuse cracking and localized cracking [4]. We show that the cubic law directly applies at the mesoscopic scale and that it is possible to compute a non linear evolution of the flow coefficient that can be used at the macroscopic scale.

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Keywords: Fracture, permeability, mesoscale, flow coefficient

Numerical Analysis for Propagation Process of Diffusion-induced Cracks

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Abstract

The moisture or the thermal diffusion in the materials due to desiccation/cooling can be the source of the excessive stress which could generate cracks. The examples of these diffusion-induced cracks are easily observed in nature such as dry-out soil fields and a cool- ing lava. These cracks often form particular patterns, for instance, the net-like patterns of the desiccation cracks and the columnar joint. The basic features of these particular pat- terns have been investigated with various materials and conditions in previous researches. The results of these researches imply that the pattern of the diffusion-induced cracks have the typical length scale corresponding to the experimental conditions.

The problem for the cracking behavior of the materials under desiccation or cooling results in the coupled problem of the multi physics: the moisture/thermal diffusion, the inhomogeneous volume change corresponding to the moisture/thermal distribution, and fracture. In this research, the coupled model of diffusion, deformation, and fracture for the diffusion- induced cracks is proposed in the framework of the continuum mechanics. Based on this coupled model, we perform the numerical analysis by using FEM and PDS-FEM developed by the authors. PDS-FEM is a fracture analysis method which can treat the deformation and fracture problem seamlessly without additional nodes or re-meshing. The analysis of FEM for the diffusion and the analysis of PDS-FEM for the deformation and the fracture are weakly coupled in this numerical analysis.

Through the numerical analysis for the diffusion-induced cracks, we observe the crack prop- agation process, the particular pattern of cracks, and the emergence of the typical length scale of the crack pattern. These simulation results show the satisfactory agreement with the experimental observations.

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Keywords: fracture, coupled problem, PDSFEM

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An unsaturated Viscoplastic Damage modelfor the creep behavior of rocks

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Abstract

Studying the delayed behavior of rocks is crucial for many engineering applications, such as mining industry, petroleum engineering, geo-hazard prediction or geological disposal facilities design. The time-dependent response of rocks may originate from different complex mechanisms, including crystal dislocation, diffusion creep and especially microcracking. The first two mechanisms are often accompanied by a relatively small amount of deformation, while the latter often implies a large volume expansion and consequently failure of rock sample. Moreover, the hydromechanical behavior of rocks is strongly affected when rocks are saturated by one or several fluids (unsaturated rocks), leading generally to a significant reduction of their long-term strength. Yet, very few models in the literature account for the pore pressure effects on the creep behavior of rocks. In this context, the present study develops a new constitutive model for the time-dependent behavior of partially saturated rocks. The delayed deformation of rocks is modeled using Viscoplasticity theory combined with Continuum Damage Mechanics on the basis of the rigorous thermodynamic framework of porous media [1]. Viscoplastic law is extended from the original Lemaitre's model using an equivalent pore pressure, an effective stress variable and a non-associated flow rule. A new anisotropic damage is suggested for unsaturated rock subjected to compressive stresses. The newly developed model contains a quite moderate number of material parameters which can be identified from the results of classic laboratory experiments. This model is validated by experimental data obtained from some brittle and quasi-brittle rocks.

Keywords: Rock, Hydromechanical coupling, Anisotropic Damage, Viscoplasticity

[*]Speaker

A coupled model for simultaneous damage, healing and capillary flow in cementitious materials

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Healing and damage processes frequently overlap in time and the two processes can never be decoupled; however, many numerical models that simulate damage and self-healing employ restrictive assumptions that do partially separate these two processes. These assumptions have included, for example, that healing always takes place under zero-strain conditions and that healing and damage are never concurrent. There are many real situations for which these assumptions are reasonable but there are others that involve simultaneous damage and healing for which a less restrictive modelling approach is required. Such simultaneous damage-healing behaviour was observed in a series of tests conducted at Cardiff University on concrete samples with inbuilt vascular networks containing cyanoacrylate. This contribution describes a new model that addresses this issue. The model uses a crack-healing cohesive zone formulation in which both the damaged and healed proportions of the cohesive zone can both grow and diminish, with no restrictions placed on the number or timing of these damage-healing events. The cohesive zone model is implemented in a finite element with strong discontinuity and coupled to a capillary flow model. The flow model simulates the transport of healing agents within the damage zone. A particular feature of the approach is the way that flow and curing of the healing agent is tracked within the damage zones, which encompass both virgin damage zones as well as regions that have re-damaged after healing. Another important aspect of the damage-healing component of the model is the way that permanent strains are computed so as to satisfy the second law of thermodynamics. This is accomplished with the assumption that the stress in a component of healing agent is zero when it cures: this applies to both null and non-zero stress and strain fields. The new coupled model is assessed using data obtained from a number of experiments conducted at Cardiff University. The primary conclusion from the work is that the new model is able to represent multiple and simultaneous damage-healing *events* with good accuracy.

Hydraulic Fracture Propagation in Inhomogeneous Poroelastic Medium

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Hydraulic fracturing is an important part of modern technologies for intensification of hydrocarbon production. The propagation of the hydraulic fracture is stimulated by the pumping of viscous fluid which creates pressure on fracture's walls high enough to overcome the rock closure stresses and cause the rock failure. Process of the hydraulic fracture growth is governed by several factors: flow of viscous fluid in a narrow fracture's gap, elastic reaction of the fracture's walls, and filtration of fluid from the fracture to the reservoir, rock failure and advance of the fracture tip.

In present work we extend the poroelastic model proposed in [3] to the case of propagating fractures. The model allows determining the porous pressure and the rock deformation coupled with the fracture disclosure and the pressure of the fracturing fluid. The material of the formation is observed as an inhomogeneous permeable medium governed by Biot poroelasticity equations [4]. The advantages of this approach in comparison with the classical approaches based on the KGD and PKN models (see [1, 2]) are the correct account for the interaction of the pore fluid with the fracturing fluid, finiteness of fluid pressure in the fracture's tip, ability for modelling of reservoirs with inhomogeneous physical properties and non-uniform prestress state. In order to account for the rock failure during fracturing, we adopt the cohesive zone model [5] as the fracture propagation criterion.

The numerical solution of the problem was carried out by the finite element method with the use of a modification of the algorithm proposed in [3]. The numerical convergence of the algorithm is verified. Using the proposed model we thoroughly investigate the influence of the pore pressure and rock deformation on the fracture propagation and fracture geometry. In the series of numerical experiments, we demonstrate the influence of the pore pressure distribution on the fracture dynamics in the layered reservoir with permeability contrast. The simulation results are interpreted in terms of the calculated non-uniform backstress acting as an extra closure stress on the fracture walls due to fluid filtration outside the fracture. It is shown that the symmetry of fracture wings is essentially sensitive to such inhomogeneity of the poroelastic medium.

All results are demonstrated in 2D, but the model can be extended to the 3D case where the qualitative conclusions will hold as well.

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Hydraulic fracture interaction in multi-stage fracturing analysis using zero-thickness interface elements

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Hydraulic fracturing is a technique employed in low permeability reservoirs stimulation which basically consists of generating a sequence of parallel equally-spaced fractures ("multi-stage fracturing"). The generation of a fracture causes the modification of the local stress state, and therefore in the case of a multi-stage procedure, the fracture propagation may be modified by the injection sequence, as it is observed via microseismic monitoring [1].

In the present study, technique is analyzed using the finite element method with zero-thickness interface elements for the geo-mechanical modelling of discontinuities [2]. The strategy consists of inserting interface elements in between standard (continuum) elements in order to allow for jumps in the displacement solution fields. For the mechanical problem, their kinematic constitutive variables are relative displacements, and the corresponding static variables are stress tractions. The constitutive relationship is established via a fracture-based model with elasto-plastic structure [3]. Concerning the hydraulic problem, the continuum is considered poroelastic, and the interface formulation includes both the longitudinal flow (with a longitudinal conductivity parameter strongly dependent on the fracture aperture), as well as and the transversal flow across the element [4]. Squeeze-out effects are also considered via the appropriate source/sink terms along continuum and discontinuities.

Previous work by the authors focused on the validation of the method and the analysis a single fracture plane problem [5]. In this case the analysis is generalized to allow free propagation of fractures along any mesh lines, by pre-inserting interface elements between all continuum elements. The results presented in this paper analyse the effects of material, mainly fracture-related properties, and the effects of the fracture job sequence.

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Finite element modelling of permeability: from diffuse micro-cracking to localized crack opening

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Several experimental studies available in the literature have shown that permeability increases from the initiation of diffuse micro-cracking, until the localized macro-cracking. This disorder provides a preferential path for the penetration of fluids and ultimately affects the durability/safety of structures.

In this work, a macroscopic model intended to predict the change of permeability with respect to cracking is proposed. This development allows both diffuse and localized damages to be considered when computing the permeability.

In compression/shear, diffuse micro-cracking is initiated with respect to the material expansion. In this stage, the permeability model assumes the material periodically damaged with uniform parallel cracks. The model adopts Poiseuille's law and uses the transverse expansions (dilatancy), obtained thanks to a non-associated Drucker-Prager yield function to compute the anisotropic permeability components. A correlation between the size of the 'inclusions' and crack spacing was found, it led to a decreasing crack spacing when the diameter of the 'inclusions' decreases.

In tension, Poiseuille's law is used again to compute the flow rate through the macroscopic crack. The permeability model uses the orthotropic crack opening informations provided by an anisotropic damage model to compute the permeability components. In addition, an anisotropic Hillerborg method based on the finite element size in the main direction of cracking is used to deal with the crack localization aspect. The implementation ensures the same total flow rate whatever the mesh sizes.

Keywords: Permeability; Anisotropy; Dilatancy; Crack opening.

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Numerical modelling of hydraulic fracturing in anisotropic sedimentary rocks

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A numerical approach coupling the extended rigid block spring method (RBSM) and the discrete fracture network model (DFN) is proposed to study the hydraulic fracturing process in anisotropic sedimentary rocks. In this approach, the anisotropic rock is first discretized by an assembly of rigid and impermeable blocks based on an anisotropic Voronoi diagram. Fluid flows through interfaces between blocks, which constitute a "complete facture network". The extended RBSM method [1], in which both tensile and shear failure are considered, is used to describe mechanical behaviour of rocks such as elastic deformation, damage and crack propagation induced by loading. The macroscopic mechanical behaviour is related to the deformation and failure of interfaces between blocks. An anisotropic constitutive model for interfaces is employed for the description of macroscopic anisotropic properties in both deformation and strength [2]. A DFN model, which can produce the same macroscopic hydraulic conductivity as the intact rock with an equivalent "fracture network" [3], is developed to simulate the transient fluid flow process. The interaction between fluid pressure and mechanical response is described by an effective stress concept. The coupling model is then used to simulate the process of hydraulic fracturing in a pre-cracked anisotropic rock as illustrated in Figure 1. The fluid pressure in the pre-crack holds constant as 20MPa during the whole process. The progressive fracturing process is well produced. Effects of confining pressure and bedding planes orientation with respect to the vertical direction on fracturing process are investigated. It is found that the bedding planes have significant effects on fracture patterns. They generally provide a preferential path for cracking. Furthermore, as the vertical stress increases, the length of hydraulic fracture gets larger and the effect of bedding planes on fracturing becomes weaker.

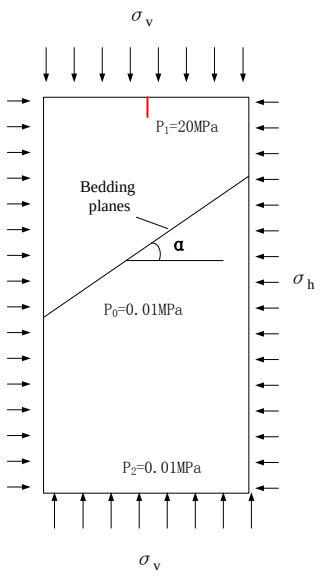
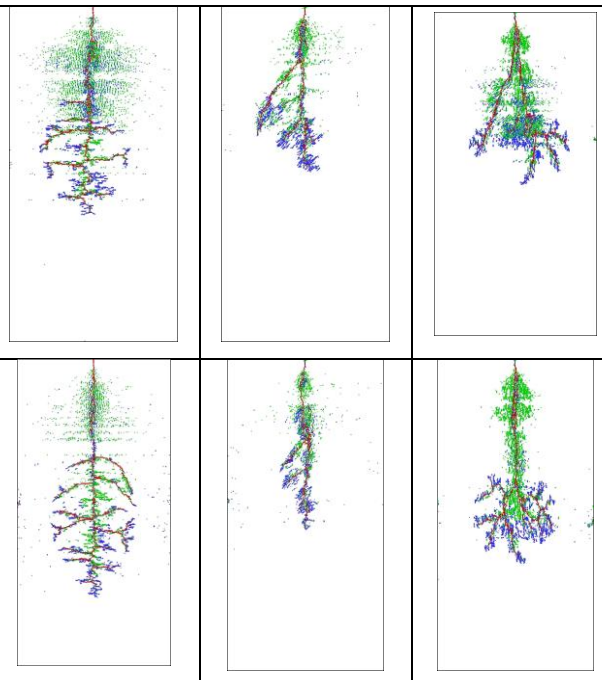


Figure 1. Boundary condition for simulation of hydraulic fracturing



σ_v=10MPa			
σ_v=20MPa			
α=0°	α=45°	σ_v=90°	

Figure 2. Hydraulic fracturing patterns for different steps of vertical stress and different bedding orientations when the horizontal stress remains at 5MPa (red-large tensile crack; blue-small tensile crack; green-shear crack)

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Estimation of structural permeability through the Thick Level Set method and anisotropic mesh adaptation

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Structural permeability is an essential quantity for critical civil engineer structures such as nuclear power plants. Indeed, leakage rate are of prime importance for the durability and the safety of containment vessels. However, this quantity is linked to the micro and macro-cracks that develop in the material due to the external loadings. The numerical prediction of the permeability is thus an essential objective. The evolution of the permeability has been shown to follow three different stages. In the early stage, diffuse micro-cracking causes a slight increase in the permeability. Then, the transition between diffuse and localized cracks causes an important increase in the permeability, and finally the permeability is driven by the opening of the macro-cracks. In this case, permeability and crack opening can be linked through a (modified) Poiseuille's law that takes into account crack roughness.

The objective of this contribution is to study crack opening and permeability in this third phase. Continuum damage models are usually considered to model diffuse micro-cracking. The same method is also used to model the localized cracking regime, even if the method is unable to represent the creation of localized cracks. In this case crack opening can be obtained thanks to post-processing strategies such as [3]. In this contribution, the Thick Level Set method (TLS) [1, 2] is considered to model both diffuse micro-cracking and localized cracks. Indeed, the method is able to represent seamlessly macro-cracks when damage reaches unity. This explicit representation of the crack surface makes possible to extract crack opening with very simple post-precessing techniques. The accuracy of the method will be assessed against experimental data. Moreover, the use of advanced anisotropic remeshing techniques [4] will be considered in order to improve the numerical efficiency of the method.

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Modelling of intersection between hydraulic and natural fractures using the eXtended Finite Element Method

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Abstract

An effective hydraulic fracture treatment in naturally fractured reservoirs should cross and connect the natural fracture system, increasing the effective surface area of the wellbore and consequently its production. However, those interactions may also interfere and inhibit fracture growth and proppant placement, having an adverse effect on the production rates and increasing the treatment costs. As observed in laboratory and field tests, the intersec- tion between a hydraulic and a natural fracture may result in different patterns, such as arrest, diversion through the natural fracture, crossing (penetration) or offsetting. As these are complex phenomena that depend on several parameters, such as in-situ stress and angle between fractures, a more realistic simulation of those intersections is needed to improve production predictions.

A recently developed tool based in the eXtended Finite Element Method (XFEM) is presented. This tool allows both hydraulic and natural fractures to be modelled numerically by introducing different nodal enrichments for each fracture, allowing fracture intersections. The differential equations consider the non-linear coupling between the mechanical behaviour of fractures in a porous medium and the flow in the fracture, which depends on its aperture through a cubic law. The enrichment functions in every calculation increment and the propagation of hydraulic and natural fractures are defined by a geometric processor.

In this presentation, results of simulations of the intersection between hydraulic and natural fractures are shown and discussed. Good agreement with data from laboratory tests in the bibliography is obtained.

Keywords: Hydraulic Fracture, XFEM, Naturally Fractured Reservoirs, Fracture interaction

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Modeling the growth of planar 3D hydraulic fractures in the presence of in-situ stress contrast

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Hydraulic fractures are tensile (mode I) fractures propagating under in-situ compressive stresses due to the injection of a fluid at a given rate. Although the primary industrial application is related to the enhancement of the permeability of petroleum and geothermal reservoirs, the technique is also used in block caving mining. In most sedimentary basin, the in-situ stress tensor at depth is sufficiently deviatoric and the maximum stress is vertical. The created fracture thus propagates in a vertical plane perpendicular to the minimum in-situ stress direction. However, the value of the minimum horizontal stress typically exhibits vertical variations between sedimentary layers.

In this contribution, we present an efficient numerical scheme for the propagation of a planar 3D hydraulic fracture based on the implicit level set algorithm first proposed by Peirce and Detournay (2008) [1]. This scheme recognizes the highly non-linear and multiscale nature of the elasto-hydrodynamic problem near the fracture tip e.g.[2, 3]. It couples the solution of a semi-infinite hydraulic fracture in the tip region with a classical discretization of the fracture away from the front. It allows the accurate solution of both viscous and toughness dominated propagation regimes on a relatively coarse grid. The elasticity and lubrication equations are solved in a fully coupled manner using respectively boundary element and finite volume. The planar fracture is discretized by a Cartersian grid, and the fracture front is represented as a level set. Due to the restrictive CFL condition of the elasto-hydrodynamics system of equations, the evolution of the fracture front is solved implicitly over a time-step. The current fracture velocity at any given point along the fracture front is thus solved for iteratively.

After benchmarking the scheme with known solutions for the viscous and toughness (storage and leak-off) dominated propagation of a radial hydraulic fracture, we perform comparisons with laboratory experiments where stress contrasts were carefully machined [4]. We then investigate numerically several configurations with a fine-scale vertical variation of the value of the minimum horizontal stress and discuss its influence on the development of the fracture geometry for different propagation regimes.

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Phase field modeling of hydraulic fracturing with interfacial damage in highly heterogeneous fluid-saturated porous media

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Abstract

In this work, we propose a numerical framework for modeling hydraulic fracturing or cracking in fluid-saturated porous media, taking into account: (a) the presence of heterogeneities; (b) interfacial damage between the inclusions and the matrix; (c) fluid flow within both matrix and interface cracks; (d) the possibility to define the geometry of the heteroge- neous media in the form of regular grids of voxels e.g. as obtained from experimental imaging techniques. The developed numerical framework is based on the phase field method with a regularized description of both bulk and interface discontinuities, extended to a fully coupled hydro-mechanical framework. Both 2D and 3D examples are presented for hydro-mechanical microcracking initiation and propagation in voxel-based models of complex heterogeneous media with interfacial damage between the inclusions and the matrix.

Keywords: Hydraulic fracturing, Phase field method, Crack propagation, Heterogeneous materials, Voxel, based models

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The Influence of Pore Pressure on Formation Stability after Hydraulic Fracturing

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Abstract

Hydraulic fracturing is a technique that is nowadays common practice. With Hydraulic fracturing, stimulation of low permeability reservoirs is possible thus production of hydrocarbons is enhanced with the application of this method. Stimulation is possible via the creation of a fracture around the wellbore and when is created it is packed with proppant to prevent closure after the hydraulic pressure is diffused. As a result the created fracture provides a highly conductive pathway for the flow of hydrocarbons towards the wellbore. In this work we examine the importance of the pore fluid pressure in the modelling of a fluid driven fracture in plastic and poroelastoplastic formations under plane strain conditions. The fracture is driven by pumping of an incompressible viscous fluid at the fracture inlet in both non porous and porous formations. Rock deformation is modelled with the Mohr Coulomb yield criterion with associative flow rule, suitable for cohesive frictional materials. Fluid flow in the fracture is modelled by lubrication theory. For the porous formations, the movement of the pore fluid is assumed to obey the Darcy law and has the same nature as the fracturing fluid. For the fracture propagation criterion we use the cohesive zone which has proven to be accurate in many contributions. Then the finite element method is employed to compute the solution for the fracture length, fracture opening and propagation pressure as a function of time and distance from the pumping inlet. We also perform a stability analysis by obtaining the stresses during pumping and shut-in.

It is demonstrated that during fracture propagation, the fracture tip causes plastic defor- mation of the material with the direct result of reducing (softening) the insitu stress field ahead of the tip compared to the initial compressive state. After shut-in, due to permanent deformation, the stresses do not recover as in the elastic case thus creating high risks for formation failure. We show that the plastic deformations in porous formations are more profound owing to the pore pressure of the surrounding rocks. Finally we quantify the phenomenon by introducing a yield factor for the porous formations so as to characterize the risk of formation failure under injection and shut-in conditions.

Keywords: Hydraulic fracturing, Finite Elements, Poroelastoplasticity, Cohesive zone models, Petroleum fracture mechancis

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Benchmark CARPIUC

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The proposed benchmark consists in simulating crack propagation tests performed on mortar, with any type of adequate material model or numerical method. Two crack propagation tests are proposed, inspired to some extent by the well-known Nooru-Mohamed [1] tests. They present initiation, propagation, reorientation, link-up and branching. The goal is to compare your simulation results with the measured crack paths and force-displacement curves.

Beam-particle approach to model the quasi-brittle behaviour of concrete CARPIUC Benchmark

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Discrete Elements Models (lattice models or particle models) are designed to describe discontinuous mediums. Unfortunately, their use for structural computations is still limited because of the mesh density required for such modeling. However, those discrete methods can be used as a virtual testing tool – to establish and identify the equations of a macroscopic model [1] – or as a post-treatment tool – to extract a fine description of the cracking pattern from a continuous computation [2].

Lattice models have been introduced to solve classical problems of elasticity [3] and extended to study the brittle [4] and quasi-brittle behaviour [5, 6] in tension after the development of computational simulation. One should note that these models cannot describe the fracturing process in compressive mode.

Particle models have been proposed to study the behaviour of granular assemblies and thus only contact forces were needed to model the interactions between the particles [7]. A modification was proposed to model cohesive interactions and thus materials such as concrete [8]. Unfortunately, such modelling of the cohesion of granular materials generally lacks the simplicity of the lattice models and thus its computation time is much higher.

The model used here combines the lattice approach and the particle approach [9, 10, 11]. This combination allows to correctly reproduce the failure pattern for compressive or tensile simulations.

This beam-particle approach has also been partially validated on test cases of mixed-mode failure [11]. The confrontation with the two test cases constituting the CARPIUC Benchmark will give us further insights in the ability of our approach to capture the complex behaviour of concrete during failure.

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Local adaptive refinement method applied to Cohesive Zone Models for heterogeneous materials

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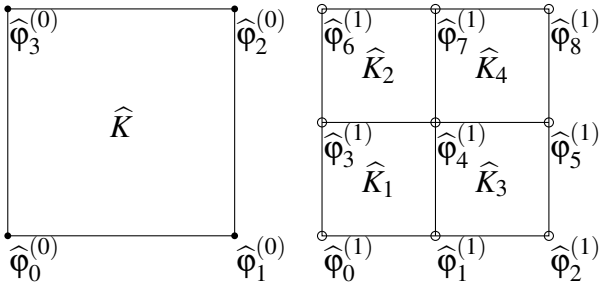
Adaptive mesh refinement devoted to crack propagation problems rely on an adjustement of a spatial resolution in the region of interest of the discretized domain in order to achieve higher accuracy. Two main issues arise from such a spatial refinement: an increase of the computational cost and a possible decrease of the shape quality of some elements located in the coarse-to-fine transition region. A solution consists in adjusting the density of the mesh by performing *local* refinement of an existing mesh. In this work, the CHARMS method (Conforming Hierarchical Adaptive Refinement MethodS [1]) is investigated and applied to the Cohesive Zone Models (CZM).

CHARMS is based on the refinement of basis functions rather than on the refinement of the finite elements and thus allows non conformities. These non conformities are geometrical: the approximation spaces remain H^1-conform. These possibly geometric non conformities of the adapted mesh are implicitly handled. To perform refinement with this method, a refinement pattern (see Figure 1) is localy and recursively applied in regions of interest which generate nested approximation spaces. Any basis function in a coarse approximation space can be written as a linear combinaison of finer basis functions. These linear combinations define child-parent relationships between basis functions of two consecutive refinement levels.



$$\begin{aligned}
\widehat{\varphi}_0^{(0)} &= \widehat{\varphi}_0^{(1)} + \tfrac{1}{2}\widehat{\varphi}_1^{(1)} + \tfrac{1}{2}\widehat{\varphi}_3^{(1)} + \tfrac{1}{4}\widehat{\varphi}_4^{(1)} \\
\widehat{\varphi}_1^{(0)} &= \widehat{\varphi}_2^{(1)} + \tfrac{1}{2}\widehat{\varphi}_1^{(1)} + \tfrac{1}{2}\widehat{\varphi}_5^{(1)} + \tfrac{1}{4}\widehat{\varphi}_4^{(1)} \\
\widehat{\varphi}_2^{(0)} &= \widehat{\varphi}_8^{(1)} + \tfrac{1}{2}\widehat{\varphi}_5^{(1)} + \tfrac{1}{2}\widehat{\varphi}_7^{(1)} + \tfrac{1}{4}\widehat{\varphi}_4^{(1)} \\
\widehat{\varphi}_3^{(0)} &= \widehat{\varphi}_6^{(1)} + \tfrac{1}{2}\widehat{\varphi}_3^{(1)} + \tfrac{1}{2}\widehat{\varphi}_7^{(1)} + \tfrac{1}{4}\widehat{\varphi}_4^{(1)}
\end{aligned}$$

Figure 1: Refinement pattern of a $\mathbb{Q}_1$ square element and associated refinement equations.

The CZM are based on a micromechanical approach and allow to perform a fine study of the crack initiation, crack propagation and other complex phenomena such as crack closure and crack branching. In this study, CZM are treated as a bulk-cohesive Finite Element method: the surface behavior is seen as a softening part which takes into account damage and the bulk hardening part that describes the bulk behavior. Whereas cohesive models give convenient results, this approach can be time consuming when the needed accuracy must be high. The aim of this study is to applied local adaptive refinement and introduce cohesive models in the refined regions to decrease computational time.

CHARMS has been implemented in the software Pelicans [3] and the CZM are handled by the softawre LMGC90 [4] to resolve contacts. Simulations are performed using Xper [2] that binds these two softwares.

To predict regions of interest (where cracks may propagate), a refinement criterion based on the gradient of energy is used. Once the refinement is performed, cohesive models are introduced at the interfaces of refined elements. Regions with cohesive models are solved using LMGC90 and the Non-Smooth Contact Dynamics method [5], and regions with no refinement are treated with the Finite Element method.

Using this strategy allows to obtain fine results in regions of interest while keeping a reasonable computational time.

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Modelling Mixed Mode Fracture of Cementitious Materials Using Microplane Model with Relaxed Kinematic Constraint - CARPIUC Benchmark

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Abstract

The benchmark specimens tested by Carpiuc et al. [1] under complex loading conditions have been numerically simulated. The analysis was performed employing 3D FE software MASA, developed at the University of Stuttgart. The constitutive law used for quasibrittle materials is the microplane model with relaxed kinematic constraint [2]. The two experimental geometries, namely single and double notched specimen, were modelled and subjected to the specified test loading paths.

In this work the details of the numerical modelling procedure, boundary and loading conditions are presented and the results are discussed in terms of force-displacement behaviour, crack initiation, propagation, reorientation and branching. The study demonstrated the suit- ability of the employed modelling procedure and microplane model to realistically capture the complex response of cementitious materials to proportional and non-proportional combinations of loading.

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Keywords: complex loading, crack propagation, crack reorientation, crack branching, microplane model

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A phase field method for modelling of crack propagation and initiation under complex loadings

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The phase field method is a versatile simulation framework for studying initiation and propagation of complex crack networks without dependence to the finite element mesh. A new technique has been developed to study the micro cracking by prescribing the local displacements measured by digital image correlation over the boundary of the sample during the numerical simulations [1, 2]. The various advantages of the phase field method for experimental validation are discussed. Qualitative and quantitative comparisons between numerical predictions and experimental data are provided. We show that the phase field method can predict accurately crack initiation and propagation with respect to experiments, when the material parameters, including the characteristic length are identified by other simple experimental tests.

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Phase-field simulation of interactive mixed-mode fracture tests on cement mortar with full-field displacement boundary conditions

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Phase-field modeling is an elegant approach to simulate complicated fracture processes, including crack initiation, propagation, merging and branching in a unified framework without the need for ad-hoc criteria and on a fixed mesh [1]. These capabilities can only be fully validated through the comparison with experiments featuring crack development histories and patterns of sufficient complexity. As opposed to conventional mixed-mode fracture tests with predefined loading, interactive tests with multiaxial loading which are controlled during the propagation of the cracks can create more complex and stable crack propagation patterns [2]. Moreover, the development of measurement techniques such as digital image correlation (DIC) provides the possibility to quantitatively characterize the full-field kinematics during the tests. In this work, full-field displacements measured by DIC during interactive mixed-mode fracture tests on cement mortar specimens are adopted as boundary conditions for phase-field numerical simulations. Qualitative and quantitative comparisons are illustrated, demonstrating the capability of the phase-field approach to predict complex mixed-mode fracture phenomena in cement mortar and suggesting possible further developments.

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Non-local damage model to simulate the quasi-brittle behaviour of concrete CARPIUC Benchmark

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The experimental results of the CARPIUC benchmark are simulated with a nonlocal (i.e., gradient-based) damage model [1,2] using the Code_Aster soSware [3]. First, both faces of the sample are analysed in in-plane simulations, second, the results are confirmed with a 3D modeling. The importance of using accurate boundary conditions while performing the numerical simulations is shown by applying different simplifications to the measured ones. The numerical simulations are congruous to the experimental results only when full-field boundary conditions are prescribed.

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Simulation of the Carpiuc test with the Thick Level Set model

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Abstract

The Thick Level Set model, introduced in [1, 2], is a non-local damage model embedding fracture mechanics discontinuity. By taking advantage of its damage driven capability this method is well adapted to branching and coalescence situation that appears in the Carpiuc benchmark.

Compare to all previous TLS publication this work adds a new loading control that intermix energy dissipation driven evolution with varying loading state. Many features of the TLS method have been tested with this benchmark and are presented in this work. Among them we can cite searching for initiation, branching, coalescence, tracking and analyzing the crack closure, ...

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