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New computational strategies for fracture

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MARIE CURIE ACTIONS

List of Abstracts

The stress-at-a-distance failure criterion applied to thermosets

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Abstract

The limits, under pure mode I or pure mode II, of a single parameter fracture mechanics criterion to predict cracking initiation are well known in a number of problems. A single G_{Ic} or K_{Ic} value is not sufficient to encompass complex constraint effects associated to large scale plasticity, to different test configurations involving large variations in stress triaxiality, and/or thickness effects, or in the absence of a sharp pre-crack like such as in the case of notches. Although more sophisticated multi-parameter options exist, the choice to work with a two-parameter model is the natural extension at minimum extra complexity in an engineering context. A choice has to be made between combining typically an energy condition, a critical stress, a strain-based criterion, an internal length and/or a critical displacement leading to different approaches such as the cohesive zone model based on traction separation law, the finite fracture mechanics, or the stress-at-a-distance model. Three applications of the stress-at-a-distance model, in the context of fracture of thermosets, will be briefly presented to reveal its, partly underestimated, potential. The first is the prediction of bondline thickness effect on the toughness of adhesive joints for which the stress at a distance worked much better than a cohesive zone model, and this for adhesives ranging from brittle to ductile [1]. The second is the application to the fracture of a highly crosslinked thermoset, the RTM6 epoxy resin, with excellent predictive potential for different loading conditions and geometries [2,3]. The third one is a recent application to determine the failure and crack path in an architected nylon joint for composite bonding [4]. We will insist on the physical meaning of the “critical stress” and of the “distance” and discuss the pro and cons of the approach.

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Exploring Deformation and Fracture in Transformation-Induced Plasticity Alloys: A Multiscale Modeling Approach

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Abstract

The modelling of deformation response in Transformation Induced Plasticity (TRIP) alloys continues to be a dynamic field of research, driven by their remarkable blend of strength and ductility. In this presentation, we unveil a multiscale physically based constitutive model aimed at predicting the intricate microstructural behaviour of these alloys under mechanical loading. Our approach incorporates Austenite and Martensite plasticity through a standard finite strain single crystal plasticity methodology intricately linked with martensite formation kinetics to facilitate the simultaneous evolution of all three mechanisms. The model is validated against macroscopic experimental data for austenitic stainless steel, and we propose an efficient calibration procedure for constitutive parameters employing a composite Bayesian Optimization strategy. We embed the model within a computational homogenisation framework to bridge the microscopic phenomena with macroscopic structural responses. The framework enables the analysis of failure, even when the evolution and propagation of cohesive micro-cracks induce material instability. The development of this macro-continuous/micro-discontinuous formulation is grounded in the Method of Multiscale Virtual Power, from which dynamic equilibrium and homogenisation equations are derived, ensuring a variationally consistent scale transition. Moreover, to address numerical instabilities associated with fracture problems, particularly snap-back behaviour, two strategies for handling fracture problems with instabilities within an implicit solution are discussed: an arc-length technique and an extension of quasi-static formulation into a dynamic regime. We illustrate the efficacy of our approach through examples, showcasing its ability to explore and predict the performance of materials of interest, thus underscoring its potential to advance the understanding and engineering of TRIP alloys and related materials.

Multiscale simulation of fracture and fatigue in composites with data-driven acceleration

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Abstract

Composite laminates are multiscale materials by design, with a layered mesostructure and a microstructure of fibers and matrix. Failure analysis is often performed on the mesoscale, where unidirectional plies are homogenized and delamination take place on zero-thickness interfaces. However, it remains challenging to formulate accurate mesoscale models to describe the nonlinear response of the composite material in all its complexity. One such example is crack growth under cyclic loading, where challenges firstly center around formulating appropriate constitutive models with limited number of input parameters, and secondly around developing efficient algorithms to step through time without resolving all loading cycles explicitly.

When the material response is complex, it can be appealing to resort to the microscale, where intricate material behavior emerges from the interaction between simpler constitutive models and the microstructural geometry. In cases where the mesoscopic variations are also non-trivial, a fully coupled multiscale approach is then required, where micromodels take the place of the homogenized stress/strain relation, or, in presence of localization, of the traction/separation relation. To avoid the excessive computational costs that come with fully coupled multiscale simulations, machine learning techniques can be used to replace the micromodel with a data-driven surrogate that is faster to evaluate. However, to limit the amount of data required for training reliable surrogates, dedicated machine learning techniques are needed that employ active learning and/or incorporate physics-based models in the architecture of the surrogate model.

In this presentation, recent advances in the multiscale modeling of composites are presented. Particular attention is paid to research on computational stratagies for modeling fatigue on the microscale and the mesoscale and to data-driven acceleration techniques for performing fully coupled two-scale analysis.

Can machine learning help computational fracture mechanics?

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Abstract

The talk discusses recent research performed in the group of the speaker, as well as more generally in the scientific community, to deploy machine learning tools for computational fracture mechanics. Two examples are the use of physics-informed machine learning to solve the partial differential equations stemming from phase-field models of brittle fracture, and the use of sparse or symbolic regression methods to automatically discover a fracture model from experimental data. Many challenges, a few solutions and some ideas for the next steps are highlighted.

Second-order computational homogenisation on mesh regularization of strain-softening localization

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Abstract

Finite element simulations supported by non-local damage constitutive models introduce the effect of an internal length scale parameter on the predicted mechanical response. This kind of model is of particular relevance for the analysis of structures in the presence of strain localization, to avoid mesh dependency issues on the predicted response and the width of the localization band.

In the framework of multi-scale models based on computational homogenization, where the effect of heterogeneous microstructures is naturally accounted for in the macroscopic response, second-order homogenization models are characterized by the introduction of a length scale parameter and, consequently, of non-local effects. However, the relationship between second-order homogenization models and macroscopic non-local models is still under-explored. Therefore, mesh regularization of strain-softening localization achieved with non-local damage models is compared with the regularization obtained in multi-scale analysis, by introducing second-order homogenisation, where the RVE length plays the role of an internal length scale parameter. Since structure failure and strain localization can be induced by microstructures containing voids as damage precursors, the recent model proposed in [1] is employed in the muti-scale analysis.

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Seawater Immersion and its Effect on the Fatigue Behaviour of Glass/Epoxy laminates

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Abstract

Fibre-reinforced polymer composites are frequently used in marine environments which may limit their durability.

This study investigates the impact of long-term exposure (up to 910 days) to natural seawater on the fatigue behaviour and on chemical changes of glass fibre-reinforced polymers (GFRP). Laminates were produced and immersed in natural seawater for immersion periods ranging from 0 to 910 days with their weight being regularly measured. For the tested stress range, the fatigue life of the samples that underwent immersion for 230 days was approximately 66% of the fatigue life observed in the control samples. This reduction further increased to 95% when the immersion period extended to 910 days. Additionally, possible changes in the chemical structure of various regions within the specimen were assessed using Fourier-transform infrared (FTIR) spectroscopy to investigate the impacts of immersion. The findings indicated that regions in proximity to permeable surfaces exhibited more notable chemical changes compared to those located further away, even after the sample reached weight saturation. The changes in the chemical composition of the epoxy resin, especially visible in areas near the permeable surfaces, may have influenced the bonding properties between the fibres and the matrix, potentially promoting a more frequent fibre-matrix debonding, as observed in the SEM analysis of the immersed specimens.

Detection of the defect or process zone at the tip of the V-notch from DIC combined with the coupled criterion and the generalized stress intensity factor: experimental and numerical analysis

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Abstract

During the loading of a V-notch under mode I, the coupled criterion analysis predicts, for instance for an initial notch angle larger than 90°, an abrupt crack propagation, resulting in stress-based and energy release rate-based criteria which have to be fulfilled simultaneously (see for instance [1], among many others). However, it is likely that, in this case, a process zone is formed prior to the event which we aim to detect and characterize experimentally. A similar issue is the detection of a small defect or small crack at the tip of the V-notch as analyzed by D. Leguillon [2]. We present an experimental analysis that aims to demonstrate that these effects can be evidenced and characterized from the analysis of the notch tip displacement field by Digital Image Correlation (DIC). A similar analysis [3] has been conducted on PMMA in which it was shown that the crack tip displacement field informs on the initiation and development of a process zone until the propagation of a crack. The present analysis is inspired by both references [2-3], but mainly by D. Leguillon's [2] work which is based on the calculations of the generalized stress intensity factors and in particular the first corrective term derived from a matched asymptotic expansion procedure around a notch. The experimental estimation of the generalized stress intensity factor from DIC has been demonstrated in a recent work [4]. This is further extended to address the determination of the length of a process zone or a short crack, following D. Leguillon's methodology. The material under consideration is a commercial PMMA, which exhibits a brittle failure under mode I at room temperature. Various notch angles are considered from 90° to 120°, with a notch in the form of a rhombus loaded under uniaxial compression.

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Experimental and numerical investigation of the crack velocity at the initiation of an abrupt crack propagation in a V-notch under bending: a coupled criterion analysis

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Abstract

In the coupled criterion, the identification of the strength and critical energy release rate is often made under the assumption that kinetic effects can be neglected during abrupt crack formation in a V-notched sample loaded under bending, or at the onset of crack propagation from the circular hole of various radii in a plate under uniaxial tension. Recent studies [1-2], have questioned this assumption for the latter case and showed that neglecting inertial effects and related dissipation may raise to discrepancies in the identification of the failure stress and/or the critical energy release rate. While it has been demonstrated theoretically, experimental evidences are still awaited. In this study, we carried out experiment with V-notches under 3-points bending and tensile tests on plates with circular holes of various radii. For each sample, on one face a speckle is deposited to carry out a Digital Image Correlation analysis and get the displacement field prior to the onset of abrupt crack propagation. This serves in measuring the generalized stress intensity factor for the samples with V-notches and the local strain fields around the circular hole, as a result deriving the stored elastic energy. The opposite surface faces a high speed camera (Phantom, T4040) which could recorded up to 440k frames per second allowing the tracking of the crack path in time. The crack velocity was then derived. This is thought to shed some light on the conditions for which kinetic effects need to be accounted for or not. The material under consideration is a commercial PMMA.. The experimental study is supplemented with finite elements calculations of the failure process, the damage being described by a phase field method [3].

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A novel analytical tool for rapid laminate design of crash structures

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Abstract

Energy absorption structures in high performance motorsport and aerospace applications are ever-increasingly manufactured from carbon fibre reinforced polymer (CFRP) material systems due to their superior specific energy absorption capabilities over those of classical metallic and polymeric alternatives.

Concerning the design of crash structures, most of the effort has been directed towards developing Finite Element (FE) macro-scale and meso-scale modelling approaches. However, their significant computational cost makes these more suited to the detailed design stages. At the initial stages, engineers are still faced with the difficult task of material selection and laminate sizing, and their choices are typically based on subjective experience in previous design cycles.

In this work we propose a novel analytical tool offering rapid laminate sizing for composite crash structures. Using the same macro-scale approach as current industry-employed FE models, and an experimentally-determined dataset of input energy absorption parameters for a commercial woven CFRP, the analytical tool is tasked with the determination of an initial laminate sizing of a standard Formula 1 Side Impact Structure design. The performance target is set equal to the smoothened load-displacement behaviour obtained in previous experimental works [1]. This study aims to showcase the potential of the new tool in the initial design stages of crash structures, before a more detailed analysis can be conducted through higher fidelity numerical models.

ACKNOWLEDGEMENTS

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Modification of nominal strength scaling laws taking pseudo-ductility into consideration

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Abstract

Composite laminates are inherently brittle due to their linear-elastic constituents, necessitating significant safety factor reductions in the design of damage-tolerant structures. Thin-ply laminates are becoming increasingly attractive for their improved resistance to free-edge delamination and reduced variability in material properties [1]. However, they further exacerbate the brittleness of composite laminates. Recent research has focused on achieving a ductility-like behaviour ("pseudo-ductility") in composite laminates. Most studies on pseudo-ductile composites are experimental. Beyond the inherent challenges of achieving pseudo-ductility, they encounter additional obstacles related to the complex interplay between ply thickness and properties, such as translaminar toughness, stress concentration, and unnotched strength [2]. Numerical studies, on the other hand, are often done retrospectively to support experimental findings. By incorporating dimensional analysis, numerical and simplified finite element models, we strive to identify the essential parameters that enhance the laminate-level responses -- specifically, translaminar toughness, stress concentration, and notched strength -- to direct future experimental efforts.

We first investigate the influence of pseudo-ductility on the notched strength and size-effect behaviour of typical specimens of quasi-isotropic pseudo-ductile composite materials. Our previous findings reveal that pseudo-ductility enhances translaminar toughness and nominal strength recovery but can negatively affect specimens below a critical notch size [4]. The universal Bažant Size Effect Law (SEL) is modified to account for the non-recoverable pseudo-ductile damage past the pseudo-yield strength [3]. The proposed modifications to the nominal strength scaling laws characterise the notched strengths for any given notch radius and the size effect of pseudo-ductility. The modifications are applied to centre-cracked (CC), elliptical hole (EH), and open-hole (OH) specimens for a wide range of pseudo-ductile materials to ascertain their validity. Moreover, the proposed modifications to nominal strength predictions agree with FE estimates across all three notch shapes (CC, EH, and OH). Our findings serve as a valuable tool for understanding and assessing pseudo-ductile composites' notched strength or size-effect behaviour [5].

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Multi-fibre Failure Prediction using the Principle of Minimum Total Energy subjected to a Stress Condition (PMTE-SC)

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Abstract

A computational algorithm based on the Principle of Minimum Total Energy subjected to a Stress Condition (PMTE-SC) is used to study one of the main failure mechanisms in composites: debonding along fibre-matrix interface under transverse loads. Particular attention is paid to the discussion about the symmetric and non-symmetric character of the debond onset and growth as a function of the interface and bimaterial system parameters for a single fibre-matrix system under remote transverse tension. The considered bimaterial system includes a glass fibre and an epoxy matrix which is common in fibre reinforced composite (FRC) laminates. The current algorithm uses a two-dimensional (2D) plane strain formulation in the finite element code Abaqus, together with Python scripts that perform a time-stepping procedure that minimizes the total energy functional. The behaviour of the fibre–matrix interface is modelled using a Linear-Elastic Brittle Interface Model (LEBIM) programmed by means of a User Material Subroutine for Abaqus. Finally, an analysis of the crack pattern caused by multiple fibre-matrix debonding is carried out, as it can result in a crack path (transverse crack in the 90° layer) or the appearance of isolated debonds.

Predicting transverse cracking and delamination in composites. Applications of the coupled criterion of the finite fracture mechanics

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Abstract

Transverse cracking and delamination are prominent damage mechanisms at the mesoscopic level in multidirectional composite laminates. While these mechanisms may not initially cause a significant stiffness reduction, they can propagate and lead to other forms of damage, as well as impact various material properties such as permeability.

The coupled criterion of finite fracture mechanics has been widely employed to forecast transverse cracking and delamination in composites. Existing models in the literature encompass transverse crack initiation, progression, accumulation, and subsequent or isolated delamination. These models generally exhibit good correlation with experimental findings, accurately predicting critical stress, strain, and crack morphology. Notably, these models rely solely on well-established material properties and are founded on quasi- or fully-analytical analyses.

This study provides an overview of the various models proposed for predicting these damage mechanisms using the coupled criterion of finite fracture mechanics. It critically examines and compares these models against experimental data, highlighting their strengths and weaknesses and suggesting avenues for further development.

Influence of the failure criteria on the failure strength prediction of filled-hole compressive tests using carbon fibre reinforced polymer laminates

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Abstract

In recent decades, several computational models have emerged at the mesoscale level to predict the fracture of composite materials. However, the complex failure mechanisms of composites lead to a significant challenge in developing models that can consistently predict diverse loading conditions. Additionally, the lack of standardised multiaxial tests has hindered the consensus for establishing failure envelopes and criteria for predicting the fracture of composites. This work employs an in-house constitutive model, implemented in a finite element code, to predict the failure strength of several filled-hole compressive carbon/epoxy experimental specimens. The tests vary in stacking sequences, sizes, bolt preloads, and other parameters. The analysis focuses on the influence of the selected failure criterion on the predictions. The findings indicate a significant impact of the failure envelope on both the failure compressive strength and developed failure mechanisms. Therefore, accurately establishing failure envelopes is just as important as defining the model input parameters. These results highlight the significance of accurately establishing failure criteria, rather than prioritising the development of complex models.

Crack onset in stretched open hole PMMA plates considering linear viscoelastic behaviour

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Abstract

The problem of the crack nucleation in PMMA holed plates, subjected to tensile stress is addressed through the coupled stress and energy criterion in the framework of the Finite Fracture Mechanics (CCFFM), considering linear viscoelastic behaviour.

An experimental campaign was made, where tensile coupons were tested at several strain rates, yielding distinct stress-strain curves, confirming the viscoelastic nature of the material. From these tests and stress-strain curves it was possible to estimate the viscoelastic parameters by means of the Prony series technique. Additionally Three Point Bending (TPB) flatwise coupons (without any notch) were also tested at different standard strain rates and also at maximum strain rates assumed in holed plates, in order to study the effect of the small but highly stressed volume at the plate hole border. For a better fitting of the experimental results, higher strength values obtained by TPB flatwise coupons at stress maxima, for the viscoelastic material model, are used in the CCFFM predictions. A new PMMA strength value was obtained for the linear viscoelastic material model.

A linear viscoelastic numerical model was implemented by employing the Incremental-Virtual Crack Closure Technique (I-VCCT) for the energy criterion part. Plane stress state is considered for all studies. Based on experimental data for holed plates, an inverse procedure is performed, using the CCFFM, in order to estimate the strength and fracture properties to use in both material models, providing very good correlations of the CCFFM predictions with the experimental results. The viscoelastic model is compared with previous results of linear elastic model. Both models predicted the expected size effect in holed specimens.

Damage evolution modelling of fibre-reinforced polymer composites using a smeared crack approach

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Abstract

In this work, a novel formulation of the 3D smeared crack model for damage propagation under longitudinal and transverse failure modes is presented using a continuum damage approach. This formulation is developed to facilitate the implementation in an implicit solver, increasing solution robustness and computational efficiency in quasi-static and long-duration analyses. The constitutive model includes the material elastic plastic behaviour in the transverse direction, and failure initiation incorporates a stress-invariant approach for transverse failure and kinking failure, seamless integrated with the posterior damage evolution. The performance of the model is evaluated using monotonic and non-monotonic damage evolution, verified with single element tests to demonstrate the consistency of the proposed formulation regarding failure load and energy dissipation. Additional benchmark examples, including off-axis and open-hole tests, are performed to validate the proposed modelling approach with experimental results. The results show good agreement with experiments for the predicted plastic response, failure loads, and notch size effect.

Analysis of unfolding failure using Finite Fracture Mechanics

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Abstract

In the domain of highly curved composite laminate applications, particularly used at the junction between two panels, arises a complex interplay of failure mechanisms. These mechanisms include fiber-matrix debonding, transverse cracking, delamination, fiber failure, to name a few; their accurate description is often challenging. Here we focus on the determination of the load at which the first transverse crack occurs in a highly curved composite laminate subjected to pure bending. The out-of-plane fiber-oriented laminas located in the inner radii region are more susceptible to damage because of their weaker properties considered in the transverse direction. To address the transverse cracking onset in these plies, a novel semi-analytical tool, based on the coupled stress and energy criterion within the finite fracture mechanics framework, is used to predict loads at which the crack initiates within weaker plies, when the highly curved composite laminate is loaded under opening bending moments. The stress conditions are determined through laminate theory applied to the undamaged geometry, while the incremental energy conditions are numerically assessed using VCCT, leading to a coupled theoretical framework for evaluation of critical parameters associated with crack initiation. Different hypotheses are considered to analyze the crack nucleation behavior. Additionally, the capability of this tool is further assessed by predicting the existence of a size effect for the geometry at hand, mainly ruled by the ratio between the radius of curvature and the ply thickness.

Computational modeling of progressive high-cycle fatigue in composite laminates

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Abstract

The analysis of high-cycle fatigue crack propagation in composite laminates has seen significant developments in the last decade. However, there are still challenges in developing accurate and efficient progressive failure methodologies for simulating multidirectional laminates where fatigue cracks first initiate before they propagate. Moreover, several interacting damage processes must be considered, such as transverse matrix cracking, delamination and ultimately fiber breakage, which endangers robustness of the simulations.

In this contribution, we present an accurate, efficient and robust progressive high-cycle fatigue framework for mesoscale laminate analysis. A mixed-mode fatigue cohesive zone model [1], covering initiation and propagation of cracks, is embedded in a progressive failure framework for describing inter- and intra-laminar damage [2]. XFEM is used to allow for discrete transverse cracks at arbitrary locations, such that the complete failure process, with a transition from distributed cracking to localized failure, can be accurately simulated.
Moreover, the effect of thermal residual stresses due to the curing process is taken into account with an adaptive cycle jumping scheme where explicit load cycles are applied to compute the local stress ratio, which governs the material response under cyclic loads.

The numerical framework is applied to the simulation of two quasi-isotropic composite laminates with a complex interaction of transverse matrix cracking and delamination. The model is validated against experiments and shows an excellent correlation in terms of predicted fatigue life and damage patterns. Furthermore, it is demonstrated that using the local stress ratio instead of the global load ratio is important for accurately predicting the fatigue life of the composite laminates.

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A Finite Fracture Mechanics model to predict free edge delamination in angle ply laminates

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Abstract

We explore the phenomenon of free edge delamination in layered structures, focusing on symmetric angle ply laminates within the Finite Fracture Mechanics (FFM) framework. The weakly singular stress state near free edges, attributed to elastic mismatch between adjacent plies, facilitates delamination, termed as free edge delamination. Our study emphasizes the importance of computing interlaminar stresses and energy release rate, in addition to intrinsic properties like fracture toughness and strength, for effective FFM criteria evaluation.

Utilizing a comprehensive three-dimensional Finite Element Method (FEM) model, we express these quantities as non-dimensionalized functions, streamlining their determination for all laminate configurations through dimensional analysis. A semi-elliptically shaped crack, initiated at the dissimilar interface post-crack onset, serves as a focal point. We derive crack dimensions at unstable propagation stages through an optimization problem within the FFM framework.

For validation, we compare the FFM-based predictions of laminate fracture with experimental results from the literature, encompassing various laminate types (AS1/3501-6, T800/914, G947/M18) and layups ([±10n]s, [±15n]s, [±20n]s, [±30n]s). Our findings reveal a noteworthy agreement between the predicted outcomes and experimental observations, affirming the efficacy of the proposed approach.

Crack impinging on a curved weak interface: Penetration or deflection?

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Abstract

Curved weak interfaces present promising advantages to be implemented as crack arrestors in structures designed under the damage tolerant-design principles. Among other advantages, they neither add extra weight nor significantly affect the global stiffness of the structural element, in contrast with alternative crack arrestor concepts. To be employed as a crack arrestor, it is key that the interface can deviate the crack. If the crack penetrates across the interface, the effect of the weak interface as a crack arrestor is canceled. Given this, this work studies how to set the interface parameters to promote crack deviation along the interface. In particular, following the dimensional analysis of the problem, the effect of three significant dimensionless parameters is studied: interface to bulk fracture toughness, interface to bulk tensile strength, and the interface curvature radius normalized with the material characteristic length. The corresponding analysis is carried out using three approaches widely applied for the prediction of cracking events: Linear Elastic Fracture Mechanics and Finite Fracture Mechanics. The results present a clear effect of some parameters, such as the ratio of the interface to bulk fracture toughness, for which the three approaches agree. However, the results are moderately diverse in they correspond to the effect of the ratio of the interface to bulk tensile strength and are quite divergent concerning the effect of the radius. The results are interpreted and explained as a consequence of the main assumptions behind the approaches studied.

Influence of length of fiber damage models on the final prediction

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Abstract

Fiber damage models are highly used in the realm of unidirectional (UD) composites, owing to their capacity to aid the understanding of the underlying mechanisms governing composite failure. This failure mechanism stems from the stochastic nature of fiber strength, the load transfer from damaged to undamaged fibers (load-sharing), and the activation of fiber segments after the first damage event takes place (multifragmentation). Although these models can adeptly capture these three fundamental mechanisms, their development typically relies on multiple assumptions, necessitating appropriate definitions [1].

For UD composites, the models are commonly developed having a length (along the direction of the fiber) which is a parameter defined by the user. The fiber strengths are then generated using this length in a Weibull distribution. However, the length used in the Weibull distribution refers to the length of the actual specimen and should not be related to the model's length. Therefore, a distinction must be made considering the assumptions of the length and two lengths must be defined: (1) the model's length, which corresponds to the fiber length, and (2) the length employed in generating fiber strengths in the Weibull distribution.

This study investigates these two pivotal parameters (the two different lengths) that influence the three damage mechanisms (the stochastic nature of fiber damage, the load-sharing, and the multifragmentation). Parametric 3D finite element models of an epoxy reinforced with 50% carbon fibers are developed, considering the two lengths, and subsequently compared to analytical models and experimental data from the open literature [1].

The results underscore the importance of the distinction between the two lengths, and it is underlined that the length used in the Weibull distribution must be related to the physical length of the specimen and not to the model's length. The comparative analysis among models led to the conclusion that the stochastic nature of fiber strength is correctly captured and remains unaffected by the model's length when load-sharing and multifragmentation are not presented. This was, in particular, achieved by models with lengths close to one fiber diameter. These models are only influenced by the length used in the Weibull distribution,

which further allows using models containing fewer elements thus being more computationally efficient.

Nonetheless, it is emphasized that the model's length can influence both the load-sharing and the multifragmentation mechanisms, underscoring its pivotal role in composite failure analysis. When these two mechanisms are presented in real structures, using models with larger lengths is a necessity.

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CERAMIC FRACTURE AT THE MICRO-SCALE. COMPARISON BETWEEN FINITE FRACTURE MECHANICS AND PHASE FIELD MODELLING

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Abstract

Within the framework of Finite Fracture Mechanics (FFM), one of the fundamental ingredients of this methodology is that a crack is assumed to jump a given finite length at onset. This can be formulated through the invocation of the Coupled Criterion (CC) [1], stating that this length depends on the material toughness, the tensile strength but also the geometry. Complying with a different vision, according to the Phase Field (PF) model [2] there exists a length related to the size of the damaged region, called the phase field length scale. Both the PF length scale and the nucleation length obtained by the CC are proportional to the Irwin length defined from the material toughness and tensile strength. At the macro-scale, they are small compared to any dimension of the structure, whereas at the micro-scale both lengths are of the same order of magnitude or even larger and can interact with the dimensions of the structure.

The aim of this work is to analyze how the answer brought by the CC and the PF model evolves when descending the scales from the cm-scale to the µm-scale and even nm-scale. Based on previous results, it can be argued that both the CC and the PF model provide satisfactory predictions of cracking events in solids. However, this can be a controversial issue at smaller scales of analysis due to a lack of energy because of the smallness of the specimens. This is attributed to the fact that at such scales it is seen that the corresponding results are much sensitive to the toughness but less sensitive to the tensile strength. Several case studies are analyzed to compare both methodologies, and the role of the length scale in both.

Bearing/Pull-through Failure Envelope of Composite Joints: Novel Experimental Setup and Numerical Validation

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Abstract

Current industry practice to connect composite structural panels still relies on the extensive use of bolted joints. However, due to their anisotropic nature, composite materials joining techniques represent a true design challenge, as their behaviour can change with, e.g. layup, material, geometry and environmental conditions. For this reason, the behaviour of composite bolted joints has been the subject of research studies for many years. Particular focus has been given to in-plane and out-of-plane performance of mechanically fastened composites. However, in real-life applications, e.g. for L-junctions and single lap joints of thin laminates, mechanically fastened joints are subject not only to pure bearing or pure pull-through, but have to sustain a combination of both loading scenarios [1,2].

Here, a novel test rig for determining the failure envelope of composite fastened joints under combined bearing and pull-through loading conditions is designed, tested and validated. The proposed device is compatible with a standard testing machine and captures the critical interactions between the two loading mechanisms for pull-through to bearing ratios ranging from 0.2 up to 0.8, allowing the characterization of the behaviour of composite joints under realistic loading scenarios. The multiaxial failure envelope for a carbon-fibre-based composite laminate is obtained experimentally and the performed tests are shown to fall within the limit values obtained for the pure bearing and pure pull-through loading conditions, obtained following well-established ASTM standards [3,4]. High-fidelity finite element simulations [5] are used to support the validation of the test methodology: the ability of the fixture to maintain a constant mixed load ratio during the whole test was numerically confirmed and a detailed analysis of the failure modes provided further insights into the main degradation mechanisms occurring during the experiments. A very good agreement between the numerical and experimental results is obtained for the entire failure envelope, with the numerical predictions falling between +-10% relative errors, further validating the constitutive modelling predictive capabilities.

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Different strategies for dealing with locking phenomena using elastoplastic models.

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Abstract

Volumetric locking is a well-known pathology that affects elastic-plastic models based on incompressible plastic models. The effect of this and the mechanism to alleviate it has been studied for decades. This work involves two types of modelling. On one hand, ductile fracture models, which are formulated as a result of combining elastic-plastic models and the phase field approach to fracture. Most of them are based on a local formulation of the elastic-plastic problem coupled in different manners with a non-local gradient damage model. On the other hand, another typology can be addressed using the micromorphic approach to gradient-extended models. This methodology is based on the introduction of the non-local plasticity formulation through a global variable, adding a penalty and a gradient terms in the energetic formulation. This work aims to study how this pathology influences this type of models and possible solutions. Some representative and well-known problems are studied with special emphasis on studying the discrepancies found when the volumetric locking is alleviated or not.

A phase-field anisotropic model for the multiscale analysis of short fiber reinforced polymers

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Abstract

Understanding and modeling the fracture mechanical behavior of short glass fiber reinforced polymers (SFRPs) is challenging: the strong heterogeneity induced by the manufacturing process causes a tight coupling of the material microstructure to the effective response on the component scale. Aiming to account for this microstructural complexity, fracture is approached using a multiscale approach. Typically manufactured via injection molding, SFRP components exhibit locally varying microstructural configurations which render fracture modelling a challenging task. To resolve the microstructure induced anisotropy and its relationship with the macroscopic material behavior, the well established isotropic phase field models of brittle fracture [1, 2] is extended towards the anisotropic case making use of the fiber orientation interpolation concept. To create the database, the anisotropic elastic coefficients are obtained from previously executed micromechanical simulations. The performance of the simulation method is demonstrated by means of several numerical analyses and the prediction quality together with the limitations of the proposed method are demonstrated. Therefore, an innovative approach is proposed using an offline training of a database plus a fiber interpolation concept to take into account the heterogeneity of the material. The approach is fully integrated into the seamless simulation chain for SFRPs ranging from the manufacturing process to the structure mechanical fracture analysis. The limitations of the approach stemming from the underlying assumptions are quantified and further development needs are identified.

Analysis of Delamination Growth in Three-Point Bending Test: Influence of Friction Coefficient and Elastic Moduli Mismatch

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Abstract

A numerical methodology is introduced to analyze laminates with delamination cracks under bending loads. In particular, delamination cracks between laminas of dissimilar materials are considered. The finite element method is utilized to model the geometry of a three-point bending test with an interlaminar crack, accounting for the influence of friction on crack propagation. It is shown that friction weakens the stress singularity at the crack tip in an approximately linear manner, which implies that the classical linear elastic fracture mechanics based on infinitesimal crack propagation cannot be applied to the case of delamination cracks between dissimilar materials. Thus, the application of the Coupled Criterion of Finite Fracture Mechanics is considered in the present work. This approach allows for determining the minimum load required for interface crack growth. A finite element model in ABAQUS is employed for the three-point bending test, investigating the impact of both the friction coefficient and the ratio of elasticity moduli of the laminas on the critical load necessary for crack growth. An approximately linear correlation is observed between the critical load and the friction coefficient, with the slope showing dependence on the ratio of elasticity moduli. These findings contribute to an enhanced understanding of factors influencing delamination growth, underscoring the importance of considering friction in structural integrity assessment.

Fast Estimation of interlaminar Fracture Properties and Shear Hardening Behavior in Fiber-Reinforced Composites

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Abstract

In recent decades, there has been a growing interest in creating computational models for predicting the inelastic deformation and fracture of polymer composites, particularly within the aerospace and automotive industries. This trend arises from the need to minimize both product development time and costs while aiming to develop and produce more competitive products.

The Smeared Crack Model (SCM) [1] serves as a comprehensive 3D model predicting the initiation and progression of ply failure mechanisms. However, obtaining a substantial amount of input properties is necessary, and determining them through experiments or inverse calibration proves to be challenging. Building upon the work of Tsai and Melo [2], it has been demonstrated that it is possible to estimate the elastic and strength properties of laminate composites accurately using limited data.

Drawing inspiration from this research, a procedure has been developed to rapidly estimate the toughness and strength properties of a unidirectional composite. Furthermore, the SCM is enhanced with a novel plasticity prediction method that relies on shear strength and elastic modulus to improve its predictive capabilities. The accuracy of the proposed estimations and subsequent numerical results is demonstrated through illustrative examples.

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Application of generic path-following methods to phase-field fracture simulation

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Abstract

The phase-field approach to fracture has emerged as a powerful tool to simulate the nucleation and growth of cracks in a structure. In the past two decades, it has been extensively applied to fracture problems as it captures crack initiation, propagation, and interaction without explicitly tracking the crack path.

One of the most popular algorithms to solve phase-field problems is the alternate minimization. However, it can suffer from slow convergence, especially when dealing with unstable crack propagation. Moreover, force-controlled loading often leads to unstable crack propagation and the lack of equilibrium solution after the crack propagation, preventing their use.

Path-following methods offer a promising solution to those limitations, enabling the tracking of unstable crack propagation while preserving the equilibrium during the whole loading (Rastiello et al., 2022). Based on various control strategies, these methods also improve the solver stability. Singh et al. (2016) and May et al. (2016) proposed path-following approaches specifically tailored to the resolution scheme of Miehe et al. (2010) based on crack surface and fracture dissipation. Additionally, Wu (2018) adapted the nodal displacement control (Borst, 1987) and the fracture surface control (Singh et al., 2016) to the alternate minimization. Nevertheless, the first approach is problem-dependent, and the second approach may fail under force loading (Rastiello et al., 2022).

This work proposes a generic path-following method applicable to various fracture problems, regardless of geometry, boundary conditions, or fracture model complexity, by leveraging the maximum strain increment control (Chen & Schreyer, 1990). This method is model-independent, as it relies solely on the displacement field, and problem-independent, it does not rely on a specific choice of control DOF.

After presenting the modified alternative minimization solver, we demonstrate its effectiveness through simulations of crack propagation in the SENT test. The results are compared to a semi-analytical solution based on LEFM and to the alternate minimization solution. Notably, the classic alternate minimization fails to

capture the snap-back (instability under displacement control) observed in the semi-analytical method. The proposed approach correctly captures this phenomenon, which converges towards the semi-analytical solution. Then, this method is also applied to the simulation of Compact Tension (CT) experiments, in which the selection of numerical boundary conditions at the pinhole significantly influences the fracture behavior (Triclot et al., 2023). The proposed solver renders the application of force boundary conditions possible, better representing the experimental conditions.

LOCKING TREATMENT OF PENALTY-BASED GRADIENT-ENHANCED DAMAGE FORMULATION FOR FAILURE OF COMPRESSIBLE AND NEARLY INCOMPRESSIBLE HYPERELASTIC MATERIALS

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Abstract

Soft materials are of major interest for biomechanics applications due to their high deformability and susceptibility to experience damage events under different loading scenarios. The present study is concerned with modelling damage evolution processes in these nonlinear materials whose structural responses are prone to locking when low-order kinematic interpolation is employed in the context of nonlinear Finite Element schemes. For this reason, a pair of gradient-enhanced continuum damage (CDM) schemes are proposed with the aim of tackling mechanical failure problems in applications that exhibit shear and volumetric locking. In particular, we present the consistent formulation and the assessment of the corresponding performance of (i) a mixed displacement-enhanced assumed strain (EAS) Q1Q1E24 employing a total Lagrangian formulation, and (ii) a three-field mixed displacement-pressure-Jacobian Q1Q1P0 formulation. The novel Q1Q1E24 and Q1Q1P0 formulations are consistently derived and numerically implemented, providing a satisfactory agreement with respect to ABAQUS built-in elements handling the treatment of shear and volumetric locking, respectively, in conjunction to the modelling damage phenomena via the use of a penalty-based gradient-enhanced formulation. This performance is examined via several numerical applications. Furthermore, the final example justifies the need for a formulation combining both mixed FE approaches to simulate problems encompassing both locking issues (shear and volumetric locking), which can be performed using a combination of the Q1Q1E24 and Q1Q1P0 herein proposed.

A phase-field model for contact-induced fracture of quasi-brittle materials

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Abstract

A coupled formulation involving the phase-field approach to fracture for the simulation of cracking in a brittle bulk and the MPJR (eMbedded Profile for Joint Roughness) interface finite elements developed to solve the nonconformal contact problem between rough bodies of any shape and the substrate is herein proposed and tested in relation to complex indentation problems. The method is exploited to simulate the nucleation and the growth of cone-shaped cracks caused by the indentation of a substrate by a smooth spherical indenter. The same indentation problem involving also roughness superimposed onto the spherical indenter is addressed for the very first time, and numerical predictions are compared with selected experimental results taken from the literature, showing the high potential of the method to solve this class of strongly coupled nonlinear problems relevant for a wide range of technological applications.

INNOVATIVE FINITE ELEMENT APPROACH FOR PREDICTING CRACK ONSET AND GROWTH BASED ON THE PRINCIPLE OF MINIMUM TOTAL ENERGY SUBJECTED TO A STRESS CONDITION

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Abstract

In the context of Finite Fracture Mechanics (FFM), Leguillon (2002) introduced the Coupled Criterion of FFM (CCFFM), which forms the foundation of this study. According to CCFFM, both stress and incremental energy criteria are indispensable for the sudden initiation of a crack in a finite extension. Later, with the aim of addressing complex fracture problems including the onset and propagation of multiple internal cracks and interface cracks, Mantic (2014) proposed a modified version of CCFFM, known as the Principle of Minimal Total Energy under Stress Condition (PMTE-SC). This modification is particularly advantageous for a versatile computational implementation employing a load-stepping technique, addressing challenges related to the initiation and propagation of multiple cracks. The formulation of PMTE-SC allows the total energy to be expressed as a separately convex function of the fields of displacements, and damage variables defined along potentially new crack advances, facilitating the application of efficient and stable optimization techniques to minimize total energy with constraints.

To efficiently incorporate PMTE-SC into the ABAQUS Finite Element Method (FEM) code, we utilize UINTER, a subroutine managing the interaction between two surfaces. In this case, the interaction between surfaces of a potentially new crack advances is modeled using a continuous distribution of springs exhibiting linear elastic behavior. The mixed-mode constitutive law of these springs was described by Mantic et al (2015). The code calculates the change in potential energy using the incremental virtual crack closure technique (VCCT), which accurately reflects the change in potential elastic energy due to specific crack growth, viewed incrementally.

The developed method provides a novel approach to characterize crack onset and propagation based on CCFFM. It predicts instantaneous crack onset or propagation without the need for infinitesimal crack growth, allowing for the simultaneous appearance of multiple fractures. The computational algorithm, based on the PMTE-SC formulation, has been implemented using ABAQUS and

Python scripts. Extensive testing confirms the validity, adaptability, and reliability of the proposed methodology. Rigorous examinations of mixed-mode crack scenarios, including the L-shaped plate, Single Edge Notched Plate (SENP) under shear, and the Double-Edge Notched Test evaluating Biaxial Tension and Shear, demonstrate the versatility of the approach. Validation against the classical CCFFM approach yields essentially identical results, paving the way for exploring more complex problems related to the initiation and growth of multiple cracks and delaminations.

Evaluation of Fatigue Life in Notched Composite Laminates Using Finite Fracture Mechanics and Theory of Critical Distance

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Abstract

In this study, criteria in the framework of Finite Fracture Mechanics (FFM) and Theory of Critical Distances (TCD) are employed, in conjunction with semi-analytical relations, to assess the fatigue life of orthotropic notched laminated composites under tension-tension cycling loading conditions. From a modelling point of view, model inputs are represented by the critical cyclic stress and the stress intensity factor at failure, which can be obtained through stress-life data from plain and cracked specimens, respectively. Noteworthy, the proposed approaches can be applied to any notched geometry and layup. Herein, they are validated by conducting a comprehensive experimental program on composite laminates, featuring two distinct layups and weakened by holes of two different radii. The proposed approaches show a low computational cost, and require a fairly low number of characterizing tests; nevertheless, both FFM and TCD models demonstrate promising predictions for the fatigue life of composites – the coefficient of determination R^2 ranging from 0.81 to 0.86 – without the need for inverse calibration of material properties or deviation from standardized testing procedures. Finally, a parametric study is performed to investigate the failure size effect behavior in drilled composites.

Off-axis strength and failure of notched thin-ply laminates

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Abstract

Advances in aeronautical design have increased the use of composite structures and, thus, the ability to simulate their response and obtain accurate strength predictions, is of prominent interest. With emphasis being given to notched components, that often appear in aeronautical structures (e.g., bolted, riveted parts), this work evaluates the off-axis (i.e., referring to loading on a direction that does not coincide with one of the principal axes of orthotropy of the plate) open hole tension (OHT) response of thin-ply laminates. Thin-ply laminates (i.e., plies of thicknesses under 0.1 mm) that have been shown in the literature to behave differently during failure when compared to "standard" ones (i.e., made up of plies of thicknesses over 0.1 mm) with final failure tending to happen in the form of a single through thickness crack (net-section failure) [1]. From a modelling perspective this motivates the use of novel techniques formulated for brittle fracture, such as the phase field method (PF) and Finite fracture mechanics (FFM), to provide an efficient modelling basis following an equivalent single layer (ESL) representation of the composite laminated plate. To validate and test the applicability of these methods experiments are conducted on thin-ply laminates of a varying level of anisotropy, from weak (quasi-isotropic) to strong (cross-ply). The experiments show that the weakly anisotropic laminates fail in net-section crack-like failure patterns while, interestingly, contrary to what the literature has shown so far, the strongly anisotropic laminates presented premature failure events and delaminations that are characteristic of standard grade composites failure. For the former laminates both methods are applied and compared as to their predictability. The PF method [2] demonstrates successful predictions of crack path and strength with a maximum observed error of 4.8%, contrary to the coupled FFM criterion that seems to in this case fall short. This is notwithstanding the issues and uncertainties pertaining to assumptions made for this method (e.g., stress failure criterion) yet to be solved for the application of this method that could improve it.

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Machine Learning-Accelerated Predictions of Design Allowable of Composite Laminates

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Abstract

The generation of design allowables for composite laminates is of utmost importance for the design and certification of the composite structures used in the aerospace industry. The determination of these design allowables, usually relies on expensive and time-consuming experimental test campaigns. With the increase in computational power, and the development of high-fidelity numerical models that accurately represent the response of composite materials, alternatives to generate design allowables based on finite element simulations have also been sought out to reduce the certification costs. However, these solutions are still computationally expensive. The recent advances in machine learning techniques open a new window of possibilities for the faster prediction of the structural response of materials, by allowing the definition of surrogate models that continuously and analytically describe the design space [1].

In this work, a database of open-hole high-fidelity simulations [2,3] is generated and used to train machine learning algorithms, resulting in surrogate models that can predict the notched strength of several materials, layups and notched geometries.

The trained machine learning algorithms are shown to be able to predict the strength of open-hole multidirectional composite coupons with the precision provided by high-fidelity simulation in milliseconds, corresponding to a time-to-prediction speed-up of over 10k times.

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Predicting compression strength and design allowables of composite laminates after impact: A machine learning methodology

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Abstract

This study introduces a novel machine learning-based methodology to predict the compression strength and design allowables of composite laminates after impact, which can efficiently assess impact damage. Initially, to balance computational efficiency and high fidelity of simulation, a finite element model is established using conventional shell elements and cohesive surfaces. Then, a damage transfer algorithm is utilized computational costs between low velocity impact(LVI) and compression after impact(CAI) model, which helps reduce computational costs compared to modeling the LVI and CAI sequentially. The developed method shows a 60% reduction in computational time , while accurately capturing damage patterns and compression strength. A sensitivity analysis is conducted to identify key material properties and model parameters influencing strength. The results are used to generate a database for machine learning training. Finally, three different machine learning algorithms, including XGBoost, Gaussian Process and Artificial Neural Network, are employed to predict the distribution of compressive strength after impact, obtaining the corresponding B-basis allowables. All algorithms are evaluated using appropriate performance metrics. This novel integrated computational and machine learning framework provides an efficient way to evaluate compression strength of composite laminate after impact and obtain design allowables.

Identification of mode I fracture toughness in GFRP/Al and GFRP/Cu joints for structural batteries

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Abstract

In recent years, many studies have been performed to achieve more efficient, more sustainable, lighter, greener, and safer batteries. In this regard, the de- sign of structural batteries with the capability of carrying mechanical loads while storing electric energy can be a breakthrough in energy storage devices. Metal/Glass fibre laminate configurations are promising architectural approaches for structural batteries; however, despite providing good mechanical strength, their elastic mismatch promotes the onset and propagation of cracks along the interface, affecting directly the ultimate mechanical properties, the equilibrium of the structure, and the electrochemical efficiency of the battery. To this end, the bonding between the metal and the composite layer is of utmost importance. In this study, we examined the impact of various metal surface treatments, such as sulfo-ferric etching, NaOH/HNO3 chemical etching, and Sol-Gel anodizing of Aluminum 2024-T3, as well as FeCl3 chemical etching and Sol-Gel anodizing of Copper, on the mode I interlaminar fracture toughness of two important composite/metal configurations suitable for structural batteries: Glass Fibre Reinforced Laminate/Aluminum (GFRP/Al) and Glass Fibre Reinforced Laminate/Copper (GFRP/Cu). The obtained results were then compared with untreated conditions and with the baseline GFRP/GFRP configuration. GFRP/metal coupons with reduced residual thermal stresses were designed and double cantilever beam (DCB) tests were performed to measure the mode I fracture toughness. The surface characterization of the metals was performed by using contact angle test to estimate the surface free energy, while Coherence Scanning Interferometry (CSI) was used to measure the surface roughness and surface topography. In this work, using the classical laminate theory (CLT) and strain based theory, a code was developed for the estimation of the glass fibre composite stacking sequence, with same flexural stiffness of a given metal arm to achieve pure mode I loading. The results were validated by numerical three-dimensional virtual crack closure technique (3D-VCCT).

A new crack-tip element for the logarithmic stress-singularity of Mode-III cracks in spring interfaces

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Abstract

A new crack-tip finite element able to improve the accuracy of Finite Element Method (FEM) solutions for cracks growing along the Winkler-type spring interfaces between linear elastic adherents is proposed. The spring model for interface fracture, sometimes called Linear-Elastic (perfectly) Brittle Interface Model (LEBIM), can be used, e.g., to analyse fracture of adhesive joints with a thin adhesive layer. Recently an analytical expression for the asymptotic elastic solution with logarithmic stress- singularity at the interface crack tip considering spring-like interface behaviour under fracture Mode III was deduced by some of the authors. Based on this asymptotic solution, a special 5-node triangular crack-tip finite element is developed. The generated special singular shape functions reproduce the radial behaviour of the first main term and shadow terms of the asymptotic solution. This special element implemented in a FEM code written in Matlab has successfully passed various patch tests with spring boundary conditions. The new element allows to model cracks in spring interfaces without the need of using excessively refined FEM meshes, which is one of the current disadvantages in the use of LEBIM when stiff spring interfaces are considered. Numerical tests carried out by h-refinement of uniform meshes show that the new singular element consistently provides significantly more accurate results than the standard finite elements, especially for stiff interfaces, which could be relevant for practical applications minimizing computational costs. The new element can also be used to solve other problems with logarithmic stress-singularities.

Physically Recurrent Neural Networks for Computational Homogenization of Composite Materials with Microscale Debonding

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Abstract

The growing use of composite materials in engineering applications has accelerated the demand for computational methods, like multiscale modeling, to accurately predict their behavior. While combining different materials helps achieve optimal structural performance, the complexity of resulting material behavior poses challenges. Multiscale methods based on computational homogenization face a computational bottleneck, limiting widespread industrial adoption. A popular approach to address this is using surrogate models, which have been used to successfully predict a wide range of constitutive behaviors. However, applications involving microscale damage and fracture remain largely unexplored.

This work aims to extend a recent surrogate model using Physically Recurrent Neural Networks[1], to include the effect of debonding at the fiber-matrix interface while capturing path-dependent behavior. In that model, the core idea is to implement the exact material models from the micromodel into one of the layers of the network. Cohesive integration points with a Cohesive Zone Model are integrated within the network, along with the bulk integration points associated to the fibers and/or matrix. The limitations of the existing architecture are discussed and taken into account for the proposal of novel architectures that better represent the stress homogenization procedure.

In the proposed layout, the history variables of cohesive points act as extra latent features that help determine the local strains of bulk points. Different architectures are evaluated starting with small training datasets. To maximize predictive accuracy and extrapolation capabilities of the network, various configurations of bulk and cohesive points are explored, along with different training dataset types and sizes.

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Material Parameter Sensitivity Analysis for Intralaminar Damage of Laminated Composites through Direct Differentiation

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Abstract

Understanding the effect of the material parameter variability on the mechanical response of laminated composites is of great importance in non-linear Finite Element (FE) applications and in many engineering problems. Not only an accurate sensitivity analysis enables to estimate how much each parameter under consideration affects the response, but the linearization of the output provides also the possibility to propagate in an inexpensive way the material uncertainties, hence resulting useful in the context of Uncertainty Quantification and Propagation employing stochastic perturbation techniques. This is particularly important in simulations concerning laminated composite materials using up-to-date damage models [2] which often lead to computationally intensive simulations. In this paper, a material parameter sensitivity study is carried out in the context of continuum damage mechanics applied to laminated composites. The sensitivity with respect to the input material variables is estimated in an inexpensive way from a single run of the FE model using the so-called Direct Differentiation Method (DDM) [1]. The material parameters include elastic moduli, strengths and fracture toughnesses. A semi-analytical approach was used, rendering much simpler the implementation in a FE code. For a more precise computation, the Complex Step Differentiation (CSD) method [3] was employed. Furthermore, in order to reduce even more the computational cost, the DDM was implemented as a post-processing step using a reduced number of time increments. The obtained results show that the linearization carried out allow to estimate relatively well the reaction force developed by some specimens under tension as the material parameters change their values and to follow the weight of each parameter on the mechanical response during the load history.

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ON THE ENERGY DECOMPOSITION IN VARIATIONAL PHASE-FIELD MODELS FOR BRITTLE FRACTURE UNDER MULTI-AXIAL STRESS STATES

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Abstract

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

In this presentation, staying within the realm of variational approaches, we discuss existing modifications based on energy decomposition, their shortcomings, and the requirements for an effective energy decomposition method to model crack nucleation and propagation. Finally, we introduce a new energy decomposition, the star-convex model, that solves (at least partially) the issues with the existing ones [4].

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Cortical bone fracture toughness and ultimate stress/strain

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Abstract

Bone fracture prediction by CT-based finite element analysis based on maximum principal strain criterion can predict fracture initiation load within 80% accuracy (conservative prediction) [1]. It cannot predict the crack path which may also be of interest for clinical application.

Phase Field Models (PFMs) may improve bone fracture predictions [2], however, PFM predictions are highly influenced by the heterogeneous critical Energy Release Rate (ERR) G_{Ic} , critical ultimate stress and Young modulus of the bone.

In an attempt to improve fracture initiation and crack path in human long bones by PFM we apply numerical-experimental methods to determine the material properties of bone tissue so to be used in conjunction with CT-based FEA. We firstly focus on the femoral cortex and failure in transverse direction (perpendicular to osteons).

Human fresh frozen femurs were CT-scanned to obtain bone density along the femur, then sliced to create three point bending specimens in which crack like defects were inserted. These specimens were then micro-CT scanned before loaded to fracture.

Since the specimens are highly heterogeneous and the specimens cannot be manufactured to be precise, FE methods must be used to determine G_{Ic} and critical ultimate strain/stress (σ_c , ε_c) once the fracture load and displacements are measured by DIC methods. Young modulus of the bone may be determined by correlation to qCT scans [4,5].

No standards are available for the determination of bone fracture toughness, so we used the standards for metal and concrete to compute the critical Stress Intensity Factor (SIF) K_{Ic} by a three-point bending test setup. These standards have been used in previous works ([6,7]) but we apply Digital Image Correlation (DIC) technique to estimate the Crack Opening Displacement involved in K_{Ic} determination and to perform post-processing FEA.

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Stress or energy isocontours for 3D interface crack initiation?

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Abstract

The Coupled Criterion CC [1] has proven to be a relevant tool for assessing debonding initiation at the fiber-matrix interface [2]. This problem can be modeled through 2D models. However, such models fail to account for the stress singularity that occurs at the free edge of single fiber composites. On the contrary, although their implementation is more challenging, 3D models enable the description of intensified fields brought by the fiber-matrix elastic mismatch. The CC requires a priori knowledge of the crack path to be implemented, which is represented by a debonding angle in 2D but involves an additional dimension in 3D.

To address this crack shape identification problem, Leguillon [3] proposed using stress isocontours derived from known stress fields. Although this method offers computational efficiency, it may not yield appropriate solutions when crack initiation is driven by the energy condition. However, determining energy isocontours using a 3D model is computationally demanding due to the necessity of investigating all potential crack geometries.

Fiber-matrix debonding initiation is thus assessed using a 3D model and the CC. Both stress and energy isocontours are employed to describe the debonding shape. Energy isocontours are determined through an algorithm and parameterized shapes to enhance efficiency. The topologies of debonding shapes obtained from both stress and energy isocontours are then compared. Similarly, CC solutions obtained through both approaches are finally compared to quantify the relevance of using stress isocontours.

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Phase-field damage models via homogenization

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Abstract

Phase-field method has become during the last two decades a powerful approach to successfully solve problems related to fracture mechanics. However, the theory still presents some limitations including unclear analytical degradation and dissipation functions and computational efficiency.

In fact, the effect of degradation on the strain energy function has been habitually computed with analytical degradation functions. In this work, we propose to understand the degradation function as the homogenization of a microstructure with a void inclusion. Thus, we replace the phase field variable by microstructure parameters. Through this, we automatically obtain an orthotropic homogenized constitutive tensor which is also supported by a physical phenomenon instead of depending on ad-hoc analytical expression.

The methodology implemented consists of two stages: (1) an offline stage where the mechanical response (constitutive tensor) of the microstructure has been computed for different void parameters and (2) a second stage where the structural simulation is computed.

Different results have been obtained from benchmark tests to validate the formulation and the computation cost has been compared with standard phase field approach.

Quasi-static failure and energy absorption of mechanically-fastened UD carbon-fibre thermoplastic composite joints

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Abstract

The introduction of novel materials into the design framework of aeronautical structures necessitates an in-depth assessment of their mechanical behaviour. Mechanically-fastened composite joints are widely used in aeronautical applications, and their load-bearing performance is typically characterised following industrial standards (e.g. ASTM D5961). These joints have also been more recently employed as specifically-designed controlled energy absorbers. In this work, a novel uni-directional (UD) carbon fibre-reinforced thermoplastic material system, stacked in a quasi-isotropic (QI) layup is tested for this application using specimens of constant thickness and varying width (*w*), loaded with two types of 6 mm-diameter (*D*) fasteners (pin or fastened bolt). To assess the energy absorption capability of this new material system, extended bearing tests are also presented for both fastener types, with a steady-state crushing plateau attained for some of the tested configurations.

The fastener type as well as the *w*/*D* and *e*/*D* ratios are shown to be deterministic in the behaviour of the joint, with the failure mode changing from net-tension to shear-out and bearing. Micrographs and X-ray imaging enable an evaluation of the manufacturing quality and an in-depth *post-mortem* analysis of both external and internal damage evolution within the coupons. The presented results, comparable to those of standard thermoset composite joints, provide a strong starting point for the future design, modelling and validation of thermoplastic composite joints, including the specific case of energy-absorbing designs.

A computational model of interface and phase-field damage for multi-domain solids exposed to dynamic loading

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Abstract

A computational model is formulated for studying dynamic crack propagation in quasi-brittle materials exposed to time-dependent loading conditions. The developed computational approach is capable of initiating and propagating cracks inside materials and along material interfaces of general multi-domain structures. Particular attention is paid to a situation of solids with inhomogeneities.

Description of the fracture processes is interpreted by internal variables and it introduces two independent damage variables to distinguish between interface and internal cracks. The variable responsible for interface cracks is defined in an adhesive interface layer of negligible thickness and through an appropriate degradation function it renders a relation between stress and strain quantities in fashion of cohesive zone models. The other variable is defined inside material domains and it is based on the theory of phase-field fracture guaranteeing the material damage to occur in a thin band of the material introducing a regularised model for internal cracks. Additional property related to both interface damage and phase-field variables is their capability to make difference between modes of fracture which may be useful for structures exposed to combined loading.

Based on a formulation using energy expressed by the Lagrangian of the system, the developed computational approach introduces within the time stepping procedure a staggered computational scheme which has a variational form. The numerical data are obtained by (sequential) quadratic programming algorithms implemented together with a finite element calculation within an in-house MATLAB code which analyses problems of fracture in multi-domain elements of structures.

Quasi-static versus dynamic Phase Field fracture models for unstable crack propagations

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Abstract

This study demonstrates that unstable crack propagation events do not meet quasi-static assumptions and therefore require dynamic modeling approaches. Comprehensive evidence is presented based on three distinct analyses conducted on multi-ligament unstable fracture conditions, including simplified Spring-Mass models, detailed quasi-static and dynamic Phase Field fracture models, and bespoke experiments using 3D printed specimens. The resultant findings unequivocally reveal that neglecting inertial effects can lead to unsafe fracture predictions, especially in the presence of energetic barriers for crack growth. Additionally, quasi-static Phase Field fracture models produce crack patterns that diverge from experimental evidence due to their oversight of the progressive diffusion of mechanical information within the continuum. Furthermore, the inability of quasi-static approaches to accurately track unstable crack propagation weakens the critical irreversibility condition of fracture. These experimentally supported insights are not exclusive to Phase Field fracture models; they apply to nearly any variational approach to fracture, including Cohesive Zone Models and Continuum Damage Mechanics.

Stability and crack nucleation in variational phase-field models of fracture: effect of length-scales and multi-axiality

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Abstract

Phase-field model for brittle fracture is widely used due to its ability to reproduce complex crack patterns, without ad hoc criteria, and to deal with the behavior of crack formation under tensile loading. However, crack nucleation under multi-axial stress states in phase-field model remains a subject of discussion with several unresolved issues. Among these, we identify the inability to flexibly set the crack nucleation criterion under multi-axial stress states and the difficulty in modeling crack nucleation in materials close to the incompressibility limit. In this contribution, we focus on the evolution of a special class of phase-field models with linear softening [1] in order to overcome the aforementioned limitations. These models provide increased flexibility in adjusting the crack nucleation criterion by allowing the use of different softening laws on the volumetric and deviatoric components of the strain energy density. However, the choice of the softening law has an impact on crack nucleation and reveals the length-scales which influence the stability of the solution. Therefore, we conduct a theoretical and numerical stability analysis, inspired by the work of [2, 3]. Through this stability analysis, we establish the limitations of this model in describing crack nucleation in nearly inextensible bars (the 1D version of almost incompressible materials) and under multi-axial stress states and we explain the connection between fracture nucleation and the competition between stored elastic energy and fracture energy.

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Combining phase-field regularization and the coupled criterion for crack initiation

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Abstract

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

PF is naturally able to describe a strength surface under homogeneous stress state, and thus indirectly incorporate a strength criterion through the chosen regularization length and energy decomposition [Molnár 2020, Molnár 2022, Doitrand2023]. This regularization acts as a process zone surrounding the main crack, which is a main difference compared to the CC where no process zone is generally considered.

The present work aims developing a CC formulation considering a process zone. The process zone is introduced based on the crack regularization brought by PF. A three-parameter CC is thus proposed to combine stress and energy criteria in presence of a process zone. The particular case where the process zone length is a priori determined based on the previously determined correlation between the regularization length and the tensile strength [Molnár 2020] is ialso investigated.

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The Atomistic Origin of Fracture Toughness

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Abstract

The talk that delves into the origins of fracture toughness in amorphous silica, focusing on the influence of a rounded crack tip and the limitations of linear elastic fracture mechanics. Griffith's theory states that in the absence of a sharp crack, the energy release rate becomes zero, rendering linear elastic fracture mechanics inadequate for assessing resistance in geometries featuring a rounded crack. To overcome this limitation, the talk employs coupled criterion and phase-field simulations to assess fracture initiation.

Through extensive large-scale atomic-scale simulations, the research identifies damage within the atomic structure. A finite element model update scheme is utilized to pinpoint the critical energy release rate and the regularization length scale during crack propagation.

In conclusion, the talk offers a comprehensive comparison of the identified properties, examining their consistency with the predictions of the homogeneous phase-field solution and the material's tensile strength. Furthermore, the research endeavors to contrast the outcomes of all three methodologies, thereby shedding light on the foundational assumptions that underlie continuum models, including phase-field and finite fracture mechanics. By exploring the interplay between crack geometry and fracture resistance, this study advances our understanding of fracture toughness in amorphous silica and contributes to the ongoing development of more accurate models for predicting fracture initiation and propagation in complex materials.