Composites 2019

7th ECCOMAS
THEMATIC CONFERENCE ON
THE MECHANICAL RESPONSE
OF COMPOSITES

BOOK OF ABSTRACTS

Editors:
A. Turon, P. Maimí & M. Fagerström
Welcome

On behalf of the European Community on Computational Methods in Applied Sciences (ECCOMAS) we are pleased to welcome you at the sixth Thematic Conference on the Mechanical Response of Composites (Composites2019). The conference is held at the University of Girona, Spain.

ECCOMAS is a scientific organisation grouping together European associations with interests in the development and application of computational methods in science and technology. The mission of ECCOMAS is to promote joint efforts of European Universities, research institutes and industries which are active in the broader field of numerical methods and computer simulation in Engineering and Applied Sciences and to address critical societal and technological problems with particular emphasis on multidisciplinary applications.

Following the very successful conferences in Porto, London, Hannover, the Azores, Bristol and Eindhoven, the seventh ECCOMAS Thematic Conference on the Mechanical Response of Composites is now held in Girona, Spain. The scope of Composites2019 is to provide a forum for the exchange of knowledge and current research and development on Composite Materials and Structures. The conference focuses on theoretical and numerical modelling and prediction of the performance of composite components as well as challenging industrial applications of recent developments. Experimental validation is also covered.

In this booklet, you will find the abstracts of all plenary lectures and contributions of the participants.

We wish you a fruitful conference and we hope that you enjoy your stay in Girona.

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Pere Maimí
Martin Fagerström

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MICROMECHANICS OF DEFORMATION AND FRACTURE IN HIGHLY CROSS-LINKED THERMOSETS – IMPACT ON COMPOSITE MODELLING

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Advanced constitutive models for polymers have been essentially developed for thermoplastics with relatively limited applications/extensions to thermosets. Recent extensions of these constitutive models provide accurate predictions over a wide range of loading configurations, strain rates and temperature, encompassing below and above transition temperature regimes, although at the prize of a very large number of parameters, often larger than 30. Still, these models, mixing phenomenological and micromechanics ingredients, are often not rich enough to capture complex behaviors such as for instance severe non-linearity upon unloading or possible size effects, while missing also micromechanical connection to the failure process. This directly impacts the development of predictive multiscale models for polymer based composites.

Based on extensive experimental test program on the highly cross-linked RTM6 epoxy, the viscoplastic response is found very similar to thermoplastics, with hardening-softening-re-hardening, large back stress upon unloading and existence of shear band patterns at very small scale [1]. Furthermore, size effects are revealed when looking at nanoindentation data as well as indirectly when looking at the response of unidirectional composites. A molecular physics-based model of the deformation process occurring through the activation of nanometer scale shear transformation zones (STZ) has been worked out [2]. The viscoplastic deformation is the result of the cooperative activation of STZ’s, sensitive to rate, temperature, stress state and stress level. This model involves only 7 parameters to identify, all with physical meaning. The model quantitatively captures the experimental trends, even some complicated responses during creep tests performed after plastic deformation at intermediate stress levels showing backward followed by forward creep. It also captures the size dependent strength resulting from large strain gradients putting a constraint on the development of the micro-shear banding process. In addition, a new micromechanics-based fracture model based on the attainment of a local maximum principal stress at the tip of microdefects is proposed and validated for a wide range of stress states [3].

The implication of these results and micromechanical models on composite modelling is not straightforward. This is addressed through the analysis of in situ SEM compression tests on thick UD carbon fiber reinforced RTM6 matrix composite, involving the determination of digital image correlation strain fields [4]. Difficulties remain to quantitatively capture the experimental response with the models identified on bulk resin data.

References
THINKING CREATIVELY ABOUT MICROSTRUCTURES AND NUMERICAL METHODS FOR COMPOSITES DESIGN

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In nature, a wealth of microstructure concepts have evolved to cope with mechanically-challenging environments; in comparison, the type of microstructures found in human-made high-performance composites occupies only a tiny fraction of the potential design space. In this presentation, we explore the challenges, current results and future potential of exploiting various bio-inspired micro-structures for improved damage tolerance and damage diffusion in CFRP. In particular, we show results from CFRP micro-structures inspired by bone, wood, nacre, the strombus gigas shell and the mantis shrimp. We show that, in some cases, these microstructures lead to over 5-fold increases in toughness [1]; in others, they lead to significant damage diffusion or to retaining structural integrity after failure [2, 3].

Let it be in the design of new composite microstructures or in the design of composite components, simulating the mechanical response of composites during damage growth has challenged researchers and engineers for various decades. Both intricate sub-critical damage patterns and multi-scale considerations constitute significant challenges for existing numerical approaches. In this presentation, we show that it is possible to formulate a new type of elements — a polymorphic element [4] — that contain floating degrees of freedom (DOF) and exist as an evolving superposition of multiple states. The floating DOF allow the representation of intricate damage patterns [5], and each of the superposed states of the polymorphic element represents an idealisation of the underlying material with different resolutions using a mesh superposition technique [6] and verifying partition of unity. During the analysis, each element evolves the superposition of different states as required to represent the actual damage that the element experiences at each stage. For instance, with polymorphic elements, as a crack grows, the region near a crack tip can be represented with continuum elements while the regions ahead and in the wake of a crack progressively revert to a structural-element representation.

References

Modern wind turbine blades are large scale, complex composite structures with variable stiffness and many ply-drops accompanied by advanced material transitions between sandwich and monolithic sections. The large design freedom makes it attractive to apply structural optimization techniques for generating competitive solutions, and this work will present two different approaches for gradient based structural optimization of wind turbine blades. Full-scale 3D FE models with no inherent restrictions on the structural design criteria to be included are applied. The objective is to minimize the mass while fulfilling a number of structural constraints together with manufacturing constraints.

The first optimization approach takes offset in the existing production method where the blade is manufactured using non-crimp fabric (NCF) fiber mats, and it parameterizes thicknesses of the NCF fiber mats and core materials used. It is demonstrated how a mass optimized 73.5 m wind turbine blade can be obtained, taking into account constraints on tip displacements, strength and buckling load factors for the 12 most important load cases while also fulfilling manufacturing constrains related to ply-drops, see also [1].

The second approach is the Discrete Material and Thickness Optimization (DMTO) method that simultaneously determines an optimum thickness variation together with the choice of material in each layer. Candidate materials such as uni-directional fiber mats oriented at different angles, NCF mats and foam material are defined, and the discrete problem of choosing the best candidate material in each layer and the number of layers is converted to a continuous problem that can be solved efficiently using gradient based optimizers, see also [2, 3, 4]. Examples demonstrate the potential of this approach for wind turbine blades and other multi-material composite structures where a number of global design criteria as well as local strength constraints and manufacturing constraints are taken into account.

References

If you please - make me a material: Examples of new perspectives for composite materials

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The IRT Saint-Exupery has acquired a range of pre-industrial pilot scale manufacturing lines that are unique in size and performance and allowing to make “on-demand” multifunctional organic or ceramic composites tailored to the applications. This was made possible thanks to the leadership of aeronautics and space groups, material suppliers, and fruitful collaborations with SMEs specialising in the manufacture of special machines. In one instance, this co-development has led to the implementation of modular and scalable impregnation lines dedicated to the understanding and development of novel high-performance carbon fibre reinforced thermoplastics for aeronautics and space. The win-win collaboration is enabling the development of specific multi-disciplinary skills, delivering technological benchmarks and proof of concepts in rapid cycles.

Pilot scale manufacturing lines are one of the cornerstones of the IRT Saint-Exupery's technological platforms, completed with material characterization and testing equipments. Dedicated organic or ceramic material projects have already supported the maturation of original concepts of functionalized materials from laboratory to pre-industrial scale. Original concepts resulting from an academic partner works were studied [1]. The addition of silver microwires in polymer matrices of the PAEK family during the carbon fibres impregnation process has resulted in an increase in the electrical conductivity of manufactured prepreg tapes. Another concept based on the addition of piezoelectric microparticles in thermoplastics matrixes showed a significant enhancement of the damping performance on composites structures [2]. The ability to choose constituents, to add functions, and develop particular material architecture tailored to the performance/cost/manufacturing targets, allows new opportunities for aerospace applications [3]. On the virtual side, highly instrumented technological platforms allow an easy bridge to simulation and virtual testing development as well. In parallel of works aiming at improving predictive capabilities of simulations, IRT Saint Exupery has committed to integrate, standardize and assess maturity of advanced modelling methods. In doing so with its industrial and academic partners, IRT wants to pave the way towards trustworthy physical test and lead time reduction.

Co-located multi-partner research projects involving academic and industrial partners allow to develop and share knowledge “end-to-end”, from laboratories, to suppliers and finally industrials. From the laboratory to the pre-industrial scale, from the material to the prototype scale, one team is delivering scientific results & transfers faster composite materials of tomorrow to industry.

References

Keynote Speakers
AN ANISOTROPIC LINEAR VISCOELASTIC CONSTITUTIVE LAW
— DIRECTION DEPENDENT TIME TEMPERATURE SHIFT
FUNCTIONS

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Organic matrix composites with thermoplastic matrix materials reinforced by continuous fibers gain increasing interest for industrial applications. Their effective behavior shows direction dependent creep and relaxation response. If the reinforcements are viscoelastic, too, also some effective time–temperature–shift functions exhibit direction dependence. For structural analyses of components made from such composites, an appropriate constitutive material law is desired. The present work is based on a constitutive material law for linear thermo-viscoelasticity in the time domain which has been developed earlier [1]. It does not only allow for anisotropic elastic behavior but also for anisotropic (i.e. direction dependent) relaxation response. Here, under the assumption of thermo-rheological simple material behavior, the model is extended to account for direction dependent time-temperature-shift functions. The developed constitutive law is implemented into the commercial FEM package ABAQUS/Standard for plane stress states and orthotropic material symmetry.

The application is demonstrated for a continuous viscoelastic fiber reinforced organic matrix composite. The effective orthotropic linear viscoelastic response of the composite is computed by means of a periodic unit cell approach. These data, evaluated at different temperatures, is used to calibrate the input for the developed material law. Predictions from the latter are compared to the results from the unit cell simulations.

References

Strength and fatigue lifetime of 3D woven composite structures with polymer matrix

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Safran Aircraft Engines has chosen 3D woven composite materials with polymer matrix for the manufacturing of the fan blades for its new generation of civil engine, because of their interesting residual properties after impact. Moreover, due to the imperative of structural mass reduction and consumption minimization for recent airliners, structures are subjected, during in-life service, to higher loadings and for longer durations. Consequently, a unified damage and failure approach to predict the strength and the lifetime of industrial composite components has been proposed. Firstly, a damage and failure model, already developed at Onera [1], describes accurately the different damage mechanisms encountered in 3D woven composites and has been validated on a large database of static tests. Secondly, this model has been extended to predict the fatigue lifetime [2] using an incremental damage model, able to predict the damage evolution during fatigue loading even for multiaxial spectral loadings. The fatigue lifetime predictions, i.e. evolution of apparent modulus and Wöhler curves for different stress ratios, are in good agreement with available tests carried-out by Safran, as reported in Figure 1. Moreover, this approach has been implemented into a commercial FE code and compared successfully with multi-instrumented tests on composite structures.

![Figure 1](image)

Figure 1. Predicted and measured a) apparent modulus evolution during cyclic fatigue tests at 60\% of the static failure load and b) Wöhler curve in the warp direction.

References


ABAQUS IMPLEMENTATION OF REGULARIZED EXTENDED FINITE ELEMENT METHOD

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Rx-FEM is a discrete damage modeling (DDM) method, which represents an approach to progressive failure modeling in composites when multiple individual damage events such as matrix cracks and delamination are introduced into the model via displacement discontinuities. Rx-FEM is a variant of the eXtended Finite Element Method (x-FEM), where a continuous approximation is used in place of the Heaviside step function. To date, this methodology has been implemented in BSAM, an in-house program, and extensively applied to static and fatigue analysis of laminated composite structures. The regularization of the Heaviside step function offers unique possibility for implementation of Rx-FEM in commercial software by using superimposed native elements of the parent software. The proposed implementation capitalizes on utilization of original Gauss integration schema in Rx-FEM even after the enrichment is introduced to accommodate a mesh independent crack. Thus, the enrich displacement field is represented by superposition of native ABAQUS elements such as CPS4, which is used in the present work. Several examples of unnotched and open hole composite unidirectional coupons are considered, including the splitting phenomenon of an axially loaded open-hole coupon. The method correctly predicts separation and fiber direction stress concentration reduction as a result of the splitting.

Figure 1. Open hole tension specimen with four 0° cracks, axial stress before cracking (a) and after separation (b).
TRANSVERSE ISOTROPY OF MICROMECHANICAL MODELS WITH PERIODIC AND WEAKLY PERIODIC BOUNDARY CONDITIONS

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Describing the mechanical response of composites in homogenized material laws is complicated by nonlinearity in the behavior of the constituents, e.g. plasticity, damage or aging of the polymer matrix. Micromechanical models that derive the composite material behavior from descriptions of the constituent behavior in combination with a representative microstructural geometry are therefore an appealing option for describing the material behavior under general loading conditions [1]. In presence of macroscopic gradients, such micromechanical models can be embedded in a multiscale model with coupling between the scales [2]. The accuracy of these multiscale approaches hinges on the representativeness of the micromodel.

The classical criterion for representativeness is that increasing the size of the micromodel should not affect its averaged response. Another criterion can be added, which is that, if no directional bias is present in the microstructure, the response of the micromodel should be isotropic. Micromodels for engineering composites often assume all fibers to be parallel and randomly distributed over the plane perpendicular to the fiber direction. This is consistent with the common assumption of transverse isotropy in homogenized descriptions of composite behavior. However, the geometry of the micromodel, typically square or hexagonal, and its boundary conditions, typically periodic boundary conditions, may affect the transverse isotropy of the micromodel response. This is particularly relevant when localized deformations are present, because the periodic boundary conditions do not allow for arbitrarily oriented localization bands. Weakly periodic boundary conditions have been proposed to overcome this effect [3].

This contribution investigates the influence of boundary conditions on the micromodel response by means of a systematic study into the transverse isotropy of micromodels with random fiber distributions. Uniaxial stress is applied in a range of directions and the averaged response of the micromodel is recorded. Different material laws are considered including hardening plasticity and softening damage. Strong and weakly periodic boundary conditions are explored. Anisotropy in the response is observed with both types of periodic boundary conditions. Moreover, this is not limited to post-peak behavior but already significant at the peak load level.

References

FIBRE BREAK INTERACTIONS IN UNIDIRECTIONAL COMPOSITES UNDER LONGITUDINAL TENSILE LOADING

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Even though various failure modes can be observed in composites, understanding the fibre break development in 0° plies is crucial for the reliable prediction of the final failure. Swolfs et al. [1] proposed a numerical model to predict the longitudinal strength of unidirectional composites. The stress field information for the load transfer from a broken fibre to intact fibres was obtained with a finite element model embedding a single break in a representative volume element. The strength model then deploys a superposition principle to assess the influence of multiple fibre breaks with the input obtained from a single fibre break. This approach, however, ignores the well-known effect of growing stress recovery length in the broken fibres with increasing cluster size.

To improve the predictions, the stress redistribution around multiple fibre breaks should be improved. It is well recognised that fibre break clusters are not limited to a single break plane (coplanar), but can also extend in the longitudinal direction (non-coplanar). A finite element study was therefore carried out on the fibre bundle level to investigate the stress field created by coplanar as well as by non-coplanar fibre break clusters. The models provide useful information for the interaction between breaks and the influence of these breaks on the stress concentrations in surrounding fibres.

The results for coplanar clusters show that the stress concentrations on the nearby fibres are amplified and are significant over larger axial and radial distance than in the single fibre break case. The failure probability of the nearby fibres is therefore clearly increased with increasing cluster size. For non-coplanar clusters, however, the results are more complex. Increasing distance between the break planes of two fibre breaks in neighbouring fibres decreased the amplification of the stress concentrations carried by the intact neighbours. In addition, the stress recovery in the broken fibres was significantly affected. With increasing axial distance between two breaks, the presence of the second fibre break can trigger significantly faster stress recovery in the first broken fibre. The conventional way to calculate the ineffective length as the length at which 90% of the stress is recovered, is shown to be flawed in this case.

These results shed new light on fibre break interactions, and the importance of correctly taking into account the coplanarity or lack thereof for the simulation of fibre break developments.

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DAMAGE AND FRACTURE OF WOVEN PLY COMPARED TO EQUIVALENT UNIDIRECTIONAL PLY LAMINATES

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The fracture of laminate composite structures is due to many mechanisms acting at different scales [1,2] and depending on the type of ply, woven or unidirectional (UD), concern the matrix or the fibers and are a function of many parameters (thickness, orientations, loads ...). Matrix-type damage usually starts with fiber/matrix decohesions that propagate in the matrix to form transverse cracks over the entire thickness of the ply. In the case of UD plies, these transverse cracks can spread over great lengths and can initiate delamination. In the case of woven plies, these transverse cracks develop over the whole thickness of the yarns but their propagation is stopped by the crossing of the yarns. In the case of a UD ply crossed laminate [0m,90m]ns in traction, the transverse cracks will not lead to the fracture of the sample immediately and they develop until the breaking of the fibers. The kinetics of development of these transverse cracks depends strongly on the parameters m and n of the laminate which complicates the modeling of these cracks. This situation is not possible for woven plies.

As shown in fig. 2, interlaminar damage such as delamination may be observed if the thickness of the number of UD plies of the same orientation increases [3]. Experimental results compared to simulations show that generally it is not necessary to model the interlaminar damage to describe the fracture of woven ply laminates [4]. The elements presented above will be developed in the paper based on experimental results and, only for the description of intralaminar damage, compared to simulations. For unidirectional ply laminates, the limits of this type of modeling depending will be underlined.

References

HIGH-FIDELITY TESTING AND INTEGRATED MODELLING OF COMPOSITE COMPONENTS AND SUB-STRUCTURES

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Many innovative developments that facilitate lightweighting, energy efficiency, safer and more damage-tolerant designs involving composite structures, are only applicable at the structural levels. They cannot readily be incorporated into composite structures like e.g. airframes or wind turbine blades because of the current validation/certification procedures, based on the ‘building block’ approach (often referred to as the ‘testing pyramid’), where design allowables are defined through testing mainly on small (coupon) length scale. The presentation will discuss why the current approach is inefficient and unsustainable, and present a route for lessening regulatory constraints, moving towards a more cost/performance optimised design philosophy, by reducing the multiple coupon level tests at the bottom of the test pyramid. Instead, structural behaviour is accounted for in a new culture of virtual design and certification at higher levels of the test pyramid, enabling significant mass savings, and reduction of design costs and development time. The advantages of high-fidelity composite substructure/component testing and its integration with multi-scale modelling will be demonstrated through recent research involving integrated testing and modelling of composite wind turbine blade structures [1], [2] and composite aero-structures [3]. The novel approach has the potential to crossover into emerging materials technologies such as high performance Additive Manufacturing, where currently no credible processes for validation and certification are in place for the structural scale.

Figure 1. Left: composite coupon test; Centre: High-fidelity composite wind blade substructure test; Right: Full scale wind blade test [1], [2].

References

Level set post-processing for automated meshing of woven composite CT scans with local fiber content control

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Next to computational geometry generation methods, methods were developed based on µCT scanned 3D images for reconstructing the 3D microstructural geometry of 3D woven composites with a view to multiscale modelling. Corresponding voxel geometries are nowadays more and more used straightforwardly for mechanical simulations [1]. However, the use of voxel geometries may be questionable for damage simulation because of the spurious stresses concentration associated with the jagged shape of the mesh at the surface of yarns.

To avoid such shortcomings, an automated methodology will be outlined to transform explicit voxel RVE geometries into implicit smoothed geometries through a level set-based processing. This is achieved by using a level set based post-processing tool of the smoothed data that suppresses interpenetrations between yarns [2], and that controls locally the fiber content by local modifications of the yarns cross sections. A subsequent conforming tetrahedral mesh can be generated based on the implicit geometrical description for finite elements simulations.

Figure 1. Scanned sample, voxel representation, smoothed geometry and generated mesh of a 3D woven composite

References

STRESS INTENSITY RANGE OF A DEBOND CRACK TIP – EFFECTS OF CYCLIC FRICTIONAL SLIDING SHEAR STRESS

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A micromechanical model analyzing the effect of the mechanical properties of the fiber/matrix interface on the endurance fatigue limit of unidirectional composites has recently been published [1]. The model analyses the situation of a single broken fiber. Two interface phenomena are described: Growth of a debond crack and frictional sliding along the debonded interface. Growth of the debond crack is described in terms of a debond energy controlling static crack growth and Paris-Erdogan law (with a threshold stress intensity range) controlling cyclic debond crack growth. Frictional sliding is modelled using a frictional shear stress that is assumed to change gradually from a static value (“first forward slip”) to a lower cyclic value after many forward and reverse interfacial slips.

The situation after many load cycles is now described. During a load cycle, forward slip occurs along the debonded fiber/matrix interface, starting from the location of the fiber break. The remainder of the debonded interface experiences sticking friction. With increasing applied load, the length of the “forward” slip zone increases, but it never reaches the debond crack tip. During unloading, slip in the reverse direction starts from the location of the fiber break. With increasing unloading, the reverse slip length increases, but does not reach the debond crack tip. At minimum applied load, the reverse slip zone just obliterates the previous forward slip zone. There is thus always sticking friction along the debonded fibre near the crack tip. Then the crack tip stress intensity factor remains unchanged. This result was found both using an analytical model and a numerical (finite element) model. When the cyclic stress intensity range is zero, no cyclic debonding is expected.

This prediction - no cyclic debond crack extension during applied cyclic loading - explains earlier experimental observations of decelerating and arresting debond cracks found in unidirectional fiber composites [2] and single filament composites [3, 4]. This finding opens the possibility that a situation with a single, isolated broken and debonded can be stable and thus a fatigue limit can exist [1].

References

A COMPUTATIONALLY-EFFICIENT MODEL FOR COMPOSITES UNDER LONGITUDINAL TENSION-TENSION FATIGUE

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Cyclic loading induces damage in composite materials, which reduces the performance and fatigue life of composite structures; predicting this effect is a computationally-challenging task, since it requires modelling how damage evolves across several scales in space and time. We present a statistical micromechanical model to predict failure of unidirectional fibre-reinforced composites under longitudinal tension-tension cyclic loading [1-2]. The model is based on a hierarchical scaling law which considers (i) the stochastic static strength of individual fibres and (ii) the fatigue response of the fibre-matrix interface. Due to its analytical formulation, the model predicts the fatigue life (Figure 1) and damage evolution (Figure 2) of unidirectional composite specimens up to virtually any size and for their entire fatigue life, in less than one minute.

Model predictions:
1% failure probability
50% failure probability
99% failure probability

Experimental results:
Gamstedt & Talreja (1999)
Total fibre-breaks
Uncorrelated fibre-breaks
2-3 broken-fibre clusters
4-7 broken-fibre clusters

Figure 1. S-N curves for a carbon/PEEK composite.

Figure 2. Damage accumulation during fatigue life of a carbon/epoxy composite.

Acknowledgements
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References
COHESIVE ANALYSIS OF SKIN-STIFFENER DEBONDING UNDER QUASI-STATIC AND CYCLIC LOADS

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The ability of the cohesive fatigue model proposed in Ref. [1] to predict the initiation and propagation of skin/stiffener separation was evaluated using a three-point bend (3PB) configuration. The 3PB specimen consists of a quasi-isotropic laminate representing the skin of a fuselage. A shorter doubler representing the flange of a stiffener is co-cured at the center of the specimen [see Fig. 1]. A simplified modeling technique was applied, in which the complex damage mechanisms involved in the separation, such as delamination migration, matrix cracking, bridging, and crack delving are represented by a mixed-mode trilinear cohesive law at the interface between the skin and the doubler. The quasi-static properties of the trilinear law were characterized in Ref. [2]. The main advantage of the proposed fatigue model is that it relies on quasi-static properties as well as engineering assumptions to compose the shape of the S-N diagram. The model does not require Paris law data, and it is capable of predicting the initiation of separation, the rate of propagation, as well as the effects of crack resistance curves and the stress ratio.

Figure 1. Tests and analysis of skin/stiffener separation under cyclic loads.

References

INFRARED THERMOGRAPHY FOR ASSESSMENT OF FATIGUE DAMAGE IN MULTIDIRECTIONAL COMPOSITES

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Infrared thermography (IRT) can provide a live display of damage growth during fatigue tests that indicate the initiations of different damage types/severities. Thermoelastic stress analysis [1] is based on the use of infrared thermography to obtain a small temperature change, associated with the thermoelastic effect, which can be directly related to the stresses. The aim of the paper is to demonstrate that IRT can be used as a tool that can quantitatively identify the onset of different damage types in a multidirectional composite during a fatigue test. Damage progression in two types of glass reinforced epoxy multidirectional laminate configurations is studied. A layup of (0, 90)₃s was manufactured, from which on-axis, cross-ply, specimens were machined, to generate progressive defects through the fatigue cycle. The second type of specimen was cut at 45° to the fibre directions, to generate shear damage and off axis cracks. An open hole tension (OHT) specimen configuration was used to localise the region of damage growth, and failure. In Figure 1, a sample of the TSA data is shown; in Figure 1 (a) it is clear that the subsurface 90° ply has failed, as evidenced by the horizontal lines. In Figure 1 (b) the area carrying little or no stress (above and below the hole) has grown and there is a clear stress concentration indicating that a crack has started at the hole. It is evident that there is rapid damage growth between 180000 and 190000 cycles with a clear large delamination around the hole shown in Figure 1 (c). In the paper, it is shown how plots of temperature and TSA data can be used quantitatively to identify the inception of different types of damage alongside an automated procedure for monitoring the progression of damage.

![Figure 1. TSA plots showing stress redistribution (same scale in all plots (K)) in (0, 90) specimen as damage progresses](image)

References

FAILURE PREDICTION IN FIBER-REINFORCED COMPOSITES BASED ON CONTINUUM DAMAGE MECHANICS

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The present study presents the application of a newly developed Continuum Damage Model (CDM), cf. [1], applied to failure prediction in composite laminates. The damage model is based on elastic damage, enabling the prediction and propagation of intralaminar damage for compression dominated loadings. To properly describe the influence of damage nucleation for tensile loading, the model in [1] is enhanced by an additional damage variable. The compressive/tensile damage variables then form the combined damage area evolution. Mesh independence is achieved through a damage evolution rule law that accounts for the damage progression without inclusion of a damage gradient term, cf. [1]. The model has been implemented into the Abaqus™/Explicit FE-code. Interlaminar failure of delamination type are also implemented in the total FE-model utilizing Cohesive Elements (CEs), natively available in Abaqus™. Numerical predictions of the load-displacement behavior due to damage evolution in open hole compression and bolted joint tests are presented.

A comprehensive methodology for fatigue-driven delamination prediction in 3D layered structures under general loading conditions

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Efficient design of layered composite structures requires advanced computational tools for predicting the occurrence of interlaminar damage under service loading conditions. Therefore, there is a need for reliable technologies and design methodologies to account for delamination under general mixed-mode and fatigue loading conditions. The current state-of-the-art models succeed in reproducing the fatigue behavior at coupon level. However, most of them are not applicable or have not been validated in three-dimensional analysis of composite components. This low level of readiness forces the design certification process to rely on empirical testing rather than predictive simulation analysis.

This work presents an integral methodology for the analysis of delamination growth in layered composite structures. First, a new computational method for simulating fatigue-driven delamination [1] applicable to large and arbitrarily shaped fracture process zones is presented. The model uses an envelope load approach and avoids making use of any fitting parameters in the link between the damage rate and the crack growth rate. Thus, all the model input parameters are obtained experimentally from coupon tests. Any variant of the Paris’ law relying on the mode-decomposed energy release rates can be used to describe the crack growth rate. To compute the mode-decomposed energy release rates, the model incorporates a new formulation for evaluating the J-integral [2] that takes into account the current loading state of the entire cohesive zone. The growth driving direction [3], defined as the normal to the damage isolines, is used to render the integration paths across the cohesive zone and to decompose the J-integral into mode I, II, and III. Unlike other available approaches for the evaluation of the energy release rate in curved cohesive zones, which are based on local information, the proposed method leads to accurate prediction of delamination propagation under mixed-mode and non-self-similar growing conditions. Secondly, the model is validated against an experimental benchmark case with varying crack growth rate and shape of the fracture process zone [4]. The test configuration is based on a wide double cantilever beam specimen with a straight mid-plane initial defect. To promote curved delamination that changes shape and crack growth rate during propagation, two reinforcements are bonded on both faces of the specimen. The delamination front is monitored with X-ray radiography, and the obtained results are compared to the numerical predictions producing highly accurate results.

In conclusion, the methodology proposed is a key step in providing a simulation framework that contributes to reducing expensive and time-consuming fatigue tests involved in the certification process of layered composite structures.

Novel Materials
PREDICTING NON-LINEAR SHEAR DEFORMATION AND FAILURE IN 3D FIBRE-REINFORCED COMPOSITES

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A class of composite materials with fully 3D fibre-reinforcements have shown weight efficient strength and stiffness characteristics, as well as promising energy absorption capabilities. In fact, Khokar et al. [1] have demonstrated that, in bending, such a 3D-CFRP I-beam has two to three times the specific energy absorption capability of a steel I-beam with equivalent geometry. Note, the considered woven reinforcement has both horizontal and vertical weft yarns interlacing warp yarns in a grid-like set. This fibre network suppresses delamination and allows for stable and progressive damage growth in a quasi-ductile manner. While the considered 3D fibre-reinforced composite shows promise, developing a computationally efficient material model is crucial to supporting the material’s widespread adoption across multiple industries.

With the ultimate goal of developing a macroscale homogenised model to predict how the material deforms and eventually fails under loading, this work proposes a candidate for a phenomenologically based orthotropic viscoelastic damage model.

Previous experimental results [2] indicate that this class of 3D fibre-reinforced composites exhibits linear material behaviour when loaded along one of the three nominal fibre directions. Shear loading however, produces a prominent non-linear response. This is likely due to the viscoelastic behaviour and damage of the polymer. In order to capture both the aforementioned linear and non-linear behaviours, a model inspired by crystal plasticity with viscoelastic slip planes is proposed. Specifically, a Norton type viscoelasticity model driven by shear tractions in preferred material planes is adopted. These planes are determined by the three reinforcement directions. As such, viscoelastic strain strictly develops when there is pronounced shear loading in these planes.

To enable the model to account for material degradation and failure, the components of the stiffness tensor are assumed to degrade in accordance with pertinent damage modes. For this purpose models for unidirectional laminated composites such as [3] (extended to 3 reinforcement directions,) as well as those for 3D fibre-reinforced composites [4], have been explored. The applicability of the proposed model is assessed against results from mechanical experiments carried out under tensile, compressive and shear loading.

References

This work presents in-situ X-ray micro computed tomography (µCT) data for a modern composite made of basalt fibres and epoxy resin. We focus on the detection and visualization of microcrack initiation and employ Digital Volume Correlation (DVC) to compute full 3D strain fields from tomography data. The basalt fibre composite investigated here is ideal for this purpose, as it provides excellent image contrast between fibres and matrix (Figure 1). In combination with a µCT-system, a resolutions with voxel size of 1.6 µm was achieved, which is well below the fibre diameter of 7–15 µm.

In-situ experiments are carried out by loading a symmetrical quasi-isotropic [0/±45/90]s laminate, in successive stages to 75% of its ultimate failure strength (UTS). Starting at 50% UTS, damage within 90° layers could be first identified. At 75% UTS, larger cracks with gap sizes on the order of 3 µm could be clearly observed. Our results show that DVC is a viable method applicable to study damage initiation and propagation in basalt fibre reinforced epoxy polymers. While most of our current understanding of failure mechanisms in composites is obtained from post-mortem analysis in the unloaded state, we suggest to validate these models using direct observation of the relevant mechanisms using non-destructive imaging techniques. Because this approach generates vast amount of data, an automated identification of e.g. microcracks is needed. We suggest that this can be solved with the application of DVC.

Figure 1. Basalt fibres offer excellent contrast for X-ray tomography (left). Digital Volume Correlation allows for the automated identification of evolving microcracks, shown in red in the right image.
Bio-inspired Bouligand architectures (Figure 1a) have been investigated in the past years to design impact damage-tolerant CFRPs structures [1]. Recently, a more complex Bouligand-based arrangement, called Herringbone [2] has attracted attention as being potentially able to further enhance the impact damage tolerance of CFRPs. In this work, we developed detailed analytical and FE-models of thin-ply CFRP Bouligand structures which have allowed us to obtain a sound understanding of Bouligand architectures, still missing in the literature, and to design impact-resistant CFRP structures. This allowed us to design thin-ply CFRP Bouligand structures with microstructures akin those of biological Bouligand materials, which we then manufactured and tested under low velocity impact and quasi static indentation. We found that we successfully mimicked the failure mechanisms of biological Bouligand structures by diffusing sub-critical helicoidal damage (Figure 1b), reducing fibre breaks and delaminations. We used the understanding acquired on Bouligand CFRP structures to design, manufacture and test, for the first time in the literature, Herringbone/Bouligand structures with thin-ply CFRPs.

Figure 1. (a) Schematic of a Bouligand structure, i.e. a helicoidal arrangement of fibrous UD layers and (b) 3D C-scan image of an impacted thin-ply CFRP Bouligand laminate.

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References

WAVE ATTENUATION CHARACTERISTICS IN A PARTICULATE FILLED NANOFIBROUS POLYIMIDE AEROGEL COMPOSITES

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Aerogel composites are being developed for space application with the improvement of mechanical properties of aerogels. Aerogel is a functional material as a good thermal insulator or sound absorber, with low density, large inner surface and low thermal conductivity. In the study, the composites were constructed from nanofibrous polyimide aerogel with the dispersed inclusion of particulate fumed silica or hollow glass microspheres. Both experiments and finite element modelling are used to investigate the effects of inclusions on the macroscopic behavior of aerogel composites on wave propagation. Finite element analysis was conducted to examine the effect of particle size, volume fraction and distribution for the composites subjected to the wave frequency in the range of 1 to 10000Hz, which provides the clear guidance to optimize the macroscopic behavior of aerogel composites. The experiments were conducted by standing wave tube in the frequency range of 500Hz to 6000Hz. Both experiments and numerical studies demonstrated the wave attenuation characteristics of particulate filled aerogel composite improved in the band of higher frequency. This new type of composites lead to improved mechanical response and provide new possibilities for wave attenuation applications in outer-space.

References

3D PRINTING OF HIGH-PERFORMANCE CONTINUOUS FIBER REINFORCED POLYMERS

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Currently, there is an increasing demand of high performance fiber reinforced composite materials for structural applications in key industry sectors (e.g., aerospace). The common feature of these applications is the lightweight design strategy, which triggers high performances of the composite part and increased design flexibility compared to traditional isotropic materials. In the same time Additive Manufacturing [1] (AM, commonly referred to as 3D Printing) has emerged as a relatively new and booming concept, a method of extreme interest for further development and innovation, due to its potential to manufacture parts with less needed infrastructure, which means less associated costs; without the need of complex and expensive tooling, preforms, or resin infusion machines; in a more flexible manner, being able to rapidly apply changes in the design, or to economically produce small batches of parts, meeting thus the needs of a more and more dynamic market; in a compact and predominantly automated and computer controlled environment for both design and manufacturing; offering the possibility to produce complex assemblies with fewer parts and fewer joining elements; resulting in almost zero manufacturing waste.

On this background, the research reported here aims to deliver an innovative solution to the specific challenge of 3D printing high performance continuous fiber reinforced polymers (CFRP) for lightweight composite applications under severe loading conditions. To prove a new paradigm in CFRP AM based on a thermoset (TS) – thermoplastic (TP) bi-matrix material system; which allows for overcoming the drawbacks and combining the advantages of the separate TS and TP based systems. The research addresses the development of new materials, processes and end-products in terms of the multiple and coupled aspects of multiphase feedstock materials; 3D printing technology for the feedstock materials; performances of the output 3D printed composites.

While the AM itself is a wide field with different specific methods for different classes of materials, our research is focused on the particular fused filament fabrication (FFF) method [2]; which has the ability to reproduce the main features, recovering thus the main advantages, of the traditionally manufactured CFRP multidirectional laminates.

Figure 1. Microstructure of 3D printed continuous fiber reinforced bi-matrix composite.

References

Fatigue I
Materials Characterization and Identification of Degradation Mechanisms in Electrically Conductive Adhesives

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Cell interconnections in crystalline silicon photovoltaic (PV) modules have traditionally been established with metallic solders. In recent embodiments of new PV modules these metallic solders are replace by electrically conductive adhesives (ECA) [1]. ECA’s are composite materials made of electrically conductive particles, mostly silver particles, and a polymer matrix. The change from metallic solders to ECA’s represents a significant material change, but the durability and reliability of such modules continues to be assessed with accelerated test procedures developed for metallic solders. Therefore, an evaluation of the durability of these modules with the current test methods may yield irrelevant results and interpretations which may not represent the long-term performance of these systems. Before new accelerated test standards for ECA modules can be defined, a thorough understanding of the physical mechanisms causing material degradation at the new cell interconnect is required. Therefore, a proper characterization of the materials properties as well as the identification of damage mechanisms occurring inside the ECA or at the interfaces to the adjacent materials is necessary.

In the present work, a framework for the characterization of mechanical and electrical properties of different kinds of ECA’s is established. The viscoelastic properties are determined by Dynamical Mechanical Thermal Analysis at different moisture levels. The effects of aging are considered by preconditioning of the test samples under various environmental conditions. The obtained results are used to define a constitutive model based on the generalized Maxell formulation within the theory of linear viscoelasticity. Next to the mechanical properties, the electrical properties and especially the degradation over time is of major importance in the assessment of ECA performance incorporated in PV modules. Hence, test vehicles are designed to cause mechanical degradation of the cell interconnect subjected to thermal cyclic loading. Mechanical degradation in form of interface delamination is observed by Confocal Scanning Acoustic Microscopy and correlated to the number of applied load cycles. Deterioration of electrical properties is monitored by resistance measurements over the course of thermal cycling testing. The identified material properties as well as the mechanical and electrical damage rates are used within a developed unified constitutive model, capable of accurately predicting ECA degradation as an electrical interconnect material in PV modules.

References

ADVANCES IN THE CHARACTERISATION OF STATIC AND FATIGUE MODE II DELAMINATION BY MEANS OF THE TRANSVERSE CUT TENSION SPECIMEN

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Transverse Cut Tensile (TCT) specimens represent a potentially more effective alternative to End Notched Flexure or End Loaded Split coupons for the characterization of Mode II delamination of fibre reinforced polymer composites under both static and fatigue loading. TCT samples require a simple tensile test in which a central portion of laminae is cut in the direction transverse to the loading. Recently [1], the authors have proposed a modified TCT geometry, where artificial interlaminar delaminations are added by embedding suitable release films across the tips of the central transverse cut. The present work reports on some experimental setups and evaluations showing how the modified TCT test enables a number of advantages when supported by specific experimental stress analysis tools.

In particular, a full field non-contact Thermoelastic Stress Analysis (TSA) has been implemented to monitor the thermoelastic signal on test coupons. Under quasi-static loading, the thermographic and thermoelastic signals acquired on the thickness edge of the sample allow the correct identification of the onset of delamination, thus improving the evaluation of the critical energy release rate $G_{IIC}$. Under fatigue loading, the thermoelastic signal, acquired from both edge and front sample faces, allows the quick and effective evaluation of the delamination front shape and growth, providing a mean for measuring delaminations growth rates that can be exploited in data reduction schemes for the determination of Paris-like fatigue laws.

Another improvement in the adoption of the TCT sample under fatigue loading is presented, consisting in monitoring the delamination growth by means of suitable extensometers. In particular, a strain formulation of $G_{II}$ is used and tests are performed under strain control, using extensometers whose gauge lengths comprise the delaminated zone. When fatigue is carried out under strain control, exploiting the signal from the same extensometer, $G_{II}$ is progressively reduced by the delaminations growth, due to a concurrent increase of the sample compliance. This evolving scenario will eventually bring to a natural crack arrest. When this occurs, the corresponding energy release rate will provide the fatigue threshold $G_{IIth}$ of the material. One advantage of the presented methodology is the possibility to characterize both the fatigue threshold and Paris-law coefficients with a reduced number of samples and a significantly reduced testing time.

References

Damage evolution in unidirectional (UD) carbon/epoxy composites under tension-tension fatigue load in fiber direction is modeled taking into account the Weibull-type probability distribution of fiber failures. A coupled stress and energy criterion [1] is used to show that co-planar failure of a fiber close to a broken fiber is energetically more favorable than debonding between the broken fiber and the matrix around the fiber break, but that both are possible at stresses significantly below the failure stress of the composite. Stress concentrations in fibers adjacent to isolated broken fibers are calculated by finite element simulations as a function of the distance between the fibers and of the debond length (Figure 1, left). Their influence on the failure probability of the adjacent fibers is evaluated taking into account the local stress profile. This probability increases as the debonds grow (Figure 1, right), which is the case during fatigue loading [2]. The model predicts several phenomena recently observed by high-speed X-ray tomography in UD composite plies aligned with the loading direction [3], such as (i) the absence of large clusters of coplanar fiber breaks until just before final failure, (ii) these clusters appear by simultaneous breaking of every fiber in th

![Figure 1. Left: stress profile in fibers adjacent to a broken and debonded fiber. Right: resulting failure probability for different debond lengths.](image)

**References**


Experiments on vibration fatigue of thermoplastic components

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Carbon fibre reinforced plastics are nowadays often used in several fields, not much is yet known about the fatigue behaviour. Thermoplastic composites are significantly more sensitive to crack growth under vibration loading compared to metals and ceramics [1]. The fracture toughness is, however, better than that of thermosets [1]. This paper covers vibration loading on thermoplastic matrices using a high cycle frequency by vibration testing method. The specimens are made of a 16-layered polyphenylene sulphide (PPS) laminate reinforced by unidirectional carbon fibres, and a cut-ply was introduced as stress raiser. The cut-ply was located ten millimetres from the midspan and placed in the third upmost layer. The objective of the experiments is to measure the crack growth developed at the cut-ply by monitoring several dynamic parameters. For doing that, a special setup was arranged to conduct the vibration testing by sine dwelling (see Figure 1a), in which a laser vibrometer measured the vibration response. Three-point bending tests were also carried out before and after the fatigue test to measure the static stiffness; the dynamic one was also measured before and after any endurance. One of the novelties, presented in this paper, is the harmonic analysis of the vibration response while the fatigue was initiated and progressed. Figure 1b, present the typical frequency trace measurable by sine dwelling, whereas in Figure 1c a trace of a super-harmonic frequency of that is showed for two samples. Figure 1d shows the extended delamination caused by one fatigue test. The three-point bend tests, after HCF trial, showed that the overall static stiffness of all specimens reduced. Two specimens showed a stiffness reduction of more than 25 percent.

References

ENVIRONMENTAL DEGRADATION OF GLASS FIBRE REINFORCED POLYMERS - IDENTIFYING DOMINANT ASPECTS

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A basic understanding of how and to what extent moisture affects the durability of fibre reinforced polymers (FRP) is essential, as both the diversity of constituents and the use in marine and offshore applications is increasing. In order to identify and understand the most decisive aspects, as illustrated in Figure 1, and to determine general correlations, a large number of static and cyclic investigations were carried out. For this purpose, various material combinations of FRP were subjected to several conditioning environments and subsequently mechanically tested. In particular, it turned out that the fibre-matrix interphase has the largest influence on most properties under consideration of static as well as fatigue loads. For example, it could be shown that the choice of a matrix resin determines the transverse tension and interphase properties at dry conditions, but its resistivity against moisture degradation is mainly dominated by the network formed with the fibre sizing. Furthermore, testing at several points in time revealed that the fatigue properties of a composite, that has been shown to degrade strongly due to immersion in 50 °C artificial salt water, only decrease noticeably with high water content. For the development of a prediction model to describe a composites marine performance, it is therefore not possible to simply deduce the fatigue properties from the static properties. Rather, an understanding of the influence on the respective damage mechanisms is required in order to improve the selection and design of materials. Additionally, it is important to consider the impact of the conditioning temperature, as many materials show excessive reductions of their performance, especially under hot-wet conditions.

Figure 1. Schematic model representation of the main effects of moisture on the constituents of fibre reinforced polymers.
Fatigue II
FATIGUE DAMAGE MODELLING AND RESIDUAL STRENGTH OF NOTCHED CARBON/EPOXY LAMINATES

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The presence of fatigue damage significantly affects the global stiffness and the ultimate strength of a notched composite. The experimental observations have revealed that different damage mechanisms occur. While the static strength is controlled by the translaminar cohesive law with fibre fracture, the fatigue strength is controlled by the progressive failure of the matrix and by delamination. These forms of damage alleviate the stress concentration at the notch and thus suppress fibre fracture. As a consequence, the overall mechanical properties are significantly degraded but the post-fatigue residual strength can be larger than the pristine one. This work presents a new computational damage model to simulate fatigue damage and residual strength. The model is based on an extension of the meso-scale continuum damage model developed by Maimí et al. [1, 2], but it is also coupled with the cohesive zone model by Turon et al. [3]. Both models are controlled by a cycle jump strategy implemented inside an explicit finite element code. The model capability is tested by simulating open-hole and double-edge notched specimens.

Figure 1. Damage mechanisms in a quasi-isotropic carbon/epoxy open-hole specimen subjected to static, tension-tension fatigue and post-fatigue residual strength.

References


Experiments on damage growth in CRFP laminates by using vibration testing

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This paper presents an attempt to grow a crack in delamination by vibration testing. A sample was designed by using prepreg HexPly M21 and with the following stacking sequence [90,0cut,90cut,0,90,90,0,90,0,90]. The objective was to open a transverse crack very quickly and have the crack becoming interlaminar. The specimen was vibrated at its first bending mode with the cut-ply offset from the clamping region of about 10mm. The vibration testing was performed according to methodology developed in [1]. The specimen is excited at fixed vibration amplitude and excitation frequency. The response phase is tracked for the duration of 1.5M cycles. The excitation frequency was readjusted to resonance when a criterion was met. The crack becomes interlaminar as expected (see Figure 1a). The response phase trace, made of several segments, shows the rate of crack opening (see Figure 1b). By collecting the slopes of from the response phase a rate of crack growth can be traced.

![Figure 1](image1.png)

Figure 1. A micrograph with crack size in (a), the response phase in the red box in (b) and the slopes measured from the response phase in (c)

References

PARAMETER IDENTIFICATION FOR FATIGUE DAMAGE MODEL THROUGH ENHANCED TEST METHODS

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The classical approach for predicting failure in composite structures is to determine ply level properties by testing of uni-directional test coupons and assessing ply stresses computed from lamination theory by stress based failure criteria. This approach implies the assumptions that (1) the coupon correctly represents the load response of a single ply and (2) a ply embedded in a laminate behaves in the same way as the single ply. The second assumption has already been proven incorrect due to the "in-situ effect" of embedded plies and the possibility of load transfer to neighboring plies. Furthermore, uni-directional coupons are often not representative of typical plies within a laminate due to production effects.

A more realistic approach would be to determine ply properties based on laminate tests which include the embedding effect on ply behavior. The problem with measuring the response of an embedded ply by standard test methods is that, on the one hand, failure of an embedded ply is usually difficult to detect and, on the other hand, that ply stresses leading to failure cannot be measured directly in experiments. Instead, ply stresses at failure can only be back computed from overall strains (measured at the specimen's surface), however, the result then depends on the constitutive law assumed (i.e. elastic, plastic, or damage material models and anisotropy of evolution laws).

In the current work, a method to determine parameters for a composite fatigue model from laminate tests (i.e. to determine the response of an embedded ply) is presented. The method is based on an enhanced testing procedure employing tension tests with regular coupon specimens of various laminate lay-ups which are tested applying a special loading procedure and instrumentation (optical crack detection, thermo-camera, digital image correlation) [1]. A physically based constitutive model, able to capture plasticity and matrix cracking mechanisms qualitatively, is employed in Finite Element models of the test setup. The model parameters controlling the evolution of damage and plasticity are calibrated through optimization procedures minimizing the difference between numerical and experimental results.

References

In the last decades, a huge effort was made to investigate the fatigue damage behavior of composite structures. The characteristic of fatigue damage mechanism depends strongly on the applied mean stress - in particular on the number of load reversals - and the stress amplitude [1]. In order to reliably analyze composite structures under realistic cyclic loading scenarios, it is essential to consider the influence of reversed cyclic loading on its damage evolution.

In [2], the damage initiation and propagation in cross-ply laminates under quasi-static and fatigue loading at different stress ratios with respect to the influence of load reversals were experimentally investigated. Based on that, the recently developed layer-based fatigue damage model (FDM) [3], was extended and calibrated for CFRP composites for homogenous stress states [4].

In this contribution, the fatigue damage behavior of CFRP composites is investigated under complex stress states. Firstly, three-point bending tests are performed on coupon specimens at different stress ratios. The specimens are clamped at both ends in order to generate complex stress states. The fatigue damage evolution is investigated in particular with respect to the influence of load reversals. Secondly, detailed 3D finite element simulations of the bending tests are performed employing the FDM. The layer-wise degradation of the strength and stiffness properties, depending on the failure mode, as well as the evolution of the deflection, is calculated at different stress ratios. Finally, the capability of the FDM for predicting the fatigue damage behavior under complex stress states is critically discussed and assessed.

References

PREDICTION OF THE CRACK DENSITY EVOLUTION AND THE STIFFNESS LOSS IN COMPOSITE LAMINATES UNDER CYCLIC LOADINGS

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In this work, a damage-based procedure for predicting the crack density evolution and the consequent stiffness degradation in composite laminates under multiaxial cyclic loadings is described. This procedure combines the crack density prediction model and the stress redistribution model presented by the authors in Ref. [1] and [2], respectively. In particular, the initiation of multiple cracks in the plies of a laminate is predicted by means of crack initiation S-N curves expressed in terms of effective stresses (to account for multiaxial conditions), considering also the stochastic nature of the phenomenon. In fact, each ply is divided into a number of statistical elements, each of them having its own resistance to crack initiation according to a given probability distribution. The crack propagation is predicted through Paris-like curves expressed in terms of effective Energy Release Rates (ERRs) to account for the presence of mode I and II contributions. The interaction between cracks in the same ply and in different plies, determining the stress distributions and the ERR values, is treated through an optimal shear lag model [2]. The same model is then used to predict the stiffness degradation, on the basis of the predicted crack density. The procedure is validated through a large bulk of experimental data from the literature on different materials and lay-ups, also under variable amplitude block loadings. An example for cross-ply laminates is shown in Figure 1.

![Figure 1. a) Crack density and b) the stiffness loss in [0/90]s glass/epoxy laminates](image)

References


Numerical Techniques
AN ANISOTROPIC COHESIVE PHASE-FIELD MODEL FOR INTRA-LAMINAR DAMAGE IN FABRIC REINFORCED COMPOSITES

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Thin fabric-reinforced composites are widely utilized in the aerospace industry due to their ability to provide higher strengths with reduced laminate weights. Damage modeling of such laminates is a challenging task because of their quasi-brittle fracture behavior. This involves fibre breakage which results in a sudden loss of strength with minimum crack openings and subsequent fibre pull-out which results in a further, although gradual, strength loss. To effectively model such damage behavior, it is necessary to account for the cohesive forces evolving within the fracture process zone. Furthermore, the interaction of the failure mechanisms pertinent to both the fibres and the matrix necessitate the definition of anisotropic damage models.

The phase-field method has provided a robust alternative to conventional damage modeling approaches and has proven its capability in modeling complex crack patterns without needing any predefined crack initiation location or crack-paths. However, most of its applications relate to the simulation of brittle fractures, which are manifested by a sudden drop in strength as soon as the damage initiates. In the present work, a cohesive phase-field model is proposed for simulating intra-laminar fracture in fabric-reinforced composite laminates. The anisotropic characteristics of different composite damage modes are captured by defining an appropriate structural tensor. Furthermore, a 2-parameter quasi-quadratic degradation function is implemented to calibrate experimental strain softening curves, which can be used for accurate damage predictions in fabric composites. The implementation is done using Abaqus subroutines with conventional S4 shell elements, and the accuracy of proposed damage model is validated against experimental results.

References

AN ADAPTIVE MULTI-MODEL APPROACH FOR DAMAGE PROGRESS SIMULATIONS IN COMPOSITE STRUCTURES

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The growing industrial interest for predictive virtual testing makes the development of advanced numerical tools essential to achieve confident and realistic complex numerical simulations. For instance, one may wonder to what extent an initial defect affects the global behavior of a slender composite structure under compressive quasi-static loading. The resolution of this problem requires expertises in both numerical approaches and material constitutive behaviors while several non-linearities sources are arisen such as large deformation and material on-going degradation.

Responding to those problematics, this work presents an adaptive multi-model method. Like other multiscale approaches ([1],[2]), our technique attempts (i) to put in each location of the structure just the right amount of complexity in terms of discretization and material behavior, (ii) be non intrusive for the FE code in order to be used easily in industrial design offices. In this respect, the structure is divided in parts with two different models separated by a boundary that is allowed to evolve during the simulation in order to gain in overall computation time. The parts that concentrate non-linearities are modeled using a complex non-linear damage constitutive law and a multi-layered solid mesh. An advanced mesoscale model [3] is chosen in order to take into account several material non-linearities and to correctly predict a laminate’s degradation processes. The remaining part of the structure has a simpler elastic behavior and a coarser shell mesh. The local area, which is at first concentrated around the defective zone, evolves according to the progression of damage during the simulation process.

Such an approach induces dealing with coupling conditions between the two zones, model adaptation criterion, remeshing process and field transfer aspects which will be detailed related to our implementation within a commercial finite element solver. Numerical assessments will be presented in the context of composite structures to demonstrate the efficiency of this strategy.

References

EXPERIMENTAL INVESTIGATION AND NUMERICAL SIMULATION OF HYGROTHERMAL AGING IN FIBER-REINFORCED COMPOSITES

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Predicting mechanical degradation of fiber-reinforced composites caused by hygrothermal aging (exposure to high temperatures and moisture ingression) is a challenging task for which no comprehensive solution is currently available. Physical and chemical phenomena (e.g. plasticization, hydrolysis, interface debonding) acting at the microscopic length scale and at different time scales with different degrees of reversibility interact nonlinearly and lead to complex macroscopic degradation behavior. Therefore, realistic prediction of composite material durability requires microscopic mechanical tests and observation techniques as well as high-fidelity multiscale and multiphysics numerical models.

This work investigates the phenomenon of hygrothermal aging in unidirectional composites through a combination of micro- and macroscopic experiments and multiscale numerical modeling.Composite samples are immersed in hot water for different durations and tested both directly after aging as well as after being redried. The effects of aging on the fiber-matrix interface adhesion are investigated through single-fiber fragmentation tests in dry and saturated specimens and interfacial properties are obtained through reverse modeling. The aging mechanisms responsible for degradation are investigated through a fractographic study on aged specimens using X-ray 3D computed tomography.

Describing the resultant time- and moisture-dependent behavior with an all-encompassing phenomenological macroscopic constitutive model is a difficult task. This renders bottom-up homogenization strategies (numerical homogenization) inadequate for the problem at hand. Aging is therefore simulated with computational homogenization (FE\textsuperscript{2}), which offers an alternative approach by promoting a continuous link between scales, precluding the need for macroscopic constitutive assumptions. This multiscale stress model is coupled with a macroscopic diffusion analysis that computes the evolution of the water concentration field. A viscoelastic/viscoplastic/damage model is used to describe the resin at the microscale and cohesive-zone elements with friction are employed at the fiber-matrix interfaces. To reduce the exceedingly high computational cost of the FE\textsuperscript{2} approach, the micromodels are accelerated by a combination of two model-order reduction techniques. The resultant predictions are compared with experimental results.
MODELING OF THICK COMPOSITE STRUCTURES WITH AN EIGHT-NODE CURVED SHELL ELEMENT BY USING THE REFINED ZIGZAG THEORY

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The refined zigzag theory (RZT) developed by Tessler et al. [1] is demonstrated as a revolutionary layerwise plate theory to predict very accurate displacements, strains, and stress results when modeling thin, moderately thick, and thick regimes of laminated composite and sandwich structures. In this study, we propose an eight-node curved shell element (i.e., degenerated solid-like shell element) based on the kinematic relations of RZT. As shown in Figure 1, this new element is labeled as RZT-CS8, has seven degrees-of-freedom per each node, and is mainly attributed to perform structural analysis of curved composite structures having highly anisotropic laminae stacking sequences. The kinematic variables of the RZT-CS8 element are approximated using Lagrangian quadratic serendipity shape functions. The RZT-CS8 element enables one to model complex composite geometries with a relatively low number of elements and also to obtain the highly precise distribution of interlaminar-shear and/or axial strains and stresses through the thickness coordinate. Various numerical analyses including cylindrical and doubly-curved composite laminates subject to complex boundary conditions are performed to present the applicability and potential efficiency of the RZT-CS8 element. Finally, the comparisons with analytic/numerical solutions reveal the high predictive capabilities of the RZT-CS8 element such that confirming its viable advantages for curved laminated composite and sandwich structures.

Figure 1. Eight-node curved shell element (RZT-CS8)

References
Microscale I
A NEW TESTING SYSTEM TO DETERMINE THE FIBRE-MATRIX ADHESION STRENGTH BY MEANS OF PULL-OUT TESTS

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Textechno, Germany, the well-known producer of testing instruments for man-made fibers and yarns, has a focus on the development of instruments for the characterization of the physical properties of reinforcement fibers, rovings and the fiber-matrix adhesion. In this article we discuss in detail the measurement of the fiber-matrix adhesion strength by means of a new testing system which has been developed together with two research institutes, the Leibniz-Institut für Polymerforschung (IPF) in Dresden and the Faserinstitut Bremen (FIBRE). The system determines the adhesion between fiber and matrix in terms of the local interfacial shear strength, the interfacial toughness and further parameters through a reproducible single-fibre pull-out test. It is suited for all kinds of fibers as well as all kind of thermoset and thermoplastic matrices with curing and melting temperatures up to 400°C [1, 2]

Figure 1. The FIMATEST System, consisting of the FIMBOND for preparation of the single-fibre composite and FAVIMAT+ for performing the pull-out test.

References


A NUMERICAL FRAMEWORK TO ANALYZE FRACTURE IN COMPOSITE MATERIALS: FROM SIMULATED CRACK RESISTANCE CURVES TO HOMOGENIZED SOFTENING LAWS

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A numerical framework to obtain the crack resistance curve (R-curve) and its corresponding softening law for fracture analysis in composite materials under small scale bridging is presented [1]. The use case addresses the intralaminar transverse tensile fracture of a unidirectional ply of carbon fiber-reinforced polymer AS4/8552. The R-curve is computed for this material using a micromechanical embedded model corresponding to the intralaminar transverse tensile fracture toughness characteristic. The model combines an embedded cell approach with the Linear Elastic Fracture Mechanics (LEFM) displacement field to analyze the local crack growth problem including fiber/matrix interface debonding and bridging of matrix ligaments as the main energy dissipation mechanisms.

Due to the complexity of the problem, the methodology is illustrated to study the bidimensional propagation of a crack in a fiber reinforced unidirectional ply, including the fiber/matrix interface debonding and the ductile tearing of the matrix ligaments between fibers as energy dissipation mechanisms. This crack propagation problem is also known as the intralaminar crack propagation under transverse tension, characterized by the fracture toughness $G_{2+}$. The bidimensional formulation of the problem impedes the inclusion of higher length scale toughening mechanisms, as for instance, fiber bridging due to the lack of parallelism between fibers, so the material toughness and R-curve behavior obtained should be understood as lower bounds or initiation values rather than propagation over a finite crack length of some millimeters.

Parametric analyses were carried out to assess the influence of the properties of the material constituents on the R-curve behavior and on the corresponding homogenized cohesive laws. Homogenized softening laws for the crack propagation problem in a unidirectional ply are presented for a wide range of micromechanical parameters including constituent properties as the fiber/matrix interface and matrix plastic/damage behavior.

References

LONGITUDINAL TENSILE FAILURE MECHANISM IN UNIDIRECTIONAL FRP COMPOSITES BY MEANS OF COMPUTATIONAL MICROMECHANICS

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In this work, a high fidelity three-dimensional finite element modelling approach for unidirectional (UD) composites was developed to predict the phenomena associated with longitudinal tensile deformation and failure in detail. The approach is based on a periodic Representative Volume Element (RVE) on a micromechanical scale, with a random distribution of fibres, to capture the progressive damage and interaction between the fibres and the matrix. The carbon/fibre material AS4/8552 was chosen for the purpose of demonstration of the methodology [1, 2].

Besides the detailed simulation of longitudinal fracture mechanisms and their interaction, it will be demonstrated that this modelling approach allows the study of important effects on longitudinal failure, such as dynamic loading, residual thermal stresses and matrix plasticity. Moreover, it allows the determination of important parameters to the development of lower-fidelity but more time-efficient analysis tools, such as the Stress Concentration Factor (SCF) caused by the failure of single fibres, which has significant effect on the failure probability of adjacent fibres, and the critical fibre cluster. Regarding this topic, a study is done about the influence of interface debonding on the SCF. For this purpose, the interfaces between the matrix and the fibres were modelled using cohesive surfaces in order to correctly simulate the separation that occurs when a fibre breaks. This investigation revealed two important results: First, two kinds of debonding are formed based on the type of formation: 1) total debonding that form at broken fibers and encompass all the broken fiber external surface, 2) partial debonding formed at neighbouring intact fibers and encompass just some part of the intact fiber that is adjacent to broken fiber. Second, the interface debonding has a significant negative impact on the SCF. That means, with increasing interface debonding the SCF reduces and vice versa.

References:


MICROMECHANICAL MODELLING OF COMPOSITE PLY INCORPORATING A STRAIN RATE DEPENDENT CONSTITUTIVE MODEL INFORMED BY A NOVEL MICROMECHANICAL TESTING TECHNIQUE

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Design of fibre-reinforced polymer composite structures has been traditionally based on a global-to-local approach. Critical areas are identified in simulations of the entire structure and then analysed in detail using phenomenological models calibrated with costly experimental campaigns. Opposite to the former, a new strategy has been proposed, the so-called multiscale modelling or bottom-up approach. Properties of the entity at one length scale are computed and passed to the next length scale through homogenization into a constitutive model. At the first scale, the ply level, properties are estimated by computational micromechanics based on FE modelling of a Representative Volume Element (RVE) of the microstructure. A failure envelope is obtained as an output. In these models, matrix and interface properties are determined by in-situ micromechanical testing. These techniques are based on instrumented nanoindentation.

The extension of micromechanical modelling to high strain rate applications requires then extending the in-situ micromechanical testing techniques to high strain rates of testing. In the present work, a novel micromechanical testing technique for in-situ high strain rate characterization of the composite matrix is proposed. It is based on impact nanoindentation. It uses a nanoindentation device with the in-built capability of performing energy-controlled impacts. This allows pushing the testing window to the ~10^3 s^-1 range. The technique presents two main challenges: (1) the strain rate of testing cannot be kept constant; and (2) the significant instrument dynamic contribution leads to an applied load in the material much higher than the actuated force. In this work, the determination of the real applied force has been accomplished by instrumenting the impact nanoindentation system with dynamic force-sensing capability. This enables the entire load-displacement curve to be obtained at high strain rates. In parallel, an inverse analysis strategy has been devised in the framework of finite element modelling for the extraction of the rate dependent constitutive behaviour of the polymer matrix. The indentation process is modelled using a two-dimensional domain with radial symmetry. Simulations of constant-strain-rate nanoindentation are performed over a wide range of strain rates from 10^-3 to 10^3 s^-1 using the Abaqus Implicit solver. Simulations of impact nanoindentation are performed at several impact velocities and using an instrument dynamics representative of the real set-up. The Abaqus Explicit solver is used in this case.

The experimentally calibrated rate dependent constitutive model of the resin matrix is incorporated in a RVE model of the composite ply microstructure. From this, the objective is to determine a rate dependent failure envelope of the composite material that has been informed by the in-situ testing techniques.
Characterization of fiber/matrix interface cracks (debonds) has mainly focused on the evaluation of the Energy Release Rate (ERR). However, the attention has been mostly devoted to the study of a single partially debonded fiber placed in an effectively infinite medium and to the effect of a small number of nearby fibers on debond ERR [1]. In this work, the Mode I and Mode II ERRs are evaluated for debonds appearing in Representative Volume Elements (RVEs) of regular microstructures of UD (Fig. 1) and cross-ply laminates. By adopting a 2-parameters energy-based criterion for propagation [2], we then proceed to the estimation of the expected average debond size in different microstructural arrangements (see Fig. 1). Finally, the results are compared with available microscopic observations [3].

Figure 1. Estimation of debond size by comparing the total ERR to the 2-parameters expression of critical \( G_c \). Glass fiber/epoxy, \( V_f = 60\% \), \( \varepsilon_x = 1\% \).

References

INFLUENCE OF TRANSVERSE CRACKING ON STRENGTH AND FIBRE BREAK DEVELOPMENT IN CROSS-PLY LAMINATES

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The first major damage observed in cross-ply laminates under tension is usually matrix cracking in the plies with fibres oriented transverse to the load direction, also called transverse cracking. These transverse cracks themselves are often not critical for cross-ply laminate failure, but they interact with the fibre break development and hence may trigger earlier failure in the 0° plies. This interaction occurs due to the presence of strain gradients in longitudinal plies induced from transverse cracks in the transverse plies. Preferential localisation of fibre breaks near transverse crack tips was indeed observed with computed tomography [1]. One would also expect the strength to be affected, but experimental evidence of strength dependency on transverse cracking is inconclusive [2].

The fibre break model developed by Swolfs et al. [3] was extended to model unidirectional fibre bundles under non-uniform strain fields. To model cross-ply laminates, an additional layer of longitudinal elements with homogenised properties acting as a transverse ply was introduced. Transverse cracking process is represented by the elements failing, meaning cracks appearance, when their stress exceeds their strength assigned according to the Weibull distribution. The presence of transverse cracks changes strain fields in cross-ply laminates, and this is taken into account by strain factor fields for transverse and longitudinal plies. To calculate them, separate finite element models were employed, consisting of a cross-ply laminate with one or two transverse cracks in the transverse ply. After obtaining strain fields, strain factors for any location within the model are calculated as local longitudinal tensile strain divided by nominal. Implementation of these factors in the strength model is done by combining them according to transverse cracks spacing in the model.

The results show that there is an increase in the fibre break density near transverse crack tips compared to the areas farther away. Furthermore, the strength of the longitudinal ply decreases by about 6% for [0₁,90₁], and 10% for [0₁,90₂], carbon/epoxy cross-ply laminates. Both of these effects are shown to be sensitive to the transverse ply thickness. This study sheds light on how tensile failure development is affected by damage development in off-axis plies, and how these interactions reduce the composite performance.

The research leading to these results has been performed within the framework of the FiBreMoD project and has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 722626. YS and SVL acknowledge FWO Flanders and the Toray Chair, respectively.

References
Microscale II
Effect of viscoplasticity of the epoxy matrix on long-term stress redistribution around fibre breaks in a composite subjected to high static tensile load

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The wide-spread opinion persists that epoxy matrices behave in a purely brittle manner. Their plastic behaviour is commonly neglected for modelling of composites. Recent results \cite{Morelle2017}, however, show the highly strain-dependent plastic behaviour of epoxy and suggest that their creep behaviour is important for the time-dependent failure of composites. The creep strain development was therefore characterized for a commercial epoxy resin system (North Thin Ply Technology 736LT).

These measurements were then plugged into a micro-mechanical finite element model. This model represented a standard composite microstructure consisting of T700 carbon fibres at a 50\% volume fraction and was used to assess the time-dependent effect of stress redistribution around a fibre break. As the shear stresses in the matrix went down over time, the stress transfer region spreads out in fibre direction, which effectively lowers the stress concentration in the break plane but increases the effective overload in the longitudinal direction.

The results of the modelled representative volume element can be translated into a time-dependent local load sharing approximation, which is used as input data for the fibre break model from Swolfs et al. \cite{Swolfs2015}. The advanced fibre break model is able to determine the strength degradation over time of a unidirectional composite bundle exposed to high static tensile load. By studying the development of the degradation paired with the respective probability for a certain path, better lifetime predictions for continuously loaded components can be made.

Modelling predictions are intended to be verified with the help of Synchrotron Computed Tomography at the submicron scale by holding a specimen at a constant displacement. The analysis of the scan data is still ongoing.

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Decohesion is an important failure mechanism in complex 3D woven composites. It includes both debonding between reinforcing yarns and matrix, and debonding/sliding between contacting yarns in complex woven architectures. Recent work proposed an automated methodology to generate a smoothed RVE geometry without yarns interpenetration based on implicit geometries described by distance fields [1]. In its current implementation, this methodology requires the insertion of a small gap between contacting yarns to allow its discretization by finite elements, see Figure 1. However, this leads to large computational sizes with an element size that is governed by the thickness of the introduced gap which needs to be rather small to yield realistic results. Consequently, it is necessary to extend this approach to represent contacting surfaces by cohesive zone elements. This contacting surface is however arduous to find due to the implicit geometry used by the generation method.

This contribution will present a methodology to extract from the distance fields the geometry of the contacting surfaces between yarns that support the cohesive zones. This identified surface can subsequently be used in a conformal meshing methodology for the RVE extended with cohesive zones [2]. The scheme will result in a more realistic geometrical model for finite element based damage simulations.

References

Mechanical properties of DGEBA epoxy resin: Insights from coarse-grained simulations

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Coarse-grained (CG) simulations enable modeling of the polymer resins across a wide range of time and length scales compared with all-atom molecular dynamics (MD) simulations [1]. The principle of CG models is to map a set of atoms to a bead, which extends the accessible time and length scales while partially maintaining the molecular details [2]. The long-term simulations related to the effect of strain rate on the mechanical properties of polymers are made possible thanks to the concept of CG simulations. In this work, a coarse-grained (CG) model of diglycidyl ether of bisphenol A (DGEBA) with anhydride hardener is developed to study the rate-dependent mechanical properties of the epoxy resin system. The CG potentials for the polymer monomers and hardener molecules are calibrated using iterative Boltzmann inversion (IBI) method. Reducing the number of degrees of freedom during the coarse-graining procedure has a significant impact on the accuracy and predictive capability of the models. Considering this issue, the effect of different levels of coarse-graining on the mechanical properties of the epoxy resin is investigated. The applicability of the CG model in predicting the mechanical properties of the epoxy resin is evaluated through verification with MD simulations. The most promising mapping scheme, which allow us to have larger length scale while maintaining the sufficient level of atomistic details, is introduced.

Figure 1. Representation of one DGEBA monomer and three different mapping schemes for a coarse-grained model.

References

RELATIONSHIP BETWEEN PROCESSING PARAMETERS AND MECHANICAL PROPERTIES OF THICK GLASS FIBRE REINFORCED THERMOPLASTIC METHACRYLIC COMPOSITES

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As part of the energy transition, the recycling goals applicable to end-of-life materials are getting more and more demanding. Thanks to a recyclable matrix, continuous fibre reinforced thermoplastic composites have attracted growing interest over the past twenty years for the design of lightweight and high-performance structural parts. To produce such materials, specific monomers are usually vacuum-infused through glass or carbon fibres before undergoing in-situ polymerization. Though most composite parts obtained this way are only a few millimeters thick, certain applications require the manufacturing of much thicker components – up to several centimeters.

In this perspective, the present study focuses on the links between the infusion conditions, the physico-chemical state and the mechanical properties of 7-cm-thick glass fibre reinforced thermoplastic methacrylic composite plates, at both the micro- and macroscopic scales.

More precisely, composite plates are infused at different temperatures, and the evolution of the microstructure along the thickness of each sample is studied. Emphasis is placed on the characterization of porosity distribution and morphology by optical microscopy and X-ray microtomography. Additionally, chromatographic chemical analysis is carried out for the assessment of molecular weight distribution and residual monomer content. The local mechanical response is evaluated by carrying out nano-indentation tests inside the matrix pockets, while in situ transverse compression experiments are performed within a SEM. Thermal analysis as well as a simple thermomechanical method are used to quantify the amplitude of the residual stresses. In parallel, the viscoelastic-viscoplastic response of the bare matrix is determined by combining various macroscopic tests in order to allow micromechanical modelling of representative volume elements.

Current results suggest that, while the in situ micromechanical properties of the methacrylic matrix barely vary with the infusion temperature, it strongly affects the amount and distribution of porosity in the composite part – which, in turn, governs the macroscopic mechanical properties of the final composite part and their variability.
SYNTHETIC MODELLING OF PLA–PINE PULP COMPOSITES BASED ON X–RAY MICROTOMOGRAPHY

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To produce wood plastic composites (WPCs) in construction and automotive fields, wood pulp fibres show the biggest commercial growth, due to their increased reinforcing capability compared to other wood-based fillers like sawdust or wood powder. Unfortunately, a large number of experimental tests is usually required to optimize the material properties of WPCs at different fibre volume fractions. In this context, image-based modelling can help to numerically assess WPC properties by using 2D or 3D microstructural models based on X-ray microtomography (XµCT) images [1]. Furthermore, synthetic models in conjunction with stochastic methods for geometry description can allow the statistical creation of representative volume elements (RVEs) to study the effect of various fibre parameters on the WPC properties.

This work presents a method for synthetic modelling of polylactid acid (PLA) composites reinforced by pine pulp fibres. An algorithm implemented on the Simpleware platform (https://www.synopsys.com/simpleware.html) is used to extract fiber geometry and orientation statistics from the XµCT analysis. This is combined with an algorithm developed on the open source Salome platform (https://www.salome-platform.org/platform) to generate synthetic models based on the statistics identified from the XµCT analysis. Material models including plasticity for both the matrix and the interphase between fibres and matrix are used in finite element (FE) analyses to predict the WPC properties (Young’s moduli and tensile strength). Numerical results are found in agreement with experimental data from tensile tests (Figure 1).

![Figure 1. PLA+10% pine pulp fibres – Left: FE mesh of 800µm × 800µm × 1400µm RVE (matrix in red, fibres in green and interphase in white). RVE based on XµCT taken on the middle web of a dog bone specimen. Right: tensile stress-strain curves.](image-url)

References

Damage and Fracture I
NUMERICAL FAILURE PREDICTION OF FIBER-REINFORCED COMPOSITE AND FIBER METAL LAMINATE T-BOLT JOINTS FOR WIND TURBINE BLADE APPLICATIONS

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To improve the efficiency of wind energy turbines, the industry is striving for large rotor blades in order to increase the energy output per turbine. The increase of the blade length subsequently increases the torque (increased blade weight and wind loads) that needs to be carried by the blade’s root and the so-called T-bolt joints, which usually connect the blade with the turbine’s hub. It is well known from the literature, that fiber-reinforced polymer (FRP) composites provide a relatively low joint efficiency ratio compared to more ductile materials like stainless steel [1]. To increase the joint efficiency for composite T-bolt joints and mechanical composite joints in general, metallic inlays can be used to add ductility to the composite laminate. This technique and its impact on the static and fatigue behavior of mechanical composite joints has been investigated in numerous studies in the field of fiber metal laminate research [2, 3].

In this contribution, a finite element based static damage model for FRP is presented and deployed to predict the onset and evolution of the damage process, as well as the final failure, of regular GFRP and stainless steel/GFRP hybrid laminate T-bolt joints for wind turbine blade root applications. To validate the proposed FRP damage model, corresponding T-bolt bearing tests under static loading are performed. From these tests force and strain measurements, as well as double image correlation (DIC) deformation measurements, are obtained and compared with the numerical results.

In addition to the damage modelling, special emphasis is put on the numerical efficiency of the finite element model itself. The laminate, which is of several centimeter thickness, is modelled using a combination of 3D solid elements and a composite layup strategy. The latter is particularly used to represent the different non-crimped fabrics used within the laminate. This modelling technique provides a reasonable balance between accuracy and efficiency. It is shown that the presented damage model is capable of predicting the onset of damage and its progression until the final failure for mechanical T-bolt joints with sufficient accuracy.

References

AN INVESTIGATION OF DELAMINATION DAMAGE FOR LARGE SCALE STRUCTURES USING ALYA HPC CODE

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The use of cohesive zone models requires refined meshes in order to accurately predict the initiation and propagation of delamination damage. Moreover, depending on the scale of the structure the computational cost may result very expensive for generating the mesh and solving the problem. In this work we have implemented an existing interface element Turon et al. 2018 [1] for the simulation of delamination in an HPC parallel code named Alya. This is a computational mechanics code developed for large scale, massively parallel simulations of coupled multi-physics problems. Moreover, we introduce an extension of the mesh multiplication algorithm from Hozeaux et al. 2013 [2] (pre-process tool) to deal with this kind of elements. The mesh generation and the interface element are validated conducting several numerical tests at coupon and sub-component levels and predictions are compared against experiments.

![Figure 1. (a) Composite stiffened panel. (b) Mesh multiplication for interface elements.](image-url)

References


NEW TAILOR-MADE SIZING STRATEGIES FOR RECYCLED CARBON FIBRES TO IMPROVE THE MECHANICAL PROPERTIES OF POLYMERIC AND CEMENTITIOUS COMPOSITES.

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The performance of any composite material is strongly linked to the adhesion between the host matrix and the reinforcing fibre. Recycled carbon fibres are especially problematic, as they commonly possess less than a quarter of the available surface oxygen compared with virgin fibre [1], leading to reduced adhesion. The CUSTOMISIZE project will improve the interfacial adhesion between recycled carbon fibre (rCF) and polymers (thermoset and thermoplastics) and cementitious matrix to obtain composites with enhanced strength, toughness and environmental stability in comparison with state of the art rCFs.

The proposed strategy is the development of specific sizings for different matrices through the incorporation of coupling agents along the fibres (mats, non-wovens and chopped tow). These coupling agents will act by different mechanisms (covalent bond, hydrogen bond, Van der Waals interactions...) to create active points on the CF surface. New approaches, such as Steam Water Thermolysis (SWT), the use of Polyhedral Oligomeric Silesquioxanes (POSS) or Plasma Treatments (Atmospheric or Vacuum), will be used as a novel sizing base to increase rCF-matrix interfacial adhesion. Current sizing technologies (bath coating or spraying) with specific binders for each matrix will also be explored.

The specific sizing will be developed for non-woven mats and chopped tows of recycled carbon fibres. The improved rCF reinforcements will be used to produce new composites with cementitious and polymeric matrices (PU, epoxy resin, PEKK and PPS). The transformation process of thermoset composites will be achieved through the use of Resin transfer Moulding (RTM). In addition, to validate thermoplastic composites, manufacturing techniques such as compression moulding and injection moulding will be used. A complete characterization of the new composites will be undertaken, in order to ensure an enhanced interface between the filler and the matrix.

The CUSTOMISIZE project aims to bring a second life to carbon fibre that has been condemned to landfill or low-end applications that will span all stakeholders involved in the associated production chain: material suppliers, recycling industries, final part manufacturers, as well as end-users (aircraft industries).

References
SIZE EFFECT AND INTRALAMINAR FRACTURE TOUGHNESS OF FIBRE REINFORCED COMPOSITES

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The most recent analysis methods that predict fracture of polymer composite materials require not only the value of the fracture toughness, but also its relation with the increment of the crack length, i.e., the crack resistance curve. Taking the thickness of the individual ply as the representative length scale it is possible to formulate ‘mesomodels’ that account for both delamination (interlaminar cracking) and ply failure mechanisms (intralaminar cracking). The softening constitutive relation that simulates longitudinal failure, where the fracture plane is approximately perpendicular to the fibre direction, requires the fracture toughness to regularize the numerical solution; however, the crack resistance curve must also be measured to identify the different regions of the softening constitutive relation so that the failure mechanisms acting at the crack tip and along the wake of the crack are properly accounted for. Recently, Finite Fracture Mechanics models that use the laminate thickness as the representative length-scale have been developed to predict fracture of multidirectional composite laminates in the presence of stress concentrations. These methods are typically used for the preliminary design and optimisation of composite structures, and are based on the simultaneous fulfilment of a stress-based criterion, which requires a stress allowable, and of an energy based criterion, which requires the fracture toughness or the crack resistance curve. Based on the above observations, it becomes apparent that reliable test methods for the measurement of the intralaminar fracture toughness of composite laminates and of the corresponding crack resistance curve (R-curve) are required. While a strong emphasis has been placed on the use of compact tension test specimens, recent results have shown that using the current geometry of the compact tension test specimen it is not possible to measure the fracture toughness of modern resin systems that result in high values of the fracture toughness. For example, in previous attempts to measure the fracture toughness of cross-ply Hexcel’s T800/M21 carbon-epoxy laminates using the geometry proposed in the region of the specimen subjected to compressive stresses buckled: such an elastic instability renders the test results meaningless. It has been shown that using the size effect law not only is possible to measure the intralaminar fracture toughness in tension or compression (measuring therefore the R-curve associated with the propagation of a kink band), in shear and under static and dynamic. The objective of this paper is to present a summary of the latest advances on this topic.

References
PREDICTING TRANS-LAMINAR FRACTURE USING VCCT AND IN-SITU CT SCANS

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With the upsurge in use of advanced composites in the aerospace, marine and automotive industries, a comprehensive understanding of their failure mechanisms, especially trans-laminar fracture is important. Previous work on this topic was reviewed in Ref. [1]. More recently, a High-fidelity Finite Element Method (Hi-FEM) has been developed to deduce the R-curve for Mode I trans-laminar fracture based on the previous work [2-5]. The measurement of crack increments $\Delta a$ in trans-laminar fracture tests has proven challenging. There are numerous methods such as optical measurement, Digital Image Correlation (DIC) and deplying, with X-ray Computed Tomography (CT) being an especially powerful tool to examine internal damage states and measure crack growth [4]. However, multiple interrupted tests are required for crack length measurements and dye penetrant is often needed to enhance the CT scan images which may induce a negative effect on test results.

The current research aims to develop an in-situ CT scanning method to characterise Mode I trans-laminar fracture properties such as R-curves in a single continuous test. The R-curve measured using in-situ CT scans is applied with the Virtual Crack Closure Technique (VCCT) for the failure prediction of another notch configuration. A test panel was manufactured at JAXA through Vacuum assisted Resin Transfer Moulding (VaRTM). The material used was biaxial carbon Non-Crimp Fabric (NCF) with a stacking sequence of $[(45/-45)/(0/90)]_2s$. The geometry is in accordance with the ASTM E1922 standard. The in-situ CT scans are conducted in JAXA. A customized in-situ test rig has been developed as shown in Figure 1.

Figure 1. In-situ CT scanner in JAXA.

References
Damage and Fracture II
MULTI-SCALE FINITE ELEMENT MODELLING OF UNIDIRECTIONAL COMPOSITES FOR ALLOWABLE PREDICTION

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Key words: Multi-scale modelling, Micromechanics, Virtual Allowable

A common methodology to simulate the behavior of composite materials consists in considering the material as homogeneous following a so-called macroscopic approach and modelling it using a progressive damage model. Such macro-scale models describe the behavior of the undamaged material, follow the evolution of different failure criteria and progressively degrade the undamaged behavior when the failure criteria become larger than some critical threshold values, i.e. when the material is damaging eventually leading to failure. The description of the undamaged behavior, the failure criteria and the degradation of the material behavior upon damage are typically derived from experimental tests under uniaxial loading conditions. The models then make an assumption about the material behavior under multiaxial loading conditions. This comes with two main disadvantages: (i) a large number of experimental tests is required to identify all model parameters, and, (ii) the model predictions on industrial applications can sometimes be inaccurate since the material is in general seeing multiaxial loading conditions against which the model was not properly validated. The present presentation suggests mitigating these disadvantages by: (i) using a micro-scale model finite element to predict the behavior of the composite material under many different loading conditions, and, (ii) deriving an improved macro-scale model from these simulation results. The resulting macro-scale model can then be used to predict allowables (e.g. stiffness and strength of unnotched, open-hole, filled-hole, … coupons made of various laminates). The allowables computation are automated and rely on a stochastic methodology, starting from uncertainties at the microscale.

3 ACKNOWLEDGMENTS

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MODELING THE EFFECT OF MOISTURE ON THE FRACTURE BEHAVIOR OF CELLULOSE NANOPAPER

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Nanopaper made of native cellulose nanofibrils is emerging as a renewable and sustainable substrate to replace traditional plastics for organic electronics. It is in general composed of a dense fibrous network and shows superior mechanical properties compared to traditional papers because of its stronger and stiffer nanofibrils and enhanced inter-fiber bonds. The mechanical behavior of the nanofibril and the interface between nanofibrils changes due to the moisture’s influence. Scanning electron microscopy imaging in fracture surface demonstrates more pronounced pull-out of individual nanofibrils and bundles of nanofibrils in nanopaper samples with high moisture. It indicates that nanopaper undergoes a moisture-induced transition from a fiber break behavior in dry state to an inter-fiber debonding dominated behavior due to disengagement of the hydrogen bonded network and lower inter-fiber friction at high moisture. The aim of this study is to evaluate the influence of moisture on the fracture behavior of nanopaper quantitatively. To this end, a microscale crack model was proposed to reveal the observed transition phenomenon. First, the virtual microstructure was generated by simulations of nanofibrils compression to obtain the practical fiber volume fraction. Here, the fiber length, diameter, and orientation distribution were required for the generation. Then, the moisture dependent cohesive zone model was introduced as bonds in any fiber-fiber contact area, while the elastic-damage model was used to model individual fibers. The virtual mode I and II tests were performed to obtain the effective fracture properties by applying tension and shearing boundary conditions. Finally, the effective mechanical properties could be obtained by applying periodic boundary conditions and the subsequent homogenization procedure. The results show the importance of moisture on the stress transfer between nanofibrils.
DEVELOPMENT OF VISCOPLASTIC STRAINS DURING CREEP IN POLYPROPYLENE/CARBON NANOTUBE COMPOSITES

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Viscoelastic-viscoplastic behavior of polypropylene (PP) filled with multiwall carbon nanotubes (MWCNT) have been studied in tensile creep and recovery tests. Nanocomposite samples with various concentrations of MWCNT (2, 5, 8, 10, 15 wt.%) were produced by using PP/MWCNT masterbatch via calendaring technique and hot pressing. Creep test regimes with different stresses, loading time, and number of cycles were applied to cover wide range of strains. Electrical resistivity during the creep-recovery cycles was controlled and correlated with the overall strain changes and accumulation of the irreversible strains in nanocomposites.

Nanocomposites are characterized by lower creep strains compared to the neat PP, however rather high data scatter related to microstructural inhomogeneity of the material is observed. This resulted in uncertainties with the analysis of viscoplastic strain evolution with the increasing stress and time according to the well-known Zapas and Crissman model [1]. To overcome data scatter for materials with high variability a “single specimen methodology” and pre-conditioning under cyclic loading are used. However, both methods do not fully exclude contribution of viscoelastic and damage-accumulated strains into the viscoplastic strain evolution.

In the present study, the residual strain as a function of the total creep strain is considered. It is shown, that the residual strains of the neat PP and PP/MWCNT nanocomposites determined in creep-recovery tests under different stresses and loading times fit on a common curve finely described by an exponential function with two independent parameters. Moreover, similar dependences were obtained and generalized for the creep data for a variety of polymers and composites from literature. An analogy between the determined empirical function with the existing damage and viscoplastic models is highlighted [1, 2]. An advantage of the proposed method for the analysis of the residual strains is in its implicit coupling of viscoelastic, viscoplastic, and damage effects. This makes it possible to estimate an extent of irreversible structural changes in polymers with changes in loading time, stress, temperature, and content of the filler. The accumulated residual strains in PP/MWCNT composites finely correlate with the residual electrical resistance justifying practical importance of using “self-sensing” materials for the analysis of long-term performance.

References

NUMERICAL MODELLING OF THE EFFECTS OF TEMPERATURE AND MOISTURE ON MECHANICAL RESPONSE

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Hi-fidelity finite element models with physically based failure criteria are now well established for fiber reinforced composites, giving good accuracy at standard room temperature conditions. However, the mechanical properties of fiber reinforced composites, especially the matrix and fiber/matrix interface are sensitive to in-service conditions such as, temperature and humidity[1]. These degradation effects are rarely accounted for in predictive failure models and have only thus far been presented as either independent temperature or moisture models[2]. No effective and comprehensive failure models or criteria exist for hot-wet conditions. In this work, a semi-empirical model based on Zhurkov’s kinetic theory[3] was developed for hygro-thermal strength degradation of both the composite plies and interfaces of a thermoset epoxy laminate along with empirically based models for stiffness and fracture energy. These models were implemented in a Continuum Damage Model (CDM) based user material subroutine in the Abaqus Explicit finite element software, and validated against experimental data available in the literature[1] for various configurations.

Figure 1. Open hole tensile test [45/0/-45/90]2S (a) 45° ply matrix cracks (red) and (b) failure strength comparison of dry and hot-wet specimens

Figure 1 shows the results of open hole tensile test of room temperature dry (RTD) and elevated temperature wet (ETW) specimens. The predicted strength values are within the error limits of the experimental data. For this specific configuration, ETW strength increases (~12%) from RTD due to the hygro-thermal residual stresses of interface and matrix. Other cases, such as in-plane shear and short beam strength show considerable knock down.

References

Formulation of a Cohesive Zone Model with Humidity and Temperature Effects for Modelling Bonded Joints

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The use of cohesive zone models (CZM) has become an important tool to capture the composites response under different loading modes. CZM has been proved as a good method to simulate interlaminar fracture [1]. However, the experimental determination of the cohesive law and its dependence on the environmental effects is still an open issue. In the present work, a new approach that introduces the effects of temperature and humidity on the cohesive law shape is developed. The method is implemented on the formulation proposed by Turon et al. [1] using a trilinear cohesive law. The constitutive model is implemented in the commercial FE program ABAQUS using user element subroutine. The numerical model is validated by comparing the results of simulations of pure-mode fracture toughness tests and the available experimental work done by the authors, where two types of adhesive bonded joints (Wet aged and non-aged) were tested under three temperatures (-55 °C, Room Temperature (RT) and 80 °C). The wet specimens were stored in an environmental chamber at 70°/85 RH until saturation, and the non-aged specimens were stored in the laboratory under controlled conditions at RT. As an example, Figure 1 illustrates the load-displacement curve of a DCB test, where the numerical simulation is compared to the experimental test, shows a good agreement between the FE and experimental results is obtained.

![Figure 1. Experimental load-displacement curves of a DCB test compared to FEM results.](image)

References

Damage and Fracture III
Fibre reinforced composites (FRCs) are notoriously known to show variation in strength under compression. Different analytical, numerical and experimental investigations have been carried out in past few decades to quantify the uncertainty in axial compression strength. In these investigations, the random waviness of the reinforcing fibers was identified as the decisive element determining compressive strength. Slaughter and Fleck [1] showed that undulations in unidirectional FRCs, which show a random spatial distribution, adhere to power spectral density distribution in frequency domain. This distribution is characteristic for a particular composites material. Spectral analysis is a well-known and reliable method for generating distributions of random fields in many areas such as surface roughness for contact mechanics and realistic water-surfaces for ocean optics and computer generated imagery among others. However, experimental characterization of power spectral density for this class of materials is somewhat lacking in literature. It was shown through a numerical investigation in [2] that this varying material imperfection leads to the uncertainty in strength most dominant for pure compression loading but also present in mixed loading cases such as compression-shear. The scatter in strength values diminishes as one moves away from pure compression loading axis. However, an experimental campaign to validate finite element analyses results of this investigation is needed.

In this contribution, power spectral density of fibre misalignment is quantified. This is done by performing CT-scans on the material at different depths in in-plane and out-of-plane directions non-intrusively over multiple samples. By measuring fibre deviations from their respective mean paths in CT-scans and performing subsequent Fourier analyses for all data sets, a statistical average power spectral density as a material characteristic is obtained.

In a subsequent material strength testing campaign using the same samples as used in CT-scans, the variation in strength under compression and compression-shear loadings is quantified in a probabilistic manner. By using an in-house built combined loading fixture and performing failure testing of 25 samples for each load case, sufficient data is obtained to capture the probability distribution of strength values.

References

Micro-mechanical modelling of longitudinal compression in unidirectional composites: effect of misalignment

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Unidirectional composites exhibit their best performances when loaded in the longitudinal direction, exploiting the high stiffness and strength of the reinforcements. In longitudinal compression, the strength is significantly lower if compared to tension. This is due to the inherent material imperfections, such as fibre misalignment, that trigger the formation of kink bands and micro-buckling of fibres under compression. The phenomena involved in longitudinal compression are very complex. According to some authors [1], failure is governed by the matrix yielding and the fibre-matrix debonding, promoted by fibre misalignment. Predictive models in the literature consider these phenomena to capture the kink band formation [2].

In this work, a micromechanical model based on finite elements is used to simulate the longitudinal compressive behaviour of a unidirectional composite. The microstructure is generated based on an algorithm published in [3], extended to include misalignment. The features of the model are: i) fibre-matrix interfaces modelled with cohesive elements, ii) matrix plasticity and damage, to account for the non-linear behaviour of the matrix; iii) sinusoidal misalignment and iv) random geometrical arrangement in the transverse direction. The results of this investigation are compared with other similar works in the literature, both with finite element and analytical formulations [2,4].

The results of this work are the first part of a broader research, aimed to investigate more realistic 3D misalignments and its effect on compressive strength.

Acknowledgments
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References

Mesoscale modeling of carbon fiber spread tow fabric subjected to in-plane loading

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Ultra-light composites have been produced through the spread tow technology. The reason behind the spread tow fabric’s success originates from its unique woven structure. By interlacing wide spread thin flat tapes, instead of regular (and thicker) yarns, a smaller number of interstices are obtained which leads to less crimp and less accumulation of resin pockets and hence increased fiber volume fraction. In addition, straighter fibers and thinner plies are obtained which also contribute to improved mechanical performance in terms of both stiffness and strength [1]. Yet another benefit is that the carbon fiber spread tow fabric composites combine the high performance of pre-impregnated tape-based composites and the high draping ability of woven fabric composites.

It has been shown in previous studies [2-3] that for very thin plies, the crack initiation is delayed, and the matrix cracks appear more closely to final failure. This mechanism requires further investigation and understanding. In the current study, a mesoscale finite element model of a carbon fiber spread tow plain woven composite has been realized, which can be used to analyze the effect of ply thicknesses down to 0.04 mm. The model has been used to study the effect of tow thickness and spacing on the stiffness knock down (due to crimp) and on the initial damage development. By applying shifted periodic boundary conditions through the thickness, also the effect of periodic layer shifting can be analyzed without having to discretize and model more than one layer of the composite.

References
NONDIMENSIONAL BUCKLING EQUATIONS OF SANDWICH CYLINDRICAL SHELLS WITH A SHEAR DEFORMABLE CORE

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The use of sandwich composite allows for structures to be tailored to reduce structural weight, increase strength and stiffness. Designers have a broad design space to improve the structural performance since they can tailor the mechanical properties by a suitable selection of laminate stacking sequence and core material and thickness.

The use of nondimensional equations presents the advantage of reducing the number of variables while preserving the extensive design space. Since the same set of nondimensional parameters may correspond to many different sandwich constructions, nondimensional equations can therefore be used to characterize structural behavior and facilitate design. The nondimensional parameters of these equations can also be utilized as the basis for a scaling procedure [1].

This work addresses the nondimensionalisation of the buckling equations of sandwich cylindrical shells made of anisotropic facings with a bonded orthotropic core. Cylindrical shells often constitute a primary structural element, where axial buckling is a critical design load. In sandwich cylindrical shells with shear deformable core, transverse shear deformation influence is to be considered in the study of buckling behavior [2].

The presented nondimensional equations are based on the work of Nemeth [3] for composite laminates. This study aims to extend the work to the case where the transverse shear deformations of the core are not negligible. An approximate analytic solution for the axial buckling load is obtained. The procedure yields a solution in terms of a series of nondimensional parameters.

The inclusion of nondimensional transverse shear parameters helps to determine the compressive buckling strength more accurately. The developed equations will be used to study the buckling of sandwich cylindrical shells for space structures applications, highlighting when the effect of transverse shear becomes relevant. These cases will be verified by finite element analyses using the commercial code Abaqus.

References

ON THE COMPRESSION BEHAVIOUR IN FIBER DIRECTION AND TRANSVERSE DAMAGE INFLUENCE ON COMPRESSIONAL FAILURE

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Compressive behaviour of a Glass/Epoxy unbalanced woven composite (Excel M42ST/1055) was assessed via four points flexion and compressive tests. Flexion tests highlighted the linear behaviour of the glass fiber (Fig. 1), contrary to carbon fibers [1], yet failure always occurred in traction for a strain lower than 3.5%. Compressive failure strain was found via compressive tests at around 3.5%. The result of these tests shows how compressive strength is higher than tensile strain for the studied material.

In a second part compressive failure of a Carbon fiber reinforced Epoxy matrix unidirectional composite (T700GC/M10) was studied and simulated. A particular layup was used to induce compressive failure during a tensile test. The chosen layup [45, −45, 90°/2]s presents a ply at 90° where compressive stress is induced by a “scissors effect” of the ±45°, it also presents a high level of transverse damage due to the positive transverse stress [2]. Post-mortem observation of the samples seems to confirm the compressive failure of the ply (Fig. 2).

Figure 1: Glass/Epoxy Behaviour

Figure 2: [45, −45, 90°/2]s Post-Mortem Image

Acknowledgements

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References

THE MODE OF THE BUCKLING DELAMINATION OF THE PZT/METAL/PZT SANDWICH RECTANGULAR PLATE WITH INTERFACE EMBEDDED RECTANGULAR CRACKS

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In this study it is considered the buckling delamination problems of a PZT/Metal/PZT rectangular thick plate with interface embedded cracks. Under uniformly distributed uniaxial compressive static forces on two end planes, cracks contained by the plate is going to open and in a certain value of this forces buckling delamination of the plate occur. In the practical application owing to some values of geometrical and material parameters, different buckling delamination mode or surface wrinkles of the plate can be seen [1,2]. Our aim is to determine the buckling delamination modes of the considered plate as well as to determine the effect of geometrical and material parameters on these surface wrinkles.

Theoretical investigations are made within the scope of the 3D linearized theory of stability loss with utilizing the piecewise homogeneous body model using the electro-elasticity theory [3,4]. It is supposed that there is an interface embedded crack between the face and core layers and this plate is loaded with the uniformly-distributed compressive forces acting on two opposite end planes. Considering some boundary conditions mathematical modeling of the considered problems are made and solution to these boundary-value problems are made numerically using 3D FEM coded by the authors. Buckling delamination mode of the considered PZT sandwich plate and the effect of the problem parameters on this buckling mode are analyzed and try to clarify.

References
Damage and Fracture IV
A gradient enhanced continuum approach towards shear cutting of carbon fiber reinforced plastics

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A geometrically nonlinear approach towards shear cutting of carbon fiber reinforced plastics (CFRP) is developed. The material model aims at simulating the initiation and evolution of damage through the cutting process. In order to simulate crack propagation using a damage model, a gradient enhanced formulation of damage is implemented [1]. Experimental tests on tensile specimens were carried out as well as shear and cutting experiments. The tensile experiments suggest a brittle damaging behavior which is introduced in the material model. Cutting experiments suggest a distinction between matrix and fiber damage which is implemented in the material model as well. The distinction between fiber and matrix damage is implemented in terms of a two surface approach.

Material parameters are fitted using experimental results and an estimation of the quality of the fit is given.

Goal of the development of this new material model is to gain more insight into the material response of CFRP during shear cutting. While the material response on shear cutting of different metals is well known, there exists little to none knowledge of the material behavior of CFRP. This lack of knowledge prohibits the use of blanking in mass manufacturing of CFRP as it would be useful in car manufacturing. Therefore the gained knowledge about the cutting behavior is considered a crucial part of paving the way for CFRP into mass production [2].

References


THE IMPORTANCE OF ACCOUNTING FOR LARGE SHEAR DEFORMATIONS ON MODELLING MATRIX FAILURE OF THERMOPLASTIC AND THERMOSET COMPOSITES

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The use of thermoplastic composite materials is gaining momentum in the transportation sector due to their improved mechanical properties, ‘unlimited’ shelf life and it offers a number of advantages that can benefit cost-efficient and high-volume manufacturing such as out-of-autoclave consolidation and thermoplastic welding [1]. However, their mechanical behaviour and the validity of analysis methodologies that were originally developed for thermoset composites are not yet well understood. A numerical investigation is performed to study different approaches [2,3] that represent matrix cracks in continuum damage models and results are compared to benchmarks from literature. Furthermore, virtual coupon tests are performed and compared against experimental data from both thermoplastic (AS4D/PEKK) and thermoset (AS4/8552) composites [2]. It was found that traditional strain based continuum damage models have difficulty in accurately predicting matrix failure and their interaction with delaminations due to the presence of large shear deformations. The failure modes are highly influenced at both the local and global scale (Figure 1) and it is shown that accounting for large shear deformations in continuum damage models is important for both thermoset and thermoplastic composites.

![Figure 1. Matrix failure due to large deformation at the local (left) and global (right) scale](image)

References
EFFECT OF FIBRE ORIENTATION ON CHIP FORMATION IN CFRP COMPOSITES MACHINING: FE STUDY

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This work is focussed on developing a finite-element (FE) model of orthogonal cutting of carbon/epoxy (CFRP) composite. Understanding mechanics of chip formation in machining of unidirectional CFRP laminates is of particular interest; various fibre orientations ranging from 0° to 135° are considered for this purpose.

Effectiveness of employed damage activation algorithms, (i.e. Hashin’s- and Puck’s criteria-) in modelling of CFRP material removal is assessed. FE results showed that, for fibre orientations other than 0°, the chip formation mechanism is largely driven by cutter’s shearing action ahead of its tip leading to smaller cracks in epoxy matrix (refer Figures 1b and d). In case of fibres orientated in the same direction as cutter’s feed (i.e. 0°), however, larger cracks are formed due to fibres bending ahead of the tool tip (refer Figure 1a) before being sheared away – leading to excessive compressive- and bending stresses in the surrounding region. In fibres with the orientation perpendicular to cutter’s feed (i.e. 90°), excessive fibre-matrix debonding could be observed as cracks mostly run parallel to fibres (refer Figure 1c). Of course, the severity of the sub-surface damage in all these case depends on the cutting parameters (such as feed rate and depth-of-cut). It is envisaged that the FE model will allow useful insights in selection of appropriate cutting parameters to mitigate machining induced damage in composites.

Figure 1. Chip formation of different unidirectional carbon fibre laminates studied with different fibre orientations: (a) 0°, (b) 45°, (c) 90° and (d) 135°
MODELING OF HONEYCOMB CORE SANDWICH PANELS UNDERGOING INTERFACIAL CRACK PROPAGATION

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Payload fairings are large shell structures mounted atop launch vehicles that protect the payload from aerodynamic and acoustic loads during launch. For NASA’s space launch systems heavy lift vehicle, the design of such payload fairings involves separable petals composed of aluminum honeycomb sandwich panels with carbon fiber reinforced polymer (CFRP) facesheets, see Figure 1.

Figure 1. Representation of the sandwich panel with aluminum honeycomb core.

Coupon testing revealed that substantial fiber bridging occurred at the interface of the honeycomb core and the CFRP facesheet. To account for fiber bridging a novel cohesive zone traction-separation law has been developed for 2D simulations in [1] and extended to 3D in [2]. In the current work, results of the 2D and 3D simulations are compared and the transfer between the corresponding parameters is shown.

References

A CONSTITUTIVE MODEL FOR FIBER REINFORCED POLYMER PLIES – PLASTIC YIELDING WITH KINEMATIC BEHAVIOR

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Because non-quasi-isotropic laminates made from unidirectional Fiber Reinforced Polymers (FRPs) are being deployed more frequently, it becomes increasingly important to treat the matrix-dominated damage and failure modes, which heavily affect the laminates load-bearing capabilities. To further improve the predictions concerning matrix related plasticity, an extension to the plasticity formulation of the constitutive model for fiber reinforced polymers, proposed in [1, 2], is presented. The existing model predicts plastic strain accumulation and uses continuum damage mechanics to model the stiffness degradation accompanied by strain hardening as well as strain softening behavior.

The extension aims at modeling the plastic yielding with combined kinematic and isotropic hardening, which has been observed in experiments [3]. Due to the characteristic behavior of the material, the internal state variables as well as the evolution equations are set up in an anisotropic manner. In order to avoid regularization techniques for the plasticity formulation, the softening material behavior is entirely treated within the damage framework. The rate constitutive equations are integrated numerically using an implicit scheme to be used in a material subroutine UMAT for ABAQUS/Standard (SIMULIA, Providence, RI, USA).

The capabilities of the model are demonstrated on an angle-ply-laminates under quasi-static load cycles and the predictions are compared to experimental data.

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References


Impact I
Self piercing riveting on composite plates

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Self-piercing riveting (SPR) is used as a fast and robust technique to join dissimilar sheet metals. Nowadays the development of electric car programs has increased the interest of using composite in mixed material structures. First experimental studies appears in the year 2009 while only few contributions [1] can be found regarding the use of numerical simulations to reproduce this complex phenomenon.

In this work it has been developed a numerical tool able to simulate the SPR technique between an aluminum sheet, carbon fibre plate and steel rivet. The commercial FEM code Abaqus/Explicit has been used for reproducing the dynamic behaviour of the SPR process. Aluminium and steel material models take into account both temperature and strain rate dependences. Regarding the carbon fibre plate an efficient approach has been proposed to reproduce the intralaminar behaviour. A 3D VUSDFLD subroutine has been used to take into account both the failure mechanism and the damage process. Cohesive interactions has been used to simulate interlaminar failure. The numerical model has been validated by means of an experimental test in which the force time curve is obtained. Also the main numerical damage process has been studied for a deeper analysis of the SPR process.

Figure 1. Experimental and numerical front view of the SPR process.

References

ENERGY ABSORPTION CAPABILITIES OF COMPOSITE CELLULAR MECHANICAL METAMATERIALS

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Approximately 1.35 million people die each year due to road accidents and The Sustainable Development Goal, SDG’s, aim of reducing the number of road traffic deaths by 50%, by 2020, remains unsatisfactory [1]. These figures provide the motivation for the frequent improvement in vehicle crashworthiness. An approach to improve vehicle crashworthiness, considered in this paper, is by utilising the unique properties exhibited by cellular mechanical metamaterials. In this paper, the influence of periodic cellular mechanical metamaterials with hexagonal unit cells and varying wall-thickness were investigated relative to crashworthiness. An auto-generated algorithm was developed to computationally model the metamaterial shown in Fig. 1c (the materials applied in the computational model are the base materials – nylon and onyx – used by Markforged Mark Two 3D printers); undertake crush simulation; and output the parameters – SEA, PCF, and CFE – required for improved crashworthiness. The parameters were compared to those of a monolithic material (Fig. 1a) and hexagonal cellular material with uniform wall-thickness (Fig. 1b). The metamaterial exhibited lower PCF and CFE close to the monolithic. However, the SEA was lower as well. Compared to the cellular material, the metamaterial had higher SEA, CFE, but also PCF. Since the optimal design for improved crashworthiness requires high CFE and SEA, but low PCF, additional studies involving optimisation and geometrical study needs to be carried out.

Figure 1. Auto-generated computational model of a) monolithic material, b) cellular material c) cellular mechanical metamaterial with hexagonal structures, with varying wall-thickness.

References

A computational study of the ballistic performance of UHMW-PE composites: looking beyond fibre properties

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Composites reinforced with Dyneema® fibres exhibit superior ballistic properties owing to the highly oriented molecular chains in the intra fibrillar structure. In literature, ballistic properties of the composites have been strongly related to the high specific strength & modulus of the reinforcement fibre - but recent experiments have shown that other ply properties also influence the ballistic performance of these composites under dynamic loading. There are different failure mechanisms at play that can lead to different modes of penetration[1, 2]. Insight into how these underlying mechanisms depend on ply level properties can help in developing better ballistic composites. Through this motivation a detailed computational study is carried out to mark out this dependence in the form of a mechanism map.

As a first step, onset of failure is studied using a plane strain dynamic impact finite element simulations of a rigid cylindrical impactor onto an infinite UHMW-PE cross-ply beam. A homogenized ply level constitutive model with transversely isotropic elasticity and crystal plasticity was incorporated - in order to capture the anisotropic interaction between the fibre and the matrix within the ply. The results from each simulation were then used to track the onset of tensile fibre failure within the plies and the mode of failure was identified. The overall parametric dependency was represented as an impact map. Fibre topology was incorporated into the model through modifications of the parameters in the ply constitutive model and its effect on failure modes was studied using two separate impact maps - one for the fibre system (circular fibres embedded in a matrix) and one for a corresponding equivalent tape system (continuous microstructure, with no individual fibres discernible).

The results of the simulations indicated an improvement in resistance against failure under ballistic loads in tape systems when compared with the equivalent fibre systems. An additional operative failure mode was observed to be present for the tape systems which is absent in the fibre system. To extend the study to capture failure mode propagation and switching - a viscous damage model is developed & implemented into the constitutive model to capture quasi brittle fibre failure.

References

EXPERIMENTAL INVESTIGATION OF THE QUASI-STATIC AND DYNAMIC CRUSHING OF 2D WOVEN CFRP FORMULA 1 CRASH STRUCTURES

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Recent developments in high-fidelity and robust composite damage modelling facilitate a better understanding of the crushing behavior of carbon fibre crash structures. In-turn, the final designs of such structures can be further optimized within shorter timeframes, by significantly reducing the extent of experimental crash testing and replacing with simulation. This reduction in testing is especially useful in Formula 1 (F1), where the design cycles are very short.

One of the currently debated issues in the field of composite damage modelling is the effects of strain-rate on the crush response of such composite components. In particular, limited literature is available on the variation in crush behavior of woven CFRP structures subjected to different crush velocities [1].

This work presents an experimental comparison between the quasi-static and dynamic crushing behavior of a standard F1 Side-Impact-Structure (SIS). The quasi-static experiments were carried out using a tensile testing machine, while the dynamic crush tests were performed following the standard F1 crash test setup.

References

EFFECT OF STRAIN RATE AT COMPRESSIVE LOADING OF UNIDIRECTIONAL PLIES IN STRUCTURAL COMPOSITES

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Efficient models for fibre reinforced polymeric composites are in high demand, e.g. in the automotive industry; however, the dynamic behavior of composites is not very well understood, especially not for crash and impact events. To address this demand, we present a novel transversely-isotropic viscoelastic-viscoplastic constitutive model for a unidirectional carbon-epoxy composite. The model applies to the ply scale and it is based on a structure tensor formulation along the lines set out in Larsson et al [1] for the representation of fiber compression/extension and shear. By focusing on the matrix shear dominated response under compressive loading of the ply (prior to the nucleation of damage), the homogenized model properly captures the non-linear rate dependent anisotropic ply behavior. The present formulation is applied to simulate quasi-static and dynamic off-axis experimental results of IM7-8552 in compression [2]. As shown in Figure 1, an excellent correlation was found between the measured and numerically predicted stress – strain response.

Figure 1. Model validation with quasi-static & dynamic response from off-axis compression test. [2]

References


Numerical modelling of woven CFRP fluid-filled tubes subjected to high-velocity impact.

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Composite structures are increasingly used in aerospace industry due to its excellent stiffness and strength-to-weight ratio. However it is well knows its poor performance under impact loading. Bird strikes, hailstones or runaway debris are examples of impact situations that are considered due to the high probability of occurrence and disastrous consequences. One of the most important factors in aircraft vulnerability is the effect of the Hydrodynamic Ram (HRAM) phenomenon, when a impact takes place in the wings where fuel tanks are presented. While the object is penetrating the tank, it transfers its momentum and kinetic energy through the fluid to the surrounding structure, increasing the risk of excessive damage and failure in the structure [1].

In this work, numerical simulations of fluid-filled carbon/epoxy woven laminates square tubes (150 x 150 x 750 mm\textsuperscript{3}) subjected to impact (12.5 mm steel spheres) are shown. Impact velocities ranges from 600 up to 900 m/s. The simulations are performed with the finite element code LS-DYNA using the Multi Material Arbitrary Lagrangian Eulerian (MM-ALE) and the Smooth Particle Hydrodynamics (SPH) approach to reproduce the Fluid Structure Interaction (FSI). Woven composite material is modelled using an user subroutine capable of reproducing intralaminar failure modes. Interlaminar damage has been simulated by means of cohesive interactions. Experimental tests providing the pressure in different points of the fluid, failure of the walls and cavity evolution for different impact velocities and filling levels are compared with the numerical results in order to assess the validity and accuracy of the model to reproduce such a complex phenomenon (Fig. 1).

Figure 1. Experimental and numerical failures appeared on the CFRP tube. Left: MM-ALE. Right: SPH

References

Impact II
COMPOSITE SANDWICH PANELS USING NOVEL 3D PRINTED AUXETIC CORES FOR BLAST MITIGATION

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Explosions, impact and crash can have catastrophic consequences on the defence, aerospace, and marine sectors, among many others. Commonly, sandwich panels protect against severe loading scenarios as they feature high energy absorption and minimised deflection, whilst being lightweight and easily deployable. Sandwich cores generally consist of honeycombs or foam, however these possess a positive Poisson’s ratio. Recently, a new class of blast-proof panels which feature auxetic materials, have been proposed as promising novel structures under severe loading [1]. Auxetics describe a sub-group of meta-materials which exhibit counterintuitive behaviour and possess a negative Poisson’s ratio. Therefore, auxetics have been found to offer enhanced structural properties including: high energy absorption, shear and fracture resistance [2], making them ideally suited to blast loading scenarios.

This work investigates the response of composite sandwich panels which feature auxetic lattices subjected to blast loading. Figure 1 presents the panels investigated with auxetic architectures, including: (a) double arrowhead, (b) re-entrant and (c) rotated re-entrant. These cores have been compared to a non-auxetic (d) hexagonal topology within finite element software, Abaqus®. For the comparison of materials performance, two different materials are selected which are Nylon and Onyx® (a combination of Nylon and micro-carbon fibers). Under imposed blast loading, auxetic structures are known to densify and respond with a reduced lower face sheet displacement. Additionally, a non-reinforced Nylon was found to present lower post blast deflection, highlighting its suitability over the Onyx®. Because of their energy absorbing capability, auxetics reduce post blast deflection with the double arrowhead providing the greatest reduction. Therefore, the presented auxetic architectures provide superior blast protection for future protective structures.

![Figure 1](image.png)

Figure 1. Investigated sandwich panels featuring auxetic (a) double arrowhead, (b) re-entrant and (c) rotated re-entrant and non-auxetic (d) hexagonal core architectures.

References


**ARBITRARY LAGRANGIAN EULERIAN METHOD TO STUDY GEL PROJECTILE IMPACTS AGAINST COMPOSITE NAVAL PLATES**

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Underwater Explosions (UNDEX) is a subject of high interest not only for military organizations but also for commercial industry. The analytical and numerical tools that have been developed until these days have allowed studying the energy transport mechanisms occurred in UNDEX and its interaction with man-crafted structures, allowing also improving the structural scantlings and defense systems against these kinds of treats. Similar approaches are used as well to study the instantaneous high-pressure impact loads such as slamming, which is one of the most important design loads in the vast majority of applications in naval engineering, especially in the field of composites materials. However, performing experimental tests of these events is not only a costly but also a complicated process, due to the hazards involved in handling explosives and the limited organizations that have licenses to develop such tests. On the other hand, the use of alternative methods such as gas cannon testing for studying the damage initiation and evolution of composites materials has been limited to the aerospace industry, while few researches has been made in the field of ship design.

This work presents the results and validation against experimental tests of a numerical model built on a nonlinear explicit finite element software for simulating the impact of gel projectiles against naval composite plates. An impactor with water properties is modeled using an Arbitrary Lagrangian Eulerian approach, in order to capture adequately its large deformation as well as the shock and stagnation pressures, whereas a single shell approach along through thickness integration points is used for modelling the composite plate, both being coupled by the means of a Fluid Structure Interaction algorithm. A composite orthotropic material law along failure criteria associated with failure modes, based on Chang-Chang Criterion, is then used for evaluating the different intra-laminar failure modes that may occur in the impacted plates such as fiber rupture, fiber compressive failure, matrix cracking and matrix compressive failure.

The results obtained with this model present a good correlation with the experimental gas cannon tests performed during the project campaign, allowing to determine, for different types of CFRP and GFRP laminates, the different plate response phases with respect to the impact energies: elastic response, initiation of matrix cracking due to tension loads and finally fiber rupture. The numerical model presented in this paper will be further used as reference for the development of analytical formulations for designing thin composite structures subjected to soft projectile impacts, UNDEX or slamming events.

**Keywords:** Fluid Structure Interaction, Arbitrary Lagrangian Eulerian method, Intra-laminar damage, Composites Modelling, Soft Body Impact.
References


COMPUTATIONAL ASSESSMENT OF CFRP CHANNELS UNDER AXIAL CRUSH LOADS

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The excellent specific mechanical properties of carbon fiber-reinforced plastic (CFRP) composite materials have led to their use in various structural applications in the automotive and aerospace sectors. Owing to their inherent mass specific energy absorption capabilities, CFRPs may also be suitable candidates for primary energy absorbing structures. Currently, the Finite Element Method (FEM) is widely used to simulate the impact performance of CFRP structures [1], which has drawn interest from both academic and industry researchers. Furthermore, since laminated CFRP materials have many parameters that influence their performance, virtual testing has become a necessary step to decrease the amount of experimental testing during product development [2]. However, accurately predicting the impact performance of CFRP structures using numerical approaches remains challenging due to the complex failure modes exhibited by these heterogenous orthotropic materials. In this investigation, the applicability of using a common LS-DYNA composite material model, MAT054, for simulating the axial crush response of CFRP channel geometries under axial crush loads was assessed. Both hat and corrugated channel geometries with two different laminate stacking sequences, [0,±45,90]s and [±45,02]s, were considered. Results of the simulations with non-calibrated material model parameters were compared with available experimental data for one channel geometry, and then parameter calibration was conducted to improve correlation. Thereafter, the calibrated material models were used to conduct independent axial crush simulations with distinct composite layups. Finally, a comparative study of variation of peak forces and specific energy absorption (SEA) was performed with the variation of non-physical parameters in MAT054 (see Figure 1).

Figure 1. Axial crush simulation of CFRP hat channel using MAT054: (a) Influence of SLIMC1 on force-displacement response, (b) deformation of channel at various simulation time steps.
FREE VIBRATION ANALYSIS OF THIN E-FGM PLATES RESTING ON ELASTIC FOUNDATION BY USING THE DYNAMIC STIFFNESS METHOD

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This paper concerns with the development of dynamic stiffness method (DSM) [1] to investigate the free vibration behavior of thin rectangular functionally graded material (FGM) plate resting on elastic foundation. It is assumed that the mechanical properties of the FGM plate vary across the thickness according to an exponential law (E-FGM). Both Winkler’s and Pasternak foundations are modelled as the two parameter elastic foundation [2]. Hamilton’s principle is utilized to formulate the governing differential equation of motion by considering the classical plate theory in conjunction with the concept of physical neutral surface. The effect of rotary inertia is also incorporated. Closed form Levy type analytical solution is used to solve the differential equation of motion. Thereafter, the dynamic stiffness matrix is formulated by suitably imposing the displacements and force boundary conditions at different edges. The exact natural frequencies are computed from this dynamic stiffness matrix by applying Wittrick-Williams algorithm [3]. For the validation of the present method, the DSM results are compared with the existing literature and found that the DSM results are more accurate than the published literature [4]. Additionally, a new set of accurate results are reported which can be treated as benchmark solutions for comparison in the future. Lastly, the effect of various foundation parameters, plate aspect ratios, and boundary conditions on the natural frequency of the E-FGM plate are investigated. It is concluded that the proposed methodology is reliable, efficient and accurate for analyzing the free vibration behavior of E-FGM plates resting on elastic foundation.

References

MECHANICAL RESPONSE OF HYBRID SHIELDS BASED ON NONWOVEN FABRICS

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Nonwoven fabrics made up of high strength fibres are a lightweight solution for ballistic protection. They are composed by a random fibre network consolidated by means of thermal, chemical or mechanical bonds. They present outstanding deformability and energy absorption capacity, resulting in an efficient ballistic protection against small fragments. Nonwovens can be combined with conventional materials to improve the energy absorption capacity without sacrificing the structural performance of the original components. This study reviews the potential of nonwovens to improve the ballistic performance of conventional protection systems for aerospace, automotive and defence applications.

To this end, a multi-scale virtual testing framework was developed in the finite element code Abaqus/Explicit. A needle-punched Dyneema nonwoven fabric was selected for this study and a multi-scale constitutive model was implemented to predict the impact response [2]. The model provided the constitutive response for a mesodomain of the fabric corresponding to the volume associated to a finite element and was divided in two blocks; network and fibre models. Material parameters were identified by means of a multi-scale experimental campaign [1] and model validation was accomplished for several impact configurations [3].

The model was used to determine the performance of multilayered nonwoven systems, finding high dependency on the energy absorption capacity of the shields with the relative spacing between layers. In particular, a beneficial contribution of air gaps was identified. Afterwards, the performance of hybrid shields was numerically determined and compared. Interaction between projectile, woven/composite/metal and nonwoven was detailed analysed and the complex coupled failure mechanisms were obtained. The numerical results showed that the hybrid shields outperformed the single material configurations in terms of the ballistic limit when placing the nonwoven at the front impact face [4]. Furthermore, hybridisation provided higher energy dissipation than the sum of the energies dissipated individually by the shield components above the ballistic limit, leading to an enhanced energy absorption capacity.

References

Delamination I
Cohesive elements are the preferred choice to simulate inter-ply delamination in composites. This is due to their robustness, ease of use and availability in most major commercial finite element software. However, with cohesive elements one needs a very fine mesh to correctly reproduce the experimentally observed failure process. This is due to the requirement of having a minimum number of elements in the process zone ahead of the crack tip. This severely limits their applicability beyond coupon scale models, due to computational time requirements. The present work addresses this issue by enriching the cohesive element nodes with additional rotational degrees of freedom in an explicit finite element formulation, which allows quadratic displacement approximation within the elements. The attached solid ply elements are automatically enriched since they share common nodes with the cohesive elements. Benchmark examples are demonstrated, clearly showing accurate delamination onset and stable delamination growth prediction using relatively large elements and with computational time saving.

Figure 1. Force-displacement response of double cantilever beam models with coarse meshes. Linear cohesive elements (blue dotted line) vs. augmented cohesive elements (red solid line).

Acknowledgement

The authors would like to acknowledge the support of Rolls-Royce plc for this research through the Composites University Technology Centre (UTC) at the University of Bristol, UK.
AN ADAPTIVE ISOGEOEMTRIC CONTINUUM SHELL ELEMENT FOR EFFICIENT MODELLING OF DELAMINATION GROWTH

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To accurately predict damage growth in large, thin-walled composite structures, it is required to have models that are both valid and computational efficient. In this respect, isogeometric continuum shell elements provide an interesting option. First of all, the higher order continuity achieved via isogeometric analysis yields an increased in-plane smoothness that enable the use of larger shell elements. In addition, the high in-plane continuity also leads to that in-plane derivatives of in-plane stresses are continuous across element edges, thereby allowing for element-local recovery procedures for the prediction of out-of-plane stresses [2, 3].

Furthermore, as shown by Hosseini et al. [1], it is in an isogeometric continuum shell modelling framework rather straightforward to modify the through-thickness kinematics to incorporate weak and strong discontinuities. By introducing weak discontinuities at ply interfaces, the through-thickness strain discontinuities at these locations are explicitly accounted for. This enables a much better 3D strain and stress prediction, something which is key for a good estimation of the amount of intralaminar damage. By introducing strong discontinuities, the element is also capable to represent initiation and growth of one or several delamination cracks.

In the current contribution, we extend the shell formulation from [1] into an adaptive continuum shell that allows for an update of the through-thickness kinematics at any required time instant during the simulation. The adaptivity is facilitated by that the through-thickness kinematical enrichment can be achieved by so-called ”knot insertion”, a step which can be fully automated due to the hierarchical nature of the isogeometric approximation functions.

As a result, the current shell provides a good basis for an accurate but also computationally efficient prediction of the progressive failure in laminates, without a-priory knowledge of where damage will occur. Results show that the adaptive modelling framework works well, both to predict the full 3D stress states in multiaxial laminates, but also to capture growth of delaminations. Furthermore, in comparison to a fully resolved model, the adaptive approach gives significant time savings even for simple analyses where significant parts of the domain exhibit delamination growth. This implies that computational efforts (time and memory) can be considerably reduced when using this adaptive concept in large-scale analyses where damage develop only in a confined, but initially unknown area of the structure.

References

C^1 COHESIVE ELEMENT MODELS FOR 3D DELAMINATION

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Cohesive Element (CE) is a practical and versatile means of modelling delamination onset and propagation in composites. The standard CE technology, however, suffers from the well-known mesh size constraint, which requires multiple CEs in the cohesive zone to well reproduce the solution fields, namely the traction and damage distributions. The present work proposes a solution to overcome this cohesive zone limit by using a C^1 Kirchhoff triangular plate element for substrates and a compatible cohesive element for interfaces. The triangular element shape, instead of a quadrilateral one, is preferred since triangles have more flexibility in modelling complex geometries. Current results for a 3D Double Cantilever Beam analysis show that very good agreement with reference solutions from standard-CE models can be obtained with coarse meshes of up to 10-mm elements (Figure 1).

Figure 1. Load-displacement curves for the double-cantilever beam test. The reference solution is plotted together with the results from the proposed model, for different mesh sizes of the delaminating region.
DELAMINATED REISSNER BEAM WITH NON-LINEAR CONTACT LAW BETWEEN LAYERS

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In the present contribution we are concerned with the modelling of a contact between layers of (partially) delaminated beams. Governing equations are derived from Reissner's geometrically exact theory, [1]. The solution is found using finite element method. Special attention is given to modelling the binding layer between elements of the neighbouring fibres. Defined properties of interlaminar layers are based on specific physical limitations, such as contact, friction between layers, cohesive forces, glue properties or properties of the binding resin.

We conducted experiments with delaminated beams where the crack geometry is known in advance and no propagation is considered. The beam is thick and made of rubber material with relatively low Young’s modulus and linear material characteristic in the elastic region. Photographs of beams deformed under its own weight show good agreement of numerical results with the measurements, as shown in Figure 1.

Figure 1. Numerical and experimental results of a delaminated cantilever beam.

References

ELEMENT-LOCAL STRESS RECOVERY IN LINEAR SHELLS

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The introduction of laminated fibre reinforced polymers (FRP) in the automotive industry is strongly dependent on accurate and efficient modelling tools to predict the correct energy absorption in crash simulations. To increase the efficiency of such large-scale simulations, we have implemented an adaptive enrichment methodology for modelling of multiple and arbitrarily located delamination cracks using an equivalent single-layer shell model [1] as a user element in the commercial FE solver LS-DYNA. In summary the methodology starts the simulation with one shell element through the thickness. By identifying critical ply interfaces using a recovery technique of the transverse stresses, the element can then firstly be through-the-thickness refined to improve the stress prediction and secondly cohesive interface elements can be inserted such that delaminations can be modelled.

However, in [1] the stress recovery technique was based on a non-local super-convergent patch polynomial fit, which is not suitable for a user LS-DYNA implementation as non-local information is hard to obtain. Instead we aim to utilize the Extended 2D recovery technique by Rolfes and colleagues [2], [3]. A known drawback with this technique is that the recovery of the transverse normal stress, which is made from the in-plane derivatives of the shear force, requires quadratic approximation of the out-of-plane displacements. Again, this is not suitable for our user element implementation in LS-DYNA, which we choose to base on a solid shell formulation with linear approximation due to numerical efficiency.

Several authors have presented alternatives to estimate the transverse normal stress in linear shell elements, e.g. by neglecting shear forces [4] or making an assumption on the ratio of the shear force variation [5]. In this contribution we will examine the possibility to utilise the transverse normal stress from the FE-solution, available when using solid shell elements. We will benchmark this approach in a range of geometries with different modelling resolutions. If successful, our methodology will feature an element-wise stress recovery technique capable of estimating all transverse stresses even using a linear element. In the long run the methodology can enable computationally efficient simulations of delamination failure in composite structures and help to develop crash structures made of laminated FRP.

References
Delamination II
IDENTIFICATION OF THE COHESIVE LAW PARAMETERS TO MAXIMISE THE FRACTURE RESISTANCE IN THE PRESENCE OF MULTIPLE CRACKS

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Composite materials and structures are susceptible to delamination due to their low fracture resistance and this can lead to a decrease of the structural integrity [1]. Several techniques have been developed to improve the fracture resistance e.g. z-pinning [2]. In the present work, we investigate the fracture resistance increase using an alternative approach e.g. by introducing multiple cracks (Fig. 1a). The work is inspired by the experimental results of Rask and Sørensen [3] and the analytical and numerical modelling for mode I of Goutianos and Sørensen [4].

A Double Beam Cantilever (DCB) beam specimen (thickness \(2H\)) with two cracks is used to investigate the dependence of the fracture resistance, under mix mode, on the cohesive law parameters of both cracks, the distance between the two cracks and the peak tractions to the elasticity of the composite ratios. Fig. 1b shows an example for mode I, with an increase by a factor of 2 for a particular case.

References


MICROMECHANICAL INVESTIGATIONS OF CROSS-OVER FIBER BRIDGING

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Fibers that bridge the fracture surfaces in the wake of the crack tip can significantly enhance the delamination resistance for some polymer composite laminates [1-3]. In the current study, both detailed finite element analyses and a novel semi-analytical micromechanical model are employed to investigate the effects of fiber, matrix and interface properties on the macroscopic bridging law (traction-separation law), see Figure 1.

The semi-analytical model includes debonding between fiber and matrix, large deflections of the bridging fibers as well as buckling of fibers in compression. The predictions made by the proposed semi-analytical micromechanical model are shown to be in excellent agreement with those made by detailed finite element models.

![Figure 1. Schematic of the micromechanical model.](image)

The most important model prediction is that increasing the fiber/matrix interface may not be the best way to increase the delamination resistance of the laminate.

References

DO FIBRE BREAKS AFFECT DELAMINATION PROPAGATION IN UNIDIRECTIONAL INTERLAYER HYBRID COMPOSITES?

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Fibre-hybrid composites are widely used in transport, wind energy and sports applications due to their design versatility and lower cost compared to all-carbon fibre composites. Interlayer hybrids, where the fibre types are dispersed in layers, are the easiest to manufacture and therefore the most commonly used. The larger design freedom of hybrids is a result of the richer taxonomy in their failure mechanisms.

The failure mechanism of unidirectional (UD) hybrid composites is determined at the moment of the fracture of the low elongation (LE) fibre layer [1]. If the energy released in by the LE layer cannot be absorbed by the high elongation fibre layers, delamination is triggered. The propagation of the delamination depends not only on the constituent properties but also on the damage state of the composite. This damage includes LE fibre breaks, which in interlayer hybrids control the LE layer fracture and the final failure of the composite.

The work presented here takes the fibre breaks as the fundamental damage [2] and scales it up to predict layer fractures and the initiation and propagation of delamination between layers of different fibre type. Upon the first LE layer fracture, the model determines the energy release rate due to an increment $\Delta d$ of the delamination length (see Figure 1). If the energy release rate is higher than the mode II interlaminar fracture toughness, the delamination propagates by $\Delta d$. The fibre break damage influences the energy release rate and therefore the delamination propagation. The stress field in the delaminated state is predicted using finite element models (FEM) with pre-defined delamination lengths. By combining the FEM predictions with the fibre break damage development we are able to predict different failure modes in UD interlayer hybrid composites under tension.

Figure 1. Interlayer fibre-hybrid packing with a layer fracture and partial delaminated interface.

References
A SMEARED COHESIVE LAW FOR MODELLING Z-PINNED COMPOSITE LAMINATES’ DELAMINATION

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Z-pinning is a technique used to increase the damage tolerance of composite laminates. One of the difficulties faced by industrial designers is the lack of a dimensioning tool which can simplify application of the concept to structural components. The present contribution will detail a novel numerical framework combining a semi-analytical micro-mechanical model with a smeared cohesive zone law, directly applicable to Finite Element models.

In this framework, the micro-mechanical model is used as a pre-processing tool to generate the bridging map data of an individual Z-pin based on its geometry, aerial density, laminate thickness and composite material properties. The bridging map data is output into an LS-DYNA compatible format file, where a user subroutine for cohesive behaviour has been developed. This subroutine implements the smeared effect of the bridging map data throughout the cohesive element area using a method named Energy Equivalent Bridging Map (EEBM). This method computes cohesive forces at the integration points by projecting the energy dissipated and displacement to failure (both functions of the applied mode-mixity, stored in the bridging map) into the mode I and mode II planes (see Figure 1).

Validation of this framework has been performed by comparing the numerical predictions of the bridging effect on Z-pinned laminates at different mode-mixities against experimental benchmarks. A Double Cantilever Beam (Mode I), three different Mixed-Mode Bending and End-Loaded Split (Mode II) tests were carried out and the predicted results are in excellent agreement with experimental data (see Figure 2 for DCB test results).

\begin{figure}
\centering
\includegraphics[width=0.4\textwidth]{energy_equivalent_bridging_map.png}
\caption{Energy Equivalent Bridging Map.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.4\textwidth]{dcb_benchmark_result.png}
\caption{DCB benchmark result.}
\end{figure}

Acknowledgements

The authors would like to acknowledge the support of Rolls-Royce plc for this research through the Composites University Technology Centre (UTC) at the University of Bristol, UK.
Thermoplastic composites offer various advantages, e.g., rapid manufacturing cycle, excellent impact performance, recyclability, that drive the automotive industry to employs these materials. Material parameters are selected and optimized to enhance the resistance to damage and failure, especially during impact. A comprehensive study on the effects of matrix behaviors (ductility, strength, stiffness) on the propagation of transverse crack and delamination in thermoplastic composites under out-of-plane loading is somewhat limited. Here, we summarized our comprehensive studies (in both computation and experiment) on the effect of matrix behaviors on such damage modes in continuous glass reinforced polypropylene (GF/PP) system. Computational micromechanics using reliable representative volume element was performed to simulate the effect of matrix ductility on transverse crack propagation in a single ply [1]. Then, an experimental study elucidating the transverse crack and its transition to delamination at micro-level was performed using customized 3-point bending device within scanning electron microscope [2]. To clarify such behavior at macro-level, we performed quasi-static indentation on GF/PP cross-ply laminates [3]. We found that matrix has a minor influence on transverse crack behavior where the damage initiation and failure is governed by interfiber distance (here, micromechanical simulation result is consistent with micro-scale test result). In contrast, matrix has a major influence on delamination growth where it is strongly dictated by the interlaminar fracture toughness in Mode I and II.

References


AN EXPERIMENTAL CHARACTERIZATION AND NUMERICAL MODELING OF THE EFFECT OF INTRALAMINAR DAMAGE ON DELAMINATION OF CFRP

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Interaction between intralaminar and interlaminar damages have been studied for better failure prediction of laminated composites since the past three decades [1]. Both experimental and numerical studies have been proposed to showcase this coupling mainly between transverse crack and delamination. Experimentally, several publications based on open-hole tensile tests and unnotched laminate tensile tests have been performed and showed that the delamination toughness is somehow modified by the density of transverse cracks in the plies adjacent to the delaminating interface [2]. Numerically, modeling of this coupling has been achieved by two main routes: (1) introducing explicitly micromechanics cracks to induce stress concentration that naturally leads to the coupling between transverse crack and delamination [3], or (2) introducing artificial coupling making the damage state of the interface dependent on the transverse crack densities of the adjacent plies through non-local continuum damage mechanics obtained by micro to meso homogenization [1, 4]. The former suffers from high computational cost and severe slow convergence rate while the latter requires intrusive implementation in commercial FE packages.

In this work, our objectives are (1) to systematically investigate the effect of transverse cracks on the delamination toughness (2) to propose a local, non-intrusive, easy-to-implement and pragmatic approach to depict the experimentally observed coupling between transverse cracks and delamination with new cohesive elements formulations. We performed experiments by imposing in-plane strain to [0₈|9₀₂]ₘ laminates to create various levels of transverse crack densities and then continue performing double cantilever beam (DCB) test to evaluate the evolution of the delamination toughness. Finally, we proposed a new cohesive element specifically designed to capture the coupling. Such an approach is aligned with micromechanical models [?] and in good agreement with experimental results.

References

Delamination III
EXPERIMENTAL RESPONSE AND NUMERICAL MODELLING OF CRACK MIGRATION ON ANGLE-PLY LAMINATES

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Delamination is a well-known damage mode exhibited by laminated composites and has been extensively studied in unidirectional laminates. Nevertheless, for the case of more general configurations, like angle-ply laminates, their behavior is not fully understood yet, since crack migration may extend through adjacent plies [1]. An experimental campaign was carried out by evaluating fracture response of different antisymmetric angle-ply laminates through DCB tests [2]. The investigated laminates (+θ//-θ, where // denotes the initial pre-crack plane) present fiber bridging phenomena with successive crack migrations in the adjacent plies, as shown in Figure 1a.

In the literature, numerical modeling of the crack migration mechanism has been addressed by using enriched finite element techniques (see for example [3]). However, experimental observations of the test described previously suggest that crack migration and coalescence might be observed, so a modeling strategy based on the explicit discretization of cracks using cohesive elements (CE) was selected to model the observed mechanisms (see Figure 1b). The numerical model is exploited to improve our understanding on the crack migration phenomena and the influence of other parameters on it, like the effect of the constituents’ properties, e.g. matrix toughness, fiber/matrix interface. The adopted technique captures the essential features of the observed failure phenomena.

Figure 1. a) X-ray CT fractography of a DCB coupon of a +45°//-45° angle-ply laminate [2]. b) Damage distribution in the FE model of a +45°//-45° angle-ply laminate.

References


A MIXED-MODE MULTI-LINEAR COHESIVE LAW: NUMERICAL FORMULATION, MODEL IDENTIFICATION AND DELAMINATION WITH R-CURVE BEHAVIOR

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Delamination poses a severe threat against the reliability of modern composite structures. This makes tools for accurate prediction of delamination of high interest to composite engineers. The cohesive zone model (CZM) is an efficient tool in this regard, which in all practical use involves the finite element method. However, the accuracy of the CZM is highly sensitive to the presence and interaction of underlying failure mechanisms. During delamination growth in many fiber reinforced plastics, a zone of bridging fibers often develops in the wake of the crack tip. This causes different governing failure mechanisms in separate regions of the fracture process zone, which is difficult to represent in current CZMs. Additionally, the conventional CZMs are often semi-empirical as the cohesive law has a predefined shape.

One objective of this paper is to develop a CZM with sufficient degrees of freedom in the cohesive law to model the constitutive behaviour of complex and multi-scale mechanisms in the fracture process zone. Another important feature of the proposed cohesive law is that it eliminates a priori shape assumptions. This is accomplished by developing a multi-linear mixed-mode cohesive law consisting of an arbitrary number of line segments. The CZM is implemented in an interface element through user programmable features in ANSYS Mechanical APDL. A constitutive tangent stiffness tensor and an internal force vector is derived to enable implicit finite element analysis.

A key challenge to apply the multi-linear cohesive law, and other advanced cohesive laws in general, is the identification of model parameters. A second objective of this work is to develop a methodology for accurate identification of parameters in the multi-linear cohesive law. The proposed methodology is an inverse approach, which identifies parameters of the multi-linear cohesive law by use of optimization techniques. A gradient-based search strategy iteratively varies the model parameters to minimize an error in structural response between an experiment and a parametric finite element model.

The multilinear cohesive law and the method for inverse parameter identification is demonstrated in a quasi-static mode I fracture mechanical test. A glass fiber-epoxy UD laminated double cantilever beam specimen is subjected to pure moment loading, and displays a significant amount of fiber bridging as the crack advances. The identification methodology proves robust in obtaining identical cohesive laws, independently of the initial guess supplied to the gradient-based optimization algorithm and other settings contained in the methodology. The simulation reproduce experimental data with good agreement on global (i.e. specimen) level and local (i.e. crack tip) level. The proposed CZM demonstrates to be very effective in predicting R-curve behavior, and proves to be indispensable in comparison to the conventional cohesive laws with linear and bi-linear softening.
Double cantilever beam (DCB) is the standard specimen for determining fracture resistance in mode I. This is usually done by using simple data-reduction schemes that combine linear-elastic fracture mechanics (LEFM) and beam theory (either Euler-Bernoulli or Timoshenko). On the other hand, a richer modelling of the problem through the use of cohesive-zone models (CZMs) is also possible and widely used. This approach, unlike LEFM, allows us to accurately model problems where a relatively large damage process zone (DPZ) develops in front of the crack tip before failure. However, a rigorous study on the relationship between LEFM and CZM seems to be lacking and quantities like the critical energy release rate (Gc) the critical value of the J integral (Jc) used in non-linear fracture mechanics (NLFM) and the area under the traction-separation law of CZM (work of separation) are often misinterpreted.

In our recent work [1,2], we have shown that, unlike what is often stated in the literature, LEFM can be accurately adopted for DCB problems even in cases with large DPZ (ductile failure). We have demonstrated in a general case, neither Gc nor Jc is equal to the area under the traction-separation law of CZM. Moreover, we have shown that the difference between Gc and Jc, and therefore the applicability of LEFM to problems with quasi-brittle failure, is not due to the size of the DPZ, but it is due to the change of the energy dissipated in front of the crack tip with crack propagation. Additionally, we have proposed a novel data-reduction scheme called 'Enhanced simple beam theory' (ESBT) that is based on Timoshenko beam theory and LEFM, and, unlike all the data-reduction schemes currently used in standards, does not require the measurement of the crack length. Using input data from the numerical model (virtual-experiments), ESBT has proven to be extremely accurate in predicting the input value of the work of separation even for cases with extremely large DPZ.

We have also made a contribution in making the CZM model for DCB extremely fast, accurate and robust in the same time. First, we have shown that, for modelling the arms of a DCB, Timoshenko beam finite elements can be used instead of plane-stress 2D solid finite elements without a noticeable loss in accuracy [2]. Secondly, we have developed a closed-form solution for a DCB with arms modelled as Timoshenko beams and a bi-linear CZM at the interface [3]. This solution, that is completely free of any convergence problems or numerical errors, is also implemented in an open-source software.

References
DISBOND DETECTION IN COMPOSITE SCARF JOINTS USING ELECTROMECHANICAL IMPEDANCE BASED TECHNIQUE

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Due to the lack of continuity of fibres, adhesive joints are generally the weakest part of a composite structure [1]. This work is an investigation into the feasibility of using the electromechanical impedance technique for detecting disbonds in a scarf joint with an external patch at the top. Lead zirconium titanate (PZT) patches [2] have been considered to act as sensors and actuators as shown in figure 1. Finite element simulation has been carried out incorporating the effect of contact nonlinearity at the disbonds using ANSYS to find out both drive point and cross impedances considering different sizes and locations of disbonds and laminates of various lamination sequences. Damage indicators based on the root mean square deviation and peak locations have been formed from the impedance data. The entire data obtained from each joint set is divided into a training set and testing set. A feed forward neural network has been trained using the training set for detecting the disbonds from the damage indices. The efficiency of the network in detecting the disbonds has been tested using the testing set. Table 1 shows the comparison of the size and location of actual and predicted disbonds in a joint with symmetric cross ply laminate base and repair. Locations 1, 2 and 3 are the bonds between upper patch and base, upper patch and repair, base and repair respectively. As an extension of the work, experimental validation is being conducted now.

<table>
<thead>
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<th>Disbond size (mm\textsuperscript{2})</th>
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<tr>
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<td>Predicted</td>
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</tr>
<tr>
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<td>4.20</td>
</tr>
<tr>
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<td>8.00</td>
<td>8.50</td>
</tr>
</tbody>
</table>

Figure 1: Scarf joint with PZTs

Table 1: Actual and predicted disbonds

References


Delamination IV (Ticoajo Project)
Design of hybrid joints CFRP-metal Fracture toughness determination under Mode I and Mode II loading

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The Natural Laminar Flow (NLF) airfoils are shaped in such a way to delay as much as possible laminar to turbulent flow transitions in cruise in order to decrease viscous drag. NLF airfoils have better performance, lowering the fuel consumption and reducing carbon dioxide (CO2) emissions. The technological improvements of this topic are inspired through Hybrid Laminar Flow Control (HLFC) technology, under Clean Sky 2 platform.

New structures concepts for airfoils are being developed, in order to reduce CO2 to the atmosphere, but also these concepts must be focused on technologies oriented in recurring and non-recurring cost reduction. Such is the case focused on the One Shot process in composite manufacturing. The main purpose of this work is the hybrid joint, Titanium-Composite, on One shot process.

The work describes a new challenge in the design and experimental methods used to determine specimen dimensions for dissimilar or Asymmetric hybrid Double Cantilever Beam (ADCB) for Mode I and Asymmetric End Notched Flexure (AENF) for the determination of Mode II (shear) fracture toughness, GIC and GIIC. The fracture toughness describes the resistance to fracturing of hybrid Ti-Carbon joints manufactured throughout OOA processes. These parameters are therefore important when simulating the failure of aeronautical structures using aircraft fracture mechanics principles under static and dynamic loading conditions.

References

FATIGUE FRACTURE BEHAVIOUR OF DISSIMILAR METAL-COMPOSITE ADHESIVE JOINTS FOR AEROSPACE APPLICATIONS: AN EXPERIMENTAL STUDY

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Structures that are being assembled by fibre-epoxy composites and lightweight metals by adhesive bonding are constantly finding new applications in a range of industries such as aerospace, automotive and wind energy. Nevertheless, the fatigue fracture behaviour of such adhesive joints has not been sufficiently studied in literature. In the present work, the fatigue performance of titanium-CFRP adhesive joints under mode I loading is investigated. The adhesive joint under study is presented in previous work [1] and is primarily intended for aerospace applications; it is composed from two thin adherents, one titanium sheet and one CFRP laminate, and is reinforced from both sides with two thick aluminum beams to increase its flexural stiffness and ensure the non-yielding of the metallic parts. The dynamic interfacial fracture resistance is in the focus and aspects such as the loading that defines the crack propagation threshold as well as the determination of an appropriate Paris law are under investigation. Appropriate data reduction schemes, capable to analyze experimental measurements from asymmetric bi-material geometries are briefly discussed as well. The fatigue crack growth rate (FCG) da/dN is determined with two methods; i) through visual inspections with a special camera, and ii) through an effective crack length which utilizes the changes in experimental compliance. The compliance of the asymmetric bending-extension coupled sub-laminates is analytically derived. Detailed results are given, and useful conclusions are obtained for the crack propagation in such complex metal-composite adhesive joints.

References

ON THE FRACTURE BEHAVIOR OF METAL-COMPOSITE ADHESIVE JOINTS WITH RESIDUAL THERMAL STRESSES AND MULTIPLE CRACKS

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The present work presents results from the numerical analysis of the fracture behavior of a new structural adhesive joint with inherent residual thermal stresses and multiple cracks, loaded using the double cantilever beam (DCB) configuration. The new adhesive joint consists of thin titanium and CFRP adherents and is destined for application in the hybrid laminar flow control systems of future aircrafts [1].

The joint was manufactured at elevated temperature, which induced residual thermal stresses to the joint. After completion of the manufacturing process, the joint was stiffened with two thick aluminum beams to prevent titanium yielding during the subsequent experiments. For the needs of the DCB experiments, we created an artificial disbonding at the interface plane between titanium and CFRP. The issues related with the design, manufacturing, and experimental testing of the new joint under DCB are covered in our previous works [1, 2].

During the DCB experiments we detected the creation and propagation of a delamination crack between the first and the second layer of the CFRP laminate, together with the propagation of the primary crack along the titanium-composite interface. Thus, in the present work we use the cohesive zone modeling (CZM) method to model the mechanical behavior of the joint under DCB loading and with consideration of the double crack effect. A standard procedure is used for the determination of cohesive element properties using as input the strain energy release rate (SERR) value derived from previous analyses [1]. The secondary crack is modeled and the effect of its presence on the load-displacement response of the specimen is revealed. The present CZM results are compared with previous finite element analyses (FEA) using the virtual crack closure technique (VCCT) [1], which ignore the multiple cracks effect, and experimental results [1, 2].

In contrast to the VCCT, the CZM is capable of satisfactorily predicting the experimental load-displacement response of the metal-composite adhesive joint with residual thermal stresses and multiple cracks.

References

Moment loading testing and data reduction for characterizing the fracture toughness of hybrid joints

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A generic hybrid joint configuration for application in aircraft wing designed using Hybrid Laminar Flow Control (HLFC) is studied in the Clean-Sky 2 TicoAjo project. The metal and composite adherents have different thicknesses, and two metallic backing beams of different thicknesses are applied on both sides of the specimen to ensure the non-yielding of the metallic adherent. The study includes different technologies for the adhesive bonding of the dissimilar materials: co-bonding with and without adhesive, secondary bonding for thermoset composites and secondary bonding with thermoplastic material. The aim of the research is to derive the fracture toughness of the joint under different loading and environmental conditions.

Special attention is given to the in-house developed double cantilever beam (DCB) and the end-notched flexure (ENF) specimens using the moment loading test setup as investigated by Sørensen [1], see Figure 1. Residual thermal stresses are considered in the analysis of test results. The paper presents and discusses the results from DCB and ENF quasi-static interlaminar fracture tests at elevated and room temperature conditions and the data reductions techniques. The test results are evaluated to determine the fracture toughness and optimal bonding technology for the TicoAjo joint. The advantage of using the moment loading test setup is that the delamination crack distance does not need to be monitored during the test and that the mixed mode loading is easy to vary.

![Figure 1: The hybrid joint coupon (left); the schematic test setup (middle) [1]; the moment loading test setup at NLR (right)](image)

INFLUENCE OF LASER PRETREATMENT ON FRACTURE TOUGHNESS OF HYBRID CFRP/METAL CO-CURED JOINTS

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Reducing drag is an essential target for aircraft design. Friction drag represents about 40% of the total drag for common aircraft. Some commercial aircrafts like Boeing 737, the proportion of friction drag is even higher. Natural Laminar Flow (NLF) airfoils are shaped in such a way to delay as much as possible laminar to turbulent flow transitions in cruise in order to decrease viscous drag. NLF airfoils have better performance, lowering the fuel consumption and reducing carbon dioxide (CO2) emissions. The technological improvements of this topic are inspired through Hybrid Laminar Flow Control (HLFC) technology, under Clean Sky 2 platform. This will strengthen innovative advances in the next generation of aircrafts; overcoming the risks and the technologies eventually to join the next market window to replace the present fleet.

Improving the surface treatment of titanium for hybrid joints can increase the adhesion performance between CFRP/Metal for HLFC technology. The results indicate that treatment with IR lasers can potentially be used for pretreatment of titanium to manufacture titanium/composite hybrid joints of high quality and durability as required by aircraft industry. The work describes the effect of fracture toughness using specimens treated by IR lasers to increase the surface friction and consequently the best adhesion with the CFRP. The results are compared with other specimens considering sanded pretreatment. It was demonstrated the improvements of the Titanium surface pretreatment applying the by IR lasers technology.
Optimization I
OPTIMISATION OF ALIGNED DISCONTINUOUS COMPOSITES FOR TAILORED MECHANICAL PERFORMANCE

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Aligned discontinuous composites (ADCs) offer tailorability in their mechanical response through careful design of their microstructure. However, increased tailorability leads to increased design complexity, which makes it difficult to optimise ADC material systems.

An efficient yet accurate virtual testing framework (VTF) \cite{1} is used to simulate the mechanical response of ADCs, which takes several orders of magnitude less time to compute than alternative analysis techniques. In this work, the VTF is combined with an intelligent Bayesian optimisation routine, which uses a surrogate model to approximate the objective function and find optimal solutions with minimal objective function evaluations. Optimisable variables include the fibre types, their hybridisation ratio, fibre length, and matrix properties.

Single-objective optimisation analysis is used to fully exploit the tailorability of ADCs and identify systems with maximum strength, stiffness, or ductility (Figure 1). Multi-objective optimisation is used to identify Pareto fronts with optimal trade-offs between competing properties (Figure 2). As the VTF produces a non-deterministic output, the estimated Pareto front (formed using the surrogate model) produces a more accurate representation of the mean response. The surrogate model is also used to complete a sensitivity analysis (Figure 2) without making further evaluations of the objective function, thus maximising efficiency.

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References

MULTISCALE VIRTUAL TESTING FRAMEWORK TO OPTIMIZE INTERLACED COMPOSITES FOR IMPACT APPLICATIONS

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The pursuit of weight savings in the aerospace and automotive industries has led to the increasing use of composites in structural applications. The primary factor limiting further adoption of composite materials is their poor response to out-of-plane impact loading [1]. Improving the impact tolerance of composite laminates is primarily an exercise in arresting the formation and propagation of delamination. There are two routes to achieve this objective; modification of the properties of a laminate’s constituents, or modification of its architecture. Although existing architectural methods – e.g. z-pinning, stitching etc. – have been proven to increase impact tolerance, they also negatively affect a laminate’s undamaged strength and stiffness [2].

The objective of this research project is to develop laminates with improved impact tolerance which retain much of the in-plane stiffness and strength of angle ply laminates. This is accomplished through the interlacing of thin unidirectional tapes, see Figure 1 below. Interlaced laminates arrest delamination in a similar fashion to weaving, but have a higher stiffness and strength than woven laminates due to fewer fiber undulations.

A multiscale virtual testing framework was developed using Python and Abaqus to determine optimal interlacing patterns. Virtual tensile tests were conducted to compare the in-plane stiffness, strength, and resistance to delamination of interlaced and angle ply laminates. Stress concentrations at fiber undulations were determined through micro-mechanical numerical modeling. Experimental testing of interlaced and baseline laminates (without interlacing) was conducted to validate simulations. The extent of delamination in the deformed laminates was determined using c-scans.

![Figure 1. Layup sequence for a 2-ply (4 layer) interlaced composite laminate](image-url)

References


Towards an analytical and numerical design approach for Tailored Textiles

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Tailored Textiles (TT), see Figure 1, are load path optimized fiber-reinforced plastics, which offer the potential to improve weight saving as well as the cost-efficiency in manufacturing composite structures [1]. However, they are not widely used to industrial applications yet. For applying TT successfully the achievable cost and weight saving must be assessable in the early stages of the Product Development Process (PDP) to make an initial decision if TT technology fulfills the company’s targets best. An important part of the PDP is the design of the investigated structure. Nowadays, quasi-isotropic structures can be designed using the classical laminate theory or with the help of commercial FE-tools. However, the design of composites with TT is more complicated due to the additional rovings. In this paper, different analytical and numerical design approaches in order to design composite structures with TT are investigated. Based on a model developed by Szablewski [2] the engineering constants of composites reinforced with TT are calculated analytically. The rebar approach is used in order to represent the reinforcement numerically. Finally, these approaches are evaluated and assessed.

References

**LAYLA: DETERMINISTIC LAYUP OPTIMISATION OF COMPOSITE LAMINATES**

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Tailoring fibre orientations in composite laminates is central to the optimisation of aerospace structures for weight reduction. However, in spite of the many efforts in the engineering community, the optimisation of a laminate layup remains a non-trivial task due to the number of discrete variables defining a stacking sequence, as well as, the nonlinear relationships between fibre orientations and stiffness properties. To tackle this issue, the optimisation problem is often broken-down into two steps. First, fibre angles design variables are replaced by lamination parameters, i.e. continuous variables characterising the laminates’ homogenised stiffness properties. A gradient-based optimisation is then performed to obtain a set of optimised lamination parameters. Next, a second optimiser is employed to retrieve the stacking sequence that best matches the lamination parameters from the first step. A second optimisation is required because, in general, generating the tree of all possible stacking sequences exhaustively, to evaluate their fitness, is not computationally viable. Due to the discrete nature of the problem, solving the second step optimisation requires the use of integer programming techniques. Meta-heuristics methods are usually employed to this aim [1]. However, meta-heuristic optimisers suffer from poor convergence behaviour as the number of design variables increases, leading to detrimental and unpredicted losses in structural performance from the first to the second optimisation step.

To address this issue, we developed LAYLA, a deterministic optimiser that retrieves the **LAYout of LAminates** from lamination parameters. Stacking sequences are divided into groups of plies for which the fibre orientations are retrieved successively and iteratively. The optimisation sub-problems are solved using an in-house deterministic and combinatorial optimiser inspired by branch and bound algorithms. The optimiser’s novelty resides in the ability to control the level of exploration of the search trees and in a specifically-designed fitness function. Additionally, the optimisation procedure accounts for many of the stacking sequences design and manufacturing guidelines (e.g. symmetry and balance). As a result, manufacturable laminate layouts, closely matching target lamination parameters, are retrieved within seconds or minutes.

The authors will demonstrate the capabilities of the proposed stacking sequence optimiser. Compared to a genetic algorithm, our technique retrieves stacking sequences at least 13 times faster for ply counts as low as 40, with the retrieved lamination parameters closer to their targets. Moreover, for the design of thicker laminates, improved convergence towards the 1st-level properties is noticed, while computational times only increase linearly with the number of plies. Overall, the proposed optimisation technique will be shown to retrieve stacking sequences efficiently, allowing for the rapid optimisation of lightweight composite structures with thick laminates.

**References**

BLASTS: DETERMINISTIC BLENDED LAMINATE STACKING SEQUENCE OPTIMISATION

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The loading conditions across large composite shells structures usually vary over the structure’s width and length. Thus, dividing composite shells into several panels of different thickness and laminate layout is common practice to reduce the weight, a highly sought-after goal in aerospace engineering. Variation of the shell’s cross-section is possible by dropping plies at the panels’ boundaries. However, the strength of the multi-panel structures is significantly influenced by ply drops, due to interlaminar stresses that promote delamination. Design guidelines aim at mitigating the effect of ply drops on strength and at ensuring structural integrity with continuous plies across panel’s boundaries. Furthermore, stacking sequence mismatch at the panel boundaries increase the manufacturing complexity. Notably, butted edges should be avoided. The challenge is to design manufacturable multi-panel structures that satisfy global continuity and strength requirements, with panel layouts adapted to local loadings. The process employed to design such laminated structures is referred to as ‘blending’.

The blending optimisation problem is usually characterised by a large number of discrete design variables, such as the fibre orientations, typically restricted to 0, ±45 and 90°. At present, no optimisation technique can be used to retrieve the global optima of such problems in a reasonable computational time. Instead, the design space is generally reduced by selecting predefined ply drop layouts to reduce the number of design variables. For example, with guide-based blending, the panel’s stacking sequences all derive from a guide stacking sequence, a thickness distribution and the positions of the successive ply drops [1]. Moreover, the meta-heuristic optimisers usually employed to solve the blending problems suffer from poor convergence behaviour as the number of design variables increases. As a result, sub-optimal designs may be obtained with detrimental losses in structural performance.

The authors will present BLASTS, a novel optimiser for the design of Blended LAminates STacking Sequences. Stacking sequences are divided into groups of plies for which the fibre orientations are retrieved successively and iteratively, similarly than in previous work from the authors. For each optimisation sub-problems, a few ply drop layouts that satisfy design guidelines are randomly generated by examining the thickness difference for the group of plies across panel’s boundaries. The ply angle optimisations are then performed using an in-house deterministic and combinatorial code inspired by branch and bound algorithms. As a result, manufacturable blended laminate layouts are retrieved within minutes. The blending optimisation tool will be demonstrated for the benchmark 18-panel horseshoe problem.

References

Optimization II
This study focuses on the first-level problem of the multi-scale two-level (MS2L) optimisation strategy [1], that aims at determining, at the variable angle-tow (VAT) laminate macroscopic scale, the optimum distribution of the laminate mechanical properties over the structure in order to satisfy the requirements of the problem at hand. At the first level of the MS2L procedure, the VAT laminate is modelled as an equivalent homogeneous anisotropic plate whose mechanical behaviour is described in terms of polar parameters (which vary locally over the structure). The First-order Shear Deformation Theory (FSDT) is used to take into account for the influence of the transverse shear stiffness on the overall mechanical response of the VAT composite in the Finite Element (FE) model, see [2], and the B-spline surfaces are employed to represent the polar parameters fields. The advantage of using the Verchery’s polar method [3] is in the fact that the elastic response of the structure at the macro-scale is described in terms of tensor invariants, the so-called polar parameters, having a precise physical meaning (which is linked to the elastic symmetries of the material).

The effectiveness of the proposed approach is proven on a meaningfull benchmark: the maximisation of the first buckling load of a VAT composite subject to feasibility and geometric constraints. In order to speed up the optimisation process, the expression of the gradient of each physical response is determined in a closed form in terms of the design variables describing the shape of the generic B-Spline surface the related polar parameter field over the structure. In particular, the design variables are the polar parameters defined at each point of the control net of the B-Spline surface. The derivation of the analytical form of the gradient of the first buckling factor is anything but trivial and exploits two main properties of B-Spline blending functions: the strong convex-hull property and the local support property. Thanks to the B-Spline surfaces formalism, the optimised solution are no longer related to the mesh of the FE model, rather they are fully CAD-compatible and can be directly passed (in the form of an IGES file) to the software of the automated fibre placement (AFP) machine for manufacturing purposes.

References

OPTIMISATION OF THE POSTBUCKLING BEHAVIOUR OF VARIOUS ANGLE TOW COMPOSITE STRUCTURES USING A KOITER ALGORITHM

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Variable Angle Tow (VAT) laminates have notably enhanced the possibilities of tailoring the stiffness properties of thin-walled structures. This increased freedom meets the need for designing lighter-weight structures. Consequently, buckling and postbuckling phenomena often lead the structural response and have to be considered from the preliminary design stages [1]. As a result, optimisation strategies of both the buckling and postbuckling behaviour, able to deal with many variables, are required. Even if much work has been done in the last years, many issues remain. The most critical aspect regards the need for an efficient and general strategy to evaluate the post-buckling behaviour and a robust optimisation algorithm, able to deal with non-convex problems.

In this work, an optimisation strategy of variable angle tow composite structures is proposed. A multi-modal Koiter asymptotic approach is used to evaluate the non-linear structural behaviour and stochastic minimisation algorithms are employed to solve the optimisation problem. The process is based on a fibre path parameterisation and the optimisation variables are the fibre orientations. Many parameters can be used as objective function, as collapse load, transverse displacement or maximum strain. The Koiter method is based on the construction of a reduced order model leading to a notable reduction of the size of the nonlinear system of equilibrium equations, thereby making its solution rapid and inexpensive. It is implemented within a hybrid-stress solid-shell Finite Element environment that makes the algorithm efficient, accurate and avoids well-known locking phenomena [2]. The approach has no limitations concerning geometry and boundary conditions. Moreover, during the optimisation process, it allows the effects of geometrical imperfections to be considered. Manufacturing constraints can also readily included in the optimisation strategy.

The viability of the proposed strategy is confirmed by the numerical optimisation of a full scale structure. This work shows the possibility of performing an efficient and robust optimisation process with a multi-modal Koiter asymptotic approach, which represents a valid support for the design of buckling dominated structures.

References

HAIRMATE PROJECT: DESIGN, MANUFACTURING AND TESTING OF AN HYBRID AIRCRAFT SEATING

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The main purpose of the HAIRMATE project [1] is to manufacture and test an innovative commercial aircraft seating, designed to be produced mainly with CFRP components, in conjunction with some metallic elements. The original design of the seating was developed in the HAIRD project [2-4], where a lightweight (less than 10 kg per person) seat was proposed, being at the same time highly recyclable and easy to disassemble and dismantle.

The HAIRMATE project aims to improve the original design from the point of view of manufacturability and structural assessment. During the first part of the project, the seat will be redesigned considering the several moulds fabrication. From the point of view of the structural analysis in front of an impact event, more sophisticated computations will be performed, considering the nonlinear behavior of the materials. With regards of the damage of the materials, an extensive characterization campaign is being performed to capture the different materials configurations behaviors. During the last part of the HAIRMATE project, the seat will be manufactured and tested for certification (frontal 16G impact and 14G landing impact). Some minor redesigns are to be expected during this stage of the project.

Figure 1. Render of HAIRD seating in an Airbus A320.

References

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BEND-FREE ELLIPSOID OF REVOLUTION UNDER UNIFORM INTERNAL PRESSURE

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Shells are commonly used in several structural applications due to their specific load carrying capabilities. One of the most interesting features of shell structures is that they can resist external loads by developing membrane stresses yet, in general, also generate inefficient bending deformations and stresses. In this study, a pressurized composite ellipsoid of revolution is designed for zero bending and curvature change. To this end, the stiffness properties of the elliptical composite shell structure is tailored by fibre steering using an analytical model described in [1]. A definition of bend-free state, independent from the amount of internal pressure, is presented first. Based on this definition, the state of bending and curvature change due to internal pressure in the baseline and tailored structures are assessed by finite element analysis. The results show that up to a certain level of ellipticity, a bend-free state is achievable by fibre steering in elliptical composite shells of revolution. Figure 1 shows one of the several cases studied in this study in which the internal pressure-induced bending state of an isotropic ellipsoidal shell of revolution is compared with its tailored composite counterpart. As shown in Figure 1, by tailoring the stiffness via fibre steering the internal pressure-induced bending is suppressed throughout the structure, while in the isotropic case (baseline), there is considerable bending developed by the external load especially near the equator.

![Figure 1: Internal pressure-induced bending contour maps in a) isotropic and b) fibre-steered structure](image)

References

VIRTUAL MANUFACTURING AS AN ESSENTIAL TOOL FOR THE VIRTUAL TESTING AND OPTIMIZATION OF COMPOSITE PRESSURE VESSELS

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Composite pressure vessels for automotive and aerospace applications are certified based on several performance tests, e.g., composite hydrogen tanks for automotive applications are required to pass a series of burst, drop and cycle tests. From a design-by-analysis perspective it is very attractive to reduce the number of these expensive and time-consuming tests by virtual testing. Clearly there is a need for accurate and reliable simulation procedures to enable the required virtual tests. Important influences arising from the manufacturing process can only be described using a simulation of the process itself, i.e., virtual manufacturing. The most important effects include fiber mis-alignment, crossing, spreading, bridging and overlapping. These effects are primarily geometric in nature and are caused by the actual winding pattern which cannot be represented by stacked continuous layers. Furthermore, a variable fiber volume fraction is to a large degree a consequence of these geometric features. In addition, optimized structures may require local reinforcements which cannot be adequately described by a layered model. A new modeling approach using the enhanced filament winding simulation is proposed [1]. The aim is to resolve the local fiber architecture arising from the filament winding process, going beyond the laminate theory. The model is implemented with a fiber-bundle element which can be seen as an extension of reinforcing elements [2]. The most important geometric manufacturing effects are incorporated on the structural level. The model gives more accurate representations of the layer thickness and fiber orientation distributions and improves the prediction of the local stiffness and strength properties. As an alternative, a two-scale approach may be based on the proposed modeling but reduces the computational cost. Applications are in the design of engineering structures, e.g., composite hydrogen tanks for automotive applications and composite solid rocket motor cases for aerospace applications. Exemplary results are presented for the analysis of the structural case of a solid rocket motor and are compared with previous analysis results using a layered modeling approach [3].

References


In this work, the multi-scale two-level (MS2L) optimisation strategy [1] has been enhanced by integrating a global-local (GL) finite element (FE) modelling approach in order to deal with the problem of the preliminary optimisation of typical aeronautical composite structures.

In order to properly design the composite structure, three different working scales, each one with specific requirements, have been identified: the “global” macroscopic scale of the whole structure (e.g. a fuselage or a wing); the “local” macroscopic scale of the stiffened panels composing the structure and the mesoscopic scale of the laminae constituting the laminates.

In the presented strategy, the optimisation takes place in two steps. The first step involves both "global" and "local" macroscopic scale of the structure; the output of this step is the set of geometrical and macroscopic mechanical variables of each laminate composing the structure (laminate seen as an equivalent homogeneous anisotropic plate in the framework of the polar formalism [2, 3]). Suitable FE models are developed to evaluate the mechanical responses of the structures at both global and local scales and linked together through the use of a GL approach. The second optimisation step focuses on the mesoscopic scale of the generic laminate and aims at retrieving a suitable stack meeting the optimum value of the variables provided by the first step of the procedure. The solution search for both steps is carried out by means of the ERASMUS (EvolutionaRy Algorithm for optimiSation of ModUlar Systems) algorithm [4].

The effectiveness of the proposed approach is shown on a meaningful benchmark: the least-weight design of a composite fuselage barrel undergoing multiple loading conditions and subject to mechanical constraints (i.e. on the stiffness of the structure, on buckling and failure loads). Results are compared with those obtained from an analogous optimised aluminium solution.

References

Effect Of Defects
Mechanical properties of CFRP are deteriorated due to defects generated during the manufacturing process. Fiber waviness is one of commonly caused fiber irregularities. It is assumed to cause uneven load shearing between the waved fibers and the surrounding fibers but evaluation of its influence is almost limited macroscopic. In this study, the authors experimentally clarify the non-uniform fiber stress distribution resulted from fiber waviness in a microscopic scale. Local stress in fiber was measured directly in μm order spatial resolution by using micro-Raman spectroscopy.

Unidirectional CFRP laminate plates with one in-plane wave of a sinusoidal curve in the center were employed and applied tensile load. To obtain stress distribution in the plane perpendicular to tensile load, it was scanned transversely along the line across the apex(A) and the inflection point(B) of the wavy fibers. And also fiber stresses along the waved fiber and its surrounding straight fiber were measured.

Figure 1 shows the fiber stress distributions in cross section perpendicular to the tensile load direction. From the figure uneven fiber stress distribution was noticed that smaller stress than the average stress arose in the wavy fibers and larger stress occurred in the surrounding straight fibers. The difference in stress varied with curvature of the waviness and increases as curvature increases. In case of the ration of amplitude to wavelength, A/λ=0.053, the maximum stress reached about 1.5 times the average stress. The stress distributions through the apex point and that through the inflection point were almost the same. Our microscopic observations revealed in detail the nonuniform stress distribution caused by fiber waviness.

Figure 1. Fiber stress distribution along the cross plane perpendicular to the tensile direction.
THE EFFECT OF VOIDS ON THE MECHANICAL BEHAVIOUR OF UD-PLIES

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In the production of components made of fiber-reinforced composites, manufacturing induced flaws cannot be prevented completely, at least without increasing production costs. Glass fiber reinforced composites for rotor blades of wind turbines are a particularly cost driven application, hence certain imperfections are often accepted. Voids are one of the typical defects in this application. The presence of voids has a negative influence on the matrix-dominated mechanical properties, such as strength in the transverse direction of the fiber [1].

In the past, approaches for the computational determination of effective or homogenized material properties were often based only on a relative void volume content as a single parameter for the representation of this imperfection. Although it is common practice to relate and evaluate the influence of voids directly to the void volume content alone, it has been shown to be insufficient [2]. Recently there have been approaches to investigate how the shape, size and position of voids influence the mechanical properties in addition to the void content. In [3], techniques for the consideration of voids in a numerical model were developed. This model was then used to investigate the influence of void shape and location on the effective material properties. An extended description of voids in a numerical model requires the definition of suitable parameters accounting for size and shape of voids. The definition and calibration of such a parametrization extending beyond a simple description via a single void volume content variable poses a substantial challenge. In particular, this holds true when additional properties relating to size and shape are considered in a statistical manner.

In this contribution, the effect of voids on the homogenized, nonlinear stress-strain relation is investigated via numerical and experimental techniques. For this purpose, statistical data regarding void size and position are gathered by measurements from unidirectional specimens. The specimens are manufactured by a vacuum infusion process with deliberately inserted void defects. The collected statistical data is then incorporated into a numerical model. Subsequent experimental tests at coupon level are used to validate the numerical models.

References

A STATISTICAL APPROACH FOR DETERMINING THE CLUSTER DEVELOPMENT IN UNIDIRECTIONAL COMPOSITE MATERIALS UNDER FIBRE TENSILE LOADING

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The fibre tensile failure of composite materials is mainly dominated by the formation of clusters of broken fibres. This is in turn governed by the stochastic strength of the fibres as well as the stress redistribution around broken fibres. When a fibre fails, the fibre locally loses its stress carrying capability, but it is then recovered due to shear transfer in the matrix over a distance known as ineffective length. Throughout this region, the neighbour intact fibres are subjected into stress concentration. As the load is incremented, clusters of broken fibres start to form, and at some point, a critical cluster propagates unstably leading to final failure [1]. Currently, the literature has determined the formation of clusters using metrics based on the distance between broken fibres to establish whether they form a cluster or not [1, 2]. In this work, a statistical method called factorial analysis [3] is used to obtain the formation of clusters. The failure development of different hybrid and non-hybrid composite materials is simulated under fibre tensile loading using a progressive failure model [1], see Figure 1. Results show that the proposed statistical approach is a robust method for determining the cluster development.

![Figure 1. Schema of the progressive failure model: a) 3D view, b) 2D view.](image)

References

Numerical assessment of porosity defect in composite structures

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Reducing the cost of manufacturing of primary structures can be achieved by better control of the manufacturing tolerances and acceptable levels of variability. Predicting the effect of defects can also help clear quality concerns that affect the amount of parts that require repairs or need to be scrapped.

In this talk, a numerical method is presented for the assessment of the effect of variable distribution of porosity defects in composite structures at the macro scale.

A numerical method is first implemented to simulate random porous zones over the 3D surface the composite part. Two material configurations are considered: the sane one and the porous one. In the numerical model, each element of the part mesh is assigned one of the two materials. The random choice between the two materials for each element is based on the simulation of a Gaussian random field over the 3D surface [1] and using a truncation procedure to deduce the porous zones.

A Monte Carlo simulation method is used to study the effect of random porosity on the mechanical performance of the structure. To illustrate this approach, the case of a stiffened panel with a compression load case is considered and the mechanical performance is evaluated. By taking all the samples of random porosity distributions which have high values for the displacement and stress, the critical zones of the structure are identified.

Based on these predictive methods, a methodology could further be defined to select more critical areas for inspection and potentially reduce time required for quality controls.

**References**

The subject of research is the computational analysis of the effect of imperfections on mechanical behaviour of composites, with specific attention on filament wound structures considering their particular microstructure and loading conditions. The origins of scatter are diverse but the present contribution focuses on two typical kinds of microstructural variability: irregularity of fibre architecture and variation of fibre strength, and their effect on strength and transverse stiffness of fibre reinforced composites at the micro-scale.

For statistical modelling a set of periodic representative volume elements (RVE) with randomly located misaligned fibres are generated. Figure 1a shows one realisation which includes 12 (partial) filaments, each with a 7µm diameter. The finite element models are built in ABAQUS using the embedded element method. The second source of variability – variation of fibre strength – is introduced by means of the Weibull distribution. Material models include three failure mechanisms: matrix and fibre fracture, and failure of fibre/matrix cohesive interface. The prime focus of variability analysis is on the initiation and propagation of matrix/filament de-bonding, more particularly the effect of reinforcement topology on the area of de-bonding. Figure 1b shows such development of de-bonding with increase of deformation. In a next step, constitutive models developed upon the basis of statistical analysis of the simulation results, will be used to generate distributions of properties for meso-level models.

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Multiscale Analysis
Ceramic matrix composites exhibit intricate multi-scale architecture. Therefore, prediction of their thermo-mechanical behavior necessitates a sound knowledge of their inner structure. We have developed an original segmentation method [1] to build realistic numerical models using X-ray micro-computed tomography and a prior geometric model. These high-fidelity models, which are depicted on Fig 1a and b, are compatible with further finite element simulations at the mesoscopic scale. Direct mesoscale simulations allow incorporating a large amount of microstructural details, but also necessitate significant computational resources; an approximate macro-scale description may be sufficient to evaluate the elastic properties, or even to simulate damage initiation. Therefore, we propose a meso-macro modeling framework where the behavior of the macro-elements is derived from the knowledge of the local direction and volume fraction of constituents, thanks to the mesoscale segmentation. The constitutive equation of the macro-elements is obtained through an equivalent lamina. This drastically reduces the size of the model while keeping an approximate description of the local anisotropy and heterogeneities. Elastic and damage simulations are performed on both meso- and macroscale models and are compared in terms of global stiffness and local stress fields (cf. Fig. 1c and d). The accuracy of the enriched macroscale models will be evaluated depending on the size of macro-elements. For a given quantity of interest, the error with respect to the reference mesoscale model will help to determine the adequate level of description.

Figure 1. X-ray micro-computed tomography of a woven CMC junction (a) and corresponding meso-scale FE model (b). Visualization of the local stress field for the mesoscale (c) and the enriched macroscale models (d).

References

Virtual performance characterization of 3D textile reinforced composites: multi-scale modelling and efficient scale bridging

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Classical 2D composite laminates are known to suffer from limited through-thickness strength and resistance against delamination. Composites with a 3D textile reinforcement have the ability to overcome these limitations. However, the assessment of the mechanical performance during the material design process can be cumbersome due to the uncertainty about the impact of the material structure. Moreover, existing composite design rules are commonly based on a traditional laminate theory and cannot be applied directly.

The present contribution introduces an end-to-end multiscale approach for the virtual characterization of the mechanical performance of 3D textile reinforced composites. Originating from the mechanical properties of the raw constituents, the performance is gradually characterized on different length scales. The link between the length scales is performed through the identification of the effective orthotropic stiffness and strength properties. While standard energy-equivalence based homogenization approaches as in [1, 2, 3, 4] can be directly applied for the link between the micro and meso scale. The application for the scale bridging between the meso and macro scale leads to a poor prediction of the out-of-plane performance. To overcome this issue, a novel homogenization approach has been implemented that allows to calculate effective material properties based on a meso scale unit cell and to transfer relevant structural information from the meso scale to the part level. Embedding of the overall approach in the commercial FEM package ESI Virtual Performance Solution (VPS) allows for a direct application of the solution to industrial problems.

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References
HOMOGENISATION OF POROUS PZT CERAMICS WITH LOCAL ALLOYING PORE SURFACES UNDER THE INFLUENCE OF HETEROGENEOUS BY INTENSITY AND DIRECTION POLARIZATION FIELD

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Porous piezoelectric materials can be effectively used as active materials for piezoelectric transducers in hydroacoustic and medical ultrasound applications. However, the stiffness of porous PZT ceramics decreases with the porosity growth. In order to increase the stiffness, recently a method of transporting microparticles of various materials into piezoceramic skeleton was introduced. The application of this method allows one to obtain porous piezoceramic materials, for example, with alloying pore surfaces. This work continues author's investigations of homogenization models for porous piezoelectric composites with metalized pore surfaces [1, 2]. In order to determine effective properties of these composite materials, we used the effective moduli method and the finite element method with algorithms of building the representative volumes with closed porosity structure. The local alloying was modeled by the boundary conditions of free electrodes and elastic shells on the parts of pore surfaces. Next, we simulated the polarization field around the pores that was heterogeneous by intensity and direction. In order to do this, we previously solved the electrostatic problem for the dielectric porous material by the finite element method. Further, based on the obtained electric field, the polarization field was found. After that, every volumetric finite element of a representative volume was associated with a new coordinate system so that the third axis was chosen codirectional to the element’s polarization vector. The material properties for each finite element were also recalculated in accordance with the found intensities of the polarization field. As a result, we obtained a representative volume with inhomogeneous properties of PZT ceramic matrix. The experiments showed that the porosity growth resulted in the increase of various piezoelectric coefficients and dielectric permittivities. These unusual properties can improve the use of piezoelectric composites with alloying pore surfaces in hydroacoustics and medical ultrasound [3]. This research was done in the framework of the RFBR project 16-58-48009 IND_omi and DST.

References


A viscoelastic damage model for nanoparticle/polymer nanocomposites at finite strain: A multiscale approach

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Experimental tests show that nonlinear viscoelasticity characterizes the mechanical behavior of boehmite nanoparticle (BNP)/epoxy nanocomposites. This paper presents the development and numerical implementation of a physically based constitutive model for BNP/epoxy nanocomposites undergoing finite strain. The proposed constitutive model allows capturing the main features of the stress-strain relationship of BNP/epoxy nanocomposites, including the nonlinear hyperelastic, time-dependent and softening behavior. The characterizing feature of this study is to propose a methodological framework based on molecular dynamics simulations and experimental tests to identify the material parameters for the model. The concept of strain amplification is adopted to account for the effect of nanoparticles on the stress–strain response [1]. The time-dependent viscoelastic deformation under loading is described using the Eyring model [2]. The stress softening behavior is captured by a monotonically increasing function of deformation, so-called softening variable. The results show that the model predictions of stress-strain relationships are in good agreement with experimental data at different BNP weight fractions. Finally, the constitutive model is implemented in the finite element analysis and examined by means of a benchmark example. Experimental–numerical validation confirms the predictive capability of the present modeling framework, which provides a suitable tool for analyzing BNP/epoxy nanocomposites.

Figure 1. Summary of the proposed viscoelastic damage constitutive model for nanoparticle/epoxy nanocomposites.

References

A DYNAMIC SPRING ELEMENT MODEL FOR THE PREDICTION OF LONGITUDINAL FAILURE OF POLYMER

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The need to understand the failure mechanisms in composite materials at the micro level has gained additional importance due to the pressing need to develop high performance materials for more demanding applications. This understanding makes it possible to develop a new generation of polymer composite materials in-silico.

To understand fibre dominated failure it is necessary to have accurate models that are able to capture the main failure mechanisms in this type of failure. Although complex micromechanical models that capture these mechanisms exist, they are computationally expensive and can only be used for a limited representative volume element sizes [1]. Simplified models are, therefore, necessary to allow faster predictions, although at the cost of some accuracy. The faster computation times of simplified models allow also the study of more material variations and can be used for optimization purposes.

In this work, an extension of the Spring Element Model [2] to a random fibre packing and hybrid composites is presented. Additionally, this model extends the Spring Element Model to consider the dynamic effects of fibre failure. The dynamic stress waves that propagates within the intact fibres increases that surround the broken one increase the stress concentrations and, therefore, increase the failure probability of these fibres. This dynamic effect will change the formation process of clusters of broken fibres, which will influence the predicted behaviour of the material. A study on the influence of the dynamic effects on the local stress fields surrounding a broken fibre and on the behaviour of the material is done for both non-hybrid and hybrid composites.

References

Characterization
EXPERIMENTAL CHARACTERISATION AND MODELLING OF MULTIDIRECTIONAL CFRP COMPOSITES SUBJECTED TO COMBINED TENSION/COMPRESSION-SHEAR LOADING

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Multidirectional composite laminates made from Carbon Fibre Reinforced Polymer (CFRP) materials are used for lightweight aero, marine or automotive structures in areas of high loading and multiaxial stress states. They exhibit not only high specific stiffness and strength, but can also be tailored/optimised by variation of the stacking sequence, fibre orientations and ply thicknesses. Multidirectional CFRP laminates are designed using modelling techniques and failure theories, which have rarely been validated against multiaxial experimental data [1]. Consequently, there is a clear need for benchmarking and validation of model predictions against high-fidelity experimental data. In this study, three quasi-isotropic multidirectional CFRP laminates (Figure 1) were tested using a novel Modified Arcan Fixture (MAF), which can induce combined tension/shear or compression/shear loading [2]. The laminates were chosen to challenge current failure theories, as well as to establish guidelines for design. Digital Image Correlation (DIC) was used to obtain full field strain maps on both specimen sides, and X-ray scanning was used to identify manufacturing defects and initial failure modes. A nonlinear Finite Element (FE) model of the MAF specimen was developed accounting for the nonlinear behaviour of the UD plies subjected to transverse compression and shear stresses [3]. Failure initiation was predicted using the LaRC failure functions [4]. Upon failure initiation, the ply elastic properties were degraded based on a simple selective damage model. FE model predictions were compared against the multiaxial experimental data, and guidelines for the design of multidirectional laminates were formulated.

![Figure 1. Lay-up of the investigated multidirectional CFRP laminates.](image-url)

References

Characterization of the non-linear mechanical response of biaxially-tested angle-ply laminates

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Although carbon fibre reinforced polymer composites usually exhibit a linear- brittle elastic behaviour, there are some ways of obtaining a pseudo-ductile behaviour in these materials, in order to reach higher failure strains, and therefore, a larger strain energy absorption. Angle-ply laminates, and especially [±45°]ₜₐₜₜ lay-ups, are good examples of this highly non-linear behaviour, which have been studied mainly under uniaxial tensile loads and, recently, under flexural loading [1]. Nevertheless, the typical composite structures are frequently subjected to multiaxial stress states, which can not be accurately characterized by means of standardized testing. Hence, more experimental data is necessary to completely understand the non-linear response of angle-ply laminates when submitted to more realistic load scenarios. However, multiaxial testing, and specifically, biaxial tests are costly to perform extensively, leading to look for a numerical approach alternative.

In the present work an experimental analysis of the biaxial response of angle-ply laminates is performed by means of cruciform-shaped specimen with a methodology based on previous works with glass-fibre reinforced polymer [2,3], in this case with special attention to the pseudo-ductile behaviour. In addition to the experimental results, novel numerical models based on damage initiation and accumulation are developed and compared with good agreement with the experimental evidences. It is important to note that this meso-mechanic numerical simulation is able to predict accurately the initiation of pseudo-ductility under different multiaxial stress-strain states. Finally, the influence of slight deviations in the load application in both directions of the biaxial test is detailed experimentally and numerically, which helps to understand the importance of the load regulation in this kind of testing.

References


NUMERICAL BESPOKE TEST METHOD DEVELOPMENT TO INVESTIGATE THE INFLUENCE OF THROUGH-THICKNESS COMPRESSION AND SHEAR STRESSES ON THE LONGITUDINAL FIBRE TENSILE STRENGTH OF CFRP

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The fibre direction strength of unidirectional carbon fibre reinforced polymers (CFRP) is an important design parameter for lightweight applications. It is more difficult to predict the composite strength under complex stress states. Research has shown that high through-thickness (TT) compression stresses interact with the longitudinal tensile stresses, resulting in decreased tensile loading resistance [1]. High TT stresses can occur in load transfer areas, for instance when components are clamped. Such a stress state is defined by high TT compression, TT shear and longitudinal tensile stresses. The influence of TT shear stresses, especially in combination with TT compression, on the longitudinal fibre tensile strength has not yet been fully investigated.

Finite element analysis (FEA) was used to design a bespoke biaxial test method (Figure 1) which is based on a four-point bending test with offset indentors to investigate the influence of the complex TT compression and shear stress states on longitudinal fibre tensile failure. Superimposed TT compression and shear stresses are generated, if the centres of the opposite indenters are close enough and slightly offset. Hybrid specimens with CFRP material in the middle and support material on the outside are used to generate failure at the to be investigated stress state. Digital image correlation (DIC) can assist tracking the specimen failure location and strain state. By combining DIC and FEA data, the stress state at the failure load can be determined to investigate the influence of different stress ratios.

Figure 1. Bespoke test method FEA model

A 3-dimensional FEA model was developed, which can capture edge effects, delaminations, thermal residual stresses and loading sequence effects. The FEA model was used for the design of the bespoke test method and for analysis of the experiments to understand the influence and interactions of the main process parameters. Results show that different TT compression to shear stress ratios can be investigated with a single jig. Due to the biaxial test machine the ratio of longitudinal fibre tensile stresses to the TT compression and shear stresses can be also varied. The range of different stress states that can be achieved will be presented in this work. Furthermore, possible difficulties related to non-linear material behaviour, design and measurement accuracies will be discussed.

References

ASSESSMENT OF INDENTATION-INDUCED DAMAGE MECHANISMS IN THICK-WALLED COMPOSITE CYLINDERS

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In order to unravel the damage mechanisms occurring in composite-overwrapped pressure vessels (COPVs) subjected to crash conditions, a combined experimental and numerical study has been performed. For the purpose of generality and simplicity, quasi-static indentations on filament-wound cylinders are considered first, instead of geometrically complex impacts on COPVs.

These cylinders are analysed both experimentally and computationally. For the experiments, filament-wound cylinders with different thicknesses, lengths and lay-ups are loaded using cubic-formed impactors. The same and additional variations are considered in the numerical model. The developed numerical model consists of multiple composite layers, which are modelled with continuum shell elements. Delaminations are represented by cohesive elements. The model uses a 3D failure law since the complex stress state requires the out-of-plane stress components to be accounted for.

The variation of the wall thickness serves to assess how failure mechanisms change when transitioning from thin-wall to thick-wall cylinders. Theoretically, in thin-walled cylinders, the deformation is governed by bending and the occurring stresses are thus in-plane. For larger wall-thicknesses, the thick-wall effect becomes increasingly important. This effect causes out-of-plane normal and shear stresses to become increasingly significant compared to the in-plane bending stresses. As a result, failure mechanisms such as delamination and fibre kinking become more prone to occur. The experimental results are used to identify which mechanisms occur, and the numerical model is subsequently exploited to analyse the responsible mechanism.

Several cylinder lengths are considered to investigate the behaviour under uniformly distributed loads and for local intrusion of the impactor in the cylinder. Furthermore, different lay-ups are studied to investigate the stiffness irregularity at the cross-over from one orientation to another. The corresponding difference in stiffness causes interface shear stresses which trigger interlaminar failure. Finally, in view of its future use in pressure vessel applications, the influence of a tensile preload (internal pressure) on the occurring failure mechanisms is studied.
Identification of the constitutive properties of additive manufacturing composites using the Finite Element Method Updating

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On the one hand, the identification of the constitutive properties in fiber reinforced polymers requires different and repeated experimental tests. The Finite Element Method Updating (FEMU) technique was introduced with the aim of reducing the number of tests involved and the number of repetitions [1] using intensive computation and full displacement fields. The characterization is carried out with a test (dynamic or static), a numerical technique (FE) and the measure of a heterogeneous displacement field. The solutions proposed so far under this methodology have been mainly oriented to metal materials [2], carbon and glass fiber composite materials and polymer matrix [3,4]. On the other hand, the mechanical properties of the parts produced different additive manufacturing techniques such as Fused Deposition Modeling (FDM) are not homogeneous. In fact, these properties not only vary with the considered direction, but they can also change from one location to another due to the manufacturing process itself. Therefore, the use of FEMU can be very useful to identify the constitutive properties of additive manufacturing parts. This study focuses on predicting the apparent elastic constants of composite materials from additive manufacturing. The solution proposed uses Gauss-Newton optimization algorithm [5], which operates with a FE model and a deformation field measured with a digital image correlation technique (DIC). The method is applied to the tensile test of unidirectional 3D printed composite specimens. The results obtained confirm the robustness of the method to deduce the constitutive properties and the corresponding variation when different printing orientations are considered.

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This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union’s Horizon 2020 research and innovation programme under grant agreement No 821300. This publication reflects only the author’s views and the European Union is not liable for any use that may be made of the information contained therein.
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