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Modelling and simulation methodology for unidirectional composite laminates in a Virtual Test Lab framework

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A B S T R A C T

A reliable virtual testing framework for unidirectionally laminated composites is presented that allows the prediction of failure loads and modes of general in-plane coupons with great realism. This is a toolset based on finite element analysis that relies on a cohesive-frictional constitutive formulation coupled with the kinematics of penalty-based contact surfaces, on sophisticated three-dimensional continuum damage models, and overall on a modelling approach based on mesh structuring and crack-band erosion to capture the appropriate crack paths in unidirectional fibre reinforced plies. An extensive and rigorous validation of the overall approach is presented, demonstrating that the virtual testing laboratory is robust and can be reliably used in for composite materials screening, design and certification.

1. Introduction

Fibre Reinforced Polymers (FRP) have become widely used in structural applications for the aerospace, automotive, energy and sports sectors. Owing to their unique combination of specific mechanical properties (high stiffness, strength, toughness and energy absorption combined with low density), these materials are excellent candidates for lightweight structures, in spite of their high cost. To improve the economic case in favour of FRP, the reduction of costs related to their manufacturing, design and certification is imperative and constitutes one of the pressing engineering issues of today. Whilst efficiency gains on the production side are being achieved with out-of-autoclave and automated manufacturing technologies, design and certification requirements still imply extensive and costly experimental test programmes which could turn out to be infeasible due to the large number of design possibilities, large number of material properties and variables to study, combined with the absence of reliable design tools [1]. To face the challenge of cost reduction on this side, the development of reliable computational tools able to accurately predict the full mechanical response of FRP from elastic behaviour to damage onset and progressive structural collapse is inevitable. Reliable Virtual Testing can accelerate materials screening and design processes, which are specially complex in the aeronautical sector, and lead to an effective simplification of certification procedures. Moreover, an accessible virtual testing, screening and design approach is possibly the way to expand the application of FRP to other sectors of economical activity.

Virtual testing of laminated composites involves the use of the meso-scale, in this way accounting for the individual plies and ply interfaces within a finite element (FE) analysis approach. At this scale, the complex ply and interface damage and failure mechanisms, as well as their interactions, can be simulated in order to predict the final failure of FRP specimens. In this way, it is possible to establish laminate material allowables that can be used for the purpose of laminate design. However, due to the complex nature of the sub-critical damage modes such as transverse matrix cracks, axial splits (fibre/matrix shearing) and delamination, the prediction of ultimate strength is one of the major challenges in virtual testing of composites [2,3]. In recent years, significant progress has been made in meso-modelling of FRP laminates, specially at material constitutive level, but several issues still remain a challenge, such as the physically-sound simulation of the progression of damage mechanisms that lead to the final failure of composite coupons.

Because the possible failure mode and loci are known in advance, the usual approach to model delamination is the explicit introduction of split planes at the ply interfaces whose traction-separation behaviour is governed by cohesive laws. The appropriate kinematic description is achieved by means of cohesive elements, which require through-thickness conforming meshes, or by means cohesive contact surface behaviour that allows the flexibility of distinct meshes on different plies. On the other hand, the possible intralaminar failure modes and location are not known *a priori*. Therefore, the most common

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methodology to simulate the behaviour of the plies is Continuum Damage Modelling (CDM). However, due to its dependency on mesh size and orientation of mesh lines, by itself, the CDM approach cannot ensure the correct kinematic representation of the laminate damage modes, in this way compromising the accurate determination of failure loads. In order to force damage localization along physically-sound crack paths, several authors have proposed the introduction of artificial split planes in the ply FE discretization whose traction-separation behaviour is determined by cohesive laws, e.g. [4–6]. A more general solution is the extension of the traditional FE method to include extra degrees of freedom and displacement functions, the so-called extended FE methods (e.g. [7–9]). Owing to the use of these discrete crack methods, the correct representation of failure modes in particular composite coupons, e.g. open-hole tension, has been achieved [10,11]. Moreover, it has been shown that these techniques are well suited to tackle competing laminate damage mechanisms such as delamination and matrix cracking, allowing the correct representation of event such as delamination migration [12,13]. However, these numerical strategies are computationally expensive in comparison with CDM which limits their potential use in larger structures.

Although accurate numerical approaches have been proposed for particular configurations, to the knowledge of the authors there is no efficient and reliable numerical framework for physically-based simulation of general virtual testing of composites coupons including multiple test standard used for material certification such as in-plane unnotched tension/compression (UNT/UNC), in-plane shear (IPS), open-hole tension/compression (OHT/OHC), low velocity impact (LVI), compression after impact (CAI), bolt bearing, etc. This paper presents an efficient and robust virtual testing toolset to perform reliable simulation of unidirectional composite laminated coupons that predicts competing ply and interface damage mechanisms and, overall, laminate failure modes with great realism. This virtual test framework consists of several tools, namely: i a commercially-available explicit FE solver tool (ABAQUS/Explicit [14]) to tackle the numerous sources of non-linearities in the models in an efficient way; ii) a sophisticated three-dimensional CDM for unidirectional FRP plies, implemented by means of a user subroutine in the FE solver, that enforces element erosion; iii) a surface-based cohesive-frictional modelling algorithm (native of ABAQUS/Explicit) to model ply interfaces; iv) a purpose-built automated ABAQUS plug-in, based on Python code, for the meso-modelling of unidirectional laminated coupons that applies regularized meshes, i.e. controlled mesh size, mesh-alignment and directional biasing, in this way enforcing damage localization along physically-sound crack paths. A similar strategy has been previously applied by the authors, in a less systematic way, in the simulation of LVI [15] and in the numerical analysis of effects of defects [16]. It will be demonstrated that this numerical framework guarantees the appropriate constitutive and kinematic simulation of the damage and failure of composite coupons. Henceforth, the terms 'laboratory', 'framework' and 'toolset' will be used interchangeably in the context of virtual testing.

This work demonstrates that the sound kinematic simulation of composite damage modes and the accurate prediction of failure loads can be achieved by combining conventional constitutive approaches with appropriate discretization and meshing of ply and interfaces. For the sake of contextualization, and to highlight key elements, the constitutive models are briefly introduced, with emphasis given to the their input properties. Then, the paper focuses on the details of the discretization and meshing procedures used in the virtual representation of composite coupons. The modelling tool has been scripted in the programming language Python which allows the direct interaction with ABAQUS pre-processing, simulation and post-processing capabilities. An extensive and rigorous validation of the virtual testing toolset is presented, involving the correlation between experimental and simulated failure modes and loads resulting of standard UNT, UNC, OHT and OHC tests. These analyses were performed on different laminates commonly used in design space of aeronautical structures, and on configurations containing clusters of plies with the same fibre orientation, which are not commonly used in aeronautical design, i.e. off-design configurations.

2. Modelling the deformation behaviour of unidirectional FRP

The major part of past research efforts on the simulation of composite materials has been directed at the constitutive modelling of the deformation mechanisms. However, if the appropriate kinematic simulation is not possible, the material is unable of deforming to represent those mechanisms. In general progressive failure of composite laminates, there are several potential damage modes that interact with each other, and their kinematic representation becomes a necessary condition to accurately predict the final failure of the material. This section starts by presenting the constitutive models adopted in the virtual testing framework and then focuses on the key aspects that allow the appropriate kinematic simulation of unidirectional composite coupons.

2.1. Constitutive modelling

Two distinct numerical approaches are used to model all relevant damage modes in unidirectional laminates. While interlaminar damage is assumed to occur in the form of delaminations along predefined and discrete crack planes, intralaminar damage might occur in the form of fibre breakage, fibre pull-out, kink-banding and matrix cracking at any location within the plies. While the first method is readily available in ABAQUS/Explicit [14], the second has been implemented in Fortran-coded 'VUMAT' subroutine to be used with a numerically explicit integration scheme (ABAQUS/Explicit [14]).

2.1.1. Interlaminar behaviour

The ply interface response is modelled by means of a general mixed-mode cohesive zone method coupled with frictional behaviour. The coupled cohesive-frictional approach is adopted to include the possible effects of ply friction during and after delamination. In this way, the shear stresses caused by friction at the interface are ramped progressively and proportional to the degradation of the interface, thus once the interface is fully delaminated, the surface interaction is uniquely governed by a pure Coulomb model. For the pure cohesive response, damage onset is identified by means of a quadratic interaction criterion that is a function of the interlaminar strength values for each of the damage modes. Once delamination is initiated, the cohesive tractions transferred through the interface decrease linearly to zero dissipating the fracture energy corresponding to the specific mixed-mode loading mode, as given by the BK damage propagation criterion [17]. This approach, previously used by the authors [15,16], is based on the mixed-mode cohesive zone models proposed by Camanho et al. [18] and Turon et al. [19] and is implemented in the kinematics of surface contact interaction algorithms available in ABAQUS/Explicit [14].

The combined effects of friction and cohesive behaviour has been addressed by other authors, e.g. [20], whose works eventually led to the development of cohesive element formulations that take both mechanisms into account; a capability similar to the one used in this work with cohesive-frictional surface interactions. The effect of friction on the failure of the in-plane loaded specimens analysed in this work is expected to be limited. However, the proposed methodology is meant to be applied in the virtual testing of a wide range of composite coupons, including the out-of-plane loaded drop-weight impact test, wherein friction plays a more pronounce effect on ply interface behaviour [15].

2.1.2. Ply behaviour

The unidirectional FRP plies are modelled by means of a thermodynamically-consistent CDM, based on the work of Maimí et al. [21,22], that guarantees the appropriate energy dissipation for different physically-observed fracture modes. Important modifications were