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Physically-sound simulation of low-velocity impact on fiber reinforced laminates

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ABSTRACT

A high-fidelity virtual tool for the numerical simulation of low-velocity impact damage in unidirectional composite laminates is proposed. A continuum material model for the simulation of intraply damage phenomena is implemented in a numerical scheme as a user subroutine of the commercially available Abaqus finite element package. Delaminations are simulated using of cohesive surfaces. The use of structured meshes, aligned with fiber directions allows the physically-sound simulation of matrix cracks parallel to fiber directions, and their interaction with the development of delaminations. The implementation of element erosion criteria and the application of intraply and interlaminar friction allow for the simulation of fiber splits and their entanglement, which in turn results in permanent indentation in the impacted laminate. It is shown that this simulation strategy gives sound results for impact energies bellow and above the Barely Visible Impact Damage threshold, up to laminate perforation conditions.

1. Introduction

Low-velocity impact (LVI) events occur with some frequency on composite structures such as airplane components. From ground operations to unavoidable birds, there is a range of situations where an external aircraft component may be subjected to unexpected impact loads. In most cases, such as tool dropping, the impactor has a relatively high mass and a low velocity. The damage produced may be barely visible from the outside of the laminate, in the form of a small indentation, while the inside may hide delaminations that are not easily detectable through routine inspections. The spread of these delaminations over wide areas of the structure may severely compromise its residual compressive strength. Therefore, the ability to predict the impact damage resulting from potential LVI events is of great importance in the aeronautical industry.

Traditionally, impact damage models rely on either analytical calculations or extensive experimental data. On one side, analytical predictions of the impact damage resistance and tolerance of composite laminates are overly simplified and unreliable. Several authors have proposed analytical formulations for the prediction of impact damage in composite laminates [1,2]. However, the complexity of the physical phenomena, which includes dynamic structural behavior and loading, contact, friction, damage and failure, often results in an oversimplification of the problem and limits the analytical models. Conversely, testing each promising design is time-consuming and costly. Low-cost virtual testing, by means of nonlinear finite element (FE) analyses, could replace most of the actual impact testing of laminates. The numerical approach is a more flexible and powerful alternative to analytical formulations. The possibility of modeling the constitutive behavior of each material at local (element) level adds to the capacity of simulation of complex structures under seemingly complex external loads and boundary conditions.

In the present work, a reliable numerical strategy for the simulation of impact damage in composite laminates at the meso-structural level is proposed. Under out-of-plane loads, such as impact, laminated composites may suffer damage in the form of different mechanisms such as: (i) matrix cracking and fiber failure and (ii) delaminations at interfaces between plies. If acceptable accuracy is to be expected from the numerical impact analyses, these damage phenomena need to be well captured.

Continuum damage mechanics (CDM) is an accurate framework to predict the quasi-brittle process of failure in composites, where the gradual unloading of a ply after the onset of damage is simulated by means of a material degradation model. Non-linear constitutive models defined in the context of the mechanics of continuum media have been developed and implemented in FE codes in the past [3]. The damage model used in this work is an extension to three-dimensional scenarios of the plane stress formulation proposed by Maimí et al. [4,5] for in-plane behavior. The main

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advantages of this formulation are: (i) the use of the physically-based LaRC04 failure criteria [6] for the prediction of the onset of matrix cracking and fiber fracture under tensile and compressive loads; (ii) the accounting for the effects of thickness and constraining on the apparent ply transverse tensile and shear strengths [7]; (iii) the modification of Bažants crack band model [8,9] to ensure a mesh-independent solution in scenarios where the fracture planes may have several orientations, and (iv) the simulation of crack-closure effects under load reversal cycles. Nevertheless, the application of this model is limited to the range of quasi-static loading and low strain-rate conditions, which encompass LVI events [1].

Additionally, information from the material damage mechanics at microstructural level is passed to the meso-structural level, namely the model kinematics drive matrix cracks to progress parallel to fiber directions. The importance of the correct prediction of matrix cracking in impact situations has been previously identified by some authors [10,11] who adopted the modeling technique consisting of introducing patterns of cohesive intralaminar cracks that open according to a cohesive fracture criterion. The drawbacks of this approach are the added model preprocessing difficulties and the possible influence of the cohesive penalty stiffness on the global stiffness of the impacted specimen. A different strategy was adopted by Laš and Zemčík [12] who took advantage of the preferential crack alignment with mesh lines of the intralaminar CDM model. However, the ply-to-ply stacking sequence was limited by mesh constraints. Previous simulations using conforming meshes [13–16] have shown the limitations of this strategy in the correct prediction of matrix cracking directionality, a characteristic that strongly interferes with other damage mechanisms such as delamination and perforation.

In this work, several modeling techniques are explored in an effort to correctly capture the impact phenomenology, in particular the relevant damage mechanisms. The influence of material-aligned and non-aligned meshes on the LVI response is studied, as well as the influence of using cohesive elements or cohesive contacting surfaces. In the case of cohesive elements, a stabilization technique is explored to avoid sharp, non-physical oscillations during crack opening. The study converges in that the most accurate methodology is as follows. Each laminate ply is modeled using a single layer of reduce-integration brick elements associated with the constitutive model presented below. The interfaces between the plies are simulated by means of traction-separation cohesive behavior, and post-decohesion friction, coupled with a surface contact algorithm [17]. This constitutes a reliable numerical tool for the prediction of delamination under several loading scenarios, and allows for non-conforming meshes between delaminating plies. These are generated by aligning the mesh on each ply with fiber directions in order to correctly simulate matrix cracking. Element erosion and the application of friction allow the simulation of fiber splits and their entanglement which results in the permanent indentation of the impacted specimen.

A brief description of the material models used in this work is given in Section 2. In Section 3, several techniques for impact modeling are explored, and their advantages and disadvantages are identified. In Section 4, the most suitable technique is applied to the practical simulation of the standard drop-weight impact test [18]. Finally, conclusions of this work are presented in Section 5.

2. Continuum models for impact damage

Two distinct formulations are used to simulate the damage phenomena occurring in layered composites under out-of-plane, low-velocity impact loading: (i) a continuum damage model, to address the matrix and fiber damage occurring at ply level and (ii) a cohesive damage model to account for delamination. While in the case of delamination, the crack plane is known *a priori*, the location and direction of matrix cracks and fiber breakage bands needs to be determined along with the analysis.

The intraply damage model used in this work follows the formulation developed and implemented by Maimí et al. [4,5] for in-plane stress analysis with implicit integration of the equilibrium equations. In the present case, the original formulation was extended to take into account stress states in the three-dimensional stress space and was implemented for the explicit integration method, namely it was coded as an Abaqus/Explicit VUMAT user-written subroutine [17]. The cohesive damage model is based on the explicit implementation in cohesive elements [19] and cohesive contacting surfaces [17] of the formulation initially proposed by Camanho et al. [20]. The main aspects of these models are presented in the following.

2.1. Continuum damage model for a 3D ply

For each damage mode, the ply constitutive model used in this work follows the general form schematically represented in Fig. 1a. The material response is linear-elastic until the onset of damage and, at higher strains, it softens according to an exponential law.

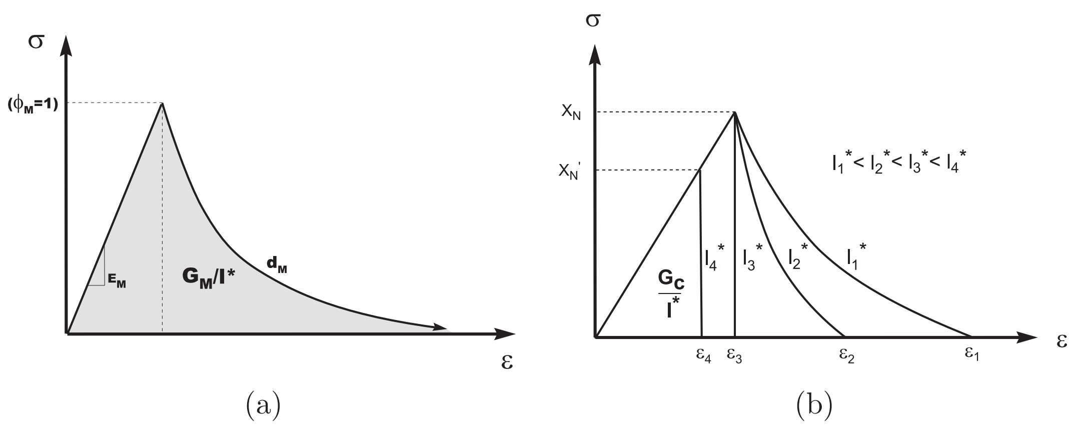

Fig. 1. Typical nominal stress–strain behavior for each material direction and illustration of the strategy used by the intraply damage model [4,5] to account for different element sizes.