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A non-linear shear damage model to reproduce permanent indentation caused by impacts in composite laminates

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ABSTRACT

For aeronautical composite structures impact damage is an issue of great concern. In service damage detection capability is related to the indentation left by impacts, thus it is crucial to understand the physical phenomena which control indentation.

Recent studies suggest that indentation is greatly affected by the out-of-plane shear properties of laminates, nevertheless the simulation of such behavior is still an open issue.

A non-linear material model, including both in-plane and out-of-plane shear, has been developed and implemented in an existing continuum-damage-mechanics-based UMAT routine for the ABAQUS code. The enhanced code can simulate the indentation caused by impacts and it has been used to simulate tests according to ASTM D7136.

The comparison of simulation results with those obtained by means of the original UMAT routine, implementing a simplified shear model, allows the assessment of the importance of out-of-plane shear in the simulation of impact events.

A comparison between simulated time histories, of both contact force and absorbed energy, and the in-house experimentally measured ones shows a remarkable agreement, allowing the code to be validated.

The non-linear out-of-plane shear model also allows permanent indentations at the end of impact simulations be obtained, which are in good agreement with the experiments.

1. Introduction

The last decades have seen a wider variety of applications of advanced composite materials in aerospace structures. Composites excellent properties, such as higher specific strength and stiffness and higher resistance to fatigue and corrosion compared to typical aerospace metallic materials, and a composite-oriented design allow for structural weight savings and for lower manufacturing and maintenance costs.

Nevertheless, composite materials suffer from many forms of failure associated to the individual behavior of the lamina constituents (matrix and fibers) and to the mutual interaction of the laminae.

In this context the effect of foreign object impact is still a source of great concern. In particular, low velocity impacts could dramatically reduce the residual strength of damaged laminates. Indeed, low energy impacts or small dropped objects, such as assembly or maintenance tools, could cause remarkable local damage in terms of matrix cracks, fiber breakages and delaminations, and, at the same time, very limited visible marks on the impacted surface [1].

Damage caused by impacts is classified according to its detectability through the indentation depth. The barely visible impact damage (BVID) is defined as the minimum indentation depth that can be detected by means of visual inspections. Damage lower than the BVID must not reduce the strength of the structure below its ultimate load capability [2].

In the scenario of impact events, composite material characterization is carried out by time-consuming and expensive experimental tests aimed at correlating different impact energy levels with damage in the impacted area and evaluating permanent indentation and residual strength of the structure.

Numerical analyses are believed to be a valid support to the experimental activity in order to reduce the number of tests and to gather, at the same time, knowledge about the interaction of the complex damage mechanisms that occur.

In particular, once the numerical model is able to reproduce key phenomena that characterize damage on simple coupons, simulations can be extended to structures of greater complexity with the aim to perform the sensitivity and design studies and to use experimental tests for validation and certification of final designs.

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The prediction of initiation and propagation of damage in impacted composite structures can be approached by means of the continuum damage mechanics (CDM) [3,4] which essentially defines material damage by means of appropriate internal state variables.

Lately, CDM has been successively implemented in FE codes to model the progressive degradation of advanced composite materials. Iannucci and Ankersen [5] developed and implemented a 2D CDM-based model for woven composite laminates under impact loading. Later, Donadon et al. [6] extended further including 3D effects. Falzon [7] and Pinho et al. [8] developed a 3D failure model for laminates, based on the Puck's theory.

Among all the models proposed for typical composite damage modes, intra-laminar shear modeling is not trivial. Indeed, shear behavior in composite laminates is markedly non-linear. Non-linearity can be attributed to different causes such as matrix plasticity, generation and coalescence of matrix micro-cracking and fiber–matrix de-bonding.

In this scenario, out-of-plane intra-laminar shear damage is believed to be responsible for the formation of the permanent indentation left after impact events. The numerical ability to correctly predict the permanent indentation in terms of depth and extension and the associated intra-laminar (matrix and fiber failure) and inter-laminar (delaminations) damage, might become crucial.

In this paper, a new 3D non-linear intra-laminar shear model has been developed and implemented in an UMAT routine for the implicit FE code ABAQUS/Standard. The numerical model is able to reproduce both in-plane and out-of-plane intra-laminar shear damage and to take into account history-dependent constitutive stress–strain relationship.

The necessary material properties required in the numerical analyses were obtained during the characterization [9] of a composite carbon–epoxy material system. Some specific data related to CDM implementation have been estimated on the basis of literature data.

A first numerical model has been developed by implementing the same constitutive law for in-plane and out-of-plane shear and it has been used for the simulation of low velocity impact tests on composite specimens according to ASTM D7136 [10].

The simulation results have been firstly compared, in terms of time histories of both contact force and dissipated energy, with those obtained by means of a previous version of the UMAT routine, which implemented a linear shear model, in order to verify the new model and to evaluate the role of non-linearity in impacts simulation.

Such numerical results have been also compared to experimentally measured ones in order to quantify the capability of the model to reproduce the experiments.

Since no literature data for the out-of-plane shear properties was available in the literature, further analyses have been performed to assess the sensitivity of the results to such properties. Hence, some constitutive key parameters have been modified in order to evaluate their effect on the time histories of both contact force and dissipated energy.

The numerical model also allowed mutual interaction between the out-of-plane shear model and the numerical delamination model be highlighted. For this purpose, the predicted delaminated areas of the analyses with different constitutive parameters have been analyzed and compared.

Eventually, the FE model incorporating the constitutive out-of-plane shear model is able to capture permanent indentations following impacts. Hence, the numerical predictions of permanent indentation depths have been compared with the measured ones.

Even though the numerical simulations are qualitatively in good agreements with the experiments, they greatly overestimate the indentation depth.

This result could be explained by the experimentally-observed progressive shear modulus reduction whose effect has been qualitatively implemented in the constitutive model and preliminarily studied.

2. Intra-laminar damage model

The intra-laminar damage model is based on a continuum damage mechanics approach [3], which exploits the principles of thermodynamics in order to describe the constitutive equations of a damaging composite material [4]. In CDM, internal state variables (ISV) are damage variables (d_i), that modify the material stiffness matrix's components to account for the progressive intra-laminar damage. These damage variables represent a measure of micro-cracks' density within a representative volume element. The CDM has been applied to mesoscale models [11], where the composite structure is idealized as a stacking sequence of homogeneous and orthotropic laminae separated by inter-laminar surfaces. When the material is completely undamaged $d_i = 0$, while $d_i = 1$ results in complete material failure, thus the constitutive laws for the damaged material are derived by means of the principle of strain equivalence [4].

Each of the damage variables can describe a specific intra-laminar damage mode. In this work the following damage modes have been considered:

Longitudinal damage under tension (d_{1T}) and compression (d_{1C}).
Transverse damage under tension (d_{2T}) and compression (d_{2C}).
In-plane shear damage within 1–2 plane, (d_4).
Out-of-plane shear damage within 1–3 plane, (d_5).
Out-of-plane shear damage within 2–3 plane, (d_6).

The in-plane longitudinal and transverse constitutive behaviors are represented by means of bi-linear laws where the irreversible damage is triggered according to different damage onset criteria.

Damage initiation due to the tensile and compressive loading in the longitudinal direction is predicted using a non-interacting strain-based failure criterion [9].

Damage initiation in transverse direction predicted using a non-interacting strain-based failure criterion for tension while for compression a stress-based damage activation function is used inspired to a simplified version of Puck's failure criteria [7,9,12,13].

In order to alleviate mesh-dependency issues related to progressive-failure analyses, the characteristic length of the elements is introduced into the constitutive laws to obtain a smeared crack approach widely used and extensively discussed in literature [14,15].

By means of this approach the fracture energy is smeared over the element volume thus obtaining a constant energy release rate per unit cracked area regardless of the element dimension; consequently the failure strain related to each damage mode is scaled according to the characteristic length of the elements.

2.1. Intra-laminar shear model

The constitutive intra-laminar shear behavior of composite laminate typically consists in a non-linear and irreversible phenomenon. This behavior can be explained by means of two distinct mechanisms: matrix plasticity and stiffness reduction due to matrix micro-cracking and fiber–matrix interface damage. The result is that the shear stress components are linked to shear strain components by means of non-linear constitutive laws.