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Impact behaviour of omega stiffened composite panels

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ABSTRACT

The mechanical response of reinforced composite structures under impact loads is particularly challenging owing to the rising of multiple and simultaneous failure phenomena. Indeed, low velocity impacts may produce intra-laminar damages, like fibre breakage and matrix cracking, and inter-laminar damages, such as delaminations and skin-stringer debonding. As already remarked, these failure phenomena often take place simultaneously, leading to a significant reduction in strength and stability of the composite components. In this paper, the behaviour of stiffened composite panels, with omega shaped stringers, under low velocity impacts is numerically investigated by means of non-linear explicit FEM analyses. Different impact energy levels are considered and correlation with experimental data is provided, in terms of impact force, displacement and energy.

A sensitivity analysis has been performed to investigate the influence of numerical models' approximations on the accuracy of the obtained numerical results. Models with an increasing level of damage simulation details have been adopted to study the effects of combined and separated intra-laminar and inter-laminar failures providing an interesting insight on the modelling requirements for an accurate simulation of the investigated phenomena.

Contents

1. Introduction

The use of composite materials keeps growing in several industrial fields such as railways, aerospace, naval and automotive thanks to their excellent properties in terms of specific strength and stiffness when compared to the traditional and innovative metallic alloys. Nevertheless, these materials have shown a limited damage tolerance when subjected to impacts.

Generally, high velocity impacts produce a localized and deep damage, this type of failure can be referred to as Visible Impact Damage (VID) having an high chance to be detected during maintenance inspections. On the other hand, low velocity impacts involve complex events such as in plane damage (fibre breakage

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and matrix cracking) and out of plane damage (delamination) that can be barely detected by a visual inspection, in such cases the resulting damage is called Barely Visible Impact Damage (BVID). Impact induced damages may lead to a substantial strength reduction of the whole structure; hence, effective numerical tools able to predict the impact damage tolerance of composite laminates are needed for a performing and safe design.

Experimental, numerical and analytical studies about impact phenomena on composite structures [1–7] can be found in literature showing that predictive models are application sensitive and that failure modes and contact issues are critical aspects to be taken into account [8,9].

The consolidated predictive methods for the on-set and growth of delaminations have reached a good reliability [10–13], on the other hand, the stress based Continuum Damage Models, used of the simulation of fibre breakage and matrix cracking [14,15], have demonstrated to be not suitable for the prediction of failure phenomena involving localized stress and material discontinuities [16–19]. Furthermore, collecting specific experimentally determined material properties, often, makes compulsory to realize wide and expensive experimental campaigns [4–9,20,21].

Inter-laminar crack propagation may be simulated, basically, by means of two main finite elements approaches: Virtual Crack Closure Technique (VCCT) and Cohesive Zone Model (CZM) [10,16,22,23]. The use of VCCT is linked to the knowledge of a pre-existing crack and to the use of adaptive re-meshing tools. The CZM does not exhibit these VCCT restrictions. Indeed, the CZM technique, based on a strength-based criterion to predict the damage initiation and on a fracture energy criterion to follow the damage evolution, provides good results for different failure modes [24]. Many works are available in literature [25–27] where the cohesive elements are used between adjacent plies to simulate delaminations' onset in cross-ply laminates under low velocity impacts.

However, several numerical analyses with CZ elements [28–30] have shown that the mesh size influences the crack propagation, invalidating the results [31]. To reduce the mesh size dependency limitations involved in the use of CZM, different energy based criteria, considering the fracture energy distributed over the volume of the elements, have been developed [32–37].

For the fibre breakage and matrix cracking simulation, as already mentioned, Continuum Damage Models (CDM), able to predict with good accuracy the onset and growth of the intra-laminar damage by introducing a degradation factor for material mechanical properties [38], are generally used. The same model has been adopted by the authors and validated against coupon data in [46]. Intra-laminar damage progression models have been adopted successfully by the authors for fatigue [47] and static problems [48]. The mechanical response, using CDM for intra-laminar damage and CZM for inter-laminar damage, on composite panels under low velocity impact for different stacking sequence is widely treated in literature [39–41] for basic composite structures, such as coupons for material characterization. On the other hand, very few works on joint numerical and experimental investigations of complex composite structures subjected to low velocity impact conditions can be found in literature [42,43]. In order to fully understand the mechanical behaviour of complex composite structures, such as reinforced panels, more experimental data and numerical models are needed. In order to show the complexity and the relevance of the impact behaviour on composite structures, in this paper, a numerical/experimental investigation is performed on an omega-stiffened laminate subjected to two impacts with different energy levels.

Correlation with experimental data is provided, in terms of impact force, displacement and energy.

Finally, a sensitivity analysis has been performed to investigate the influence of numerical models' approximations on the accuracy of the obtained numerical results. Models with an increasing level of damage simulation details have been adopted to study the effects of combined and separated intra-laminar and inter-laminar failures providing an interesting insight on the modelling requirements for an accurate simulation of the investigated phenomena.

In Section 2, a brief theoretical background on inter-laminar and intra-laminar modelling techniques is given. Section 3 provides a description of the realized FE model and the correlation of the results obtained with experimental data in terms of impact force vs. event time and displacement, and impact energy vs. event time. Experimental non-destructive evaluations have not been performed on the investigated panel hence, in this work, more emphasis has been given to the global behaviour of the structure described by force–time and force–displacement curves. In Section 4, the performed sensitivity analysis on the numerical models' approximation is presented with particular attention to the effect of inter-laminar and intra-laminar failure combination.

2. Theoretical background

Low velocity impacts on a composite laminate, usually, involve different failure mechanisms: matrix cracks, fibre failure and delaminations. Generally, matrix cracking appears first and, even if it does not considerably reduce the laminate properties, it acts as a delamination initiation trigger. Delaminations occur at the interface between different oriented layers driven by inter-laminar shear stresses, stiffness variation between the adjacent plies, and structural deflection. Consequently, the key point for a correct impact phenomenon model is the accurate simulation of the interaction between intra-laminar damage (matrix cracks and fibre failure), and inter-laminar damage (delamination). In the next sections a survey about the damage models employed in this work to simulate the failure phenomena is reported.

2.1. Intra-laminar damage model

The adopted intra-laminar damage model is based on the Continuum Damage Mechanics. Internal state variables are used as damage coefficients (d_i) in order to reduce the material stiffness and simulate the intra-laminar damage evolution.

The failure modes are based on Hashin's criteria formulation [7,8], and implemented in the FE code Abaqus/Explicit [44]. These criteria allow to evaluate the different failure modes such as tensile and compressive fibre failure, and tensile and compressive matrix cracking. Alternative failure criteria based on failure separation modes are available in literature, such as Puck's criteria. Puck proposes the concept of fracture planes for matrix compression resulting in a more phenomenological oriented approach even if an increase in the computational load is expected. However, for the purpose of this work, the Hashin's criteria have been considered satisfactorily accurate and computationally cheap. The

Table 1
Hashin's failure criteria.

Fibre tension	$\hat{\sigma}_{11}>0$	$F_{ft}=\left(\frac{\hat{\sigma}_{11}}{X^T}\right)^2+\alpha\left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2=1$
Fibre compression	$\hat{\sigma}_{11}<0$	$F_{fc}=\left(\frac{\hat{\sigma}_{11}}{X^C}\right)^2=1$
Matrix tension	$\hat{\sigma}_{22}>0$	$F_{mt}=\left(\frac{\hat{\sigma}_{22}}{Y^T}\right)^2+\left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2=1$
Matrix compression	$\hat{\sigma}_{22}<0$	$F_{mc}=\left(\frac{\hat{\sigma}_{22}}{2S^T}\right)^2+\left[\left(\frac{Y^C}{2S^T}\right)^2-1\right]\frac{\hat{\sigma}_{22}}{Y^C}+\left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2=1$