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Experimental and numerical investigations of low energy/velocity impact damage generated in 3D woven composite with polymer matrix

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ABSTRACT

3D woven composite materials have been recently used to design some engine structures in order to improve their impact resistance. The aim of this work is to study experimentally and numerically low-velocity/energy impact damage in such recent composites. Impact tests at different energy levels have been performed and analysed using microscopic observations and X-ray tomography in order to understand damage mechanisms occurring in this material. Finite element simulations have been performed using the continuum damage model, ODM-PMC, developed at Onera for 3D woven composites under static loadings. Through comparisons with the available experimental data, it has been demonstrated that the damage mechanisms are described correctly by the present model. Moreover, the residual depth after impact is also accurately predicted, allowing to generate, numerically, relations between impact energy, damaged area and residual depth, currently determined experimentally in aeronautical industries.

1. Introduction

Some critical components of aircraft structures, such as centre wing box, wings or fuselage, are now manufactured with laminated composite materials, due to their high specific mechanical properties. However, these materials are particularly sensitive to low-velocity/energy impact events such as dropped tools. These impacts on laminated composite structures generate large damaged areas inside the laminate while leaving a barely visible indent on its impacted surface. Moreover, such a damage induces a strong decrease in the residual strengths after impact [1,2], and has obliged the designers in aeronautics to use large safety margins, thus decreasing the competitiveness of carbon fibre reinforced polymer composites as compared to metallic materials. Therefore, the impact resistance of laminated composites manufactured with unidirectional plies has been widely studied for many years [1–3] from both an experimental and a numerical point of view. Experimental studies have shown that a low-velocity/energy impact induces mainly three types of damage [4–6]: large delamination cracks between plies with different orientations, matrix cracking in the different plies and also, for high enough impact energy levels, fibre failures. Due to delamination, a marked loss of residual strengths, especially under compressive loading [7], is observed for such a material. For classical Carbon/Epoxy materials, the failure of pre-impacted specimens subjected to compression is usually due to local buckling [8–10] of the plies because the delamination cracks generated during impact divide the plate into multiple sub-laminates. This local buckling can induce some propagation of delamination to the lateral edges [7] and also fibre failures in compression of some plies (due to fibre kinking). Thanks to these experimental studies, the failure mechanisms and their couplings are currently well understood for flat laminates. Therefore, the description of the large delamination cracks due to impact is clearly a key point in the modelling to predict the residual strength. To describe these discrete large cracks within the laminate, cohesive zone elements [8,11] or interaction cohesive approaches [12,13] are usually used to model delamination (both onset and propagation) in finite element codes. Only few authors [8,14,11] have succeeded in describing accurately the delamination patterns after impact because of numerical difficulties in impact simulation although explicit solvers are usually used. Moreover, very few and recent studies [14,15] have succeeded in performing impact test simulations and then compression after impact.

Due to the poor impact resistance of laminated composite materials, 3D woven composites have been recently developed to be used in structures exposed to impact. Indeed, the main advantage of these materials consists in preventing large delamination cracks thanks to the presence of yarns linking the layers together. The use of these materials for industrial applications being recent,

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only few experimental studies [4,16,17] have been dedicated to the influence of such an architecture on impact and post-impact behaviour. The observed damage mechanisms in 3D woven composites are very different from those encountered in classical laminates due to the specific architecture of such materials. Due to the complexity of the encountered damage mechanisms, only very few impact modelling studies [18] can be found in the literature and are dedicated to very specific architectures.

This work is thus dedicated to the experimental and numerical study of the damage induced by low-velocity/energy impacts, representative of dropped tools, in a new generation of 3D woven composite materials. Moreover, the present article aims to demonstrate that the Onera Damage Model for Polymer Matrix Composites (ODM-PMC), based on the continuum damage approach, is relevant for such materials and allows predicting the different quantities of interest such as damage patterns, maximum peak loads and residual dents.

Firstly, an experimental study has been performed in order to improve the understanding of the different damage mechanisms induced by impact loading through the analysis of impact damage at different energy levels. This experimental investigation is reported in Section 2. The studied 3D woven material developed by Safran Group is briefly described in Section 2.1. The experimental setup and the different measurement techniques to study the damage generated after impact are presented in Section 2.2. In Section 3, the ODM-PMC model, initially developed for 3D woven composite structures under static loadings, is presented. Then, in Section 4.1, this approach has been implemented into a finite element code to predict damage after impact at different energy levels. The details of the finite element simulations (mesh, boundary conditions ...) are given in Section 4.2. The identification process of the different parameters of this approach is also presented in Section 4.3. Finally, in Section 4.4, the comparisons between the different experimental data and the predictions of the simulations performed with ODM-PMC are presented and discussed.

2. Impact test results

2.1. 3D woven composite material

The material under investigation is a moderately unbalanced 3D woven composite material provided by Safran Group, already studied in [19], and consisting of carbon fibre yarns (48 K) embedded in an epoxy matrix. Based on the generic architecture reported in Fig. 1, the studied 3D woven composite material has been designed by Safran group in order to prevent large delamination after impact and thus to obtain good impact resistance (the exact architecture of this material is, however, confidential). The thickness of the tested material is about 11.5 mm, which is rather thick as compared to previously studied laminates or 3D woven composites. It is worth mentioning that the Representative Elementary Volume of such a material is rather large (a few centimetres) as compared to other composite materials and thus imposes to use large plates and a large diameter impactor.

2.2. Experimental device

Drop-weight impact tests on 3D woven polymer matrix composites have been performed in a Dynatup 8250 (GRC Instruments) apparatus, as illustrated in Fig. 2. During the tests, the force history has been measured with a force cell located in the impactor and the displacement history of the point opposite to impact has been measured using a laser sensor.

Due to the thickness of the specimens, the experimental device recommended in the ASTM D7136/D7136M standard [20] cannot be considered in the present study. Therefore, two different alternative experimental devices have been used in this study. It is essential to note that the boundary conditions of these two test configurations can be easily introduced into a finite element simulation, in order to analyse experimentally and numerically the available test results. The first configuration, reported in Fig. 2a, consists in holding the plate by two square jaws with a circular free zone, which diameter is equal to 70 mm. This experimental setup has been chosen in order to understand the damage and failure mechanisms encountered in 3D woven composite materials and also to be compared with finite element simulations to validate the proposed modelling. For this configuration, the dimensions of the tested plates are 100 mm $\times$ 100 mm $\times$ 11.5 mm. The steel-made impactor is hemispheric (40 mm in diameter) and its mass is set to 14.8 kg. Due to the architecture of the 3D woven composite material, the diameter of the impactor is quite large; it has been chosen in order to avoid impacting only one fibre yarn or only the matrix between yarns. Four different energy levels (60 J, 100 J, 150 J and 210 J) have been considered by changing the velocity set through adjustment of the height of the drop weight. Each test has been repeated two or three times to estimate the scattering and has been performed at room temperature. This configuration of tests is referenced in the following as configuration 1.

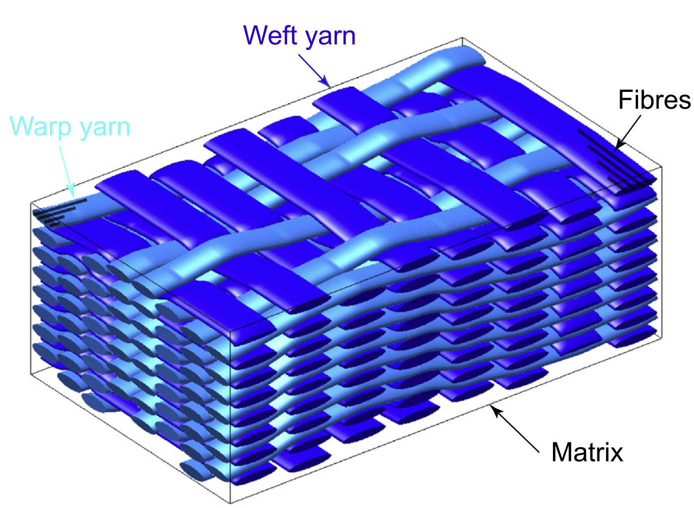

Fig. 1. Generic architecture of an unbalanced 3D woven composite material.