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Review

Numerical simulation of impact and compression after impact of asymmetrically tapered laminated CFRP

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ABSTRACT

This paper presents a numerical simulation of impact and compression after impact (CAI) of a tapered composite laminate using a discrete ply model. Three types of damage: matrix cracking, delamination and fiber rupture are considered in the model. The presence of ply drop-off generates some discontinuities in the stress field and therefore adds difficulties to the simulation.

Analyses of numerical results are performed to understand the damage and failure mechanisms in both tests. Numerical results in terms of force-displacement curves, delamination shape, CAI displacement field and residual strength are compared with experimental data. Impact simulation is in good correlation with the tests. CAI strength is under predicted and depends on quality of the meshing of the transition region. This study highlights the importance of modeling intra-ply matrix cracking for impact simulation.

1. Introduction

Impact damage tolerance of CFRP materials remains an important concern for structure design. Impact damage which is mainly characterized by matrix cracking, delamination and fiber rupture, usually propagates far beyond the impact point. Such damage is mostly present inside the laminate and is visually hard to detect from outside [1,2]. Even in the case of low velocity/low energy impact, the residual compression strength can be significantly affected. For thin composite panels, the energy threshold for visual detection of external damage (permanent indentation) corresponds already to an important loss of compression strength [3,4]. Since some aeronautical structures are inclined to tool drop and small debris impacts during their life cycle, the requirements and regulations by aviation authorities include a concept of impact damage tolerance.

Thickness tapering is commonly used to reduce the weight of composite structures, though it leads to the creation of resin rich pocket at the end of a dropped-off ply. Due to such material discontinuities and the local curvature of continuous plies, the resulting structure may fail prematurely under static or fatigue loadings [5–9]. Damage, generally in terms of matrix cracking and delamination, is triggered by a high stress concentration around the ply drop-off.

In the literature, many authors have developed numerical models for impact of composite laminates [10–14]. Depending on their level of complexity, the models are capable of reproducing some or all major types of damage: matrix cracking, delamination and fiber rupture. The meso-scale level initially introduced by Ladevèze and Allix [15] enables a faithful reproduction of impact type damage. Regarding the material laws, failure damage mechanics is generally used to simulate intra-laminar damage [11,16]. The use of cohesive elements with energy based damage model is now being used in many works to model discrete failure like delamination [17,18]. Some authors [12,19] also use it to model discrete matrix cracking and therefore define an indirect coupling between matrix cracking and delamination.

Regarding the prediction of residual strength, both analytical [20–22] and FE models [23–25] have been proposed. In some papers [23], initial impact damage is artificially introduced in the model prior to the simulation of compression. Others [24,25] are more faithful using a two-step model: an impact damage is simulated first and then followed by a simulation of the compression test.

To our knowledge, neither impact nor CAI simulation of tapered composite has been reported in the literature. This study pursues the work of Bouvet et al. [12,14,24] to develop a robust numerical model DPM (Discrete Ply Model) for predicting impact damage tolerance; i.e. simulation of impact and CAI. It is also a continuation

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of the impact of tapered laminates study described in [26] where an analysis of low velocity impact response of tapered laminates is presented. The study highlights a strong similarity with plain laminates in terms of damage mechanism. In this paper, the DPM is used to simulate the impact and CAI of a tapered specimen. The results of the numerical simulation are compared with experimental data for model validation and analysis of damage mechanisms.

2. Numerical modeling

The modeling approach is based on the work of Bouvet et al. [27]. They developed a discrete 3D FE model at the meso-scale for the simulation of impact damage of composite laminate. It has then been pursued to simulate the CAI test [24]. In this study, the capability of the model is extended to simulate both impact and CAI of a laminate with multiple internal ply drop-offs. To do so, a meshing process of the ply drop-off region has been developed and some changes regarding the material laws have been done compared to [14].

2.1. Meshing

The laminate meshing is presented in Fig. 1. It is meshed at the ply level with C3D8 volume elements. Each element represents, in the thickness direction, two plies with the same orientation. The ply elements are connected with zero thickness cohesive elements to model both delamination and transverse matrix cracking. To ease inter-ply connection, the nodes network needs to be uniform throughout the laminate which causes a twist of 45° and –45° ply elements (Fig. 1b). The element size for 0° and 90° plies is 1.25×1.25 mm^2 in the laminate plan.

One of the main challenges in impact modeling is to account for complex interactions between different types of damage. In the case of the DPM, the coupling between transverse matrix cracking and delamination is modeled through the laminate meshing. It is one of the main building blocks of the model. Cohesive elements for matrix cracking are parallel to the ply fiber orientation and defined in between each volume element. As a result, volume elements are disconnected along the ply transverse direction in case of matrix cracking. Such geometric discontinuity is used to capture indirectly the coupling between matrix cracking and delamination.

Modeling of the drop-off ply region is illustrated in Fig. 2a. The meshing represents the sub-laminate of the ply drop-off area shown in Fig. 2b. In this example, ply number 2 is terminated and plies 1 and 3 are continuous. In the thick section, inter-lamina cohesive elements are terminated at the end of the dropped-off ply. Then, a new group of cohesive elements are used to connect the continuous plies in the thin section. Note that there is no volume or cohesive elements in the resin pocket. This hypothesis is similar to assuming this area is already damaged before impact. In reality, it must be highly pre-stressed due to curing residual stress. So, to avoid any further complication of the model or longer computing time, it seemed not reasonable to develop a detailed meshing strategy of the area. In Reference [28], similar assumption has been used to simulate a tapered laminate under in-plane load. In the case of impact, the assumption is more valid since the emphasis is on the propagation of delamination rather than its initiation.

2.2. Material laws

The impact is simulated with the Abaqus® 6.11 explicit/dynamic solver and all material laws are defined in a user-subroutine VUMAT. This part describes the non-linear modeling of the different damage types: fiber failure, matrix cracking and delamination.

2.2.1. Fiber failure

Modeling of fiber failure for impact simulation requires particular considerations. In fact, fiber may fail either under traction or compression load. In both cases, a high amount of energy is released as shown in the material property of Table 1. This fiber failure energy release rate (ERR) needs to be taken into consideration to

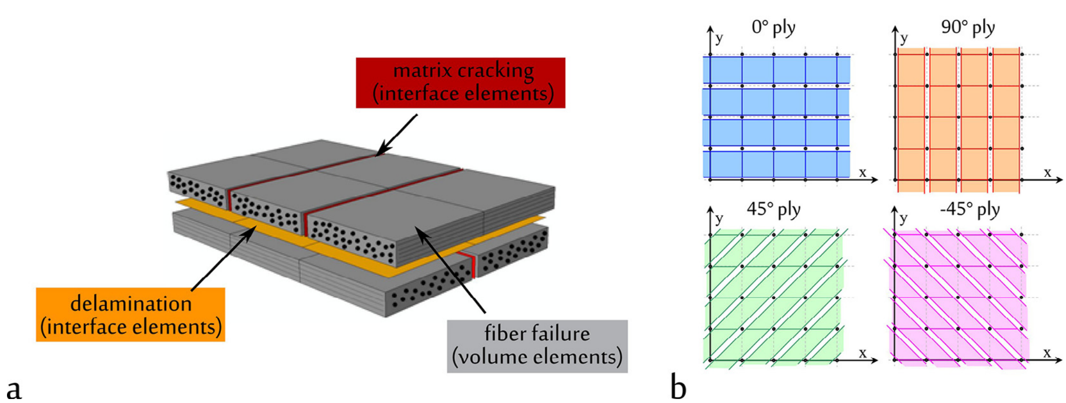

Fig. 1. Description of the Discrete Ply Model: (a) different types of damage that can be represented and (b) meshing strategy.

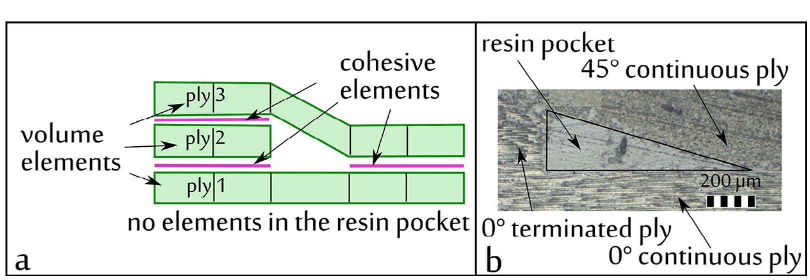

Fig. 2. (a) meshing around the resin pocket, (b) micrograph of a ply drop-off.