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Scaling effect in notched composites: The Discrete Ply Model approach

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ABSTRACT

Numerical and experimental investigations were carried out on the size effect in notched carbon/epoxy laminates. This paper presents a computational study of scaled open-hole tensile tests using the Discrete Ply Modeling (DPM) method, which has already proven efficient on both in-plane and out-of-plane loading cases, such as pull through, low velocity impact and compression after impact. The specificities of this finite element model are its discrete nature, the small number of parameters required and its robustness. Three different stacking sequences of thin plies coupled with three sizes of coupons having the same length to width ratio were tested. The results show that the model reflects the reduction in strength when the size of the specimen increases. The influence of different parameters such as mesh size, presence of discrete matrix cracks and fiber fracture toughness that should be used for clustered plies, are discussed. Comparisons with experiments demonstrate that tensile strengths, and failure scenarios and patterns are predicted with acceptable accuracy.

1. Introduction

Composite materials have now become indispensable for most transport vehicles, especially in the aerospace and astronautics sectors [1]. The assembly of structures using such materials cannot avoid the presence of holes or cut-outs, which induce stress concentrations and reduce strength. Notched strength is hence one of the design drivers for composite structures. Moreover, holes have the particularity that they can be employed to model other complex forms of damage such as impacts or through-the-thickness cracks [2]. Scaling effects are at least as important since most tests are carried out on small coupons whereas real structures are 10–100 times larger. A deeper understanding of these scaling phenomena is still required in spite of the substantial amount of research devoted to it since its discovery by Leonardo da Vinci in the early 1500s [3].

Numerous experiments have been conducted to explore the physical causes of these phenomena [4–6]. As detailed in [7], size effects can occur at different levels. At the material level, an influence of the thickness has been detected, called the "in situ" effect. This phenomenon has been analyzed by Wisnom et al. on isotropic specimens in [5]. At the structural level, it has been proven that the strength of notched composite laminates decreases with increasing notch sizes when thin plies are used. It is the latter scale that is the focus of this article. The "hole size effect" is triggered by the presence of non-critical ply-level damage such as fiber fracture, fiber splitting, delamination and matrix failure in the vicinity of the hole [8], which blunts the stress concentration. The extent of this "fracture process zone" relative to the size of the specimen explains the strength difference between small and large specimens [7].

Preliminary sizing solutions were found with the point stress or the average stress models [9,10] and all their extensions described by Awerbuch and Madhukar [11] or, more recently, with a volume based criterion developed by Hochard et al. [12]. Camanho et al. then proposed an alternative method for predicting the strength of composite laminates loaded in tension and containing holes or cracks [13]. This analytical model, based on finite fracture mechanics and first introduced by Leguillon [14], predicts failure when both stress-based and energy-based criteria are satisfied. Mohammed et al. used two-parameter cohesive laws [15] to determine the strength of an open-hole specimen. This analytical work, based on the original cohesive law concept of Dugdale [16] and Barenblatt [17] made it possible to link the failure strength to the length of the failure processing zone, and this length at failure load to the specimen dimension and geometry. Good agreement between experimental data and numerical predictions was obtained with these preliminary sizing methods for quasi isotropic laminates.

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However, experimental tests revealed the substantial influence of the stacking sequence on both failure scenarios and strengths [8,18,19]. For example, the final failure of laminates manufactured with thick plies is mainly due to delamination [5]. In our study, it was experimentally determined on plain specimens that failure strength varied by thirty percent between two stacking sequences of a laminate containing the same number of plies in each direction. These fast semi-analytical and numerical methods do not take the influence of the stacking sequence into account since they consider that strain is constant within the laminate thickness [20]. This is why a more complete numerical model is needed to predict the physics associated with these failure phenomena (delamination and transverse cracks). Following the "Virtual Testing" approach, i.e. moving from numerous, expensive experimental tests towards robust, accurate numerical simulations, a large number of models have been proposed to fit experimental data.

Some of these numerical studies of size effects on open-hole tensile composite laminates have already been described by Chen et al. [22]. They can be classified according to their level of discretization [21], from the whole continuum model without any interfaces to the most discretized type of model where the three most important types of damage (fiber failure, matrix cracking and delamination) are all represented through interfaces (Fig. 1). The latter type of model has not been developed yet, probably because of its prohibitive calculation cost. Among the models available for the "Level 1" category is the model by Camanho et al. [7] which, based on continuum damage mechanics, can predict damage onset and the extent and type of non-critical damage mechanisms, without any calibration. Abisset et al. also employ a damage mesomodel based on a continuum mechanics approach. Diffuse damage and transverse cracking are modeled with a progressive evolution law, whereas a brittle evolution law is used for fiber breakage [23]. This model has been used to predict the main features of the three failure modes of a notched specimen subjected to tensile stress. However, it is important to mention that it requires a large number of parameters to identify. "Level 2" refers to models where the delamination is modeled using discrete elements. Pinho developed a model that predicts fiber and matrix failures using smeared crack models and delamination using cohesive interfaces [22]. ONERA developed a model composed of a multi-scale progressive failure approach to describe the softening behavior of a ply failing in fiber mode and cohesive zone elements to model delamination [24]. Similarly, a physics based, progressive damage model has also been developed by Ridha et al. to represent the different damage mechanisms. The modeling strategy [25] is based on a continuum damage mechanism for in-plane damage progression and cohesive elements for delamination. Discrete elements may also be used to represent matrix cracks. For example, Wisnom and al. use a Weibull approach to predict fiber failure, cohesive elements between plies to model delamination, and within each ply to model potential splits initiating tangentially to the hole [5,26,27]. Recent discussions have concerned the need for discrete elements to correctly model matrix cracks and their interaction with delamination [28]. Pioneering this approach, the Discrete Ply Model (DPM) used in this paper employs cohesive interfaces to model matrix failure and delamination, and 3D volume elements to predict fiber failure. It should be noted that other researchers have simulated single matrix cracks using the cohesive zone model approach [29–33] but, as far as the authors know, none of them have focused on the open-hole tensile test scaling effect.

This discrete method (DPM) was initiated by Bouvet et al. for the modeling of low velocity impacts in composite panels [34] and was enhanced afterwards to capture permanent indentation [35] and to simulate compression after impact [36]. In this model, coupling between the intra- and inter-laminar damage is naturally taken into account through the use of interfaces connected by a specific mesh. This model has also been used to represent pull-through cases [37], where the effects of splitting on the load redistribution were correctly predicted. Moreover, after a modification of the hole contour mesh, the DPM has been able to predict notched strength, and failure scenarios and patterns with reasonable accuracy on different stacking sequences [38].

In this paper, open-hole tensile tests are performed and analyzed by means of the DPM method. Three different stacking sequences of thin plies coupled with three sizes of coupons with the same length to width ratio were tested. The following section gives details of the tests and samples. Then, the DPM modeling strategy is detailed and the results are compared with experimental data. Failure scenarios are analyzed and modeling choices are discussed.

2. Experimental work

2.1. Material and setup

The material investigated in the present study was Hexcel's T700-M21 carbon epoxy unidirectional tape with a nominal ply thickness of 0.125 mm. Three types of stacking sequences were

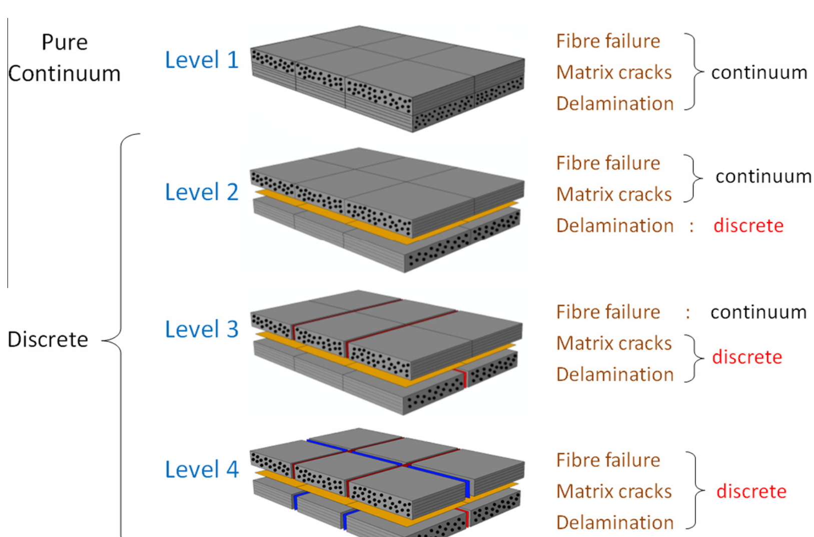

Fig. 1. Numerical damage models architectures [21].