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Progressive damage modeling of open-hole composite laminates under compression

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ABSTRACT

Despite the recent success of modeling progressive damage of open-hole fiber reinforced composites subjected to tension (OHT), it is still a challenging task to predict the strengths and the damage progression of open-hole composite laminates under compressive loading (OHC). Herein, we propose a progressive damage model for OHC based on our early model for OHT and apply it to study the size effects of OHC. In the proposed model, continuum shell elements are used to account for both in-plane and out-of-plane deformation and delamination is modeled using cohesive elements. A smeared crack model is used to model the progressive failure of composite plies. It is found that the proposed model can predict accurately the experimental strengths and damage patterns with the assumption that the translaminar fracture toughness for blocked plies increases. The different failure mechanisms of the sublaminate scaled laminates of the stacking sequence $[45/90/-45/0]_{ms}$ and the ply-level scaled laminates of stacking sequence $[45_n/90_n/-45_n/0_n]_s$ are found to be closely related to the in-plane shear stress of the central 0° ply block and the initiation of interface delamination.

1. Introduction

Fiber reinforced composites have been widely used in various industrial applications because of their advantages of weight and mechanical properties over metallic materials. It is well known that the compressive strengths of composite laminates are lower than their tensile strengths. Adding holes to the laminates further decreases the compressive strengths. Real structures often contain notches and holes; therefore the OHC strength together with the OHT strength is one of the limiting design criteria for composite structures. It is hence necessary to predict the compressive strengths of open-hole laminates at the design stage. In addition, it is very important to understand the failure mechanisms of composite laminates to help in the design of composite structures.

One of the most widely used empirical methods to predict OHC strengths is the point stress or the average stress model proposed by Whitney and Nuismer [1]. These models require two parameters, namely unnotched strength of the laminate and a characteristic distance, to be experimentally identified. A more theoretically complicated model is the cohesive zone model (CZM), which was first proposed by Dugdale [2] and Barenblatt [3] for metallic materials, was then employed to study composites by Soutis et al. [4]. It was developed to represent the damage zone of micro-buckling in the notched composite laminates under compression, hence to predict the compressive strengths of such laminates. It assumes that microbuckling initiates when the local compressive stress parallel to the 0° fibers at the hole edge reaches the unnotched strength of the laminate. The damage zone of micro-buckling surrounded by delamination at the hole is then simplified and represented by an equivalent crack. The crack is assumed to carry normal stresses which decrease linearly with the crack closing displacement. As the remote stress increases, the length of the equivalent crack grows, which represents the growth of micro-buckling. The relation between the remote stress and crack length is determined by requiring the total stress intensity factor at the tip of the equivalent crack due to the combination of the remote stress and the stresses acting across the crack equals zero. The CZM requires two parameters, the unnotched strength and the critical crack closing displacement. These parameters are not material properties and should be measured for different lay-ups. More recently, Camanho et al. [5] proposed a finite fracture mechanics model for the fast predictions of OHT strengths of composite laminates. This model requires the unnotched strength and fracture toughness as parameters. As the measurement of compressive fracture toughness or critical energy release rate of micro-buckling formation for composite materials becomes viable, this model was recently employed to predict the size effects on compressive

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failure of notched composite laminates [6]. Although the empirical and semi-empirical models can provide reasonable predictions of OHC strengths of composite laminates, extensive experiments need to be carried out to identify the extra parameters required.

Recently, progressive damage modeling has emerged as an important method to predict strengths and failure patterns for open-hole composite laminates. In particular, some progressive damage models have been employed to study the open-hole composite laminates under compression. Chang et al. [7] developed a two-dimensional progressive damage model to predict damage accumulation and the strengths of open-hole composite laminates by integrating failure criteria of Yamada-Sun and Hashin [8]. Similar progressive damage models have been developed for three-dimensional open-hole laminates with various different failure criteria [9,10]. Such progressive damage models could lead to mesh dependence and could result in inaccurate predictions. For instance, Labeas et al. [10] employed a progressive damage model using Hashin criteria to study the interaction effects between the post-buckling behavior and the various failure modes of notched composite laminates. The material stiffnesses are degraded to zeros or certain constant values. Their models show strong mesh dependency and the results predicted are deemed acceptable only for a particularly chosen case. More realistic progressive damage models involving continuous material property degradation have been developed and employed to study OHC problems [11–13]. A micromechanical constitutive model based on the concept of the ensemble-average volume for laminated composites was employed to characterize the compressive response and damage evolution in laminated plates containing a cutout by Lee and Kim [11]. The damage is controlled by the interfacial fiber debonding and nucleation of microcracks in the matrix. It is shown that the model can predict accurate results for cross-ply laminates, while it overestimates the stiffness and final failure load for angle-ply and quasi-isotropic laminates. McGregor et al. [12] developed a continuum damage mechanics model of nonlinear constitutive behavior to model the compressive failure of notched composites. An analog model composed of spring, gap, fuse and slider elements is constructed as to represent the complete force–displacement response of a representative volume element of the material. The analog model is however given as a predefined nonlinear force–displacement relationship which is difficult to determine. Moreover, most of these progressive damage models deal with the in-plane failure only. Failure mechanisms such as micro-buckling/local buckling, delamination, and splitting can hardly be incorporated into these constitutive models or the corresponding finite element models. More recently, Pinho et al. [14,15] developed a comprehensive progressive damage model based on a set of physical failure models and criteria for fiber-reinforced composites, which can distinguish the matrix and fiber failure under tensile and compressive loading. This model was employed to predict the compressive failure stresses for open-hole composite laminates for various stacking sequences by Qing and Mishnaevsky Jr. [13]. Their results show that the failure stresses predicted for $[(\pm 30)_6]_s$ agree with experimental values. However, the predictions for the other stacking sequences show about 10% to 25% discrepancy compared with experimental results.

Unlike the lack of efficient progressive damage modeling for OHC composite laminates, several computational models have been successfully developed to predict the tensile strengths and progressive damage for notched composite laminates [16–18]. Chen et al. [17] employed the smeared crack model and cohesive elements to study the size effects on OHT composite laminates; their predictions correlate well with the experiments by Wisnom et al. [19]. Ridha et al. [18] developed a progressive damage model with in-plane damage and delamination between plies to predict the OHT strengths and failure progression for notched composite laminates with varying sizes and stacking sequences. It is found that only if both the progressive delamination and in-plane damage are modeled can the OHT strengths be predicted accurately. It should be noted that the most important feature of these progressive damage models is the softening after the stress of an element reaches the peak value. Commonly, linear softening governed by the fracture toughness is employed. The tensile fracture toughness in the fiber direction is regarded as a lamina property which can be measured using compact tension or four-point bending experiments [20–22].

Despite the recent success of modeling progressive damage of open-hole fiber reinforced composites subjected to tension, it is still a challenging task to predict the strengths and the damage progression of OHC laminates. The difficulties include the convergence issues due to the instability under compression, modeling delamination under compression, modeling local buckling, and possible mesh dependency. The instability could be mitigated if the material softening can be handled using zigzagging softening curve [18]. Delamination can be modeled using cohesive elements. Local buckling may not be explicitly modeled. However, it might be well represented using 3D continuum shell elements with delamination because both of them allow the out-of-plane displacement. In addition, the smeared crack model can be used to model fiber direction compressive failure as proposed by Pinho et al. [14,15]. The total energy dissipated by the smeared crack model is equal to the energy required for the micro-buckling propagation or kink band formation, which is defined as compressive translaminar fracture toughness. Finally, the cohesive law embedded in the smeared crack model assures a mesh-independent amount of fracture energy is dissipated. It should be noted that only limited data of the compressive fracture toughness in the fiber direction is available in the existing literature. Catalanotti et al. [20] reported a compressive translaminar fracture toughness of 47.5 kJ/m^2 for IM7/8552 carbon-epoxy composites using compact compression tests while Laffan et al. [23] reported 25.9 kJ/m^2 for the same material system using four-point bending tests. Pinho et al. [24] reported a even higher compressive fracture toughness of 79.9 kJ/m^2 for T300/913 carbon-epoxy composites using compact compression tests. These values were measured at the initiation of the micro-buckling.

The objective of this work is to develop a computational model for the progressive damage modeling of OHCs. This proposed model is based on the one developed for OHTs by Ridha et al. [18], with some modifications related to compressive deformation. The finite element model consists of continuum shell elements representing each ply and cohesive layers between the adjacent plies modeling the potential delamination. The smeared crack model is employed to model both fiber and matrix failure. Geometrical nonlinearity is allowed to model the large deformation resulting from the material softening. Failure progression and size effects on the OHC laminates are then studied using this model and compared with experiments from Lee and Soutis [25].

2. Failure theory and finite element modeling

The failure model employed here includes in-plane progressive failure and delamination. The initiation of the in-plane failure is determined using Hashin criteria [8] and the subsequent propagation is modeled using energy-based linear softening law. The delamination, on the other hand is modeled using cohesive elements.

2.1. In-plane progressive failure

The Hashin criterion is used to determine the onset of in-plane failure including fiber direction failure and transverse direction failure. In each direction, the tensile and compressive failures are