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Progressive failure analysis on scaled open-hole tensile composite laminates

Hongchen Bao, Guangyan Liu *

Department of Mechanics, School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China

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ABSTRACT

Despite the rapid advances of numerical methods and theoretical models for progressive failure analysis of composites, it's still a challenge to predict the strength and damage progression of composite laminates under open-hole tension (OHT). One of the main obstacles is to capture the true stress concentration at the hole edge. It has been found that the formation of longitudinal splitting at early loading stage alleviates the extremely high stress concentration. The purpose of this study is to develop an efficient progressive damage model, employing surface-based cohesive contacts for longitudinal splitting and delamination, to predict the thickness size effect of sublaminate scaled and ply-level scaled laminates under OHT. It is found that by using aligned mesh with the fiber direction for each ply, a good correlation with experimental results can be achieved for both strengths and failure modes of the laminates.

1. Introduction

Due to their advantages such as low density, high stiffness and high strength etc., fiber-reinforced composite materials are now replacing the traditional metallic materials and widely used in aircraft, marine, automotive structures, and so on. Unlike the monolithic metallic materials, fibrous composites are usually used as laminates with plies in different orientations and each ply is composed of fiber and matrix constituents. Therefore, the failure modes of fibrous composites are much more complicated. In order to explore the potentials of composites in structural design, it becomes crucially important to understand their failure mechanisms.

The structural application of composite materials often requires the presence of holes or cut-outs. Damage will initiate and grow from these notches due to the stress concentration and finally result in strength or life reduction of composite structures. Over the past decades, many approaches have been proposed to investigate the notched strength and failure modes of composite laminates. Some of the old approaches are empirical or semi-empirical. For example, the popular point/average stress model is based on the elastic solution of stress field in the vicinity of the notch in an anisotropic plate [1]. Failure is assumed to occur when the stress at a characteristic distance or the average stress over a characteristic distance from the notch tip attains the unnotched strength. Another approach is based on the linear elastic fracture mechanics. Failure is assumed to occur if the notch, represented by an equivalent crack, reaches a critical size. The ultimate strength is related to the fracture toughness K_{IC} or strain energy release rate G_{IC} of the laminate [2,3]. Although reasonable ultimate strengths of composite laminates can be provided by these approaches if the parameters in the models are properly determined, extensive experiments need to be conducted to identify these parameters. In addition, the damage zone may not grow in a self-similar manner and the sub-critical damage prior to complete failure may interact with each other.

To take into account the stress redistribution caused by damage progression, a large body of research has been devoted to progressive failure analysis of notched composites. The material property degradation method (MPDM) [4,5] and continuum damage mechanics (CDM) approach [6,7] are the most widely used damage modeling techniques for in-plane damage modes such as matrix cracking or fiber failure; cohesive elements are typically used for interface delamination prediction [8,9]. So far most of the progressive failure analyses of notched composite laminates are based on the material property homogenization assumption, which treats composite laminae as homogenized anisotropic bodies. It has been emphasized by Liu and Tang [10] that the theoretically derived stress concentration on the open hole edge is extremely high and the finite element calculation will always be mesh-dependent. However, tested specimens show longitudinal splitting in terms of matrix cracking, which emanates from notch tips in a very early loading stage [11,12]. The formation of the splitting blunts the notches and reduces the stress concentration significantly. The

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* Corresponding author.
E-mail address: gliu@bit.edu.cn (G. Liu).

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stress relief effect of the longitudinal splitting has been studied in detail by modeling it via cohesive elements [10] or dislocation [13]. Unfortunately, the traditional damage modeling techniques, for example the MPDM, fail to model the splitting and the consequent stress relief effect because of spurious stress transfer [14].

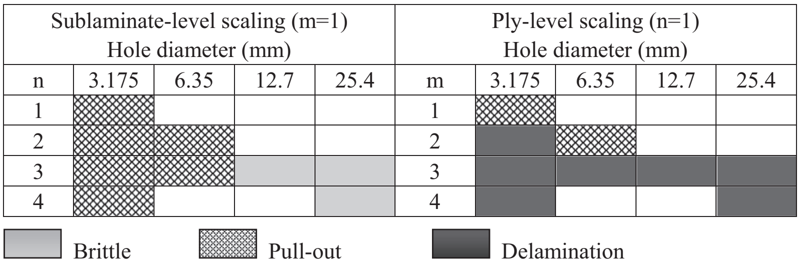
Recently, Green et al. [15] have performed a detailed experimental investigation on the size effect of open-hole tensile composite laminates with lay-up of $[45_m/90_m/-45_m/0_m]_{ns}$. Both in-plane scaling and out-of-plane scaling of specimens were considered, and the out-of-plane scaling included sublaminate scaling ($m = 1$, $n = 1, 2, 4, 8$) and ply-level scaling ($n = 1$, $m = 1, 2, 4, 8$). Three distinctive failure mechanisms were observed, namely brittle failure, pull-out, and delamination (Fig. 1). Numerical studies of the scaling effect of open-hole tensile composite laminates have been performed by many researchers and compared with the experimental results given by Green et al. [15]. Chen et al. [16] studied the size effect of both sublaminate scaled and ply-level scaled laminates. A smeared crack model was used for matrix cracking and fiber failure; cohesive elements were used for delamination prediction. Good predictions were obtained for the thickness size effect on the strength of laminates failed by pull-out. The accurate strengths for the laminates failed by delamination were not successfully predicted. van der Meer et al. [17] used a phantom-node method for explicit representation of matrix cracks, a continuum damage model for fiber failure, and interface elements for delamination. Good agreement with tested values was obtained for tensile strengths of ply-level scaled laminates. The thickness size effect of the sublaminate scaled laminates was not captured very well. Hallett et al. [18] modeled both intra-ply splitting and inter-ply delamination via cohesive elements. Special meshes were designed to accommodate the splitting paths in different plies. The model gave good predictions on the interaction between splitting and delamination and the full range of scaling effect of open-hole tensile laminates was successfully reproduced. To take full advantage of the ply thickness effect on the damage mechanisms governing the notched responses of composite laminates, Furtado et al. [19] introduced the concept of selective ply-level hybridization and demonstrated that the combination of thin off-axis plies with thicker 0° plies resulted in a globally enhanced notched behavior without compromising the unnotched responses. The basic idea is to suppress the sub-critical damage in the thin off-axis plies and promote the longitudinal splitting in the thicker 0° plies. The popular full-field non-contact optical technique, digital image correlation (DIC) was used to measure surface deformation and more importantly, to identify surface cracks by strain field discontinuities. It has been shown that the DIC is a convenient, inexpensive and effective experimental tool for sub-critical damage localization [19–21].

In conventional finite element models of composite laminates, all of the plies and interfaces possess the same mesh configuration. However, when the splitting needs to be modeled for a general laminate with any arbitrary fiber orientations, it could be formidable or extremely time-consuming to create a mesh with the same configuration for all plies, especially when more notches are present in the model. In addition, Song et al. [22] pointed out that accurate prediction of matrix cracking paths and stress redistribution after cracking requires a mesh aligned with the fiber orientation for each ply. The core of this paper is to establish a simple and reliable model to study the thickness size effect of both sublaminate scaled and ply-level scaled laminates under open-hole tension. The intra-ply splitting and inter-ply delamination were modeled by surfaced-based cohesive contacts instead of cohesive elements. In this manner, different in-plane mesh configurations were allowed for different plies and the element edges were aligned with the fiber direction for each ply.

2. Finite element model of laminates under open-hole tension

Based on the experimental work of Green et al. [15], finite element models are created in this section for open-hole tensile composite laminates with lay-up of $[45_m/90_m/-45_m/0_m]_{ns}$. Because of the limited computational power, only the thickness size effects of sublaminate scaled laminates ($m = 1$, $n = 1, 2, 4$) and ply-level scaled laminates ($n = 1$, $m = 1, 2, 4$) are studied by fixing the width the same as the smallest specimen. Fig. 2 shows the geometry of the models. The diameter of the hole d is 3.175 mm and the ply thickness t is 0.125 mm. The width w and length l of the laminates are 5 and 10 times of the hole diameter, respectively. Due to the symmetric lay-up, only one half of each laminate is modeled by applying symmetric boundary conditions in the thickness direction so as to reduce the computational time and data storage requirements. Mesh sensitivity study in thickness direction has been performed for the baseline model ($m = 1, n = 1$). It is found that there is no significant difference between results obtained by using one element or several elements to model the stacked plies with the same orientation. Therefore, for all the cases studied, one 3D continuum element (C3D8R in Abaqus notation) is selected to represent the stacked plies with the same orientation through the thickness. Fig. 3 shows the mesh for each lamina, in which the potential splitting planes in the 0° and ±45° plies are depicted by red lines, which emanate from the hole edge and extend to the free edge of the laminates along the fiber in two directions. The Hashin failure criterion [23] is used to predict matrix cracking and fiber failure in each ply. The material properties of the IM7/8552 composite system used in the models follow those of Hallett et al. [18] and Chen et al. [16], and are given in Table 1.

In the finite element model, some important modeling strategies are included, such as longitudinal splitting, surface-based cohesive contact for splitting and delamination, aligned mesh with fiber direction, and thickness dependency of longitudinal tensile fracture toughness. All of these features are explained in detail as follows.



Sublaminate-level scaling (m=1) Hole diameter (mm)					Ply-level scaling (n=1) Hole diameter (mm)				
n	3.175	6.35	12.7	25.4	m	3.175	6.35	12.7	25.4
1	▨				1	▨			
2	▨	▨			2	■	▨		
3	▨	▨	░	░	3	■	■	■	■
4	▨			░	4	■			■

░ Brittle ▨ Pull-out ■ Delamination

Fig. 1. Failure mechanisms of tested open-hole tensile composite laminates [15].