Progressive failure analysis on scaled open-hole tensile composite laminates

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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 sublamine 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.

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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 $K_C$ or strain energy release rate $G_C$ 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
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 $[45_m/90_m/\ldots/45_m/0_m]_{ns}$. Both in-plane scaling and out-of-plane scaling of specimens were considered, and the out-of-plane scaling included sublamine 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], and are given in Table 1. Because of the limited computational power, only the thickness size effects of sublamine 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 $0^\circ$ and $\pm45^\circ$ 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.

- **Sublamine-level scaling (m=1)**
  - Hole diameter (mm): 3.175, 6.35, 12.7, 25.4

- **Ply-level scaling (n=1)**
  - Hole diameter (mm): 3.175, 6.35, 12.7, 25.4

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- **Brittle**
- **Pull-out**
- **Delamination**

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

It has been reported that notched laminates will exhibit longitudinal splitting in terms of matrix cracking emanating from notch tips along the fiber direction \([11,12]\). The longitudinal splitting can blunt the hole and alleviate the stress concentration significantly \([10,13]\). As a result, the stress field is redistributed and the load-carrying capacity of the material is enhanced. In other words, ignorance of longitudinal splitting in the model will underestimate the laminate strength. In literatures \([18,24,25]\), potential splitting routes are assumed semi-empirically based on the experimental observations. For example, half and antisymmetric splitting routes are inserted tangential to the open hole along the fiber direction in \(\pm 45^\circ/C_{176}\) plies. However, the splitting may emanate from the hole edge and propagate in two directions along the fiber. Although the splitting length in one direction might be much smaller than the other, an extremely short splitting can alter the stress concentration substantially. Recently Xu et al. \([26]\) and Li et al. \([27]\) conducted an investigation on how to put the splitting paths in progressive failure analyses of composite laminates under center-notch tension and overheight compact tension, respectively. It has been found that half splitting routes in \(\pm 45^\circ\) plies led to early failure compared to experimental results, and full splitting routes in \(\pm 45^\circ\) plies gave a good prediction. In addition, the splitting routes must pass through the notch tips, otherwise a premature fiber failure will be achieved \([27]\). Given the reasons mentioned above, full splitting routes tangential to the hole are inserted along the fiber direction in each ply (except for the 90° ply) in our model.

2.2. Surface-based cohesive contact for splitting and delamination

The material property degradation method (MPDM) is widely used in damage modeling of composite laminates. However, Irave et al. \([14]\) has proved that the MPDM cannot effectively model the alleviating effect of longitudinal splitting on stress concentration because of the spurious stress transfer. Since the matrix between fibers and the interface between plies are very thin, zero thickness interface elements can be used to simulate the intra-ply splitting and inter-ply delamination \([18,24–27]\). The most popular method is the cohesive element method, which has the advantage of predicting damage initiation through a stress-based criterion without the need of an initial crack.

Zero thickness interface elements need initial coincident nodes for the top and bottom surfaces. Therefore, the same mesh configuration should be used for the two surfaces. However, when the splitting and delamination need to be modeled for a general laminate with different fiber orientations, it could be formidable and extremely time-consuming to construct a mesh with the same configuration for all plies. To simplify the meshing process, the surfaced-based cohesive contact method instead of the cohesive element method is used to model the splitting and delamination in this paper. Comparatively, it’s much easier to define contact surfaces than to create cohesive elements in most commercial finite element softwares. Similar to the cohesive element method, the surface-based cohesive contact method also combines a strength-based analysis for damage initiation and a fracture mechanics analysis for damage propagation. However, the cohesive traction-separation behavior is defined as a surface interaction property between a pair of slave-master surfaces where damage is supposed to occur, and no physical interface element is needed. Another advantage of the surface-based cohesive contact method over the cohesive element method is that it allows different mesh structures for the two contacting surfaces. In this manner, it’s very convenient to model general laminates with various stacking sequences and notch geometries.
The traction-separation laws for longitudinal splitting and delamination are assumed to be the same. Before damage initiation, the two contacting surfaces are supposed to be bonded together and the separation between them is negligibly small due to the high stiffness. Damage initiates if a quadratic interactive traction is used for damage propagation, which is governed by fracture energy dissipation. By assuming that the longitudinal tensile fracture toughness is proportional to the blocked 0° ply thickness, Chen et al. [16] and Ridha et al. [31] predicted more accurate tensile strength of open-hole laminates. Later on, Su et al. [32] made the same assumption for longitudinal compressive fracture toughness and accurately predicted the compressive strength of open-hole laminates. It was demonstrated that by neglecting this thickness effect of longitudinal compressive fracture toughness, the compressive strength would be underestimated for ply-level scaled open-hole laminates. Although no quantitative mathematical model has been established for this thickness effect of fracture toughness, the same assumption is used in this paper, i.e., the longitudinal fracture toughness is linearly scaled with respect to the thickness of blocked plies.

### 2.4. Thickness dependency of longitudinal tensile fracture toughness

Laffan et al. [29,30] performed compact tension tests on cross-ply T300/920 carbon-epoxy composite laminates and found that the longitudinal tensile fracture toughness in fiber direction has a dependence on the thickness of blocked 0° plies. Experimental results show that the longitudinal tensile fracture toughness for the 0° plies of [(90/0)8/90], laminate is 132 kJ/m². However, the corresponding value is only 57–69 kJ/m² for [(90/0)2/90], laminate. The longitudinal tensile fracture toughness is almost doubled by thickening the 0° plies. Fractographic study of fracture surfaces of the specimens reveals that thicker blocked 0° plies leads to a larger amount of fiber pull-out (Fig. 5), which in turn causes more energy dissipation. By assuming that the longitudinal tensile fracture toughness is proportional to the blocked 0° ply thickness, Chen et al. [16] and Ridha et al. [31] predicted more accurate tensile strength of open-hole laminates. Later on, Su et al. [32] made the same assumption for longitudinal compressive fracture toughness and accurately predicted the compressive strength of open-hole laminates. It was demonstrated that by neglecting this thickness effect of longitudinal compressive fracture toughness, the compressive strength would be underestimated for ply-level scaled open-hole laminates. Although no quantitative mathematical model has been established for this thickness effect of fracture toughness, the same assumption is used in this paper, i.e., the longitudinal fracture toughness is linearly scaled with respect to the thickness of blocked plies.

### 3. Results and discussion

In this section, five open-hole laminates are simulated using the commercial finite element software Abaqus/Explicit, which includes one baseline laminate of [45/90/−45/0]s, two sublamine scaled laminates of [45/90/−45/0]s2 and [45/90/−45/0]s4, and two ply-level scaled laminates of [45s/90s/−45s/0s] and [45s/90s/−45s/0s]. The laminates are loaded monotonically up to complete failure. The loading rate is small enough so that the kinetic energy in the models can be neglected.

Simulation results show that, the failure mode for the 2 mm and 4 mm thick ply-level scaled laminates [45s/90s/−45s/0s] and [45s/90s/−45s/0s] is delamination, all other laminates fail by fiber failure mode. This is in agreement with the experimental results. Fig. 6 shows the predicted applied stress versus displacement curves for all of the laminates studied. The applied stress is calculated by averaging the total reactive force at the loaded end over the gross cross-section area. After a linear region, the curves deviate from the linearity due to the development of sub-critical damage in terms of longitudinal splitting, matrix cracking and delamination. For those laminates failed by fiber failure, the applied stresses increase up to the maximum values and then abrupt load drops occur. There is only one big load drop on each curve, corresponding to the fiber fracture in the 0° plies. The laminate strengths can be determined by the maximum applied stresses in these numerically predicted curves. While for the laminates failed by delamination, the applied stress versus displacement

### Table 1

<table>
<thead>
<tr>
<th>Material properties of IM7/8552 composite system [16].</th>
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<tr>
<td>Modulus in fiber direction $E_1$ (GPa)</td>
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<tr>
<td>Transverse moduli $E_2 = E_3$ (GPa)</td>
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<tr>
<td>Shear moduli $G_{12} = G_{13}$ (GPa)</td>
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<td>Shear modulus $G_{23}$ (GPa)</td>
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<td>Poisson’s ratio $\nu_{12} = \nu_{13}$</td>
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<td>Poisson’s ratio $\nu_{23}$</td>
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<td>Longitudinal tensile strength $X_1$ (MPa)</td>
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<td>Longitudinal compressive strength $X_0$ (MPa)</td>
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<td>Transverse tensile strength $Y_1$ (MPa)</td>
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<td>Transverse compressive strength $Y_0$ (MPa)</td>
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<td>Shear strengths $S_{12} = S_{23}$ (MPa)</td>
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<td>Shear strength $S_{21}$ (MPa)</td>
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<td>Longitudinal tensile fracture toughness $G_{\ell}$ (kJ/m²)</td>
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### Table 2

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<th>Material properties of cohesive contact [16].</th>
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<td>Normal strength $N$ (MPa)</td>
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<td>Shear strength $S = S_T$ (MPa)</td>
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<tr>
<td>Normal fracture toughness $G_{\ell}^N$ (kJ/m²)</td>
</tr>
<tr>
<td>Shear fracture toughness $G_{\ell}^S = G_{\ell}^T$ (kJ/m²)</td>
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curves have more than one load drops. The first obvious load drop, at point $A$ for \([45_\alpha/90_\beta/-45_\alpha/0_\beta]\), and point $B$ for \([45_\alpha/90_\beta/-45_\alpha/0_\beta]\), corresponds to the \(-45^\circ/0^\circ\) interface delamination. At these points the laminates lose their structural integrity, so final failure is considered to occur in practical use and the laminate strengths are determined by the applied stresses at these points instead of the maximum stresses on the curves. After the first load drop, the damage continues to propagate and the $0^\circ$ plies can still sustain load until the final load drop occurs. The final big load drop corresponds to fiber breakage in the $0^\circ$ plies. The above damage process matches with the experimental observations very well.

Among the five laminates studied in this work, only tested stress–displacement curve for \([45_\alpha/90_\beta/-45_\alpha/0_\beta]\) is available from open literature [18]. To make a comparison with the experimental result, a full model with laminate length $l = 20d$ ($d$ is the hole diameter) is created and run up to final ply failure. It should be noted that the tested final ply failure load is not available, but a good agreement can be observed from Fig. 7 for the tested and simulated delamination failure load.

The comparison between predicted and tested tensile strengths of the laminates is shown in Table 3 and schematically in Fig. 8. The models generally provide a good correlation with the experimental data. The deviations between the predictions and tested data are very small and the strength errors are less than 6% of

(a) Mesh aligned with crack direction  
(b) Mesh inclined to crack direction

Fig. 4. Effect of mesh orientation on crack path in a unidirectional compact tension specimen [22].

(a) \([(90/0)_s/90]_s\)  
(b) \([(90/0_2)_s/90]_s\)

Fig. 5. Fracture surfaces of compact tension laminates [30].

Fig. 6. Simulated stress–displacement curves for the open-hole tensile laminates.

![Simulated stress–displacement curves](image)

![Fracture surfaces](image)

Fig. 7. Comparison between tested and simulated stress–displacement curves for the open-hole tensile laminate of \([45_\alpha/90_\beta/-45_\alpha/0_\beta]\).
the average tested value for different specimens. Moreover, the correct trend of reducing tensile strength with increasing specimen thickness by both sublaminate scaling and ply-level scaling is accurately captured by the model. The thickness effect of ply-level scaling on tensile strength is much more significant than that of sublaminate scaling.

As observed in experiments, finite element simulations for all laminates show that damage initiates around the hole. Because the surface 45° ply is less constrained and the matrix in 90° plies suffers transverse tension, splitting in surface 45° ply and matrix cracking in 90° plies occur first, which are followed by the splitting in other plies. Since splitting and delamination interact with each other, local delamination also forms together with splitting along the splitting lines. The local delamination initially appears at the outermost 45°/90° interface. These types of damage take place at a rather low applied stress compared to the ultimate strength. On continuation of loading, the isolated delamination and splitting gradually link together to form small damage zones. The damage extends in the width direction, but is generally bounded by the splitting lines. Finally the damage extends in the length direction, and it’s possible to break through the splitting line constraints to form a large area of damage.

Tested specimens by Green et al. [15] show two types of fiber-dominated failure mechanisms, i.e. brittle failure and pull-out failure. The brittle failure mechanism was caused by fiber failure with little sub-critical damage. The pull-out failure mechanism was caused by fiber failure with extensive sub-critical damage. Simulation results show that all fiber-dominated failure was accompanied by considerable delamination and splitting, indicating a pull-out failure mechanism. Actually the two failure mechanisms can also be identified by the occurring sequence of delamination and fiber failure [15]. If the fiber failure stress is reached in 0° plies before the outermost 45°/90° interface delamination propagates across the width of the specimen, then the failure mechanism is brittle failure. If the fiber failure stress is reached in 0° plies at a stage after the outermost 45°/90° interface delamination propagates across the width of the specimen, but before the innermost -45°/0° interface delamination propagates across the width of the specimen, then the failure mechanism is pull-out failure. Fig. 9 shows the damage map of each ply, delamination area of each interface for the 2 mm thick sublaminate scaled laminate [45/90/−45/0]_s, at the point immediately after the load drop when fiber failure occurs in 0° plies. One superimposed damage map which combines all of the intra-laminar and inter-laminar damage together is also given in Fig. 9p. The uniformly distributed black lines along fiber directions represent the predicted matrix cracking in each ply and one dominant matrix crack is drawn for each failed element. The green and red lines in Fig. 9a–h represent the predicted longitudinal splitting and fiber fracture, respectively. The shaded areas in Fig. 9i–o denote the delamination damage. It can be seen that the outermost 45°/90° interface delamination has propagated across the width of the specimen, but the innermost −45°/0° interface delamination hasn’t reached the boundary.

The image for damage of laminate [45_4/90_4/−45_4/0_4] is available from open literature [18]. For convenience and ease of comparison with the tested specimen, damage in each layer and delamination area of each interface are plotted based on the simulation results. Fig. 10 shows the damage maps at point B on the applied stress versus displacement curve in Fig. 6. It can be seen that except for the −45°/0° interface, the delamination for the other two interfaces has propagated across the width of the laminate. When the applied stress drops to point B_r, the −45°/0° interface delamination propagates abruptly to the free edges of the laminate, whereas the delamination for the other two interfaces has no much change. Fig. 11a shows the superimposed damage pattern at point B_r. In comparison with the observed damage from experiments in Fig. 11b, most of the features of damage are replicated by the finite element model. Since no fiber failure occurs in any ply at point B_r, it proves that the load drop is induced by delamination at the −45°/0° interface.

Based on the above progressive failure analyses, the difference in thickness effect on tensile strength of sublaminate scaled and ply-level scaled laminates can be explained by the different levels of delamination propagation. As for the sublaminate scaled laminates, the delamination progression will be hindered by the closer 0° ply to the top surface. Therefore, the delamination region is relatively small for these laminates. As the laminate thickness increases, it becomes more difficult for damage to propagate to the deeper plies. These laminates fails by fiber fracture and the tensile strength reduction is milder with the increasing laminate thickness. As for the ply-level scaled laminates, the blocked thicker plies can carry much bigger load than the thinner plies. Larger interlaminar stresses may be expected due to the load transfer between the blocked plies, which results in more extensive delamination [32]. With the thickness increasing, the laminate failure mode alters from fiber failure to delamination. When the −45°/0° interface delamination extends to the free edge of the laminate, final failure is deemed to occur due to the loss of structural

Table 3
Comparison between predicted and tested tensile strengths of open-hole laminates, MPa.

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<th>Sublaminate scaling</th>
<th>Prediction (error)</th>
<th>Experiment [15]</th>
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<tr>
<td>[45/90/−45/0]_s</td>
<td>548.4 (−3.79%)</td>
<td>570 (CV,7.69%)</td>
</tr>
<tr>
<td>[45/90/−45/0]_i</td>
<td>504.8 (+0.92%)</td>
<td>500 (CV,3.95%)</td>
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<tr>
<td>[45/90/−45/0]_m</td>
<td>502.3 (+5.08%)</td>
<td>478 (CV,3.09%)</td>
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<th>Ply-level scaling</th>
<th>Prediction (error)</th>
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<tr>
<td>[45/90/−45/0]_s</td>
<td>548.4 (−3.79%)</td>
<td>570 (CV,7.69%)</td>
</tr>
<tr>
<td>[45/90/−45/0]_i</td>
<td>384.7 (−2.85%)</td>
<td>396 (CV,5.18%)</td>
</tr>
<tr>
<td>[45/90/−45/0]_m</td>
<td>259.7 (−5.56%)</td>
<td>275 (CV,5.56%)</td>
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Fig. 8. Comparison between predicted and tested tensile strengths of the open-hole tensile laminates.
Fig. 9. Predicted damage of the sublaminate scaled laminate [45/90/−45/0]s after the load drop.

Fig. 10. Predicted damage of the ply-level scaled laminate [45/90/−45/0]s at the 1st load drop.

Fig. 11. Comparison of predicted damage pattern with experimental results for the ply-level scaled laminate [45/90/−45/0]s after the 1st load drop.
integrity. However, the stress in 0° ply is still much less than the fiber failure stress at this point. This results in the dramatic reduction in tensile strengths of ply-level scaled laminates.

4. Conclusion

Longitudinal splitting emanating from the hole edge may alleviate the extremely high stress concentration in open-hole composite laminates under remote tension. An efficient finite element model is developed by modeling the longitudinal splitting in each ply. Instead of cohesive elements, surfaced-based cohesive contacts have been employed to model the intra-ply longitudinal splitting as well as the inter-ply delamination. The advantages of surfaced-based cohesive contacts over cohesive elements mainly lie in two aspects. Firstly, surfaced-based cohesive contacts allow different mesh configurations for different plies and the element edges can be aligned with the fiber direction for each ply. It has been demonstrated by researchers that an aligned mesh is necessary for accurate prediction of matrix cracking paths and stress redistribution after matrix cracking. However, cohesive elements need initial coincident nodes and all of the plies must have the same mesh configuration. It is impossible to align the element edges with all fiber directions for a general laminate with any arbitrary stacking sequences. Secondly, a great effort is usually needed to insert zero-thickness cohesive elements in finite element models. Comparatively, it’s much easier to define contact surfaces for general laminates with any arbitrary lay-ups. The convenience of surface-based cohesive method is more obvious for laminates with more fiber orientations and more notches. A good correlation between finite element simulation and experimental results is achieved for both tensile strengths and failure modes of the laminates.

Failure mechanisms of sublaminate scaled laminates and ply-level scaled laminates are examined by the proposed finite element model. Because the delamination initiated at the first interface is hindered by the closer 0° ply to the top surface, sublaminate scaled laminates exhibit relatively smaller delamination regions. Finally they fail by fiber fracture and show milder strength reduction with the increasing laminate thickness. As for the ply-level scaled laminates, the flaws formed by the higher interlaminar stresses, larger delamination regions tend to occur. The extensive delamination at interfaces next to the 0° plies causes the loss of structural integrity. Therefore the tensile strengths of ply-level scaled laminates are usually much smaller than those of sublaminate scaled laminates with the same laminate thickness.

Acknowledgement

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References