FAILURE ANALYSIS OF CENTER NOTCHED CFRP LAMINATES UNDER MULTI-AXIAL LOADING

Guangyan Liu*, Hongchen Bao

Department of Mechanics, School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China
*Email: gliu@bit.edu.cn, web page: http://www.bit.edu.cn

Keywords: Multi-axial loading, Laminates, Splitting, Cohesive contact, Progressive damage

ABSTRACT

There exists extensive literatures on damage and failure mechanisms of notched fiber reinforced composite laminates under uniaxial tension or uniaxial compression, however, equivalent works of notched laminates under combined tension-shear loading are limited. In this paper, failure mechanisms of center notched quasi-isotropic composite laminates under a series of in-plane loading (including uniaxial tension, uniaxial compression and mixed tension-shear) were studied numerically. An energy based continuum damage mechanics model in conjunction with the 3D Hashin failure criterion was employed to predict matrix cracking and fiber failure in each ply. For the intra-ply longitudinal splitting and inter-ply delamination prediction, surfaced-based cohesive contacts instead of the traditionally used cohesive elements were inserted along the potential damage zones. This allows different mesh configurations for different plies and the structured mesh can be aligned with the fiber direction for each ply to accurately model the matrix crack propagation. In addition, the proper boundary conditions in finite element models were investigated in this paper for laminates loaded by 'modified Arcan rig', which uses friction gripping to transfer loading to specimens. It is found that the small rotation of the Arcan rig has a significant effect on the failure mechanisms of the laminates. By modeling the Arcan rig in the finite element analyses, the simulation results compared very well with experimental results for both failure modes and failure loads of the center notched laminates.

1 INTRODUCTION

Carbon fiber reinforced composites have been widely used in the fields of aerospace, automotive, turbine and marine because of their numerous advantages. Fiber composites are composed of fibers and matrix, which have high anisotropy and heterogeneity, but are usually treated as homogeneous anisotropic continuum on the macro scale. Unlike monolithic materials, fibrous composite materials may develop multiple failure modes. These failure modes include fiber breakage, fiber pullout, fiber kinking, fiber/matrix debonding, matrix cracking, and delamination, all of which may have strong interactions with one another. In practical engineering applications, in order to meet the requirements of manufacture, connection, maintenance and use, openings of various shapes are often required, such as circular holes, notches, cracks, etc. Generally, subcritical damages will initiate and propagate in composite materials before ultimate failure, which may extend in non self-similar manner. In order to consider the stress redistribution due to the subcritical damages, especially in the areas with stress concentration, a large number of studies have been devoted to the progressive failure analysis of laminates[1-5]. The material property degradation method (MPDM) and continuum damage mechanics (CDM) approach are the most widely used damage modeling techniques[6-10]. Under various loads, composite laminates usually have high stress concentrations at the notch edge, which makes the finite element calculation mesh dependent. Liu and Tang[11] performed a study on mesh dependency of open hole lamina under remote tension. The study found that under linear elastic condition, even with a very fine mesh, there was still a big gap between the simulated value and the theoretical value of the fiber stress at the hole edge. However, due to the low matrix strength, it has been observed from experiments that matrix splitting will emanate from notch tips and propagate along the fiber direction in notched laminates. The growth of the splitting blunts the notches and reduces the stress concentrations correspondingly. Therefore, in order to capture the stress states at the notch tips and model the progressive failure of notched laminates, the relief effect of longitudinal splitting must be accurately simulated. Considering that the matrix between fibers is extremely thin, it is proper to use zero-thickness interface elements to model the thin and straight layer of splitting. Tang et al.[12] validated the applicability of cohesive zones for longitudinal splitting by comparing the analytical solutions and the finite element results of the stress fields in the cohesive zone near the hole edge of open-hole tension laminates. Song et al.[13] illustrated that due to shear locking, damage is more inclined to propagate along element edges or element diagonals when strain-softening constitutive models are used. Traditional finite element models have the same mesh configuration for each layer, however, laminates may have arbitrary lay-ups or multiple notches, introduction of the potential splitting routes will make the mesh generation cumbersome and difficult, or even impossible to complete. In this paper, cohesive contacts were used to simulate the intra-laminar splitting and inter-laminar delamination. Compared with the spring elements or cohesive elements, cohesive contacts have more advantages. Firstly, this method is simple and convenient to define, especially for laminates with more fiber directions and/or more notches. Secondly, cohesive contacts allow different mesh structures for the two contacting surfaces, so that the mesh can be aligned with the fiber direction in each ply. Bao and Liu[14] studied the thickness size effect of sub-laminate scaled and ply-level scaled laminates under open hole tension. Numerical results showed that both ultimate strengths and failure modes of the laminates can be reasonably predicted by using aligned mesh with the fiber direction for each ply.

Recently Tan et al.[15, 16] have studied the failure mechanisms of center notched quasi-isotropic CFRP laminates under multi-axial loading, including uniaxial tension, uniaxial compression, in-plane shear and mixed tension-shear. The main work of this paper is focused on the progressive damage simulation and failure mechanism analysis of the center notched CFRP laminates under multi-axial loading. Moreover, the correct boundary conditions for simulating the laminates loaded by an Arcan rig are investigated.

2 FINITE ELEMENT ANALYSIS

Based on the experimental work of Tan et al.[15], a three-dimensional finite element model of the center notched quasi-isotropic IM7/8552 composite laminates with layup of $[45/0/-45/90]_{2s}$ was established by commercial finite element software Abaqus (Figure 1). The specimens have a length l=23mm, width w=25mm and ply thickness t=0.125mm. The central notches have a length a=6.25mm and width b=0.7mm. The laminates were pin-loaded at points A and B by using a modified Arcan rig. The two shaded triangles in Fig. 1 represent the rigid Arcan rig. The loading angle α varies from 0^{o} to 90^{o} with intervals of 15^{o} and $\alpha=0^{o}$ corresponds to uniaxial tension. Moreover, a uniaxial compressive analysis with $\alpha=180^{o}$ is also performed. If the rotational degrees of freedom are constrained and the Arcan rig can only translate in the plane of the laminate, a series of combined tension-shear loading can be achieved and the loading is simple shear when $\alpha=90^{o}$. In this case, the prescribed displacement or loading boundary conditions can be applied to the laminates directly in finite element analyses. However, due to the pin loading at points A and B, small rotation will occur for the Arcan rig and loading states of the laminates become much more complicated. In order to make a fair comparison with the experimental results, the Arcan rig must be modeled in the finite element analyses. To study the effect of Arcan rig rotation, the two loading conditions described above are considered and the corresponding simulation results are compared with experimental observations.

In the finite element analyses, the Hashin failure criterion is used to predict matrix cracking and fiber failure in each ply. To predict the intra-ply longitudinal splitting and inter-ply delamination, surfaced-based cohesive contacts instead of cohesive elements are inserted along the potential damage zones. Different in-plane mesh configurations are used for different plies and the structured mesh is aligned with the fiber direction for each ply. Fig. 2 shows the finite element mesh for each ply and the red lines represent the intra-ply splitting routes.

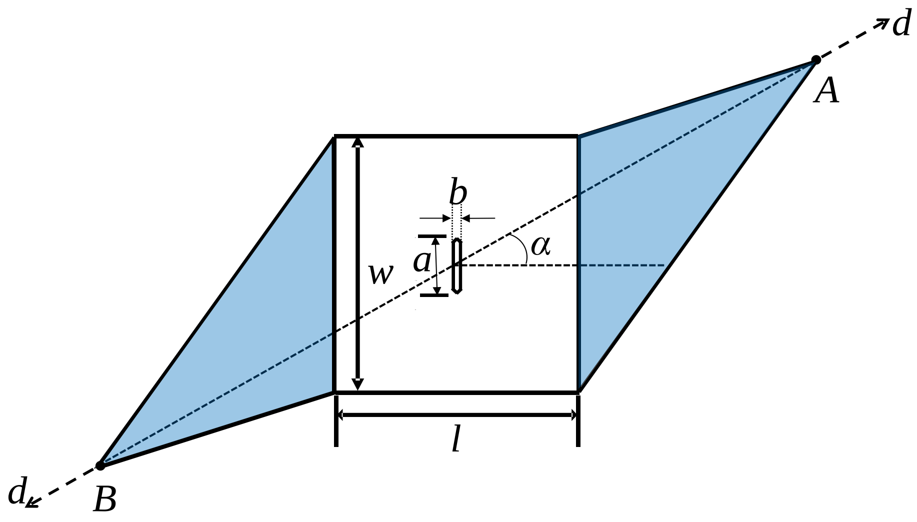

Fig. 1. Geometry of the center notched laminate loaded by an Arcan rig.

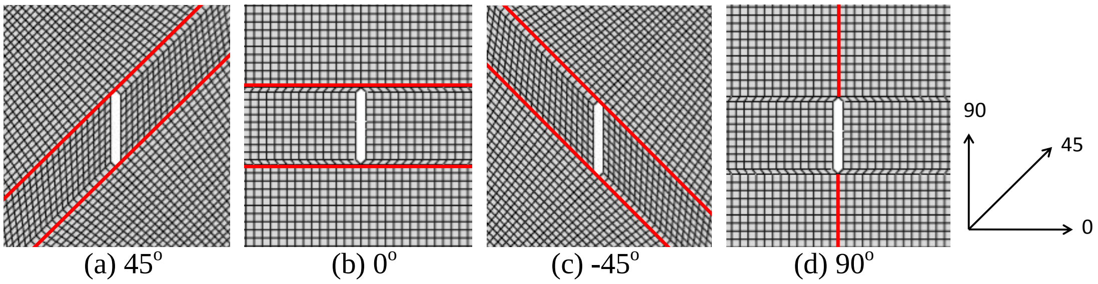

Fig. 2. Finite element mesh of the center notched laminate.

The laminates are loaded monotonically up to complete failure. The laminate strengths are determined by dividing the maximum applied loads by the cross sectional area. Fig. 3 compares the model predictions with the experimental results from Tan et al.[15]. Here 'load1' refers to the simulation results obtained by allowing rotation of the Arcan rig, and 'load2' refers to those by constraining the rotational degrees of freedom of the Arcan rig. The normal stress and shear stress components are calculated at the failure loads, and the failure envelopes are presented. In Fig. 3, different shapes are used to indicate the different dominant failure mechanisms of the laminates. Circles represent fibre tensile failure in the 0° layer, triangles represent micro-buckling failure in the

-45° layer, rectangles represent micro-buckling failure in the 0° layer, and rhombuses represent fibre tensile failure in the 45° layer. Note that when a triangle and a rhombus are put together, it means that both failure mechanisms occur simultaneously at the failure load. It can be seen from Fig. 3 that the predicted failure mechanisms and ultimate strengths are consistent with the experimental results for α=0°, 90° and 180°. However, for any loading angle α in between 0° and 90°, the two loading methods give quite different failure mechanisms and failure loads. This difference is mainly induced by the different resultant force directions at the loading points by the two loading methods. For 'load1', the resultant force directions are the same as those of the applied displacements (along line AB) due to the free rotation of the Arcan rig around the loading pins. For 'load2', the resultant forces at the two loading points are noncolinear and direct away from the applied displacement directions (Fig. 4). The moments caused by the resultant forces are balanced with those at the loading points. Since the boundary conditions for 'load 1' are more close to the real loading states in experiments than 'load2', the predicted failure mechanisms and ultimate strengths agree better with the experimental results. The main discrepancy occurs when α=30°, where the finite element model shows fiber tensile failure in the

45° layer, but the failure in experiments is governed by fiber micro-buckling in the -45° layer.

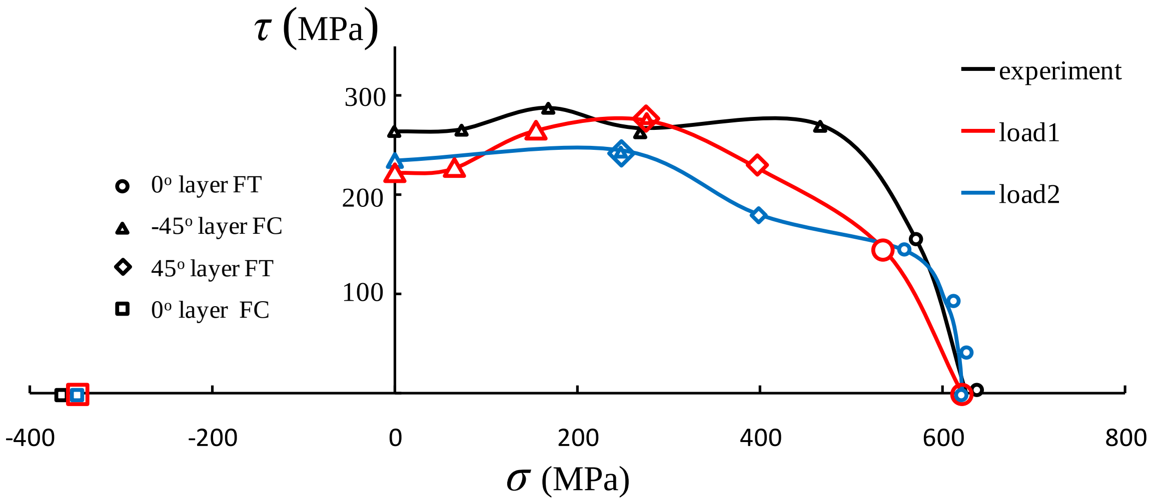

Fig. 3. A comparison of the predicted failure envelope with experimental results.

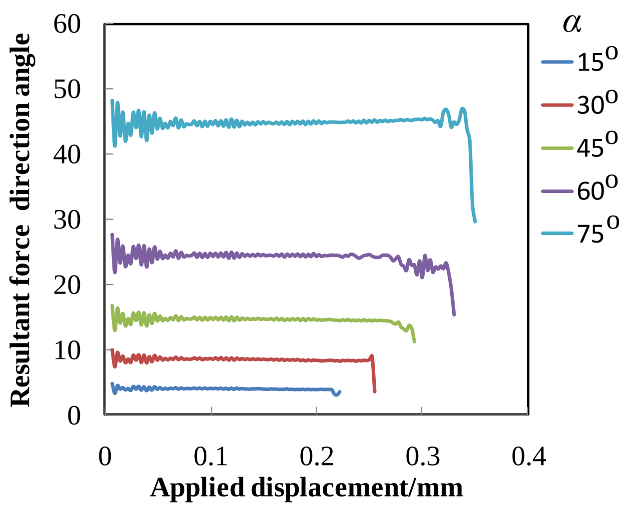

Fig. 4. Relation between the resultant force and applied displacement directions under some loading angles for 'load2'.

3 CONCLUSIONS

This paper developed an effective 3D finite element model that can reasonably predict the failure mechanisms and ultimate strengths of centre notched quasi-isotropic laminates under a series of in-plane loading (including uniaxial tension, uniaxial compression and combined tension-shear). The damage modes considered in the model include fiber tensile breakage and compressive micro-buckling, matrix cracking, longitudinal splitting and delamination. 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, which makes the mesh generation more convenient, and each layer can have different grid structures. The model only requires some basic material properties which can be measured by experiments. The validity of the finite element model is verified by comparing the simulation results with experimental observations on laminates loaded by an Arcan rig. It was found that different from the traditional understanding, the small rotation of the Arcan rig cannot be neglected and it plays an important role in predicting the failure mechanisms and failure strengths of the laminates under combined tension-shear loading. The rotational constraint of the Arcan rig results in different resultant force and displacement directions at the loading points, which is not consistent with the actual loading states in experiments. By allowing the Arcan rig to rotate, the predicted failure mechanisms and ultimate strengths of the laminates generally agree with the experimental observations for the series of in-plane loading.

ACKNOWLEDGEMENTS

The project is supported by the National Natural Science Foundation of China (11242015) and the Excellent Young Scholars Research Fund of Beijing Institute of Technology.

REFERENCES

[1] S.R. Hallett and M.R. Wisnom, Experimental investigation of progressive damage and the effect of layup in notched tensile tests, *Journal of Composite Materials*, **40**, 2006, pp. 119-141.

[2] S.R. Hallett and M.R. Wisnom, Numerical investigation of progressive damage and the effect of layup in notched tensile tests, *Journal of Composite Materials*, **40**, 2006, pp. 1229-1245.

[3] S.R. Hallett, W.G. Jiang, B. Khan and M.R. Wisnom, Modelling the interaction between matrix cracks and delamination damage in scaled quasi-isotropic specimens, *Composite Science and Technology*, **68**, 2008, pp. 80-89.

[4] S.R. Hallett, B.G. Green, W.G. Jiang, K.H. Cheung and M.R. Wisnom, The open hole tensile tests: a challenge for virtual testing of composites, *International Journal of Fracture*, **158**, 2009, pp. 169-181.

[5] B.Y. Chen, T.E. Tay, P.M. Baiz and S.T. Pinho, Numerical analysis of size effects on open-hole tensile composite laminates[J]. *Composites Part A: Applied Science & Manufacturing*, **47**, 2013, pp. 52-62.

[6] S.C. Tan and J. Perez, Progressive failure of laminated composites with a hole under compressive loading, *Journal of Reinforced Plastics & Composites*, **12**,1993, pp.1043-1057.

[7] P.P. Camanho and F.L. Matthews, A Progressive damage model for mechanically fastened joints in composite laminates, *Journal of Composite Materials*, **33**, 1999, pp.2248-2280.

[8] P. Maimí, P.P. Camanho, J.A. Mayugo and C.G. Dávila, A continuum damage model for composite laminates: Part I – Constitutive model, *Mechanics of Materials*, **39**, 2007, pp. 897-908.

[9] P. Maimí, P.P. Camanho, J.A. Mayugo and C.G. Dávila, A continuum damage model for composite laminates: Part II – Computational implementation and validation, *Mechanics of Materials*, **39**, 2007, pp. 909–919.

[10] J. Varna, R. Joffe and R. Talreja, Mixed micromechanics and continuum damage mechanics approach to transverse cracking in [S, 90n]s laminates, *Mechanics of Composite Materials*, **37**, 2001, pp. 115-126.

[11] G. Liu and K.L. Tang, Study on stress concentration in notched cross-ply laminates under tensile loading, *Journal of Composite Materials*, **50**, 2016, pp. 283-296.

[12] K.L. Tang, H.C Bao and G. Liu, Simulation on size effect of notched quasi-isotropic composite laminates under tensile loading[J]. *Journal of Reinforced Plastics and Composites*, **35**, 2016, pp. 1623-1633.

[13] K.C. Song, Y.Y. Li and C.A Rose, Continuum damage mechanics models for the analysis of progressive failure in open-hole tension laminates, *52nd AIAA Structures Structural Dynamics and Materials Conference, Denver, Colorado, April 4 -7, 2011*: 1861.

[14] H.C Bao and G. Liu, Progressive failure analysis on scaled open-hole tensile composite laminates, *Composite Structures,* **150**, 2016, pp. 173-180.

[15] J.L.Y. Tan, V.S. Deshpande and N.A. Fleck, Failure mechanisms of a notched CFRP laminate under multi-axial loading, *Composites Part A: Applied Science and Manufacturing*, **77**, 2015, pp. 56-66.

[16] J.L.Y. Tan, V.S. Deshpande and N.A. Fleck, Prediction of failure in notched carbon-fibre-reinforced-polymer laminates under multi-axial loading, *Philosophical Transactions of the Royal Society A*, **374**, 2016.