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RESEARCH ARTICLE

Finite Element Analysis of the Failure Behaviour and Mechanism of Composite Laminates with Holes Under Tension

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Abstract

In this paper, a progressive failure model is proposed for composite laminates with holes and subjected to tension. The failure criterion is implemented in ABAQUS finite element software via an in-house developed UMAT subroutine. Both fiber and matrix damage factors are used as the reference for the gradual degradation of the material properties. The progressive failure in carbon fibre-reinforced composite laminates containing holes subjected to uniaxial tension is analyzed in details. Two different composite laminate configurations are considered in this paper. The first configuration of laminates contains either a single-hole, double-hole or triple-hole with a hole diameter D of 10 mm. The second configuration of laminates contains a single central hole with various diameters of $D = 6$, 10, 16 and 20 mm. The results of the numerical simulations show that the progressive failure model is reasonably accurate in predicting the failure behaviour of the composite laminates based on both qualitative and quantitative validations. The good agreement observed between the numerical and experimental data suggests that the proposed damage model can be used for assessing progressive failure in complex composite structures.

Keywords: Composite Laminates; Progressive Failure; Damage Mechanics; Finite Element Analysis; Holes

Introduction

Fibre-reinforced composite laminates are widely used in many engineering applications such as in the design of vehicles for civil, military, aerospace and defense purposes. In the past few decades, several researchers have studied the process of damage in composites and have presented empirical and numerical models to analyze the process of damage in composite laminates [1-5].

Some earlier composite failure theories were proposed by Matzenmiller et al.[6,7], Hashin[8-10] and Puck et al[11]. Based on continuum damage mechanics (CDM) models, the failure strength of composite laminates were accurately predicted by Camanho et al.[12-15]. Maa[14] and Su[16,17] established a finite element model of damage and failure of composite laminates. Based on experimental data of some tension tests, the matrix failure and fiber failure modes were decided at the microscopic level[18]. Several notable damage models have been successfully developed by Kazuhiro et al.[19-22], and they are specifically designed to predict the tensile strengths and progressive failure in composite laminates with a hole. Based on the failure criterion and damage mechanics, failure in composite laminates was studied by Tay[23] and Lee et al.[24]. The initial and progressive failures were evaluated using the Puck failure criteria. Similar progressive failure models based on various failure criteria have also been developed for composite laminates containing through hole [25-28].

In this paper, a proposed finite element model is developed based on the progressive failure criteria mentioned in Zhangxin Guo et al. [29] to analyze the initial internal damage and the subsequent progressive failure of the internal damage in composite laminates containing holes. The results of the numerical simulation show that the progressive failure model of this paper can be used to predict, qualitatively and quantitatively, the failure behaviour and failure mechanism in composite laminates.

Experimental Investigation and Results

The test specimens used in the experimental investigation are T300/Epoxy composite laminates containing a through hole. The geometric dimensions of the composite laminates are length of 300 mm by width of 200 mm and a thickness of 3 mm. The diameter of the through hole at the centre of the laminates is 60 mm. The stacking sequence of the composite laminates is [45°/45°/0°/90°/0/0°/90°/45°/45°]S. Two reinforced aluminium alloy tabs are bonded to the two ends of each composite laminate as shown in Figure1. The dimension and geometry of specimens are shown in Figure1. The tensile test is performed using a hydraulic material test system. Figure 2 show the predicted final failure of the composite laminated specimens.

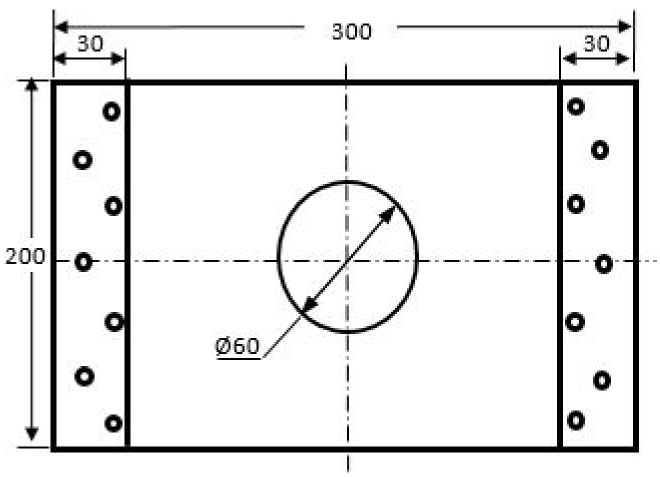


Figure 1: Geometric dimensions of the laminates

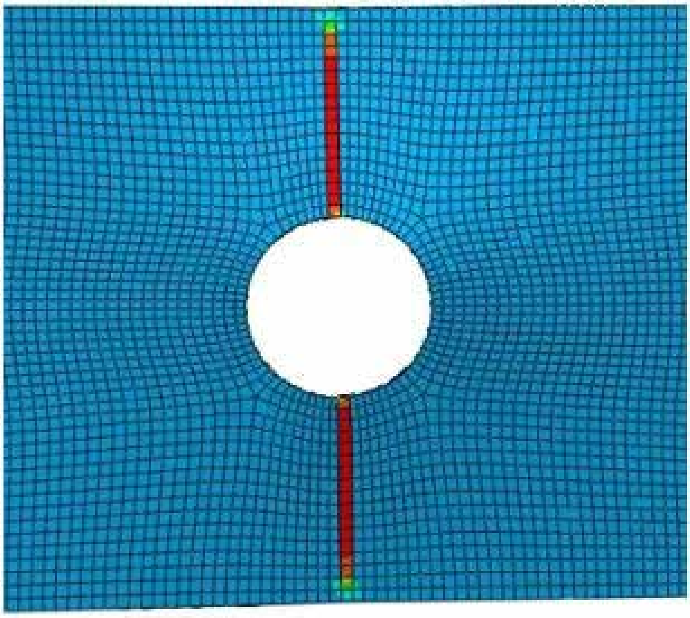


Figure 2: Final failure of composite laminated specimen

The details of the finite element model will be presented in the next section. The good correlation provides the necessary validation and confidence in the numerical model for use in predicting the progressive failure behaviour and failure mechanism in composite laminates.

Numerical simulation and discussion

The three configurations of the composite laminates used in the finite element model shown in Figure 3 are the respective composite laminates with a single-hole, double-hole and triple-hole. All holes are of diameter D = 10 mm.

Composite laminates with holes

The numerical simulation is carried out using standard ABAQUS/CAE coupled with the in-house developed subroutine to analyze the failure of composite laminates with holes. The stacking sequence of the composite laminates is [0°/-30°/30°/-45°/45/0°/-45°/45°/90°/0°]s with a total thickness of 2.5 mm. The rectangular geometry of 200 mm×100 mm and the boundary conditions of composite laminates with the three configurations of the hole are illustrated in Figure 3(a) to (c).The configuration of a single-hole, double-hole and triple-hole with a hole diameter of 10 mm are located at the centre of the composite laminates, and symmetrical with a pitch of 30 mm. The boundary conditions and geometries are consistent with the actual composite laminates used in the experimental investigation. The displacements along the left edge of the finite element model are constrained in all direction, and the displacements on the right edge of the finite element model are constrained only in the y- and z-direction. The load is implemented by applying incremental axial displacements on the right edge of the finite element model for the progressive failure analysis of the model. The material behavior of the individual composite layer is assumed to be orthotropic and the material properties of the finite element model are shown in Table 1.

Figure 4 shows the predicted distribution of the axial load vs displacement curves for the finite element model using the proposed progressive failure model. It can be seen that there is a bi-linear response before the sudden load drop. The predicted curves of reveal no traces of nonlinearity at the early stage, and then an obvious stiffness degradation of the composite laminates.

The curves in Figure 4 also indicate an important influence of the interaction for double-hole and triple-hole configuration. The peak strength is the highest for the composite laminates with single-hole compared to that for the composite laminates with multiple holes. For the composite laminates with triple-hole, their tensile strengths are about 20% lower than the composite laminates with single-hole.

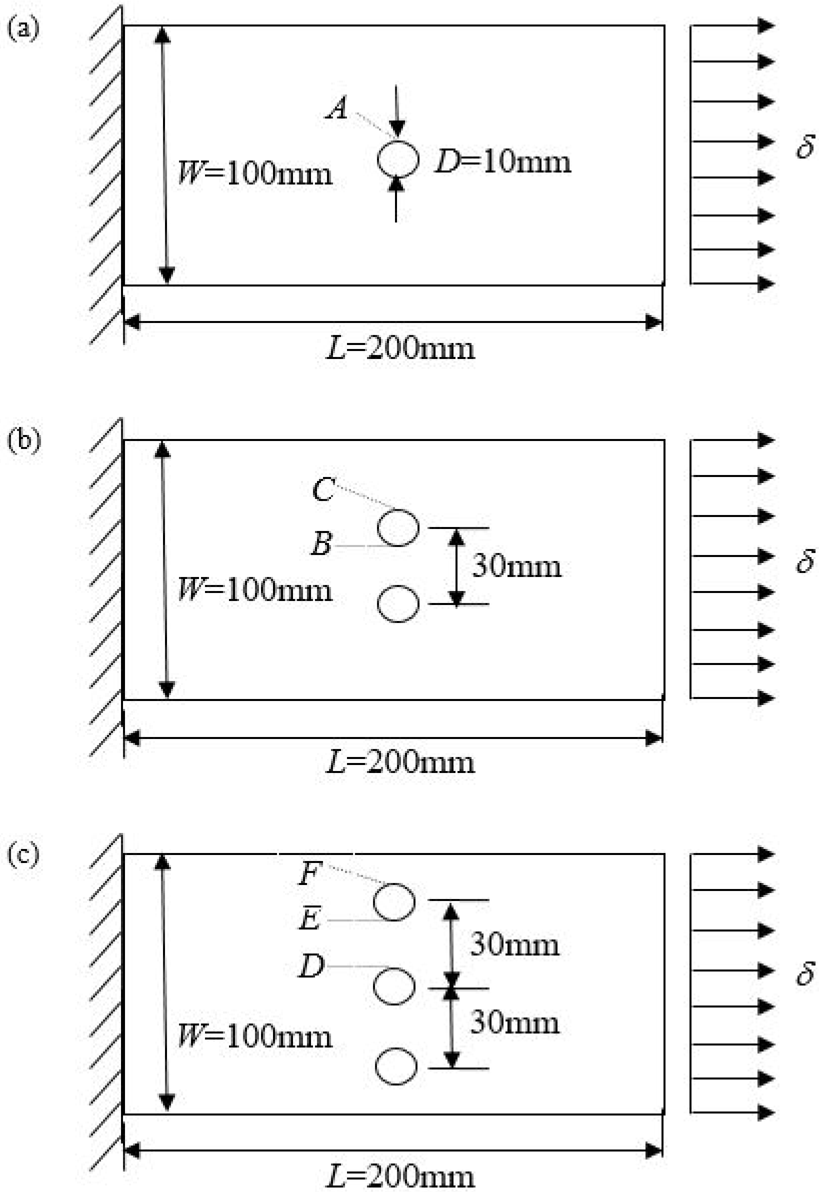


Figure 3: The geometries and boundary conditions of the laminates with hole

(a) Single-hole. (b) Double-hole. (c) Triple-hole

EL (MPa)	ET (MPa)	GLT (MPa)	GTT (MPa)	νTT	νLT (MPa)	$\acute{o}_L^{f,t}$ (MPa)	$\acute{o}_L^{f,c}$ (MPa)	$\acute{o}_T^{f,t}$ (MPa)	$\acute{o}_T^{f,c}$ (MPa)	$\hat{o}_{LT}^{f}$
55000	9500	5500	3000	0.45	0.32	500	2000	50	150	50

Table 1: Material properties for the fiber-reinforced epoxy composite laminates

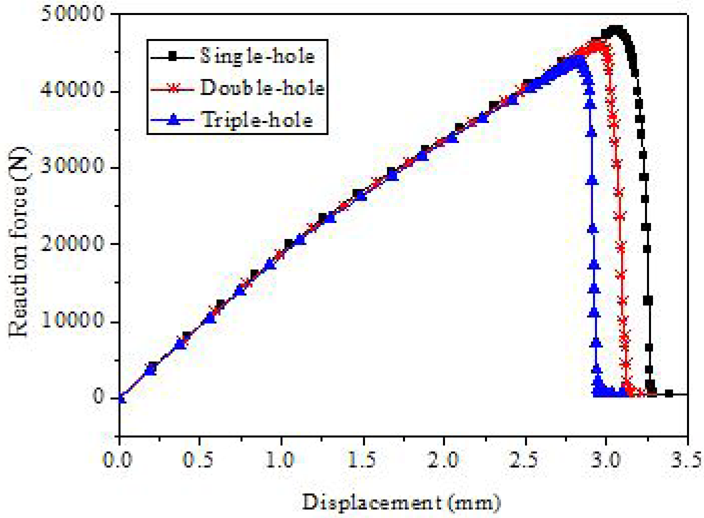
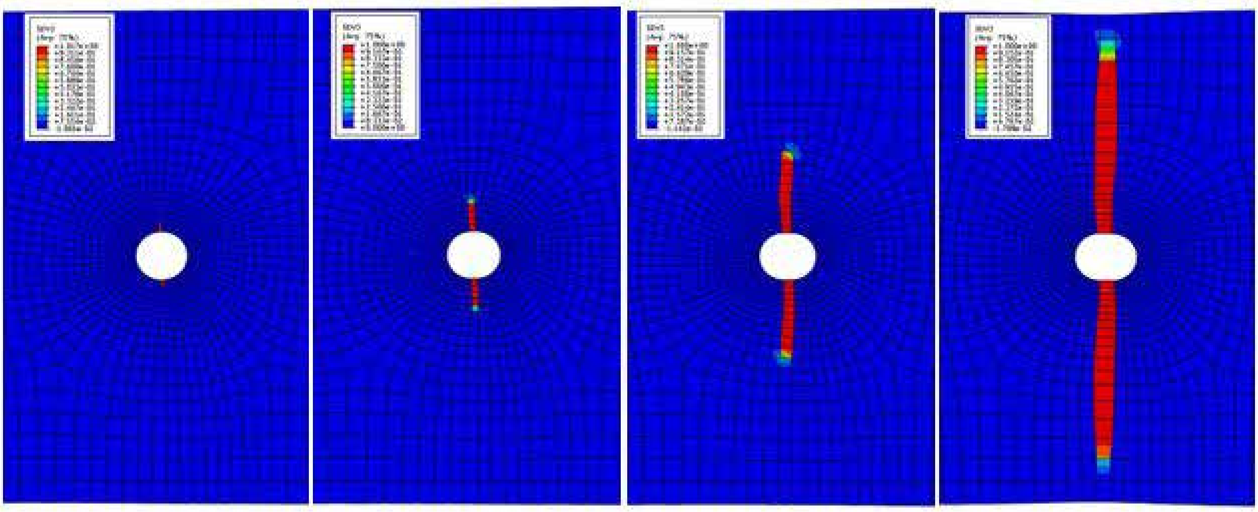
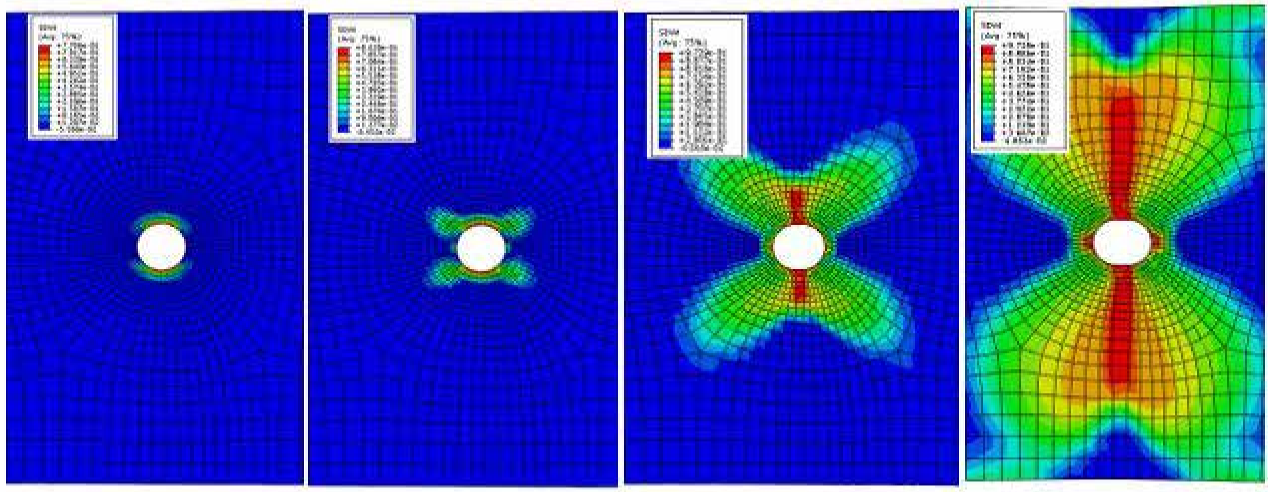


Figure 4: Comparison of the load-displacement curves of composite laminates



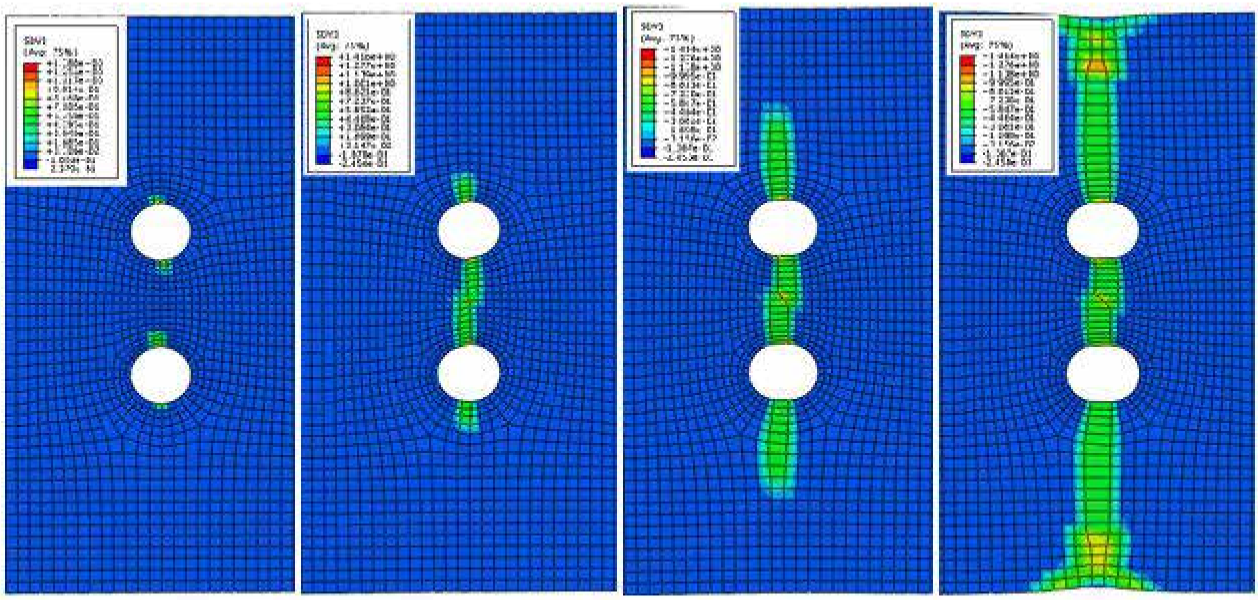
(a) Displacement=3.05mm(b) Displacement=3.11mm(c) Displacement=3.17mm(d) Displacement=3.24mm

Figure 5: Progressive fiberfailure contoursin 0°ply of composite laminate (Single-hole, D=10mm)



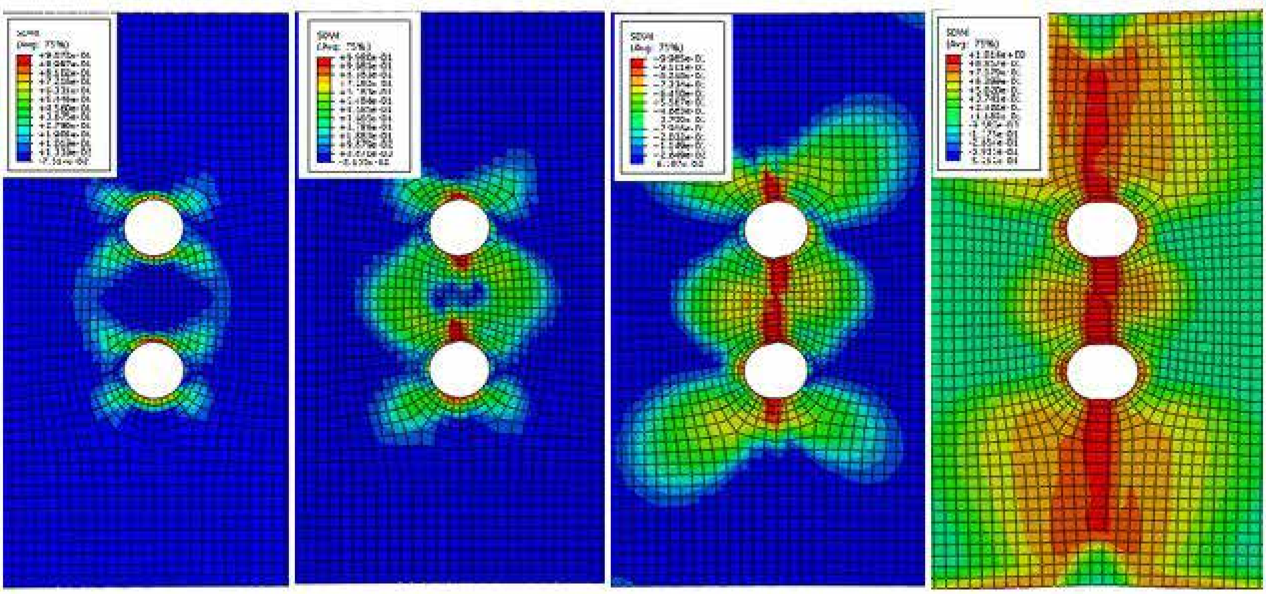
(a) Displacement=2.1mm(b) Displacement=2.8mm(c) Displacement=3.13mm(d) Displacement=3.22mm

Figure 6: Progressive matrixfailure contoursin 0°ply of composite laminate (Single-hole, *D*=10mm)



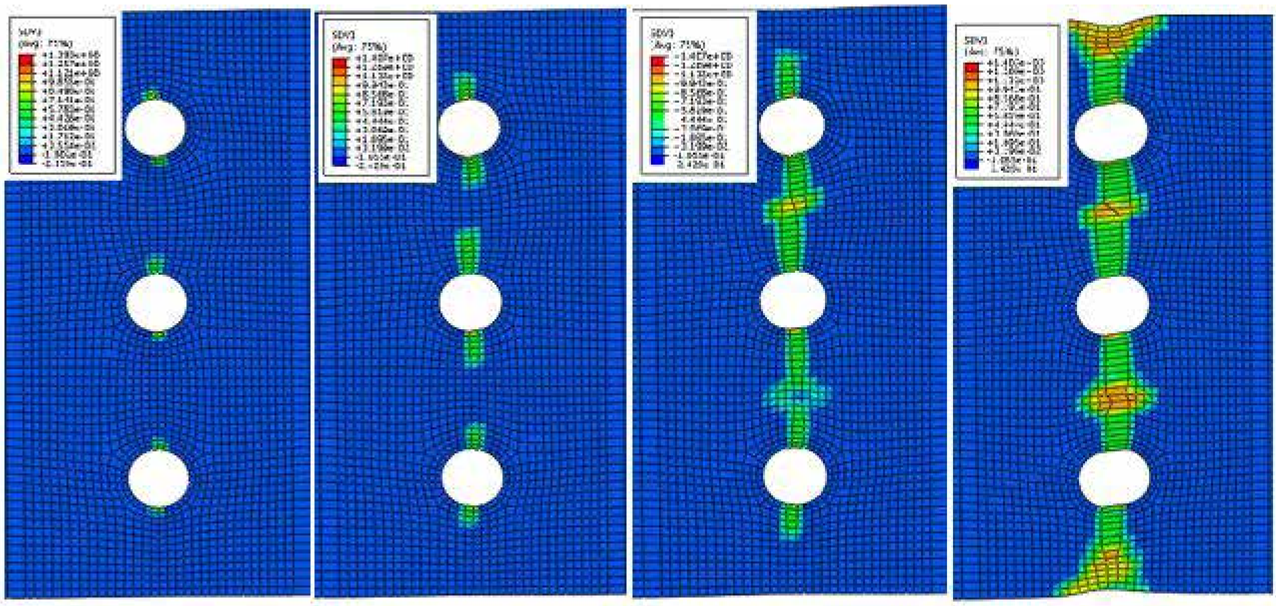
(a) Displacement=2.86mm(b) Displacement=2.92mm(c) Displacement=2.97mm(d) Displacement=3.02mm

Figure 7: Progressive fiberfailure contoursin 0°ply of composite laminate (Double-hole, *D*=10mm)



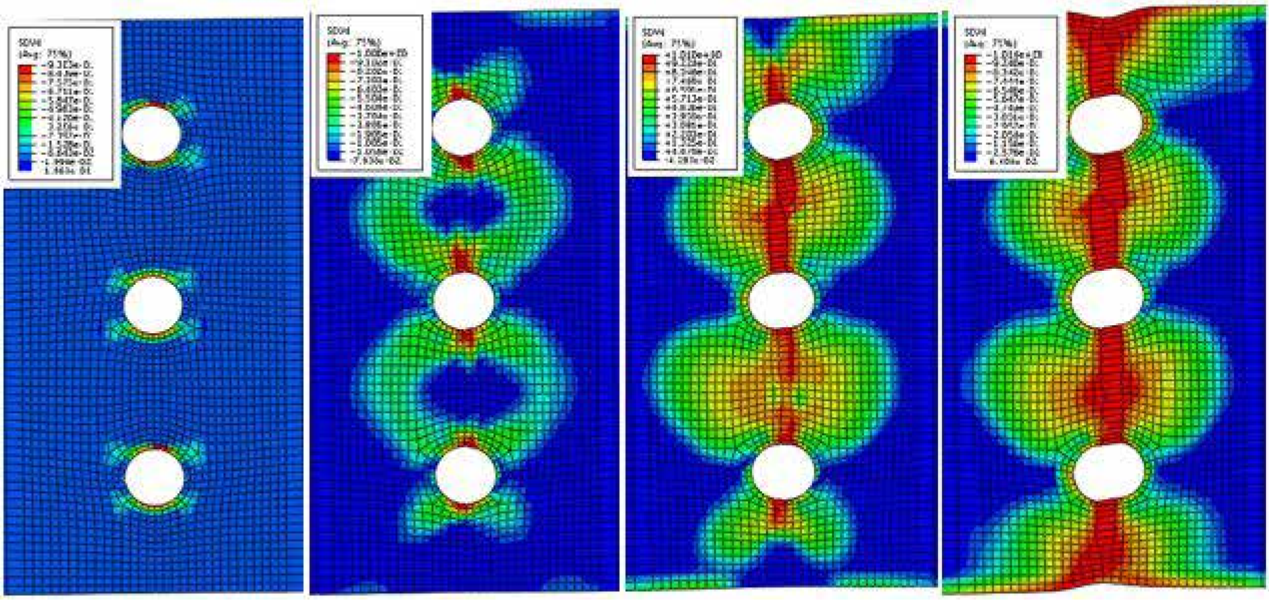
(a) Displacement=2.7mm(b) Displacement=2.87mm(c) Displacement=2.93mm(d) Displacement=3.01mm

Figure 8: Progressive matrixfailure contoursin 0°ply of composite laminate (Double-hole, *D*=10mm)



(a) Displacement=2.81mm(b) Displacement=2.88mm(c) Displacement=2.9mm(d) Displacement=2.94mm

Figure 9: Progressive fiber failure contoursin 0°ply of composite laminate (Triple-hole, *D*=10mm)



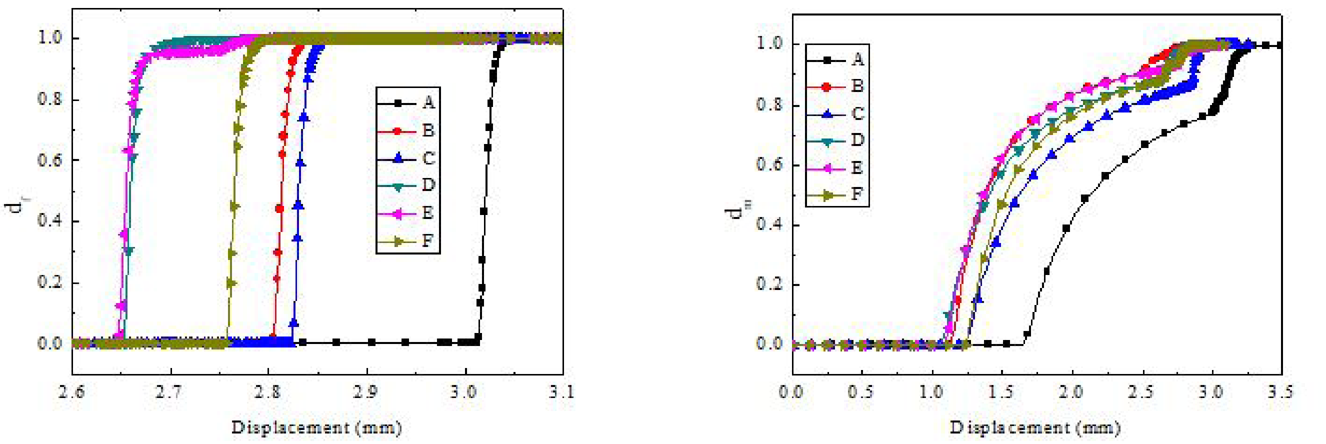
(a) Displacement=2.45mm(b) Displacement=2.86mm(c) Displacement=2.91mm(d) Displacement=2.94mm

Figure 10: Progressive matrix failure contours in 0°ply of composite laminate (Triple-hole, *D*=10mm)

In addition to the results shown in Figure 4, the finite element analysis based on the developed progressive failure method in this paper can also give a graphical illustration of the variation of fiber/matrix damage factor in every ply of the composite laminates under consideration. As an example, the initial damage and progressive failure in 0° ply of the laminates containing a hole with the diameter of 10 mm are shown in Figures 5 to 10.The damaged areas of the composite laminates are shown with the red colour. As can be seen in these figures the matrix and fibre progressive failure can be predicted using the proposed subroutine. The damage progression of the composite laminates shown in these figures corresponds to the damage load of the finite element model of Figure 4. It can also be seen from Figures 5 to 10 that damage initiated at the intersection of the through hole and the mid-line of the composite laminates where there is obvious stress concentration, and damage then propagated across the weakest sections of the composite laminates and causes final failure.

For composite laminates with multiple holes, fibre failure first occurs between holes as can be seen in Figures 7(b), 7(c), 9(b) and 9(c), and failure then propagates to the edges of the composite laminates as shown in Figures 7(d) and 9(d).The patterns of the failure evolution that reflect the mechanical response of the composite laminates (single-hole, double-hole and triple-hole) are also shown in Figures 5 to10. It can be observed that the damage evolution starts in the layer with low residual strength of the composite laminates when the maximum load is attained. These results show that the proposed finite element model can be used to simulate the progressive failure process and explain the important details of the internal damage and failure in composite laminates with holes.

The plots of variation in damage factor versus displacement plots for different locations are shown in Figure 11. The locations of *A*, *B*, *C*, *D*, *E* and *F* are indicated in Figure 3. The plots of progressive failure for 0° layer can be seen in Figures 5 to10. These figures showed that the damage initiation occurred near the edge of hole for all the three configurations. The above conclusions are of significance to researchers and designers in structural and engineering application of composite laminated structure.



(a) fiber damage factor df (b) matrix damage factor dm

Figure 11: Variation of damage factor for different locations of 0°ply

Effect of diameter on failure

Figure 12 shows effect of the hole diameter (*D*) on the damage load of composite laminates. The figure shows that the damage load of the composite laminates increases with the decrease in the diameter (*D*) of the hole. The corresponding fiber damage factor *d*f and matrix damage factor *d*m versus displacement curves are shown in Figure 13. The figure clearly shows that the trend of fiber damage and matrix damage for different hole diameters are basically identical with increasing displacements. The fiber damage factor and matrix damage factor increases with increasing hole diameter.

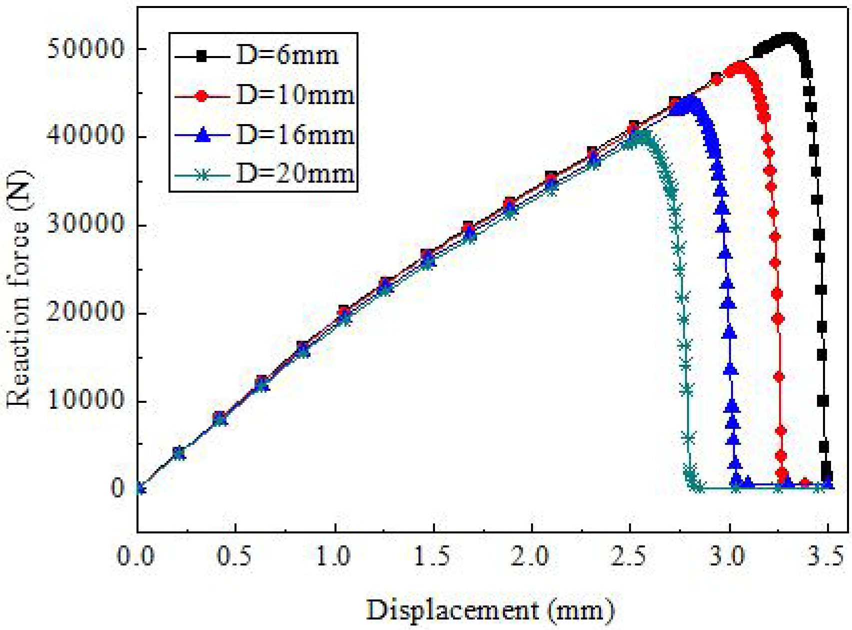


Figure 12: Predicted load-displacement curves of the laminates (*D*=6mm, *D*=10mm, *D*=16mm, *D*=20mm)

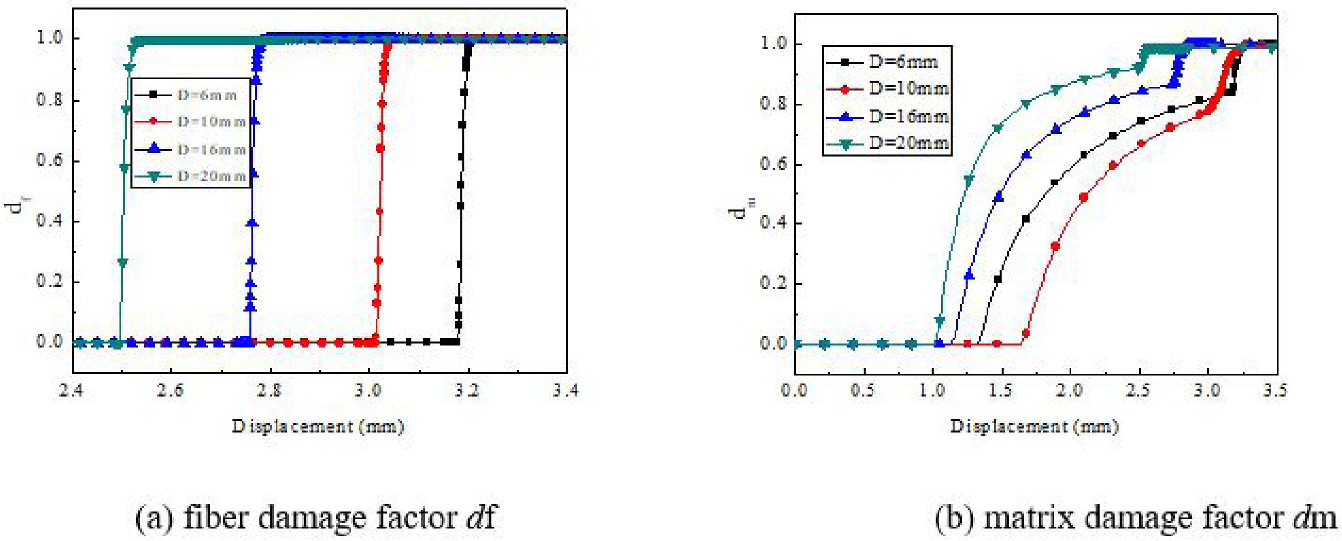


Figure 13: Variation of damage factor for different diameters of hole

Concluding Remarks

In this paper, the damage initiation and failure progression of composite laminates with holes are analyzed using an in-house developed subroutine for the finite element software ABAQUS. The beginning and development of damage in the laminates are reasonably predicted using the progressive damage criteria.

The simulation results showed that the proposed progressive failure model can be used to understand the important insights in the internal damage and failure mechanism in composite laminates with holes. Based on the proposed progressive failure subroutine, it may be feasible to analyze the structural progressive failure in complex composite structures.

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