Study on the compression and shear bearing capacity of composite stiffened plates with opening crack

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Abstract. In the process of manufacture and use, the composite stiffened plate will degrade and produce different types of cracks and damage, which limits its application. Therefore, it is significant to study the composite stiffened plate with cracks. Three-dimensional Hashin failure criterion and the gradual damage model of TAN parameter degradation are applied to simulate composite stiffened plate with long crack under uniaxial compression and pure shear load. The effects of crack angle on the ultimate compressive strength, shear strength and progressive damage of composite stiffened plates were investigated. The results show that the effect of crack angle on the compression performance of the stiffened plate is not simply linear, but the effect on the shear performance of the stiffened plate is more complicated, and the effect of crack angle on shear behavior is also related to the sequence of layer.

1. Introduction
Compared with ordinary plates, the composite stiffened plate structure has higher yield strength ratio, stability and stronger bearing capacity[1]. It is widely used in the main bearing structures such as fuselage, wing and tail of aircraft[2]. During the use of stiffened plates, the material degenerate and various types of crack appear[3]. And stiffened plate structures may need to introduce an opening design during assembly and use, although not defective, but also often considered as initial damage[4]. The static strength of the thin plate is sensitive to the opening, so evaluating the mechanical properties and ultimate strength of the cracked stiffened plates is important[5].

Zhang Jing[6] explored the influence of the central crack with different lengths and angles on the compression distribution and buckling mode of stiffened steel plates. Paik and Wang et al[7] studied the ultimate shear strength of the intact and cracked stiffened plates, considering the vertical, horizontal and oblique openings. Bayatfar[8] and Cui[9] investigated the effect of cracks on the ultimate strength of the stiffened plate under uniaxial compression. Rahbar[10] found that the longitudinal crack at the central position had no significant effect on the ultimate strength, and the ultimate strength reduction of the thin plate with edge crack was greater than the central crack. Ambur[11] used three failure modes to accurately reflect the post-buckling damage of the cracked stiffened plate under shear load. Fan[12] studied the influence of the microcrack direction and position on the buckling and post-buckling of the stiffened plate. Xu Lian[13] studied the post-buckling progressive damage path of composite stiffened plates with crack or without crack. Yu Fen[14] studied the effect of different angle grooves on the compression bearing capacity and progressive damage of Ω Type composite stiffened plate.

In order to further study the mechanical properties of composite stiffened plate with cracks under static load, a series of finite element simulations were performed on composite stiffened plates
containing crack under uniaxial compression and pure shear according to the 3D Hashin failure criterion and the degradation mode of TAN parameters. The influence of the crack angle on the ultimate strength and failure behavior of the stiffened plate are discussed.

2. Model establishment
Hughes et al.[15] found that the performance of plates with single stiffener may not represent structures with multiple longitudinal stiffeners, so the composite stiffened plate studied here consists of 5 hat stiffeners, skin with geometry of 952mm×872mm and transverse frames. Skin and hat stiffeners use X850 toughened resin carbon fiber prepreg, skin set [45/-45/-45/-45/90/45/0]s of 12 layers; hat stiffeners paving [45/0/0/-45/90]s 9 layers, single layer thickness is 0.185mm. The alloy material is selected for the transverse frame. Material parameters of the composite material and the alloy are listed in Tables 1 and 2.

| Table 1. composite material | Table 2. alloy |
|-----------------------------|----------------|
| $E_1$/GPa | 154 |
| $E_2$/GPa | 8.5 |
| $E_3$/GPa | 8.5 |
| $\mu_{12}$ | 0.35 |
| $\mu_{13}$ | 0.35 |
| $\mu_{23}$ | 0.35 |
| $G_{12}$/GPa | 4.2 |
| $G_{13}$/GPa | 4.2 |
| $G_{23}$/GPa | 4.2 |
| $E$/GPa | 70 |
| $\mu$ | 0.3 |

The compression and shear models are established by Abaqus. The skin and stiffeners all adopt the 8-node hexahedral continuum shell element SC8R, The transverse frame uses the 8-node hexahedral solid element C3D8R, and the element size is 10mm.

In Figure 1 (a), the upper and lower grip ends are coupled to the 6 freedom degrees of reference point 1 and 2 respectively, reference point 2 is clamped, reference point 1 is only free on loading direction U3. The clamp region around the shear model is coupled to the reference point in Figure 1 (b). Reference point 1 is applied load along the model diagonal which is equivalent to pure shear load.

![Figure 1. Stiffened plate model, (a)compression model, (b)shear model](image)

2.1. Sample models
13 composite stiffened plate models were designed to perform a finite element simulation, with the sample details listed in Table 3. Since the compression model is symmetrical, its crack angle is from 0° to 90°; similarly shear model’s crack angles between crack and loading direction range from 0° to 90° (angles between crack and vertical direction range 47.5° to 137.5°).

| Table 3. Detailed information of compression models C1~C4 and shear models S1~S9 |
|-----------------------------|-----------------------------|
| Model category | Number | Angle with the vertical direction | Width |
| Compression model | C1~C4 | 90°,70°,50°,30° | 2mm |
| Shear model | S1~S9 | 47.5°,60°,70°,80°,90°,100°,110°,120°,137.5° | 2mm |
2.2. Failure criterion and degradation model

The 3D Hashin criterion [16] was used as a criterion for material failure, including five criteria independent of each other. Strength of X850 tightened resin/carbon fiber prepreg is shown in Table 4. Subsequent evolution of composite damage combined with the progressive damage model of TAN parameter degradation mode [17], Material stiffness degrade according to Table 5.

| Table 4. Strength of X850 tightened resin/carbon fiber prepreg |
|-----------------------------------------------|---------------|---------------|---------------|---------------|
| $X_t$/MPa | $X_c$/MPa | $Y_t$/MPa | $Y_c$/MPa | $S$/MPa |
| 2610     | 1450     | 55         | 285         | 105        |

| Table 5. Degradation mode of composite material parameters |
|-----------------------------------------------|---------------|---------------|---------------|---------------|
| failure mode | $E_{11}$ | $E_{22}$ | $E_{33}$ | $v_{12}$ | $v_{13}$ | $v_{23}$ | $G_{12}$ | $G_{13}$ | $G_{23}$ |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| mf             | $E_{11}$       | 0.2$E_{22}$    | 0.2$E_{33}$    | 0.15$v_{12}$ | 0.15$v_{13}$ | 0.15$v_{23}$ | 0.2$G_{12}$ | 0.2$G_{13}$ | 0.2$G_{23}$ |
| mc             | $E_{11}$       | 0.4$E_{22}$    | 0.4$E_{33}$    | 0.15$v_{12}$ | 0.15$v_{13}$ | 0.15$v_{23}$ | 0.4$G_{12}$ | 0.4$G_{13}$ | 0.4$G_{23}$ |
| ft             | $0.07E_{11}$  | $0.07E_{22}$  | $E_{33}$       | 0.07$v_{12}$ | 0.07$v_{13}$ | 0.07$v_{23}$ | 0.07$G_{12}$ | 0.07$G_{13}$ | 0.07$G_{23}$ |
| fc             | $0.14E_{11}$  | $0.14E_{22}$  | $E_{33}$       | 0.14$v_{12}$ | 0.14$v_{13}$ | 0.14$v_{23}$ | 0.14$G_{12}$ | 0.14$G_{13}$ | 0.14$G_{23}$ |
| mfs            | $E_{11}$       | $0.07E_{22}$  | $E_{33}$       | 0.01$v_{12}$ | 0.01$v_{13}$ | 0.01$v_{23}$ | 0.01$G_{12}$ | $G_{13}$    | $G_{23}$    |

3. Results and discussion

3.1. Compression results

Compression displacement-load curve of stiffened plate with different angle crack is shown in Figure 2, the compression stiffness of stiffened plate on the linear stage is lower than the intact plate, but the effect of crack angle on the compression stiffness is not obvious. Under the large deformation, the ultimate compression strength of the cracked stiffened plates reduce by about 16% at least compared with intact plate. the model C4 with 40° crack has the maximum ultimate compression load, while the model C2 with 70° crack has a minimum ultimate compression load.

![Figure 2. Displacement-load curves of models C0–C4](image)

Skin appears destruction before the stiffener as shown in Figure 3. For model C1, the crack tip region first shows fiber compression destruction and fiber-matrix shear disruption, followed by matrix tensile and compression destruction. The angle of the crack has little influence on the eventual failure mode. For stiffened plates with different cracks, the destruction element extends horizontally from the crack tip until the end on the adjacent stiffener, and eventually the structure loses its bearing capacity.
Figure 3. Shear failure, fiber compression failure, matrix tensile failure and matrix compression failure of model (a) C1 and (b) C4

3.2. Shear result

The angle (crack and model diagonal) of the models S1 to S9 successively increased from 0° to 90°. Figure 4 (a) shows that value of the first order buckling load is negative affected by the crack angle since the ABAQUS believes that loading in the opposite direction is more prone to buckle. The absolute difference among the first order buckling load whether negative or positive is not obvious. The angle increases from 0° to 42.5° or from 42.5° to 90°, the shear ultimate load first increases and then decreases with the angle. When the angle reaches 42.5° or 90°, the ultimate load decreases greatly compared with the intact plate, reducing 74.4kN and 82.9kN, respectively.

In order to explore the complex relationship between crack angle and ultimate load, each layer was changed to 0°, as shown in Figure 5, the first order buckling load change regulation is still similar to the model S1~S9, while the ultimate load regulation changes, decreasing first and then increasing with β increasing. At β less than 42.5°, the ultimate load gradually decreases with β increasing; at β=42.5° (horizontal crack), the angles between crack and the model two diagonals are equal, β continue to increase, the angle (90°-β) between the crack and the another diagonal is actually decreasing gradually, the tensile load is equivalent to the compression load on the another diagonal, so the ultimate load gradually increases with the angle between crack and the another diagonal decreasing.
Figure 5. (a) First-order buckling load, (b) Ultimate shear load of the 0° layup mode

In the case of pure shear, the failure of the intact stiffened plate is mainly due to fiber compression damage in the skin, accompanied by matrix tensile failure and fiber-matrix shear failure; the structure mainly occurs in the parallel area on and around the diagonal (Figure 6(a)). The failure mode after introducing crack is still these three forms of failure, but the tensile failure of the matrix is mainly extrusive. The expansion direction of the destruction element is affected by the crack, extending along the crack tip to the intersection of the stiffener and frame. In Figure 6(b), the destructive element is not extended widely, when the $\beta$ angle increases slightly, the expansion degree of the destruction element suddenly increases, especially the matrix tensile disruption is particularly obvious.

Figure 6. Tensile fracture of the matrix, compression of fibers and shear failure (a) S0, (b) S1, (c) S5

4. Conclusion
The analysis found that:
(1) the compression ultimate load of the composite stiffened plate does not increase monotonically with the decrease of the crack angle.

(2) The compression destruction mode of the cracked composite stiffened plate is mainly shear failure, accompanied by fiber compression destruction and tensile and compression destruction of the
matrix. The destruction element extends from the crack tip in the horizontal direction to the adjacent stiffener.

3) As the angle of crack increasing from 0° to 42.5°, from 42.5° to 90°, the shear ultimate load shows a trend of increasing first and then decreasing at the limit of β=42.5°. Changing the paving angle to 0°, the shear ultimate load change regulation with the crack angle becomes simple.

4) The shear failure of the intact stiffened plate and the cracked stiffened plate is mainly the matrix tensile destruction of the skin, accompanied by fiber compression damage and fiber-matrix shear damage. The shear failure destruction element extends from the crack tip to the intersection of the stiffener and frame.

5) For both loading cases, the crack angle does not change the final form of destruction, but will have impact on the expansion path and range of the destruction element.

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