Study on Tensile Properties of Reinforced Composite Laminates with Open Holes

Ding Cong
Shanghai Aircraft Design and Research Institute, Shanghai 201200, China
Email: dingcong@comac.cc

Abstract. The performance of open-hole composite laminates with different sizes and fillets under tensile load was analyzed by experiments and finite element software of ABAQUS. The effects of different hole sizes and fillet radius on the tensile properties of laminates were discussed. The results showed that the tensile failure load decreased with the increase of the hole size, and the trend was obvious. As the fillet radius of the hole increased, the failure load tended to increase.

1. Introduction
Carbon fiber reinforced composites have been widely used in aircraft structures since the 1970s due to their high specific strength, high specific stiffness, strong designability, corrosion resistance, and good fatigue properties \cite{1}. In the design of composite structure, it is inevitable to consider the stress concentration and the reduction of bearing capacity caused by the open holes \cite{2}. Therefore, certain reinforcement measures must be taken. In order to obtain a lightweight and high-efficiency composite with open-hole reinforcement, it is necessary to study the mechanical properties and parameter selection of the typical open area reinforcement.

Many studies have been carried out at home and abroad. O’Neill analyzed the influence of asymmetric reinforcement on the strength of laminates and found that the strength of the reinforced laminates could be increased by 5% to 12% \cite{2}. Luo et al. conducted experimental research and numerical analysis on different aperture diameters in open-hole reinforcement and found that there was a reinforcement aperture with the highest reinforcement efficiency \cite{3}. The above studies have done a lot of analysis on the influence of strength by reinforcement form, reinforcement aperture, and so on. However, there is no in-depth study on the reinforcement size of open-hole composite laminates and the relationship between the reinforcement thickness and the laminates thickness.

In this paper, the strength values of composite laminates with different reinforcement diameters and thicknesses (2.68mm in thickness) were obtained through tensile tests. At the same time, the stress change and damage process of the open-hole laminates were obtained by finite element simulation using ABAQUS software.

2. Experiments and Methods
A composite laminate with a length of 1000 mm and a width of 600 mm was designed, with a circular reinforcement opening in the center of the web. The materials were 27 pieces of CYCOM977-2/12K HTS unidirectional tape. The typical size of the test piece was shown in Figure 1, the laying order was shown in Table 1, and the test piece matrix was shown in Table 2. Each test piece was attached with 15 pieces of reinforcing patches in total.
Figure 1 Dimension drawing of the typical test piece

Table 1 Ply parameters of test laminates

| Ply angle         | Nominal thickness (mm) |
|-------------------|------------------------|
| [0/±18/±36/±54/±72/90]s | 2.680                 |

Note: the ply with brackets is bi-directional fabric.

Table 2 Matrix of test piece

| Test piece number | Reinforcement parameters          | Number of test pieces |
|-------------------|-----------------------------------|-----------------------|
| 1                 | D2/D1=1.4; t2/t1=1.4              | 3                     |
| 2                 | D2/D1=1.5; t2/t1=1.4              | 3                     |
| 3                 | D2/D1=1.6; t2/t1=1.4              | 3                     |
| 4                 | D2/D1=1.4; t2/t1=1.5              | 3                     |
| 5                 | D2/D1=1.4; t2/t1=1.5              | 3                     |
| 6                 | D2/D1=1.6; t2/t1=1.5              | 3                     |
| 7                 | D2/D1=1.6; t2/t1=1.6              | 3                     |
| 8                 | D2/D1=1.5; t2/t1=1.6              | 3                     |
| 9                 | D2/D1=1.5; t2/t1=1.6              | 3                     |

Note: D2 is the diameter of reinforcing patch and D1 is the diameter of open hole. t2 is the thickness of reinforcing patch and t1 is the thickness without reinforcement.

According to ASTM D 5766/D 5766M-02 standard, 200×100 reinforcing patches with a thickness of 5 cm were glued on both sides of the two ends of the test piece. The chucks at the upper and lower ends of the testing machine were clamped on the reinforcing patches at the upper and lower ends of the test piece respectively. The WDW-1000E static testing machine was used for displacement loading, with a loading speed of 2 mm/min. The installation of the test piece was shown in Figure 2.

Figure 2 Installation diagram of test piece
3. Results and Discussion
There were three typical failure modes in the tensile test of the open-hole test piece: brittle fracture, shear failure, and mixed failure. The three typical failure modes were shown in Figure 3.

![Figure 3 Typical failure modes of test piece](image)

3.1. Results of tensile failure load test
There were 27 open-hole tensile test pieces in total, and there were 3 pieces per group. The failure modes of all the test pieces were in accordance with ASTM standards and there was no abnormal test data. The statistical results of failure load and average load of each test piece were shown in Table 3 and Figure 4

| Fillet (mm) | Hole (mm) | 50×50 | 40×40 | 30×30 |
|------------|-----------|-------|-------|-------|
| R10        |           | 101.67| 114.97| 111.13|
| R15        |           | 100.27| 108.72| 103.68|
| R20        |           | 91.12 | 107.80|-|
| R25        |           | 97.53 | -     |-|

![Figure 4 Histogram of failure load in tensile test of test piece](image)

The time-strain curve, the load-displacement curve, and the strain-load curve of the test piece with a central hole of 50 mm × 50 mm and a fillet of R20 were shown in Figures 5 to 7.
Figure 5 The time-strain curve

Figure 6 The load-displacement curve

Figure 7 The strain-load curve
3.2. Analysis of tensile failure load test

The model adopted a test piece with a hole size of 30 mm×30 mm and a fillet radius of 10 mm. The finite element model was shown in Figure 8. The boundary condition was that one end was fixed, the other end was applied with a displacement load (1000µε) of 1 mm, and both sides were free. In the simulation process, the 8-node secondary shell element S8R was adopted, and the analysis step was linear static general analysis step [4].

It can be seen that the stress concentration factor was 3.615 and the maximum tensile strain occurred at the end of the fillet of the minimum section of the structure. At this time, the reaction force of the loading point was 31.12 K. Assuming that the failure occurred when the strain reaches 10000 µε and the load displacement changed linearly, the failure load was estimated to be 111.2 KN. Compared with the actual failure load of 111.13 KN, the error was within 1%, which proved that the analysis method was effective.

The stress concentration factors and estimated failure loads of other test pieces were shown in Table 4 and Table 5.

| Table 4 Stress concentration factor of test piece |
|-----------------------------------------------|
| Fillet (mm) | Opening (mm) | 50×50 | 40×40 | 30×30 |
|-------------|-------------|-------|-------|-------|
| R10         | 4.089       | 3.819 | 3.615 |
| R15         | 3.963       | 3.898 | 4.255 |
| R20         | 3.985       | 4.452 | -     |
| R25         | 4.588       | -     | -     |

| Table 5 Estimated failure load of test piece (KN) |
|-----------------------------------------------|
| Fillet (mm) | Hole (mm) | 50×50 | 40×40 | 30×30 |
|-------------|-----------|-------|-------|-------|
| R10         | 98.8      | 105.8 | 111.2 |
| R15         | 99.9      | 106.6 | 111.7 |
| R20         | 100.5     | 107.6 | -     |
| R25         | 102.0     | -     | -     |

4. Conclusion

The test uses ASTM D 5766/D standard to obtain the failure load and strain statistics of Reinforced Composite Laminates with Open Holes. The stress concentration factors were calculated to be used in the design of similar structures. According to the test results and finite element calculations, the tensile failure load decreased obviously with the increase of the hole size of the composite. Besides, the failure load increased with the increase of the fillet radius. Therefore, circular openings should be used as far as possible.

References

[1] Niu M C Y. Airframe structural design. Aviation Industry Press; 2008.
[2] Yang NB, Zhang YN. Structural design of composite aircraft. Aviation Industry Press; 2002.
[3] Shen Z, Yang SC. Property requirement of composite systems applicable to aircraft structures. Journal of Materials Engineering. 2007; S1: 248-252.

[4] Ye CJ, Jiao JQ, Wang B, Huang T. Investigation on tensile performance of open-holed thin laminates with bi-directional cloth lamina. Journal of Mechanical Strength. 2012; 34: 767-771.

[5] Zeng L, Guan ZD, He W, Liu DB. Damage analysis of open-hole tension laminates. Acta Materiae Compositae Sinica. 2012; 1: 169-175.