Experimental and numerical studies of perforated CFRP laminates under quasi-static tensile load

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Abstract. Mechanical properties and failure modes of perforated CFRP laminate specimens under quasi-static tensile load were studied by means of experimental test and numerical simulation. Tensile tests of perforated CFRP laminates were conducted on an INSTRON electronic universal testing machine, and the progressive damage model based on 2D Hashin failure criterion was established by using the ABAQUS/Explicit software. The results showed that the discrepancy of ultimate tensile load basis on experimental test and numerical simulation was acceptable, which was less than 6.0 %. The numerical simulation method and results provide a theoretical reference for the design and application of perforated CFRP laminates.

1. Introduction
As a typical representative of advanced composite materials, carbon fiber reinforced plastic (CFRP) has been widely used in aerospace, automobile, high-speed train and other fields attributed to its characteristics of low density, high specific modulus, high specific strength and liable to design compared with traditional materials [1-6]. Specifically, the application of CFRP in Boeing 787 reaches 50%, and that in the wing and fuselage of F35 fighter takes up as much as 30%. Due to the needs of inspection, disassembly and maintenance, CFRP structures inevitably need some holes in the process of use, such as the side wall panel of the aircraft needs holes for installing doors and windows, and the internal bulkhead needs holes to make the pipeline pass through.

Early work in the area, a large number of researchers have carried out a lot of research on the strength and failure of perforated composite structures[7]. For example, Lekhnitskii [8] proposed a theoretical formula for calculating the stress concentration at the hole edge of orthotropic plates. Nuismer [9] proposed the point stress criterion and the average stress criterion for predicting the tensile strength of laminated plates with holes. Chang [10] proposed a progressive damage model for laminates with notches under tensile loading, which was used to predict the failure under tensile or compressive loading. Su et al. [11] developed a progressive damage model based on ABAQUS UMAT, and studied the effect of opening size on CFRP laminates with openings under compression load. Xu et al. [12] found that the cohesive zone model could effectively predict the mechanical properties of CFRP specimens with holes, and the error was within 10%. Wang et al. [13] found that the deformation capacity, axial stiffness and critical load of perforated glass fiber reinforced plastic (GFRP) pipes under compression load were significantly affected by different parameters.
In the practical application of CFRP structures, it is often necessary to open holes to meet various functional requirements. The purpose of this study is to understand the influence of perforated structure on the bearing capacity and failure characteristics of the CFRP laminates. In this paper, the mechanical properties and failure modes of perforated CFRP laminate are studied by experimental test and numerical simulation, which provides an important theoretical reference for the engineering application of CFRP structures.

2. Experimental methods

2.1. Sample preparation
Domestic T300 carbon fiber epoxy unidirectional prepreg was chosen to fabricate the CFRP laminates by the bladder molding process and the detailed curing process curve is shown in Figure 1. The thickness of CFRP laminates is 2.4 mm (16 plies) with a stacking sequence of [0/90/45/-45]2s. The CFRP laminates were processed into perforated tensile specimens using CNC engraving machine based on ASTM Standard D7137-07, and the schematic diagram of geometric dimension for CFRP laminate specimen is shown in Figure 2.

![Figure 1. Curing process curve of CFRP laminates.](image)

![Figure 2. Schematic diagram of specimen geometric dimension.](image)

2.2. Testing procedure
The quasi-static tensile tests were carried out on the electronic universal testing machine (INSTRON-5982, U.S.) with measuring range of 100 kN at room temperature, as shown in Figure 3. The displacement loading mode was performed, and the loading rate is 2 mm/min. The load data was recorded automatically by the testing machine, and the displacement data was measured by the 3D digital image correlation (DIC) test system (PMLAB, China). Detailed test and analysis methods can refer to the existing literatures [4, 14]. To ensure the reliability of the data, five samples were prepared and tested.
3. Numerical modelling

The load-displacement curves of perforated CFRP laminate specimens under tensile load can be obtained through the experimental study. However, it is difficult to observe internal damage of CFRP laminate specimens due to the limitation of characterization techniques. In order to study the internal damage mechanism and failure mode of perforated CFRP laminate specimens, the finite element simulation analysis was carried out based on ABAQUS/explicit solver.

3.1. Failure modes and failure criteria

The failure modes of CFRP laminate were strongly dependent on the geometry, loading direction and ply direction. The typical failure modes can be divided into in-plane failure modes and transverse failure modes. The anisotropic failure modes in ABAQUS were based on the research work of Hashin et al. [15, 16]. The damage initiation criterion of CFRP laminate was based on the Hashin failure criterion. For single-layer CFRP, four different failure modes are considered: fiber tensile fracture, fiber compression buckling and torsion, matrix cracking under transverse tension and shear force, matrix fracture under transverse pressure and shear force. According to the theory, damage begins when one of the four values of fiber tension ($F_{ft}$), fiber compression ($F_{fc}$), matrix tension ($F_{mt}$) or matrix compression ($F_{mc}$) reaches the breaking strength of CFRP.

Fiber tension ($\sigma_{11} \geq 0$):

$$F_{ft} = \sigma_{11}^2 X_T + \alpha \left( \frac{\tau_{12}}{S_L} \right)^2$$ (1)

Fiber compression ($\sigma_{11} < 0$):

$$F_{fc} = \left( \frac{\sigma_{11}}{X_C} \right)^2$$ (2)

Matrix tension ($\sigma_{22} \geq 0$):

$$F_{mt} = \left( \frac{\sigma_{22}}{X_T} \right)^2 + \alpha \left( \frac{\tau_{12}}{S_L} \right)^2$$ (3)

Matrix compression ($\sigma_{22} < 0$):

$$F_{mc} = \left( \frac{\sigma_{22}}{2 S_T} \right)^2 + \left( \frac{Y_C}{2 S_T} - 1 \right) \frac{\sigma_{22}^2}{Y_C} + \left( \frac{\tau_{12}}{S_L} \right)^2$$ (4)
where \( \sigma_{11}, \sigma_{22}, \) and \( \tau_{12} \) denote the components of stress tensor, while \( \alpha \) is the contribution coefficient that determines the role of shear stress in fiber tensile failure. \( X_T \) and \( X_C \) are the tensile strength and compressive strength of the fiber, respectively. \( Y_T \) and \( Y_C \) represent the tensile strength and compressive strength of the matrix, respectively. \( S_T \) and \( S_C \) denote the longitudinal and transverse shear strength, respectively.

\( \sigma_y \) is applied to evaluate the initiation criteria, and the calculation formula is as follows:

\[
\sigma_y = M \sigma
\]

where \( \sigma_y \) is the nominal stress, and \( M \) is the damage operator [17].

\[
M = \begin{bmatrix}
\frac{1}{1-d_t} & 0 & 0 \\
0 & \frac{1}{1-d_m} & 0 \\
0 & 0 & \frac{1}{1-d_s}
\end{bmatrix}
\]

\( d_t, d_m, \) and \( d_s \) are the internal variables of fiber failure, matrix failure, and shear failure, respectively. \( d_{ft}, d_{fc}, d_{mt}, \) and \( d_{ms} \) are the rupture damage variables of fiber tension, fiber compression, matrix tension, and matrix compression failure previously discussed, respectively. Details are given below.

\[
d_t = \begin{cases} 
  d_{ft} & \sigma_{11} \geq 0 \\
  d_{fc} & \sigma_{11} < 0 
\end{cases}
\]

\[
d_m = \begin{cases} 
  d_{mt} & \sigma_{22} \geq 0 \\
  d_{ms} & \sigma_{22} < 0 
\end{cases}
\]

\[
d_s = 1 - (1-d_{ft})(1-d_{fc})(1-d_{mt})(1-d_{ms})
\]

Detailed mechanical parameters of CFRP laminates are shown in Tables 1 and 2.

**Table 1.** Elastic modulus and Poisson’s ratio of CFRP.

| Density (kg/m³) | Elastic modulus (GPa) | Poisson’s ratio |
|----------------|-----------------------|----------------|
|                | \( E_{11} \) | \( E_{22} \) | \( v_{12} \) | \( v_{13} \) | \( v_{23} \) |
| 1614           | 135                  | 8.8            | 0.33          | 0.33          | 0.33          |

**Table 2.** Strength and damage evolution of CFRP.

| Strength (MPa) | Damage evolution (mJ/mm²) |
|----------------|--------------------------|
| \( X_T \) | \( X_C \) | \( Y_T \) | \( Y_C \) | \( S_T \) | \( S_L \) | \( G_{ft} \) | \( G_{fc} \) | \( G_{mt} \) | \( G_{ms} \) |
| 1548          | 1226                    | 55.5          | 232         | 89.9       | 89.9       | 50.5          | 30.5         | 0.22         | 1.1          |

3.2. Finite element analysis model

Full-scale finite element model of perforated CFRP laminate specimen under tensile load was established by ABAQUS. The finite element model was consistent with the specimen size and the boundary condition was consistent with the experimental clamping conditions. The left end of the model was constrained by fixed end, and the right end was loaded with displacement. The SC8R
element was used to mesh the CFRP laminates, and the stress concentration area of the circular hole was refined, as shown in Figure 4.

![Refinement mesh near the circular hole of CFRP laminate specimen.](image)

**Figure 4.** Refinement mesh near the circular hole of CFRP laminate specimen.

### 4. Results and discussion

#### 4.1. Load-displacement histories

Figure 5 plots the internal energy-time curve and kinetic energy-time curve in the numerical simulation of perforated CFRP laminate tensile specimen. It can be seen that the internal energy of the whole model is far greater than the kinetic energy before the failure of the specimen (t<0.35 ms). Therefore, the dynamic effect of using ABAQUS/explicit solver to simulate quasi-static tensile test can be ignored.

In order to verify the correctness of the progressive damage model, the simulation results were compared with the experimental results. Figure 6 shows the comparison of load-displacement curves obtained by experimental measurement and numerical prediction for CFRP laminates with 6 mm circular hole under tensile load. The displacement in the experiment was the displacement of the fixture measured by 3D-DIC test system. It can be seen that the experimental value of the tensile load was 31.82 kN, and the simulation value was 33.46 kN which was slightly higher than the experimental value. It is interesting to note that the failure displacement measured by 3D-DIC test system was slightly higher than that in the simulation. The relative errors were less than 6 %, which was within the allowable range. Generally speaking, the numerical prediction was in good agreement with the experimental measurement, which showed the correctness of the numerical model.

![Comparison of energy-time curves in the numerical simulation of tensile test.](image)

**Figure 5.** Comparison of energy-time curves in the numerical simulation of tensile test.

![Comparison of load-displacement curves in tensile test.](image)

**Figure 6.** Comparison of load-displacement curves in tensile test.
4.2. Failure modes
The existence of holes results in local stress concentration of the structure, which leads to a significant reduction in the bearing capacity of the structure, and directly affects the service life and safety of the structure. The initial damage and evolution of CFRP are more complex because of the damage of stress concentration and fiber continuity at the opening. Therefore, it is very important for the application of CFRP structures to accurately predict the effect of opening on the failure modes for CFRP specimen. When the load reached ultimate tensile load 33.46 kN, the specimen eventually failed. Four failure modes of fiber tension, fiber compression, matrix tension and matrix compression obtained by progressive damage model are shown in Figure 7. It is interesting to note that the matrix crack at the edge of the hole accelerated the fiber fracture. This is due to the rapid expansion of 90° layer and ±45° layer matrix crack, which made the matrix lose the bearing capacity, and released the stress concentration at the hole edge.

![Failure modes](image)

**Figure 7.** Failure modes of perforated CFRP laminate specimen at ultimate tensile load.

5. Conclusions
The load-displacement curves of perforated CFRP laminate specimens under tensile load were obtained by combining the INSTRON universal testing machine and 3D-DIC testing system. The progressive damage finite element model of perforated CFRP laminate specimen was established by using ABAQUS/Explicit based on 2D Hashin criterion. The tensile behavior of perforated CFRP laminate specimens was analyzed and the residual strength was predicted by the finite element mode. The maximum error between the experimental results and the predictions of tensile strength was less than 6.0%, which verified the effectiveness of the simulation calculation method. The initial damage and evolution process of perforated CFRP laminate specimens were analyzed through the finite element simulation. The finite element model established in this paper can accurately predict the behavior of damage initiation, expansion and final failure of CFRP laminate.

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