Numerical Simulation Analysis of Carbon Fiber Square Tube Single Bolt Connection Structure

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Abstract. Based on ABAQUS/Explicit, a three-dimensional finite element model of composite square tube with single bolt was established. The criteria of Hashin classification failure was used to distinguish the fiber tensile, fiber compression and matrix stretching of composite square tube under local compression loading. The four modes of matrix compression are used to obtain the load-displacement curve of the model, which is used to analyse the progressive damage failure process of the composite square tube single nail connection during quasi-static compression, and to estimate the strength of the joint.

1. Introduction
Carbon fiber composite materials have the advantages of high specific modulus, good fatigue resistance, and small coefficient of linear expansion, and are widely used in aviation, bridges, weapons and equipment. Adhesive bonding and mechanical connection are two common connection methods for composite materials. Bolts are used as fasteners to mechanically connect composite materials with high reliability and ease of handling. Carbon fiber composite square tube molding process is simple, low sensitivity of defects, in the spacecraft, truss bridges, guns and other structures often used as the main bearing components. Carbon fiber composite materials are often bolted together between square tubes to deliver larger concentrated loads. However, due to the more severe whole edge stress concentration at the hole of the bolt, and the composite material being an anisotropic brittle material, the failure mode of the carbon fiber square pipe bolted joint is more complex and the ultimate failure. Strength is difficult to theoretically calculation [1]. Therefore, the connection of composite materials, especially mechanical connections, has become a hot issue at home and abroad in recent years [2-5]. With the development of finite element technology, numerical simulation methods can effectively predict the failure of composite bolted joints [6-11].

Based on the three-dimensional accumulative damage finite element model of Hashin failure criterion, this paper uses the ABAQUS/Explicit solver to simulate the failure mode and failure process of carbon fiber square pipe bolted joints and predict the ultimate failure load.

2. Carbon Fiber Square Tube Single Nail Connection Structure Modeling

2.1. Material Model
The carbon fiber square tube is made of T300/QY8911 material, with a total of 6 layers in the thickness direction. Table 1 shows the mechanics parameters of T300/QY8911 [12].
### Table 1. Mechanical parameters of T300/QY8911 grade composites

| $E_1 / \text{GPa}$ | $E_2 = E_3 / \text{GPa}$ | $G_{12} = G_{13} / \text{GPa}$ | $G_{23} / \text{GPa}$ | $V_{12}$ | $X_T / \text{MPa}$ | $Y_T / \text{MPa}$ | $X_C / \text{MPa}$ | $Y_C / \text{MPa}$ | $S_{12} = S_{23} / \text{MPa}$ |
|-------------------|-------------------|-------------------|-------------------|-------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 135               | 8.8               | 4.47              | 3.0               | 0.33  | 3071            | 88              | 1747            | 271             | 143             |

**Figure 1. FEA model**
The indenter and bolt fastener material is Q235 steel with a modulus of elasticity of 210 GPa and a Poisson's ratio of 0.3. The three-dimensional finite element model of carbon fiber square tube single nail connection was established by ABAQUS, and the progressive damage process and ultimate failure load were analysed by the obtained load displacement curve. The finite element model is shown in Fig. 1. In the finite element model, the composite material was modelled using a C3D8R three-dimensional solid material model or an SC8R shell unit material model. The C3D8R material model is a solid element and can simulate the force in the direction of the layer thickness. However, it requires high grids and takes a long time to calculate, the calculation accuracy of the large deformation model is low [13]. Therefore, Carbon fiber square pipes are provided with two units on each layer in the thickness direction. SC8R is used to divide the grids. Bolts and indenters use C3D8R to divide the grid. Consider the contact between the bolt and the indenter, the bolt and the carbon fiber square tube, the contact type uses the surface contact of small sliding friction, the contact surface tangential use "penalty" contact, the friction coefficient is 0.3 [14], the contact surface normal is "hard" contact.

2.2. Failure criteria
Commonly used criteria for determining the failure of composite materials are: maximum stress theory, maximum strain theory, Tsai-Hill criterion, and Tsai-Wu tensor criterion. The maximum stress theory and the maximum strain theory are established on the basis that the failure modes are not coupled, and the calculation accuracy is low. The Tsai-Hill criterion is based on the same performance of the material under tensile and compressive loads. Tsai-Wu the guidelines amend this flaw, but the coefficients of these two criteria are more difficult to determine. There are four main damage modes of composite ply structure: fiber tensile fracture, fiber compression fracture, matrix tensile fracture, and matrix compression fracture. The Hashin failure criterion that comes with ABAQUS can distinguish and identify these four failure modes.

The Hashin failure criterion is an explicit expression that is easier to implement in ABAQUS/Explicit. The Hashin classification damage criterion is used to determine whether the specific damage criteria of the carbon fiber square tube under the action of the bolt extrusion load for each layer of the laminate is:

(1) Matrix tensile failure ($\sigma_{22} > 0$)
$$\left( \frac{\sigma_{22}}{Y_T} \right)^2 + \left( \frac{\tau_{12}}{S_L} \right)^2 = 1$$

(2) Matrix Compression Failure ($\sigma_{22} < 0$)
$$\left( \frac{\sigma_{22}}{Y_T} \right)^2 + \left( \frac{\tau_{12}}{S_L} \right)^2 = 1$$

(3) Fiber tensile failure ($\sigma_{11} > 0$)
$$\left( \frac{\sigma_{11}}{X_T} \right)^2 + \left( \frac{\tau_{12}}{S_L} \right)^2 = 1$$

(4) Fiber Compression Failure ($\sigma_{11} < 0$)
$$\left( \frac{\sigma_{11}}{X_C} \right)^2 = 1$$

Among them, $\sigma_{11}$ and $\sigma_{22}$ represent the axial and transverse normal stress components of the pavement; $\tau_{12}$ is the in-plane shear stress component; $X_T$ and $X_C$ represent the axial tensile strength and compressive strength of the ply; $Y_T$ and $Y_C$ represent the horizontal pull of the ply. Elongation strength and compressive strength; $S_L$ stands for in-plane shear strength.
2.3. Loads and Boundary Conditions
The coupling constraints of the reference points RP1 and RP2 at the centroids are established on the two surfaces of the fixture and the carbon fiber square tube that are in contact with the testing machine. Six directions of displacement/rotation constraints are imposed on the RP1 and RP2 at the initial analysis step. A power/explicit analysis step step1 applies a U3 direction displacement of 0.8 mm to step RP1, and the displacement loading amplitude is a smooth analysis step.

3. Simulation Results Analysis and Discussion
Fig. 2 the stress cloud diagram calculated by the finite element model and experimentally measured and the load displacement curve is shown in Fig. 3.

![Stress distribution](image)

**Figure 2. Stress distribution**
There is a serious stress concentration on the pressure side of the bolt hole. The load displacement curve is divided into three phases: In the first stage, the load-displacement curve has a linear relationship. Under the partial compressive stress of the hole formed by the bolt, the carbon fiber composite material deforms elastically, and the bearing capacity increases with increasing strain. The maximum load at the end of this phase is approximately 4.54 kN, which is obtained at about 2% D (D is the diameter of the bolt) at the edge of the hole displacement and can be used as a reference value for the engineering design load [15].

In the second stage, the load-displacement curve oscillates upward. At this stage, with the increase of compressive stress, a small part of the resin matrix that is in contact with the bolt begins to plastically destruct, and the load momentarily leads to a drop in the load. After the matrix is broken, the fiber mainly bears, and the tensile strength and compressive strength of the fiber are much higher than those of the resin. The load will rise further, so the curve rises in a wave-like manner until the composite material in the contact area of the hole is completely destroyed and the load peaks.

In the third stage, the load-displacement curve enters the wave-like decline stage, and the component undergoes severe plastic deformation over a large area. The increase of the load leads to irreversible compression or tensile failure of the fibers, and the load drops rapidly, and the entire carbon fiber square tube bolt connector completely loses its load carrying capacity. The maximum failure load is 6.79 kN, which is about 1.5 times the engineering design value.

Figure 4 shows the damage initiation and eventual damage of the element based on the Hashin criterion. (A) is the cell distribution at the initial damage, and (b) is the distribution of the damaged cell after the final evolution of the damage. The darker the color, the more serious the damage of the unit, the red one means the damage ratio is 1, and the unit is completely destroyed. It can be seen that under the action of the bolt extrusion load, the matrix is stretched and cracked, the matrix compression cracking is the main failure mode, only a small amount of fiber compression and destruction.
Figure 4. 1 Elements damage caused by compression of fibers
Figure 4. 2 Unit damage caused by stretching of fibers
Figure 4. 3 Elements damage caused by compression of the substrate
Figure 4. 4 Elements damage caused by compression of the substrate
4. Conclusion

(1) Through the finite element model, the failure modes of carbon fiber square tube under bolt compression load are distinguished, and it is found that the failure process is divided into three stages: linear elastic stage, elastic-plastic deformation stage, and complete plastic failure stage.

(2) According to the load-displacement curve calculated by ABAQUS, take the end point of the elasticity phase, that is, 2% D (D is the diameter of the bolt). The load when the edge of the hole is deformed is 4.54 kN as the engineering design load value.

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