Progressive Failure Analysis and Experiment Research of the Composite Bolted Connection

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Abstract: Bolt connection is a common engineering structure. In order to analysis the composite bolted connection, based on continuous damage mechanics method, different failure criteria are established for fiber, matrix and delamination. To improve the efficiency of engineering estimation, this paper proposed the selective parabola algorithm to solve the fracture angle and uses the linear stiffness degradation method to establish the finite element model. Firstly, composite laminates with a hole in the tension stress are analyzed by using the above model, and by comparing the test results with the experimental results, the feasibility of the model is verified. Then, the progressive failure analysis is carried out to study the composite bolted connection. The comparison between the calculation results and the test results shows that the mechanical model proposed in this paper can predict the strength of composite bolted connection under tensile load accurately and also can present the damage evolution process exactly.

1. Introduction

As a kind of high-performance material, a growing number of composites are used in mechanical structures. Composite connection structures appear in common structural forms inevitably. However, the composite fiber is cut off at the opening, which reduces the capacity of the local joint of the composite material, and the joint area is usually the weak region of the whole structure[1]. At the same time, the failure mode of composite materials is relatively complex due to its own property. Therefore, the accurate prediction of the failure mode and strength of composite bolted connection becomes more and more important, which is the key of designing and applicating of composite materials.

Camanho[2-3] and Tserpes[4] proposed different stiffness degradation modes, which should be adopted for different matrix and fiber damage types, that applied to the analysis of the connection strength of laminates with different ply sequences. Dano[5] established a two-dimensional model to calculate the composite connections, and it is found that the selection of different failure criteria and stiffness degradation models will have a greater impact on the strength of the connection. Kermaidis et al. [6] analyzed the strength and failure mode of composite connector by using Hashin[7,8] criteria and three-dimensional finite element model, and gave the failure propagation process. Zhou[9] established a three-dimensional finite element model, combined with Puck criteria[10], to study the influence of different gaps on the extrusion strength and failure mechanism of composite connection, and carried out an experimental verification. Jia Liyong et al. [11-12] established a three-dimensional model and used the Puck criteria to analyze the progressive damage of composite connection, which was verified by
experiments. Zhou Longwei established a linear degradation model for unidirectional fiber reinforced composites to describe the mechanical behavior of the composites after different failure modes.

In the analysis of composite bolted connection using continuum damage mechanics, it is necessary to establish finite model consisting of suitable failure criteria and material degradation methods. Since 1992, World Wide Failure Exercise (WWFE) compares and judges many failure criteria. It is found that the existing theories are insufficient, and no theory can give high-precision prediction results in all cases [14]. However, in the evaluation process, WWFE gives the scores and rank of each failure criteria according to different applicability problems. Then Puck criteria and Cuntze criteria are recommended to predict the ultimate failure strength of multi-directional laminates. At the same time, on the premise of ensuring the calculation accuracy, the improvement of calculation efficiency can significantly save the cost. Therefore, the one-time stiffness model shows obvious advantages.

Based on the above reasons, combined with the diversity of failure modes of composite materials, the following work is carried out: 1. According to the three different forms of damage of fiber, matrix and delamination, different failure criteria are selected, and the linear stiffness degradation method is used to establish the constitutive model by using finite element subroutine. 2. Using the above model, the tensile properties of composite laminates with holes are analyzed, and the test results are compared. 3. The tensile failure test was carried out on the composite bolted connection, and the FEM analysis of the composite bolted connection were carried out. The reliability of the model was verified by comparing the calculation results with the test results.

2. Constitutive Model

2.1. Failure Criteria

2.1.1. Fiber Failure
The fiber failure is defined by Hashin criteria [7-8].

For fiber tensile failure, the normal stress along the fiber direction of the element \( \sigma_{11} > 0 \), then the fiber failure criteria is:

\[
(f_{e})_{1} = \left( \frac{\sigma_{11}}{X_{T}} \right)^{2} + \frac{a}{X_{T}^{2}} \left( a_{12}^{2} + a_{13}^{2} \right) \geq 1 \tag{1}
\]

For fiber compression failure, the normal stress along the fiber direction of the element \( \sigma_{11} < 0 \), then the fiber failure criteria is:

\[
(f_{c})_{1} = \left( \frac{\sigma_{11}}{X_{C}} \right)^{2} \geq 1 \tag{2}
\]

2.1.2. Matrix Failure
Through a lot of experiments, it is found that there will be an inclined fracture surface parallel to the fiber direction when the matrix of the composite fails in transverse direction. The angle of fracture surface of most carbon fiber resin matrix composites is within \( 53 \pm 2 \)° range. Based on the research of Hashin, Puck introduces the influence of fracture surface on fiber failure and matrix failure, and establishes the Puck failure criteria [10].

![Fig.1 Fracture Plane for 3D Stress and The Associated Stresses](image)

Puck thinks that the matrix failure should be judged by the stress on the fracture surface. The stress component on the fracture surface (see Fig.1) is calculated as follows:

\[
\sigma_{nn} = \frac{\sigma_{22} + \sigma_{33}}{2} \cos(2\varphi) + \tau_{23}\sin(2\varphi) \tag{3}
\]
\[ \tau_{nt} = -\frac{\sigma_{22} - \sigma_{33}}{2} \sin(2\varphi) + \tau_{23}\cos(2\varphi) \quad (4) \]

\[ \tau_{ln} = \tau_{12}\cos(\varphi) + \tau_{13}\sin(\varphi) \quad (5) \]

Where: \( \sigma_{22} \) and \( \sigma_{33} \) is the transverse normal stress in the ply coordinate system, \( \tau_{nt} \) and \( \tau_{tn} \) is the normal stress and shear stress on the fracture surface, and \( \varphi \) is the angle of potential fracture surface.

When the normal stress on the fracture surface \( \sigma_{nn} < 0 \), the failure criteria of matrix is as follows:

\[ f_{mc} = \left( \frac{\tau_{nt}}{S_T - \mu_T\sigma_{nn}} \right)^2 + \left( \frac{\tau_{ln}}{S_L} \right)^2 \geq 1 \quad (6) \]

When the normal stress on the fracture surface \( \sigma_{nn} > 0 \), the failure criteria of matrix is as follows:

\[ f_{mt} = \left( \frac{\sigma_{nn}}{Y_T} \right)^2 + \left( \frac{\tau_{nt}}{S_T} \right)^2 + \left( \frac{\tau_{ln}}{S_L} \right)^2 \geq 1 \quad (7) \]

where,

\[ \mu_T = -\frac{1}{\tan(2\varphi_0)} \]

\[ S_T = Y_c\cos(\varphi_0)\left( \sin(\varphi_0) + \frac{\cos(\varphi_0)}{\tan(2\varphi_0)} \right) \]

\( \varphi_0 \) is the fracture surface angle of unidirectional plate under transverse compression. See Section 2.1.4 for calculation method. \( X_T, Y_c \) is the tensile strength and compressive strength along the fiber direction; \( Y_T, Y_c \) is the in-plane tensile strength and compressive strength perpendicular to the fiber direction \( S_L \) is the longitudinal shear strength, which is obtained through the relevant tests of single-layer plates.

2.1.3. Delamination Failure

Delamination failure can be divided into tensile delamination and compression delamination.

Tensile delamination failure, \( \sigma_{33} \geq 0 \), the failure criteria is as follows:

\[ f_{lt} = \left( \frac{\sigma_{33}}{Z_T} \right)^2 + \left( \frac{\tau_{13}}{S_L} \right)^2 \geq 1 \quad (8) \]

Compression delamination failure, \( \sigma_{33} < 0 \), the failure criteria is as follows:

\[ f_{lc} = \left( \frac{\sigma_{33}}{Z_c} \right)^2 + \left( \frac{\tau_{13}}{S_L} \right)^2 \geq 1 \quad (9) \]

2.2. Calculation of fracture angle \( \varphi_0 \)

In order to improve the calculation efficiency, the selective parabola algorithm method proposed in reference [11] is used to calculate the fracture surface angle of matrix failure in Puck failure criteria. In general, the number of local maxima of stress risk factor \( \Gamma \) is less than 4, and the angle between two adjacent maxima is more than 25 \(^\circ\), as shown in Fig. 2. Firstly, taking 10 \(^\circ\) as the interval, [-90,90] is divided into 18 sub intervals, and the interval [A,C] where the local maximum value is located. By constructing a parabola function which through three points, which is \( f(A), f(B) \) and \( f(C) \). After several iterations, the maximum value of the stress risk factor is calculated in each local maximum interval. Then the fracture angle \( \varphi_0 \) can be obtain corresponding to the global maximum value through comparing the several local maximum values.
2.3. Stiffness degradation criteria for composite

When the element satisfies the above failure criteria expression, the element will fail. By ensuring the accuracy of engineering estimation, the calculation time of the program can be reduced by using the linear degradation method. In this paper, the one-time stiffness degradation mode proposed in reference \[34\] is applied in the calculation, and the specific degradation mode is shown in Table 1.

Where the $V_f$ is the percentage of fiber content and $E_f$ is the elastic modulus of the fiber. In order to avoid the convergence problem, the degradation coefficient is set as the minimum non-zero coefficient in the program without equaling to zero.

| Failure mode          | Degradation criteria                       |
|-----------------------|--------------------------------------------|
| Fiber tension         | $E_1 = 0$, $G_{ij} = 0$                    |
| Fiber compression     | $E_1 = E_2$, $G_{ij} = 0$                  |
| Matrix tension        | $E_1 = V_fE_f$, $E_2 = 0$, $G_{ij} = 0$    |
| Matrix compression    | $E_2 = 0$, $G_{13} = 0$                    |
| Delamination in tension | $E_1 = V_fE_f$, $E_3 = 0$, $G_{13} = 0$ |
| Delamination in compression | $E_3 = 0$, $G_{23} = G_{12} = 0$ |

3. Finite element model and experiment

3.1. Composite laminated plate with a hole

Firstly, the mechanical model proposed in this paper is used to analysis the tensile properties of composite laminates with a hole, which have been studied by the tension test and experiment. The single layer thickness of the laminate is 0.12mm and the material is ccf300 / 5405 and T300 / QY8911. The mechanical property parameters and dimensions of the materials and relevant contents of the test are referred to the reference paper \[15\]. The Hashin failure criteria embedded in the software and the model proposed in this paper are used to simulate the finite element calculation, and the comparison between the calculation results and the test results is shown in Table 2. The results show that the mechanical model proposed in this paper can better predict the tensile failure load of composite laminates with a hole, which is in good agreement with the test results. It is indicated that the mechanical model proposed in this paper has certain reliability in the analysis of progressive damage and failure of composite laminates. Then the mechanical model is used to analyse the failure of composite bolted connection.

| Material         | Layer Code | Test Results/kN | Hashin Model/kN | Present Model/kN | Error  |
|------------------|------------|-----------------|-----------------|------------------|--------|
| CCF300/5405      | I          | 470             | 635             | 484.6            | 3.1%   |
|                  | II         | 473             | 639             | 486.7            | 2.9%   |
| T300/QY8911      | I          | 404             | 545             | 423.4            | 4.8%   |
|                  | II         | 406             | 548             | 421.4            | 3.8%   |
3.2. Experiment and Simulation of composite bolted connector

In order to verify the reliability of the mechanical model proposed in this paper in the calculation of composite bolt connection failure, the finite element analysis of four groups of composite bolt connections is carried out by using the model, and the experimental verification is carried out.

3.2.1. Tension test of Composite Bolted Connections

There are 6 test pieces in each group of three groups, and the specific parameters such as aperture size, ply, overall dimension and test piece number are shown in Table 3. According to ASTM D5961-17, all test pieces were tested on MTS landmark 500kN hydraulic servo material test system. Tension test was carried out at a loading rate of 1 mm / min, and load displacement data were collected. Fig. 3 shows the test and the final failure of test piece A.

![Fig.3 Tensile Test and the Failure Mode](image)

| code | Lay-up                  | Thickness /mm | Bolt diameter /mm | Tightening torque /N·m | Number of test pieces |
|------|-------------------------|---------------|-------------------|------------------------|-----------------------|
| A    | [45/0/-45/90]2s        | 2             | M5                | 4                      | 6                     |
| B    | [45/0/-45/90/45/0/-45/0]s | 2             | M5                | 4                      | 6                     |
| C    | [45/0/-45/90]4s        | 4             | M6                | 6                      | 6                     |
| D    | [45/0/-45/90/45/0/-45/0]2s | 4             | M6                | 4                      |                       |

![Fig 4 The Structure of The Test Piece](image)

3.2.2. Numerical model of Composite Bolted Connections

The model proposed in this paper is used to analysis the composite bolted connections mentioned above. The material parameters are shown in Table 4, and the interlaminar properties are obtained from the assumption of transverse isotropy. The fiber volume of composite plate is about 62% and the fiber modulus is 235 GPA, the elastic modulus of metal plate and bolt is 116 GPA, Poisson's ratio is $\nu = 0.31$, $\sigma_b = 900$MPa. The structure of the test piece is shown in Fig. 4.

![Table 4 Performance Parameters of Composite Single Layer Plate/ Unit: Mpa](image)

| E1   | E2   | E3   | G12  | G13  | G23  | v12  | v13  | v23  |
|------|------|------|------|------|------|------|------|------|
| 133e3| 9.9e3| 9.9e3*| 6.67e3| 6.67e3| 3.90e3*| 0.27 | 0.27 | 0.27*|

| XT   | XC   | YT   | YC   | ZT   | ZC   | S12  | S13  | S23  |
|------|------|------|------|------|------|------|------|------|
| 2134.2 | 1121.2 | 34.0 | 191.3 | 34.0* | 191.3* | 40.1 | 40.1 | 81.1* |
The 8-node hexahedral linear reduced integral element C3D8R is selected for composite, metal plate and bolt. The contact is set between metal plate and composite plate, hole wall and bolt, bolt head and plate surface. The general contact algorithm is used. The friction coefficient is 0.2. It is divided into n layers along the thickness direction. The n represents the total number of layers of composite laminates. The full model calculation is used. Fig. 5 is the finite element mesh diagram.

The left end of the model is fixed and the right end is applied with equal displacement tensile load. Fig. 6 shows the simulation of the restraint mode of the test piece.

3.2.3. Finite element analysis results and discussion

The damage analysis of composite bolted connection is carried out by using the model proposed in this paper. The calculation results are compared with the test results and the calculation results using the Hashin failure criteria model embedded in the finite element software. The numerical calculation results and test results are given in Table 5.

| Code | Test result/kN | Hashin model/kN | Present model/kN | Error/% |
|------|----------------|-----------------|-----------------|--------|
| A    | 9.9            | 13.4            | 10.2            | 3.5%   |
| B    | 9.8            | 12.5            | 10.2            | 3.9%   |
| C    | 26.8           | 29.2            | 28.0            | 4.3%   |
| D    | 27.3           | 30.1            | 28.6            | 4.8%   |

It can be seen that the error of the calculation results is less than 5% by using the mechanical model proposed in this paper, while the error is more than 30% when using the Hashin criteria embedding in the finite element software. Taking the A as an example, Fig. 7 shows the element damage diagrams of different damage modes and ultimate failure of the laminate calculated by the continuous damage mechanics model proposed in this paper.
It can be seen from Fig. 7 that for the single bolted connection, there are various forms of damage around the hole edge. The damage of the 0 ° layer is mainly the matrix damage, and the damage of the 45 ° layer mainly occurs along the 45 ° direction of the fiber, and finally develops to the end. The damage of the -45 ° layer is similar to that of the 45 ° layer, and the 90 ° layer damage mainly occurs in the fiber direction. In the hole edge area perpendicular to the load, due to the high stress of the main shaft, there will be fiber tensile fracture and matrix tensile damage, which will accelerate the occurrence of fiber fracture and lead to the overall failure of the laminate. By comparing the final failure mode of the test piece in Fig. 5, it can be seen that the failure mode of the finite element simulation results is basically the same as that of the test results, which indicates that the mechanical model proposed in this paper can better simulate the damage evolution process of composite bolt connectors.

Based on the mechanical model proposed in this paper, the comparison between the calculation results and the experimental results shows that the model can well simulate the damage mode of bolted connection of composite laminates under tensile load, and can accurately predict its strength. It is proved that the proposed continuous damage mechanical model combined with Puck failure criteria and Hashin failure criteria combined with one-time stiffness degradation is feasible in predicting the strength of the composite bolted connection.

4. Conclusion

1) Based on the continuous damage mechanics mechanism of composite materials, different failure criteria are established for different damage forms of fiber and matrix. In order to improve the efficiency of engineering estimation, the constitutive model of composite materials is established by using FEM subroutine and the one-time stiffness degradation method.

2) The correctness of the continuous damage mechanical model proposed in this paper is verified by comparing the calculations and the results of tensile test of composite laminated plates with a hole. Then, the failure analysis of composite bolted connection is carried on by using this model. The predicted failure load is compared with the test results, which verifies that the mechanical model proposed in this paper can accurately predict the strength of composite bolted connection.

3) By analyzing the damage evolution process of composite bolted connection, the damage initiation, propagation and final failure modes can be predicted accurately, which provides an effective analysis method for the design and analysis of composite bolted connection.

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