Progressive Failure Analysis and Strength Prediction of Composite Structures Interference-fitted with Mechanical Connections

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Abstract. The mechanical connection was the main connection means of composite structures. In this paper, a three-dimensional finite element model of progressive failure was established by business software ABAQUS. The model considered the contact between bolt and hole, progressive damage, large deformation theory, and nonlinear shear stress/strain relations. HASHIN failure criterion and TAN material property degradation criterion were adopted to study the progressive failure process of mechanical connection structure, and the effects of different interferences (0%, 0.5%, 3%) on the strength and stiffness of mechanical connection structures were investigated. The results showed that the proper interference fit could improve the bearing strength of the mechanical connection, while the excessive interference fit could reduce the bearing strength of the connection, which was in consistent with the test results.

Introduction

Advanced composite materials with high strength and modulus, excellent designing and fatigue fracture resistance performance, had made great development and wide application in aviation, spaceflight, navigation, and other fields. In order to conform a complete structure, it didn’t only own high performance composite materials, but also had excellent connect methods. The connection forms of composite materials in general could be divided into three categories: bonding, mechanical connection (also called bolted connection) and mixed connections. Due to the requirement of better repeatability and follow-up maintenance, most of the connections used mechanical connection and less used bonding. Mechanical connection was usually adopted in the transfer of high-load, and the mating mode of bolted connection was gradually developed from clearance to interference fit. However, the current design method of mechanical joint relied heavily on test data. Therefore, it was necessary to establish a reliable analytical method to accurately predict the failure and strength of composite structures with mechanical connection.

In some early literatures [1, 2], two-dimensional model was established to obtain plane stress distribution of pin-loading plate with the consideration of two-dimensional finite element theory and the classical laminated plate theory. Beam element and rigid connection element were used to connect nodes on the side of the hole and a center node of the hole [3]. Chen et al. [4] studied the effect of friction, clamping force, and lay up sequence on the bearing strength. By establishing the incremental equations and setting up the contact condition of the finite element model, the three-dimensional contact stress analysis was carried out. Sarabian [5] studied the effect of nonlinear inter-laminar shear behavior on the pin-loaded structures. The relationship between shear stress and shear strain was obtained with the frictionless condition. The results showed that the radial stress and circumferential stress at the edge of the hole were all affected by the material nonlinearity. McCarthy [6] studied the effect of clearance on the stiffness and bearing strength of single-bolted single-shear mechanical joints by amounts of tests, taking consideration of the case that the clearance was 0%, 1%, 2%, 3%. The test results showed that when the tighten torque of fastener was 0.5 Nm, the connection stiffness of laminated plate declined with the size of clearance increasing. When the size of clearance increased
from 0% to 3%, the bearing strength of 2% displacement decreased by 7%, and its stiffness reduced by 10%.

At present, the mechanical connection of composite structures in aircraft, automobile and other engineering practice is using a large number of mechanical connections with nit fit or clearance fit, but interference fit is rarely involved. Therefore, this article mainly based on the current widespread use of fiber reinforced resin matrix composites mechanical connection structure, separately considering two connection modes of sliding fit and interference fit. The corresponding analysis model of three-dimensional cumulative damage was established. Numerical simulation of the interference fit process was carried out to obtain the bearing stiffness of the two kinds of mechanical connection structures, and the connection strength of the structure was predicted, which was compared with the physical test results.

**Finite Element Model**

Parameter design method was applied in this model for the composite structure of mechanical connection, which modeled any laminated plate size, the layup sequence and interference-fit joint structure, by taking the bolt diameter d, laminated plates diameter D, layer number m, single layer thickness t and laminate plate length L and width w, the edge distance E as the important geometric parameters, to improve the analysis efficiency of interference fit and clearance fit connection model.

This model was used for simulated analysis on the laminated plate with materials of T300/QY8911 and layup sequences of \( [45^\circ/0^\circ/-45^\circ/90^\circ/0^\circ/45^\circ/0^\circ/-45^\circ/0^\circ]_8 \). Material properties of unidirectional laminated plate were as followed: 

\[
\begin{align*}
E_1 &= 135 \text{GPa}, & E_2 = E_3 &= 8.8 \text{GPa}, & G_{12} = G_{13} = G_{23} &= 4.47 \text{GPa}, \\
v_{12} = v_{13} = v_{23} &= 0.33, & X_T &= 1548 \text{MPa}, & X_C &= 1226 \text{MPa}, & Y_T &= 55.5 \text{MPa}, & Y_C &= 218 \text{MPa}, & Z_T &= 55.5 \text{MPa}, & S_{XY} &= 89.9 \text{MPa}, & S_{XZ} = S_{YZ} &= 110.5 \text{MPa}.
\end{align*}
\]

![Figure 1. A schematic of interference fitting and loading.](image)

Double-lapped single-sheer mechanical connection structure were commonly adopted, to focus on the analysis of interference fit for pre-stress distribution of composite laminated hole, establishing the 3D model of composite plate and simplified interference blind bolt connection. Three-dimensional solid 8 nodes reduced integral element (C3D8R) of ABAQUS software was used for laminated plate and interference-fit blind bolt. In this element, there were six degrees of freedom in each node, where the single layer thickness of laminated plate was taken as the corresponding element thickness (0.15 mm). There were two kinds of connection modes between blind bolt and laminated plate hole: no-clearance sliding fit and interference fit. The interference \( I \) was generally defined as:

\[
I = \frac{(d-D)}{D}. \tag{1}
\]

Where \( I \) was the interference, \( D \) was the borehole diameter of laminated plate, and \( d \) was the outer diameter of the blind bolt. Master-slave surface contact algorithm of small sliding fraction was used for sliding fit connection. When using small sliding contact, the relationship between slave points and master plate was established in the ABAQUS from the beginning of the analysis.
Once the part of master plate that interacted with slave points was determined, the relationship would remain the same during the whole analysis. By never changing the interaction relationship between master plate and slave points, it would facilitate the easier convergence of contact problem.

Due to the higher stiffness of interference blind bolt in the actual use, and the less impact of stiffness on the circumferential stress of the hole, higher Young’s modulus and rigid body were applied in the interference fit calculation, to improve the computational efficiency.

To better simulate the interference fit, it was divided into the following steps: firstly, applying hole-edge radical directional interference on laminated plate hole, and then simulating the static loading of the laminated plate mechanical connection for the blind bolt loading (see figure 1).

Progressive Failure Method

Three-dimensional stresses were accurately analyzed by establishing three-dimensional solid model of composite mechanical connection structure. Since obvious deformation would occur in the connections of laminated plate during the process of numerical simulation, the impact arising from geometric large deformation was also considered in the stress analysis.

In this model, the inner bearing load acting on the laminated plate connection was increasing by displacement loading of blind bolt. With the continuing increase of bearing load, if material damage occurred, it would lead the degradation of material property in the damage area. The material damage criteria and degradation approach were detailed in the following sections.

After occurrence of damage, the material property would be degraded in the damage area, stiffness decreased, structural stress/strain redistributed. After that, criteria were used again to determine the effectiveness.

Failure Criteria

To better judge the various damage modes occurred in the analysis process, failure criteria containing nonlinear factors [7], developed from Hashin three-dimensional failure criteria, was adopted in this article to determine the various damage of laminated plate occurred in the bearing process.

For bearing failure, when the laminated plates were damaged, connection structure still remained certain bearing capacity, and it would not lead to the tensile failure or shear failure of the whole structure. Bolt-hole bearing damage was generally caused by fiber fracture and matrix compression failure, and then single layer after the stiffness degradation would be substituted into the element calculation as a new single generation, until the load started to drop. The damage type of bearing was occurring on the composite connection at this moment.

Material Degradation

A lot of research has been done for the degradation model of material property. However, most researches were based on the simple regression models, where the corresponding material stiffness was reduced directly to 0, or different degradation factors were selected according to different materials and model types. Two degradation criteria, Change and Tan, were commonly used. Material properties of Change failure element under all failure modes were reduced to 0; Material properties of Tan failure element were reduced by different degradation factors.

Model Analysis and Verification

Progressive Failure Analysis and Strength Prediction

The connection structure of 0% sliding fit was calculated and analyzed. Table 1 described the progressive damage extension of 0°, ±45°, 90° layers with the increase of load,. After the completion of connection between bolt and hole, all elements had not failed. As the load increasing, the damage element first appeared in the 90° layer, and began in the area of maximum stress concentration, of which the damage type was matrix cracking; As the load continually going up, initial damage
occurred in the 0° layer, and the type of damage was matrix cracking and fiber fracture. Because the matrix cracking damage caused the redistribution of fiber stress, the lamination damage of 0° layer was mainly caused by fiber fracture. For ±45° layers, the damage forms of matrix cracking and fiber fracture appeared simultaneously on the outer edge of fibers. For the bearing failure of the 0% interference fit mechanical connections, matrix cracking was the main form of damage, which induced the fiber breakage, caused the decrease of the bearing capacity, and produced the final failure mode of bearing damage.

Table 1. The progressive damage of sliding fit joints in laminates.

<table>
<thead>
<tr>
<th>Layer</th>
<th>45° Layer</th>
<th>0° Layer</th>
<th>-45° Layer</th>
<th>90° Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading to 12kN</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>Loading to 18kN</td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
</tr>
</tbody>
</table>

For 0.5% interference fit joint, after applying 0.5% interference radial displacement on loading holes, only slight initial damage occurred on the 45° layer of surface layer (2 elements damage), and no damage was generated on all other layer element. After that, during the blind bolt lading process, the layer element damage was almost the same as that of 0% sliding fit.

For 3% interference fit joint, after 3% interference, large amounts of matrix cracking damage were generated around the hole-edge of laminated plate, and the fibers were all damaged. After contacting between the blind bolt and the wall of laminated hole, there was excess assembling pre-stress around the hole, hence the bearing stiffness was increased in the later loading process (see table 2).

Table 2. Progressive damage results of 3% interference fit joints in laminates.

<table>
<thead>
<tr>
<th>Layer</th>
<th>45° Layer</th>
<th>0° Layer</th>
<th>-45° Layer</th>
<th>90° Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>After interference fit</td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
</tr>
<tr>
<td>Loading to 12kN</td>
<td><img src="image13" alt="Image" /></td>
<td><img src="image14" alt="Image" /></td>
<td><img src="image15" alt="Image" /></td>
<td><img src="image16" alt="Image" /></td>
</tr>
<tr>
<td>Loading to 18kN</td>
<td><img src="image17" alt="Image" /></td>
<td><img src="image18" alt="Image" /></td>
<td><img src="image19" alt="Image" /></td>
<td><img src="image20" alt="Image" /></td>
</tr>
</tbody>
</table>

Table 2 described the damage extension process of the laminated plate layer at 3% interference fit joint. It could be seen from the damage accumulation process of whole laminated plates joint: the initial damage occurred at the layer of maximum layer angle, and started from stress concentration
area around the edge of bearing hole. Two types of damages often came in pairs. The damage firstly appeared at the maximum stress concentration area of 90° layer, and the failure type was matrix compression failure. Further, initial fiber damage occurred at the same location on 0° layer. After fibers on 0° layer were damaged, the element compressive stress was mainly undertaken by ±45° layer. Later, fiber shear failure in large area was generated on the ±45° layer. With the increase of the load, the adjacent layer was damaged subsequently. During the gradual growth of load, each layer of laminated plate extended along the bearing direction. After reaching the limited load, the bearing damage occurred in large area, which matched with the test result [8] of bearing failure mode.

Comparative Verification

The comparison between the static tensile strength results and the test results of the composite connection structure calculated by this model was shown in Table 3. It could be clearly seen that the ultimate bearing strength of three types of connection structures were different, in which the ultimate bearing strength of 0.5% interference fit joint was higher than that of the other two (ultimate bearing strength of 0% was higher than that of 3% interference fit).

<table>
<thead>
<tr>
<th>Interference / %</th>
<th>Tests Results[8] / MPa</th>
<th>Simulation Results / MPa</th>
<th>Error / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1174</td>
<td>1169</td>
<td>0.43</td>
</tr>
<tr>
<td>0.5</td>
<td>1248.7</td>
<td>1262.7</td>
<td>1.11</td>
</tr>
<tr>
<td>3</td>
<td>1090</td>
<td>1107.3</td>
<td>1.56</td>
</tr>
</tbody>
</table>

Conclusions

Finite element analysis for interference fit of the composite mechanical connection had been carried out in this article. The progressive damage model was established by considering the shear nonlinear of composite materials. Hashin failure criterion and Tan material property degradation criterion were used, and the influence of different interference (0%, 0.5%, 3%) fit mode on the connection strength and stiffness were investigated. The conclusions were drawn as below:

1) Hashin criterion could be used to well simulate the bearing progressive damage of composite mechanical connections. The model could also reflect the shear nonlinear of composites very well;
2) For interference fit mechanical connections, the interference fit of 5% did not cause any interference damage, and the ultimate bearing strength of 0.5% interference was higher than that of 0% sliding fit and 3% interference fit.

References

