Failure process analysis of T-joints under tensile load by DIC experiment and numerical simulation

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Abstract
The present paper is concerned with the strain distribution of the stress-concentration zone of a Carbon Fiber Reinforced Polymer (CFRP) T-shaped joint (T700/QY9611) subjected to tensile load up to ultimate failure. A detail 3D finite element model (FEM) based on the Cohesive Zone Method (CZM) has been established to simulate the complete failure process including the distribution and variety of strain field of the stress-concentration zone before damage, locating the initial damage position, and the propagation of the damage. The result of the simulation indicates that the triangle region always undertake the most serious strain concentration and the initial damage occur at this position. Then the damage rapidly propagates along the adhesives between the L-shaped stringers (vertical path) as well as between the skin and the L-shaped stringers (horizontal path), which result in the eventual failure of the structure. Tensile test has been conducted in an UTM operated in displacement control mode. Digital image correlation (DIC) method has been applied to capture the deformation and strain distribution in the triangle region. The test result can verify the validity of the simulation result.

Keywords: CFRP T-joint, Tensile load, The cohesive zone method (CZM), Digital image correlation (DIC)

1. Introduction
The integral design and fabrication technique of composite structures has been widely applied in advanced aerospace aircraft in both military and civilian fields, due to the advantages of the optimized structure, great load-bearing capability and the lower quality. This technique was generally regarded as a significant path to implement efficient structure. As a typical composite joint structure, the T-shaped joint assembled without riveting or bolting can be found in inlet ducts, wings, empennage and fuselages. It can enhance the structural stability and transfer the out-plane loading. The composite T-joint in this paper (as shown in Fig.1) consists of two L-Stringers, a skin and the filler. They are bonded together with J116B. Due to the special geometry and discontinuity of the components, the T-joint is potentially a weak point affecting the overall structure efficiency and integrity. Therefore, many research efforts in terms of the mechanics behavior and especially the failure mechanism of composite joint structures have been numerically and experimentally conducted among the recent advanced composite material researches.

Many study have showed that the triangle region is the most sensitive area and most failures initiate there. Vijayaraju et al. [1] conducted experimental study of failure and failure progression in T-stiffened skins. The study considered three plausible design configurations of T-stiffener with skin and indicated that damage initiated by debonding in the adhesive layer either near the last ply-drop or in the corner radius region, and progressed along the skin/stiffener interface, resulting in the ultimate failure. Jain and Verma [2] considered a co-cured T-joint configuration containing an initial existing disbonds at the skin/stiffener interface. Strains obtained from Digital Image Correlation (DIC) technique and appropriate FE method showed that damage initially occurred inside Bermuda triangle region for the pristine and disbonded specimen. Wu et al. [3] presented a study of failure mechanisms, carrying capacities, in-plane and interlaminar damage behaviors in T700/bismaleimide T-joint structures under tensile loading. A detail 3D finite element analysis based on CZM and Tsai-Wu failure criterion and the pulling test all indicate that the triangle region affects the failure mode and further determines the carrying
capacity. An experimental study of the failure load of T-joint structures has been undertaken by Trask et al. [4] with a focus on the influence of process induced defects within the deltoid region under static pull-off tension. The findings of this study suggest that the reduction in the deltoid area can be tolerated within certain limits.

The previous works mainly focus on the interfacial debonding initiation and propagation path of composite T-joint undertaking tensile load. The fracture behavior of the primary strain concentration region, the triangle filled region, has been rarely involved. The focus of this work is to figure out the strain distribution before damage and predict the initial damage in the triangle region. A detail 3D finite element model is developed to contribute to the analysis. The debonding behavior is described by the mixed-mode cohesive law.

2. Tensile tests & Digital Image Correlation (DIC) measurements

2.1 Details about the composite T-joints

The specimen involved in this study is shown in Fig. 1. It consists of three parts, two L-Stringers, a skin and the filler. The detail structure parameters of each part has been listed in Table 1. The composite parts are made of T700/QY9611 unidirectional prepreg, the thickness of which is 1.75mm. The primary mechanics parameters of this unidirectional laminate are shown in Table 2. A complete joint is assembled with adhesive, and actually there is glue laminate in the interface between two parts. Due to the extremely small thickness, the geometrical characteristics are ignored in this work.

2.2 Tensile tests

The tensile tests were carried using a Universal Testing Machine under displacement control. The loading speed is set as 1mm/min. The loading displacement and applied load are recorded. Digital image correlation (DIC) measurement is used to measure deformations and strain distribution in the triangle region. Fig. 2 show the speckled pattern on the specimen and the setup for the test.

It is observed that the failure initiated in the triangle region, then propagates towards glue layer. Fig. 3 shows the contour of $\varepsilon_{xy}$ before the failure and the failure model. These observations lead to the conclusion that there are two damage model (fraction of the triangle region and debonding) under tensile load and shear strain dictates the failure of the filling material.
Table. 1 Structure parameters of the CFRP T-joint.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension/mm</th>
<th>Lay-ups</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H$</td>
<td>220.25</td>
<td>$45^\circ/45^\circ/90^\circ/0^\circ/45^\circ/90^\circ/-45^\circ/0^\circ/-45^\circ/45^\circ$</td>
</tr>
<tr>
<td>$H_1$</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>$W$</td>
<td>200.0</td>
<td>$0^\circ/45^\circ/0^\circ/45^\circ/0^\circ/45^\circ$</td>
</tr>
<tr>
<td>$L$</td>
<td>200.0</td>
<td></td>
</tr>
<tr>
<td>$H_2$</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>5.0</td>
<td>filler</td>
</tr>
</tbody>
</table>

$H$: Height; $W$: Width; $L$: Length; $R$: Radius

Table. 2 Mechanics parameters of T700/QY9611 unidirectional laminates

<table>
<thead>
<tr>
<th>$E_i$</th>
<th>$E_2$</th>
<th>$E_3$</th>
<th>$G_{12}$</th>
<th>$G_{13}$</th>
<th>$G_{23}$</th>
<th>$v_{12}$</th>
<th>$v_{13}$</th>
<th>$v_{23}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPa</td>
<td>GPa</td>
<td>GPa</td>
<td>GPa</td>
<td>GPa</td>
<td>GPa</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>10.4</td>
<td>10.4</td>
<td>6.12</td>
<td>6.12</td>
<td>3.4</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Where, $E_i$ is Yong's modulus in $i$ direction of composite laminates; $G_{ij}$ is shear modulus of the laminates in $ij$ plane; $v_{ij}$ is Possion's ratio of the laminates in $ij$ plane.

Fig.2 the speckled pattern and the setup for the test
3. Numerical simulation of the failure process

In this numerical work, a detail three-dimensional finite element model representative of the composite T-joint is established to analyze the damage behaviours and failure modes of the T-joint undertaking a tensile load using the commercial software ABAQUS. The geometric parameters and lay-up sequences of the specimen have been listed in Table.1. In order to decrease calculation cost, a model of a quarter of the specimen has been applied, meaning the length along the normal of the cross section(similar to W) is 20mm.

The 8-node linear brick element with reduced integration and hourglass control (C3D8R in ABAQUS) has been adopted to simulate the entire T-joint model, including the L-stringers, the skin and the filling material in the triangle region. The material properties(as shown in Table 2) and direction of each layer are assigned using composite layup manager in ABAQUS. The filling material used in the triangle region is a kind of special filler for composite structure. The modulus of elasticity is 1500MPa, and poisson ratio is 0.3. The elements in this region are given material properties using section assignment. Fig. 3 presents the boundary condition and displacement load applied to the T-joint model. Two edges on the upper surface of the L-stringers 40mm-distance away from two ends (in accordance with the experiment setup) are fixed (U2=U3=0), and upward linear displacement load of 10mm is applied at top end of the model. The interaction behavior with cohesive laws is applied to describe adhesive behavior between different parts and predict debonding. The material parameters of the adhesive used in this model are shown in Table.3.

Fig. 3 (a) Contours of $\varepsilon_{xy}$ before failure; (b) Failure model in the specimen.

Fig. 4 boundary condition and applied displacement load.
Table 3 Mechanical properties of adhesive.

<table>
<thead>
<tr>
<th>$E$/MPa</th>
<th>$G$/MPa</th>
<th>$\sigma_{n0}$/MPa</th>
<th>$\sigma_{t0}$/MPa</th>
<th>$\sigma_{s0}$/MPa</th>
<th>$G_{IC}$/ (mJ/mm$^2$)</th>
<th>$G_{IIC}$/ (mJ/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>385</td>
<td>7.5</td>
<td>24</td>
<td>24</td>
<td>0.75</td>
<td>3.25</td>
</tr>
</tbody>
</table>

Where, $E$ and $G$ are Young's and shear modulus of resins, respectively; $\sigma_{n0}$, $\sigma_{t0}$ and $\sigma_{s0}$ are normal tensile strength and tangent shear strength, respectively; $G_{IC}$ and $G_{IIC}$ are, respectively, critical fracture energy release rates of I mode and II mode.

4. Results and discussions

According to the experiment, the maximum tensile load of this composite T-joint is 20.05kN, and it is slightly lower than the simulation result 22kN, as shown in Fig.4. There is hardly any stiffness degradation before complete failure of the joint. While the applied load rises to the top value, it drops down suddenly. Compared to the Load vs displacement curve from the test, the stiffness of the T-joint model is a little higher at the initial and linear elastic stage. Then the initial damage occurs, and the stiffness begins to decay. Meanwhile, the applied load continues to increase to the peak value and suddenly drops down, same as the test.

![Fig. 4 Comparison of Load displacement curve between FE simulation and experiments](image)

Further, contours of strains ($\varepsilon_{xx}$ and $\varepsilon_{yy}$) are compared with the contours obtained from DIC method, as shown in Fig.5. It is obvious that the area inside the triangle region undertakes severe strain concentration during the loading process and the strain distributions from simulations are accordant with that from test. Fig.6 presents the comparison of failure models...
Fig. 5 Comparison of strain contours at different loading between numerical simulation and test. It is observed that the horizontal and vertical path of debonding shows an agreement between the two methods. So it is concluded that the damage initiates inside the triangle region, then rapidly propagates along the adhesives between the L-shaped stringers (vertical path) as well as between the skin and the L-shaped stringers (horizontal path), which result in the eventual failure of the structure. Furthermore, the numerical mode present in this work can be used to predict failure process of composite structure more accurately if we set the failure criterion.
4. Conclusions

A detailed test and simulation studies are carried on a composite T-joint under tensile loading. Full field measurement of longitudinal and transverse strains at the triangle region of specimens is carried out using DIC technique. It is found that the initial damage occurs in the triangle region, then rapidly propagates along the adhesives between the L-shaped stringers (vertical path) as well as between the skin and the L-shaped stringers (horizontal path), which result in the eventual failure of the structure. Strain contours obtained from DIC clearly demonstrates the strain distribution in the triangle region under tensile loading and predicts the danger zone, which shows an agreement with the simulation. Load vs displacement plots obtained from simulations are compared with tests and a good corroboration is found. Further, this work can be extended to do similar research on other composite structures, and help to understand the complex response of composite structures undertaking various loadings.

references