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STUDY ON MECHANICAL PROPERTIES OF CARBON FIBER RESIN MATRIX COMPOSITE BOLTED JOINT STRUCTURE AT HIGH TEMPERATURE

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Abstract

In this paper, aiming at the high temperature environmental impact problems faced by composite materials in engineering applications, the bearing capacity of metal/carbon fiber resin matrix composite bolted connection structures at 25°C and 150°C was obtained through experimental tests, and a continuous damage model (CDM) was established. Numerical simulations were carried out to clarify the damage evolution mechanism of metal/carbon fiber resin matrix composite bolted structures at 25℃ and 150℃. The research results show that the ultimate load of the structure in the 150 ℃ environment is 10.8% lower than that in the room temperature environment, and the failure mode of the composite structure in the high temperature environment is extrusion failure, which is different from the tensile fracture along the nail hole section in the room temperature environment.

Keywords: Resin matrix composites, Bolted structures, High temperature mechanical properties, Continuous damage model, Damage evolution

1. Introduction

Carbon fiber reinforced resin matrix composites have good application prospects in the structure of high-speed aircraft due to their advantages of light weight, high specific strength and specific stiffness, strong designability, and high temperature resistance [1]. However, the high temperature environment will reduce the bearing capacity of composite materials, and at the same time affect the nail load distribution law of bolted connection structures, which brings great difficulties to the analysis of mechanical properties and damage prediction of composite bolted connection structures [2, 3].

Domestic and foreign scholars have done a lot of research on the load-bearing and damage analysis of composite bolted structures. Tserpes[4] studied the tensile behavior of bolted joints in graphite/epoxy composite laminates based on a three-dimensional progressive damage model (PDM) that combines failure criteria and material performance degradation rules, the results show that PDM can accurately predict the stiffness of composite single-lap single-bolt joint subjected to quasi-static tensile loads. McCarthy [5] developed a three-dimensional progressive damage finite element model of multi-bolt, double-lap composite joints, studied the effect of variable bolt hole clearance on bolt load, and compared the load-displacement characteristics and surface strain with the experimental results. Comparative validation showed that gaps can cause significant changes in load distribution and damage mechanisms in the joint. Zhou [6, 7] proposed a damage modeling method based on the continuous damage model (CDM) formulation and applied it to the problem of double-lap, multi-bolt, fiber-reinforced composite joints with variable clearance. The results show that the model can predict the damage of the matrix near the hole well. Zhang [8] developed a method combining the Hashin progressive damage criterion to study the effect of extreme temperatures (-55°C, 20°C and 82°C) on the damage progression of carbon fiber reinforced composite pin joints. The results show that increasing the ambient temperature will cause damage to the pin joints, decrease joint strength and increase matrix tensile damage rate. Cheng [9] analyzed the mechanical behavior of carbon fiber reinforced composite (CFRP) laminates and the effect of damage propagation, and carried out experiments and numerical simulations at room temperature and high temperature with 95 ℃. The results show that the high temperature environment has a significant effect on the bearing capacity of the structure, and the compressive strength of the sample at 95℃ is reduced by 15.5%, compared with room temperature.

To sum up, the research method of composite bolted connection structures in room temperature environment is relatively complete, but the research on the thermal-mechanical coupling analysis and the thermal matching performance of multi-nail connection structures are still not enough. Therefore, in view of the damage prediction and strength analysis problems faced by the composite connection structures in high temperature environment, in the present study, the method of combining experimental test and numerical simulation was adopted, and the load-bearing characteristics and damage mechanism of the metal/composite bolt connection structure at 25 ℃ and 150°C were investigated, which will provide support for the engineering application of composite structures.

2. Experimental Test Method

The resin matrix composite laminate is made of ZT7H/QY9611 material, the layup sequence is $[45/0/0/-45/90/0/-45/0/0/45]_s$; the metal material is 2024 aluminum alloy; the connection structure is composed of the aluminum alloys on both sides and the resin-based composite material in the middle; the connection method is three nails and double lap. The bolt pre-tightening force is 3N·m. The size of the test piece and the bonding method of the strain gauge are shown in Figure 1(a).

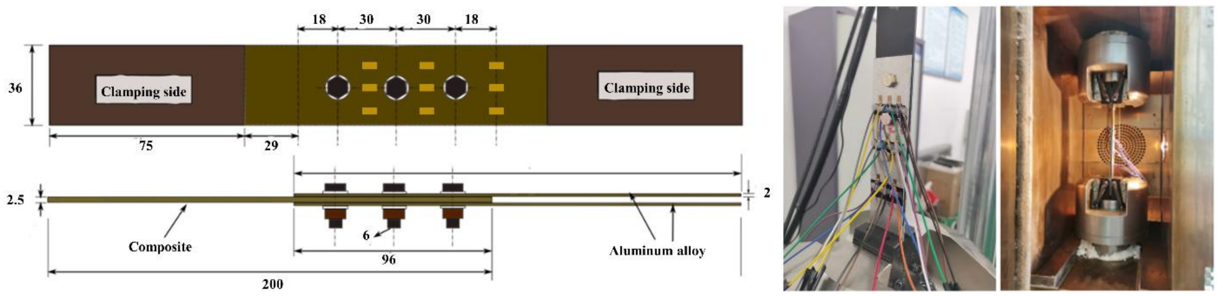


Figure 1 (a) The structural form of composite material and aluminum alloy bolted connection;

(b) Schematic diagram of the clamping method of the test piece

As shown in Figure 1(b), the tensile test was performed on the test piece on the INSTRON-5940 universal testing machine. The YD-350A temperature environment test chamber can meet the requirement of high temperature with 150 ℃. The test was carried out according to ASTM D5961/D5961M-17 [10]. After clamping the test piece to the testing machine, the environmental box was heated to 150°C (heating rate of 5°C/min) and kept for 30 minutes to make all parts of the test piece heated evenly. Then, tensile test with a loading rate of 2mm/min was carried out, and the test was stopped after the load reduced to zero or 30% of the maximum load.

3. Numerical Analysis Method

First, the secondary development was carried out based on the ABAQUS software platform using Python language to realize the parametric modeling of the metal/resin matrix composite bolted connection structure. The composite material and aluminum alloy element type are both C3D8R. One side of the test piece was clamped and constrained, and the other side was imposed the displacement to obtain the ultimate load of the structure [5].

Table 1 The plastic stress-strain relationship of 2024 aluminum alloy

Yield stress （MPa）	260	268	279	294	313	340	380	427
plastic strain	0	0.000162	0.000413	0.001036	0.002651	0.008131	0.022934	0.044134

Figure 2 shows the three-dimensional finite element model of the connection structure. The elastic modulus of the aluminum alloy is 76GPa, the Poisson's ratio is 0.33, and the constitutive model is an elastic-plastic model. The plastic stress-strain relationship was obtained by experiment and presented in Table 1.

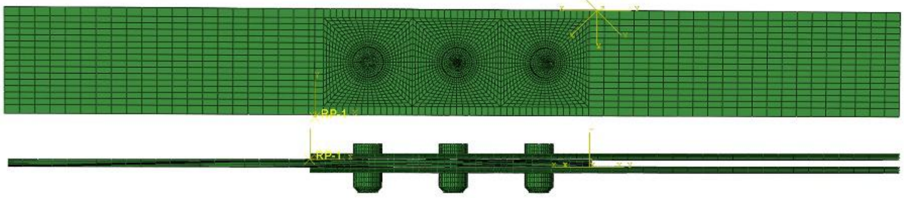


Figure 2 Finite element model of composite connection structure

The resin matrix composites use the damage analysis method based on the continuous damage model (CDM) [11], which introduces the influence of thermal expansion of the material [12]. The relevant material parameters are shown in Table 2.

Table 2 ZT7H/QY9611 composite material parameters

Elastic parameters	E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	G_{12}, G13(GPa)	G_{23} (GPa)	v_{12}, v_{13}	v_{23}
Value	143000	9370	9370	5450	3373	0.284	0.389
Strength parameters	X_T (MPa)	X_C (MPa)	Y_T (MPa)	Y_C (MPa)	S_{12} (MPa)	S_{23} (MPa)	S_{13} (MPa)
Value	2524	1430	76.7	258	168	168	97.2
Thermal expansion coefficient	α_{11}(10^{-6}/℃)			α_{22}(10^{-6}/℃)		α_{33}(10^{-6}/℃)	
Value	0.04			25		25	

4. Results and Analyses

4.1 Numerical Model Validation

Three tests were carried out under the same working conditions, the average value of the ultimate load was taken. The ultimate test loads at room temperature of 25 °C and high temperature of 150 °C were 43.6 kN and 38.9 kN, respectively. The bearing capacity of the structure in the high temperature is reduced by 10.8% compared with the room temperature environment.

The load-displacement curves obtained by numerical simulation of the composite material and the aluminum alloy bolted structure under tensile loading are basically consistent with the test curves, and the ultimate load value is close, which verifies the correctness of the numerical model and analysis method in this study (Figure 3).

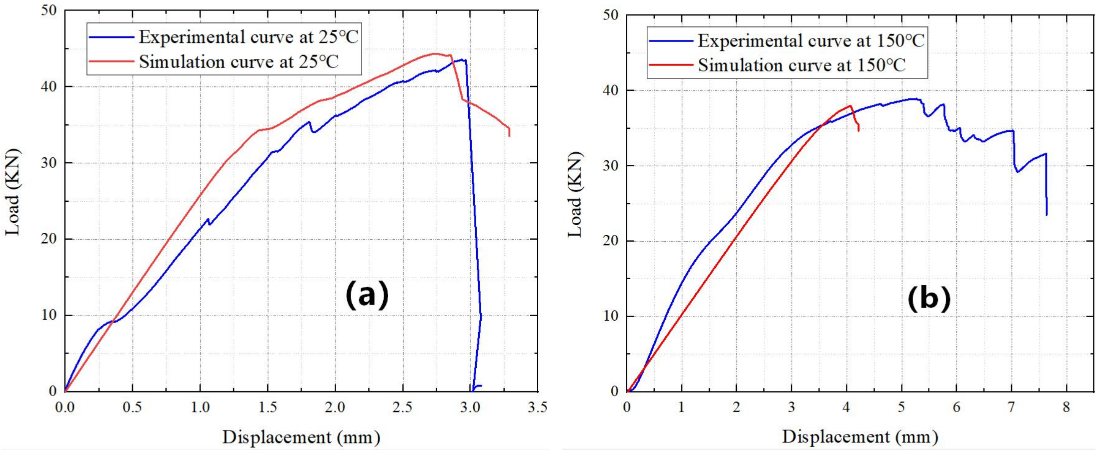


Figure 3 Test and numerical simulation load-displacement curve: (a) 25℃; (b) 150℃

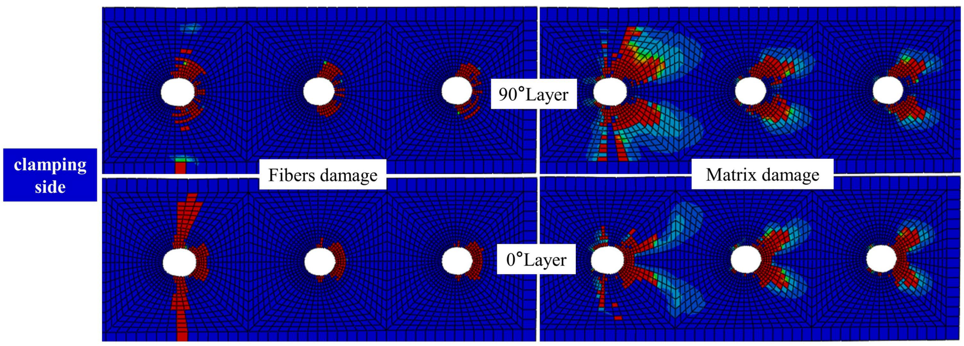
It can be seen from Figure 3(a) that the load increases in a stepwise manner with the displacement loading under the room temperature environment, and the structural stiffness gradually decreases with the increase of the number of steps. In the initial loading stage, the structural stiffness is the largest and the corresponding curve slope is the largest, and then a short plateau period gradually appears, which is because the bolt pores gradually decrease and the initial extrusion damage occurs at one of the bolt holes; when the loading continues, the structural stiffness decreases due to the structural damage expands, and the continuous extrusion of the bolt hole gradually causes a short-term load drop; in this way, until the final load suddenly drops to 0, the bearing capacity is lost due to tensile fracture at the bolt hole of the composite material.

It can be seen from Figure 3(b) that there is no obvious step shape in the load-displacement curve under the high temperature environment, but the structural stiffness change has a relatively good continuity during the loading. This is because the high temperature softens the composite resin, and the structure shows the greater plasticity leads to an increase in the loading displacement relative to the room temperature environment at the final stage close to the ultimate load of the structure. In addition, at high temperature with 150 °C, the structural load reaches its peak and then decreases-increase-decreases alternately. This is due to the extrusion damage extend at the bolt hole, and eventually the bearing capacity of the structure is gradually lost, which is different from the tensile fracture along the nail hole section in the room temperature.

4.2 Structural Damage Analyses

The failure mode of the composite plate after structural failure obtained by finite element analysis is shown in Figure 4 (the left side is the clamping side), and the stress cloud diagram of the aluminum alloy is shown in Figure 5 (the right side is the clamping side). According to Figure 4, it can be seen that in the 25°C environment, the fiber damage of the 0° layer is significantly greater than that of the 90° layer, while the damage to the matrix of the 0° layer is less than that of the 90° layer; at the same time, The degree of structural damage of the bolt hole on the leftmost side, which is nearer the clamping side, is the most serious. The fiber damage in the 0° layer runs through the entire section, and the matrix damage of the 90° layer is also distributed in most of the interfaces. Due to the expansion of the damage, tensile fracture occurs at the bolt hole on the leftmost side. In addition, from the clamping side to the connecting side, the damage degree at the bolt hole also gradually decreases, and the bolt holes on the connecting side are squeezed to different degrees.

In the high temperature environment of 150°C, the damage degree distribution of different bolts is consistent with that at 25°C, which are the damage on the clamping side is significantly greater than that at the other two bolts, and the damage at the bolt hole is also gradually decreased from the clamping side to the connecting side. Different from the 25°C environment, the damage difference between the 0° layer and the 90° layer at 150°C is small, and the leftmost damage does not penetrate the entire section, and the structural damages at the three bolts are all extrusion damage. It can be seen that under the same geometric parameters, high temperature will make the composite bolted connection structure change from tensile fracture to extrusion failure under tensile load.



(a) 25°C

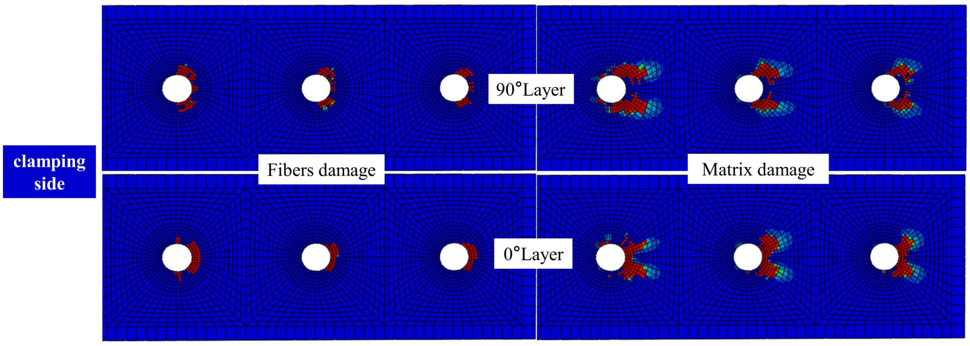


Figure 4 The finite element calculation results of structural damage of composite materials:

(a) 25℃; (b) 150℃

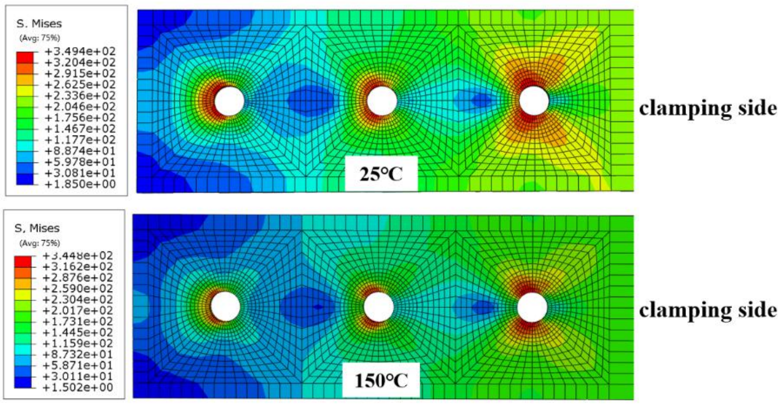


Figure 5 Stress cloud diagram of aluminum alloy

According to the stress cloud diagram of aluminum alloy in Figure 5, it can be seen that the stress level of the bolt hole near the clamping side is significantly larger than that of the other two holes, and obvious stress concentration occurs at the edge of all holes. By comparing the stress nephograms at different temperatures, it can be seen that the stress level of the hole edge in the high temperature environment is relatively lower than that in the room temperature environment. This is because the high temperature has a greater impact on the mechanical properties of the composite material than the metal, the composite panel has failed when the load is relatively small and the stress level of the metal plate is relatively low.

5. Conclusion

In the present study, the load-bearing performance and damage failure mechanism of metal/composite connection structures under room temperature (25°C) and high temperature (150°C) environments are investigated by experiments and finite element analysis. The research conclusions are as follows:

(1) The bearing capacity of the aluminum alloy/resin matrix composite bolted connection structure at high temperature is lower than that in the room temperature environment, and the ultimate load of the structure at 150°C is reduced by 10.8% compared with 25°C;

(2) The high temperature softens the resin matrix of the composite material, which leads to an increase in structural plasticity. Under the environmental condition of 150°C, the displacement after the structural failure is significantly greater than 25°C, and the high temperature will make the composite material structure change from tensile fracture to extrusion failure;

(3) When the aluminum alloy/resin matrix composite hybrid multi-nail connection structure is subjected to tensile load, the stress level of the aluminum alloy at the bolt hole near the clamping end is the largest, and the damage degree of the fiber and the matrix at the bolt hole on the clamping side of the composite material is also the largest. At the same time, due to the influence

of the bolt on the bypass load, the damage degree near the bolt hole gradually decreases from the clamping side to the connecting side.

6. Acknowledgments

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8. Copyright Statement

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