Failure Mechanism and Bearing Fatigue of Composite Mechanical Connections with High Lock and Blind Bolted Fasteners

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Abstract. In this paper, the bearing fatigue and failure of composite mechanical connections with two types of fasteners were compared and analyzed by fatigue tests. Failure mechanism of composite connections was explored from microcosmic and macroscopic aspects. From macroscopic point of view, the variation rule of hole-deformation with the increase of fatigue times was determined. Two failure modes, fretting wear and impact damage, were observed from the microscopic pictures, which combined to explain the failure mechanism of composite mechanical connections. In the end, the mechanism of interference-fit lengthening fatigue life was explored, which could be used to provide theoretical basis and experimental basis for the subsequent structural design and engineering application.

Introduction

Composite materials are widely used in aviation, automobile and other industrial fields because of their excellent mechanical properties. The fatigue failure of composite fastened connection structure was different from the fatigue failure of composite materials [1], because of the fatigue failure of composite structure not only including the components of composite material itself, also containing the contact fatigue among all parts of the structure, and the micro damage and fretting fatigue between the contact surfaces. The failure form of composite fastened structure was not the fatigue failure of composite material, but the failure of structural joint [2]. The fatigue test results showed that the fatigue failure of composite structures interference-fitted with the new type of fasteners had two modes: hole-deformation failure and fastener fracture failure [3, 4]. The size of interference [5] and the circulating load level [4] directly influenced the fatigue life [6] of bolt-hole deformation and the fatigue fracture life of fasteners.

The failure mechanism of composite mechanical joints was the result of the competition between the above two failure mechanisms. Therefore, it was necessary to explore two failure mechanisms and life prediction methods of composite mechanical joints interference-fitted with blind bolts. Based on the fatigue test data and microscopic imaging, this paper compared and studied the different hole-deformation, damage mechanism and fatigue failure of composite mechanical joints. The principle of interference fit increasing fatigue life was also studied.
Tests of Hole-deformation Failure

Fatigue Specimens of Hole-deformation Failure

Figure 1. Three types of composite bolted connections.

According to the fatigue test results [3], there were three kinds of coordination structure hole deformation fatigue failure modes, including high lock bolted H9/h9 sliding-fit connections, blind bolted 0% interference-fit and 0.5% interference-fit connections (as shown in Figure 1).

Results of Fatigue Tests

Under different cyclic stress, the fatigue failure modes of sliding-fit and low interference-fit were mainly the excessive deformation of composite material around hole. However, the fatigue life of the mechanical connection structure varied greatly due to different connection methods and sizes of connections. Figure 2 showed the typical SN curves of three kinds of connections, and the linear fitting was carried out in semi-logarithmic coordinates. It could be seen that the fatigue lives of the connections were longer with the increase of interference. Especially the gap between high lock bolted sliding-fit connections and Blind bolted 0% interference-fit connections was the most obvious. At the same cyclic stress, fatigue life had 1 ~ 2 orders of magnitude difference. The fatigue life of 0.5% interference-fit connections was 3 ~ 5 times higher than 0% interference-fit connections.

Figure 2. The typical curves of different connections.
In order to study the variation trend of the hole-deformation amount of the connected structures, the change curve of the three kinds of connections with the increase of the cycle times was given in Figure 3. It could be seen from the picture that the curve of sliding fit appeared power function form, while the curve of 0.5% interference fit was the superposition of two function form (linear function and power function). It could be concluded that when the damage amount of the hole was less than 0.5%D, the gap between bolt and hole would always be less than zero, so the fatigue failure model was a linear function. While the damage amount was more than 0.5%D, the fatigue failure model presented a form of power function.

**Failure Mechanism of Hole-deformation**

Under the action of fatigue cyclic loading, the contact slip zone was mainly cyclic contact friction fatigue, and the damage form was fretting wear. Due to no-contact area generally exiting in connections would cause a certain amount of space between bolt and hole. In the cycle test of $R=-1$, the main fatigue failure model of contact area and no-contact area was impact fatigue, of which the damage forms was the impact damage under small energy. The fatigue damage and failure mechanism of the three types of connected structures in Figure 3 were also different. According to the damage curves in Figure 3, three kinds of connected structures can be divided into two types, sliding-fit damage mode and interference-fit damage mode. So the further research on the damage mechanism should be divided into two types, and the different damage forms of mesoscopic structures should be taken into account.

**Damage Mechanism of Impact Fatigue**

Under the action of fatigue cyclic loading, the contact slip zone was mainly cyclic contact friction fatigue, and the damage form was fretting wear. Due to no-contact area generally exiting in connections would cause a certain amount of space between bolt and hole. In the cycle test of $R=-1$, the main fatigue failure model of contact area and no-contact area was impact fatigue, of which the damage forms was the impact damage under small energy. The fatigue damage and failure mechanism of the three types of connected structures in Figure 3 were also different. According to the damage curves in Figure 3, three kinds of connected structures can be divided into two types, sliding-fit damage mode and interference-fit damage mode. So the further research on the damage mechanism...
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According to Coulomb’s law, the micro-dynamic wear of composite hole was related to the normal stress and friction coefficient. Wear debris produced by the friction was hard to out of dissipation between bolt and hole because of fastened connection. Under the cyclic loading, the short-fiber and matrix were combined to form wear debris. As accumulating in the connections, wear debris came into being a dense layer of buffer layer (in Figure 4), which resulted in lower coefficient of friction around the bolt-hole, and reduced the wear and tear of composite hole, and finally to a certain extent slowed the effects of cyclic impact force.

![Figure 4. Tensile failure section picture of connected structure.](image)

On the other hand, with the continuous expansion of gap between bolt and hole, the cyclic impact load of fasteners on the composite hole would be larger and larger during the fatigue tests. Although at each cycle, the impact loading stress was within the scope of linear elasticity and the edge damage of composite hole did not occur, fatigue damage would appear on the side of hole in many times cycles of impact action. First, the multi-matrix-cracking occurred along the direction of fiber, also known as the characteristic damage state (CDS). After the CDS stage, the interlayer of composite was debonded and connected with the local crack of the composite laminates. As fatigue continued to load, interlayer phenomena continued to expand and evolve. Then, the longitudinal fiber fracture occurred, which led to significant changes in the macroscopic mechanical properties (elastic modulus, strain, etc.) of the composite laminates. After modulus of hole-edge material decreased, the deformation of hole increased, causing the greater amount of clearance and more serious impact damage, finally achieved the overall structural failure. So the hole deformation failure was the main failure mode of sliding-fit connected structure.

The wear (shown in Figure 5) also appeared between motherboard and lap plate under clamping force, which decreased as stress relaxing along the direction of thickness. The friction stress between the plates was reduced, resulting in lower bypass load and higher bearing stress. With the increase of fatigue cycles, the hole-deformation of composite increased significantly, which would also explain the reason for the exponential change (in Figure 3) of hole-deformation to cycle numbers.

![Figure 5. The wear morphology along the thickness direction.](image)

Figure 6(a) showed the microstructure diagram of the bearing fatigue failure. The burr fiber under bearing was longer. That was due to the clearance occurring in the initial stage of fatigue cycle, and matrix in the hole of laminates cracking up. Micro wear damage was very small. Due to the clearance
between bolt and hole was zero at initial fatigue stage, fretting wear was the main damage form, which made the burr fiber and matrix of composite wear away and the length of burr fiber decreased. So as shown in Figure 6(b), the burr fiber length of 0% interference fit of was significantly less than the length of Figure 6(a). Only when the edge of the hole was worn and the gap between bolt and holes began to appear, the damage form would change from fretting wear to impact damage.

(a) high lock bolted connections  (b) blind bolted connections

Figure 6. Microfailure diagram of bearing fatigue surface.

Conclusions

Based on the failure modes of composite fastened connections, this paper analyzed hole-deformation failure mechanism of sliding-fit and interference-fit, and explained the mechanism of interference-fit increasing the fatigue life at the microcosmic level. Fatigue failure of composite hole consisted of two parts, fretting wear and impact damage.

References