The Very-High-Cycle Fatigue Properties of Carbon Fiber Composite under Three-Point Bending

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Abstract. This paper starts from the need for an improved testing system of carbon fiber reinforced plastic composites (CFRP) under three-point-bending to investigate its properties under very high cycle fatigue. An improved testing system for composite material under three-point-bending very-high-cycle fatigue has been thus established. It was found that there is no traditional fatigue limit of carbon fiber composite under very high cycle loading conditions, and the CFRP ultra-high-cycle fatigue specimen exhibits three failure morphology, namely matrix damage at the intersection of fiber bundles, matrix voids near parallel sections of fiber bundles, and penetration of the matrix.

1. Introduction

Continuous fiber-reinforced composite materials, as one of the most promising materials for the development of China’s turbine engines in the future, have been widely used in aircraft engine fans and other components, thanks to its unique ability of greatly reducing the weight of the engine, the development cost of the engine, and improving the engine performance [1-3]. For example, the intake casing of the JTAGG verification machine involves the use of carbon fiber-reinforced PMR15 resin-based composite materials, which is 26% lighter than that of aluminum alloys[4]; GE90 engines have composite material as fan blades[5]. On the new generation of GEEx engines, the amount of composite materials exceeds 600 kg, accounting for about 13% of the engine weight[6]. The LAP-X1C engine of China’s C919 large aircraft also employs the use of advanced carbon fiber composite materials as the fan blades, with a total weight of 76 kg, which is 42 kg less than the weight of the CFM 56 engine fan blades[7-8].

However, the extensive use of composite materials also comes with a new problem, namely the life cycle of composite materials under ultra-high cycle vibration fatigue.

In recent years, research and engineering practice have shown that the design and testing of high-cycle fatigue of aero engine rotor structural parts at \(10^6-10^7\) cycles do not guarantee its safety due to ultra-high cycle fatigue[9]. For example, if the service life of the compressor blade that vibrates at a frequency of 1KHz reaches 2000 hours of service, the life cycle number is supposed to reach 7.2\(\times\)10^9.

Professor C. Bathias of France also pointed out in his monograph that the number of gas turbine engine component cycles can reach as many as \(10^{10}-10^{11}\) cycles[10-11].

This paper thus conducts ultra-high cycle three-point bending fatigue test on carbon fiber composite materials with an aim of exploring its damage mechanism under ultra-high cycle fatigue load, which is expected to provides a reference for the design of ultra-long life fatigue of high thrust/weight ratio engine structural parts in the future.
2. Materials and Methods

2.1. CFRP Specimens
The composite material used in this study is [0/90°], HT3/5224 carbon fiber/epoxy resin composite material, with a fiber volume fraction of 56% and the density of 1.45g/cm³. The relevant properties are listed in Table 1.

| $E_1$/ GPa | $E_2$/ GPa | $E_3$/ GPa | $\nu_{12}$ | $\nu_{13}$ | $\nu_{23}$ | $G_1$/ GPa | $G_2$/ GPa | $G_3$/ GPa |
|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| 144.70     | 9.65       | 9.65       | 0.30       | 0.30       | 0.45       | 5.2        | 5.2        | 3.4        |

The specimen size is 29mm×14mm×4mm, with a span $L_0$ of 16mm between the two support points, and the natural frequency of the sample of 20106 Hz, which meets the resonance conditions required for the ultrasonic test, and thus the ultra-high cycle fatigue tests under ultrasonic loading condition.

![Figure 1](image1.png)

(a) specimen size; (b) microscope image of the specimen

2.2. Test Setup
The ultrasonic three-point bending fatigue test system is shown in Figure 2. The test system is mainly composed of an ultrasonic frequency generator, a transducer, a displacement amplifier, a test piece, a measurement and control system, a cooling system, and a lateral stretching device.

During the test, the 50Hz AC electrical signal is converted into 20KHz mechanical vibration in the axial direction. The MTI-2100 optical fiber displacement sensor is used to monitor the high-frequency vibration displacement amplitude of the test piece in real time, and its frequency response can reach up to 500KHz. When the vibration displacement measured in the middle of the sample is not within the design range, it is here allowed to adjust the displacement by the adjustment of the power of the ultrasonic signal generator[12-15].
3. Results and Discussion

3.1. S-N Curve

As shown in Figure 3, the three-point bending ultra-high cycle fatigue test results shows that when R equals 0.2, the S/N value under the maximum stress of 428MPa is relatively large, which occurs in the high cycle cycle (106~107 times). When R equals 0.35, the S/N value at the maximum stress=436MPa is also large, which also occurs in the high cycle cycle range. This hereby indicates that the maximum stress is the traditional fatigue limit under different stress ratios R.

It can also be seen that the fatigue failure of the sample will still occur after 107 cycles corresponding to the traditional fatigue limit. In other words, after the plateau stage of the S-N curve, the curve shows a downward trend in the ultra-high cycle range. Therefore, CFRP also does not have the traditionally-defined fatigue limit, and the fatigue failure will also take place in the ultra-high cycle range. In addition, the S-N curve when R equals 0.35 is significantly higher than the S-N curve when R equals 0.2, signifying that the stress ratio R plays a certain role in the fatigue strength of the sample in the high cycle and ultra high cycle range.

![Figure 3. S-N curve of the fatigue test](image-url)
3.2. Properties of the VHCF
The optical microscope here is employed to observe the fatigue morphology of the fatigue specimen to analyze the fatigue failure characteristics as shown in Figure 4. It can be seen from the figure that the CFRP ultra-high-cycle fatigue specimen exhibits three failure morphology, namely: matrix damage at the intersection of fiber bundles (Type A, as seen in Figure 4 (a) and (b)), matrix voids near parallel sections of fiber bundles (Type B, as seen in Figure 4 (c) and (d)), and penetration of the matrix (Type C, as seen in Figure 4 (e) and (f)). The damage of the matrix at the intersection of the fiber bundles takes place at the intersection of the fibers, where the binding force of the material was reduced due to the intersection of the fibers, leading to the easy occurrence of damage; As for the morphology of matrix voids near parallel sections of fiber bundles, due to the small distance between the upper and lower fiber bundles, the impact on the matrix was increased, resulting in the relative weakness and easy damage of the matrix; The penetration of the matrix comes with a large fiber bundle spacing and a relatively large size[16].

In view of the damage voids and small size of the above-mentioned morphology, the damage morphology is thus uniformly defined as pitting erosion. However, there are no conventional failure modes such as fiber fracture, delamination or transverse cracks on ultra-high-cycle fatigue failure specimens, which point to a necessity for a further analysis of the properties of CFRP ultra-high-cycle fatigue failure.

![Figure 4](image)

Figure 4. Microstructure of specimens with different forms of ultra-high-cycle fatigue for (a) N=0, (b) N=7.6×10^{7}, (c) N=1.45×10^{8}, (d) N=6.23×10^{8}, (e) N=8.86×10^{8}, and (f) N=2.17×10^{9}

4. Conclusion
This paper focuses on the tests of carbon fiber composite by means of an ultrasonic three point bending fatigue test system to investigate its properties under very high cycle fatigue. The following conclusions were drawn:

1) An improved testing system for composite material under three-point-bending very high
cycle fatigue has been established.
2) There is no traditional fatigue limit of carbon fiber composite under very high cycle loading conditions.
3) The CFRP ultra-high-cycle fatigue specimen exhibits three failure morphology: matrix damage at the intersection of fiber bundles, matrix voids near parallel sections of fiber bundles, and penetration of the matrix.

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