RESEARCH ARTICLE

Experimental investigation of the three-point bending fatigue properties of carbon fiber composite laminates

Tao Yang*, **Mei-Hong He, Xue-Juan Niu, Yu Du**
School of Mechanical Engineering, Tianjin Polytechnic University, Tianjin 300387, China

Abstract: The three-point bending fatigue properties of carbon fiber epoxy matrix composite laminates were compared for fatigue loading stress levels of 75, 80 and 85%, and fatigue loading frequencies of 10, 15 and 20 Hz, respectively. The experimental results showed that the bending fatigue life of the composites obviously decreased with the increase of the fatigue loading stress level or the loading frequency. The fatigue damage accumulation process could be divided into three distinct stages according to the accumulation rate: fast, slow and then fast. When the loading stress level was increased from 75 to 85%, the duration of the third stage decreased from 40 to 10% of the overall fatigue life. When the loading frequency was increased from 10 to 20 Hz, the duration of the third stage increased from 20 to 40% of the overall fatigue life. Matrix cracking, fiber breaking, interface debonding and delamination were identified as the main three-point bending fatigue damage modes of the carbon fiber composite material, and the stress level and the loading frequency were found to significantly influence the fatigue failure properties of the composites.
Keywords: carbon fiber composites, three-point bending, fatigue property, stiffness degradation

*Correspondence to: Tao Yang, School of Mechanical Engineering, Tianjin Polytechnic University, Tianjin 300387, China; Email: yangtao@tjpu.edu.cn

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1 Introduction

As structural bearing material, carbon fiber composite laminates will get damaged and even wrecked during usage due to stress and other environmental factors, with fatigue being the main cause of damage[1–3]. The generation of fatigue damage as well as its expansion and accumulation in composite materials will accelerate the aging process of the materials, resulting in a serious degradation of their environmental resistance, a significant lifetime reduction and may even have catastrophic consequences[4,5]. However, due to some particular aspects of the manufacturing process and the anisotropy of the stiffness and strength of the carbon fiber composite material, the fatigue damage accumulation process and the failure modes in such materials are more complex compared to metallic materials[6–11]. Therefore, studying the fatigue properties of carbon fiber composites is very important. Several research groups have investigated the fatigue properties of carbon fiber composites both theoretically and experimentally[12–16]. For instance, Shokrieh and Lessard[17,18] conducted a 3D nonlinear finite element stress analysis to establish a progressive fatigue damage finite element model, and the residual stiffness, the residual strength and the fatigue life of composite laminates subjected to a complex fatigue load were simulated using this model. The accuracy of their model was tested experimentally under fatigue loading conditions for both tensile and compressive stress. Mao and Mahadevan[19] applied a continuum damage mechanics concept to evaluate the degradation of composite materials under cyclic loading, and proposed a mathematical model for evaluating the evolution of the fatigue damage in composite materials. This proposed model was found to be more accurate than previous models for modeling the rapid damage accumulation at early stages and near the end of the material's fatigue life. Mu *et al.*[20,21] also established a nonlinear fatigue damage cumulative model with three unknown parameters based on the hypothesis that the residual strength and the residual stiffness can be used equivalently to describe the fatigue damage in composite materials. The model was then used to predict the fatigue life and to assess the damage accumulation in composite structures. Wu *et al.*[22] proposed a phenomenological fatigue damage model based on the stiffness degradation rule of composite materials, which contains two material parameters, to describe the fatigue damage evolution and to predict the lifetime of the composite materials. Bending fatigue damage common occurs when using composite components. At present, the fatigue properties of carbon fiber composites were mainly studied using mechanical theories to establish a mathematical model in order to simulate the fatigue process and predict the fatigue life. The accuracy of these models was then verified by the tension-tension or tension-compression fatigue tests. However, knowledge on the bending fatigue properties under bending fatigue loads as well as the influence of the fatigue load and the fatigue loading frequency on the fatigue properties and bending fatigue fracture morphology is still very limited. Therefore, in this paper, we report on the three-point bending fatigue properties of carbon fiber reinforced epoxy matrix composite laminates. The stiffness degradation curve and the deflection variation curve were recorded for different bending fatigue loading stress levels and loading frequencies to characterize the progressive fatigue damage, to analyze the fatigue damage mechanism, and to discuss the effect of the fatigue loading stress level and loading frequency on the bending fatigue properties of carbon fiber composite materials. Finally, the fracture morphologies of the specimens observed for the different fatigue loading conditions are compared to discuss the different kinds of damage the material suffered when subjected to the fatigue load.

2 Material and methods

2.1 Sample preparation

In order to ensure the uniformity of each fatigue test sample, a large-size carbon fiber epoxy matrix composite was prepared. The composite consists of a laminated structure formed from pre-impregnated layers with a fiber orientation of [0°/90°] 6 s and a single layer thickness of 0.146 mm. The prepared composite was then cut into individual samples with a length of 150 mm, a width of 12.5 mm, and a thickness of 3.5 mm.

2.2 Experimental setup for the bending and fatigue test

The quasi-static three-point bending test was conducted on an ElectroPuls E10000 all-electric dynamic and static test instrument (INSTRON, USA), with the speed set to 2 mm/min. According to the ATSM D790-2003 standard, the tests were performed for a span-to-thickness ratio of 32:1. The diameter of the supporting roller was 10 mm, the distance between the two supporting rollers was 112 mm, and the test loading size is shown in Figure 1.

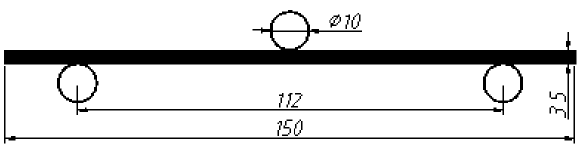


Figure 1. Sketch of three-point bending test.

The ElectroPuls E10000 was also used for the three-point bending fatigue tests. As shown in Figure 2, the tests were conducted by applying a sinusoidal waveform cyclic loading with a frequency of 10 Hz and a stress ratio R (i.e., the minimum-to-maximum-stress-ratio over one cycle) of 0.1. Three different stress levels (the ratio of the applied maximum stress in a cycle to the ultimate static bending stress of the composite specimen), i.e., 85%, 80%, 75%, were selected for the fatigue tests to study the fatigue properties of the composite materials. The test data of the load time, the load size and the deflection were recorded. In order to explore the effect of the loading frequency on the fatigue behavior of the composite, three-point bending fatigue tests were conducted by applying a sinusoidal wave-form cyclic loading with loading frequencies of 5, 10, 15, and 20 Hz, respectively, and the stress level fixed to 80%, again using the ElectroPuls E10000 test instrument. The failure cycles, stiffness degradation and deflection of the materials under different loading frequencies were analyzed.

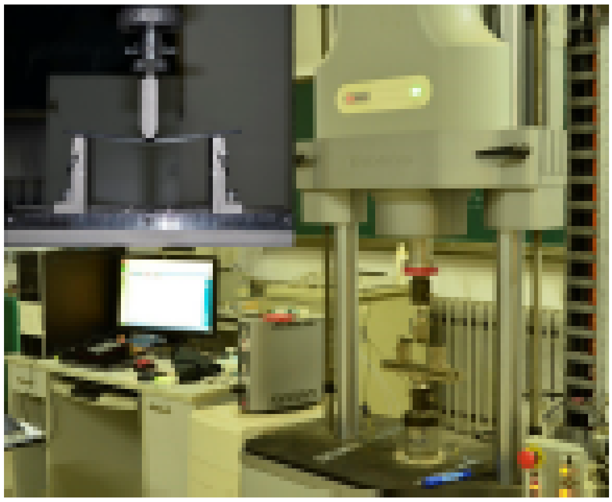


Figure 2. Physical map of three-point bending fatigue test for composite materials test.

3 Results and discussion

3.1 Quasi-static three-point bending test

Three composites laminate samples were selected for the quasi-static three-point bending tests, and denoted as samples 1#, 2#, 3#, respectively. The load-deflection curves of the carbon fiber composite laminates recorded during the quasi-static bending tests are presented in Figure 3. According to the results, the uniformity of the specimens is good. The curves can be described using a linear function before the maximum bending load of the materials is reached, and during this stage, the carbon fiber composite materials behaves similarly to a linear elastic material, which shows that the carbon fibers play a major role in bearing the load. When the maximum bending load is reached, the amplitudes of the curves are rapidly decrease, which results in the partial breaking of the fiber and considerable material damage. Then, a slight rebound can be observed followed by a sharp decline, which is attributed to the remaining fiber and matrix materials.

The experimental data obtained from the quasi-static bending tests performed on the three specimens was processed, and the ultimate stress ($\sigma_m ax$) and the bending modulus (varepsilon$_f$) of the carbon fiber epoxy resin composites were calculated using Eq. (1) and Eq. (2), respectively [23]:

$$\sigma = \frac{3FL}{2bh^2} \tag{1}$$

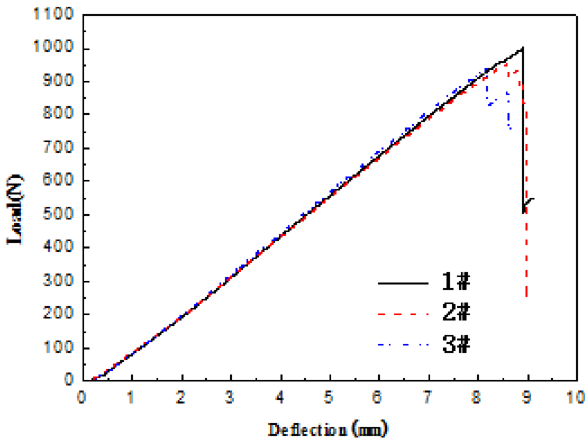


Figure 3. Quasi-static bending Load-Deflection curve.

$$E = \frac{\Delta F L^3}{4\Delta b h^3} \tag{2}$$

where F is the load applied to the central part of the specimen, ΔF the increment of F, ΔF the central deflection increment, L, b and h are the distance between the two supporting rollers, and the width and thickness of the specimen, respectively. The maximum bending load(F_{max}), ultimate stress(σ_{max}), bending modulus(F_f), the maximum deflection(ω_{max}) and the maximum strain(ε_{max}) obtained for each specimen are compared in Table 1. The average value of the mechanical parameters of the three specimens were calculated as reference values for the three-point bending fatigue test. Finally, the maximum bending load was selected to 965.023N and the ultimate stress was selected to 1058.630 MPa.

Table 1. The mechanical parameters of the quasi-static three-point bending

	F_{max}(N)	σ_{max}(MPa)	E_f(GPa)	ω_{max}(mm)	ε_{max}(%)
1#	1000.789	1097.866	40.412	8.912	1.492
2#	954.813	1047.43	37.566	8.607	1.441
3#	939.466	1030.594	36.387	8.167	1.367

3.2 Results of the Three-point bending fatigue tests for different bending fatigue stress levels

The failure cycle number was determined to 26705, 59290, 94825 for a stress level of 85, 80, and 75%, respectively. For comparison, the stiffness (ε) of the specimens during the fatigue testing was calculated and normalized by, and the extent of the fatigue damage was indicated as percentage of the overall fatigue life (i.e., the ratio of the numbers of cycles in the cyclic loading test to the failure cycle number in %). The obtained stiffness degradation curve and the maximum deflection curve of the carbon fiber composites are compared in Figure 4 and Figure 5 for the three different stress levels.

The results first revealed that, with the increase of the number of stress cycles, the overall trends observed for stiffness and the deflection of the samples are very similar for the three different stress levels. At the same time, the decreasement of stiffness and the variation on deflection of the samples can be divided into three distinct stages.

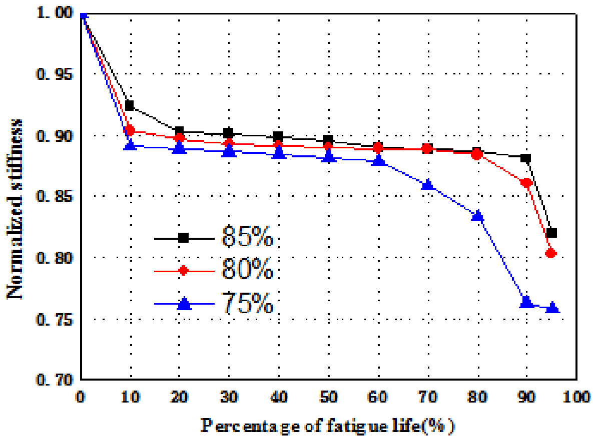


Figure 4. Stiffness degradation curves of the composite materials under three stress levels.

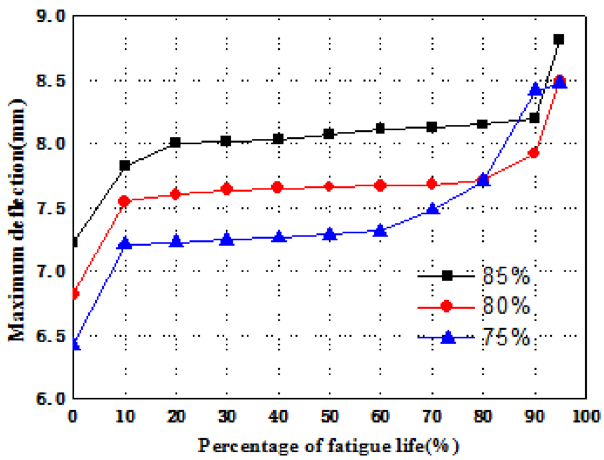


Figure 5. The deflection curves of the composite materials under three stress levels.

Initial stage (the first stage), the stiffness rapidly decreased and the deflection rapidly increased. At this stage, the cyclic loading was applied to the specimens, and, after a certain number of stress cycles, the resin began to show signs of crack initiation and expansion, which resulted in the rapid decrease of stiffness and the rapid increase of the deflection. Only a small number of stress cycles was required to reach this stage, and therefore the duration was comparatively short.

The middle stage (the second stage), the stiffness slowly decreased and the deflection slowly continuous increased. At this stage, the cracks in the matrix expanded from the outer surface layers to the inner layers of the composites along the thickness direction, and the cracks between the fiber and matrix expanded along the fiber length direction. At the same time, because the stresses in the thickness direction of the material were different, interface debonding and delamination began to gradually occur, as illustrated in Figure 6. A large number of cycles were required to reach the end of the second stage, so the duration is longer. The second stage takes up the majority of the whole fatigue process, resulting in a slow change of the mechanical properties of the material.

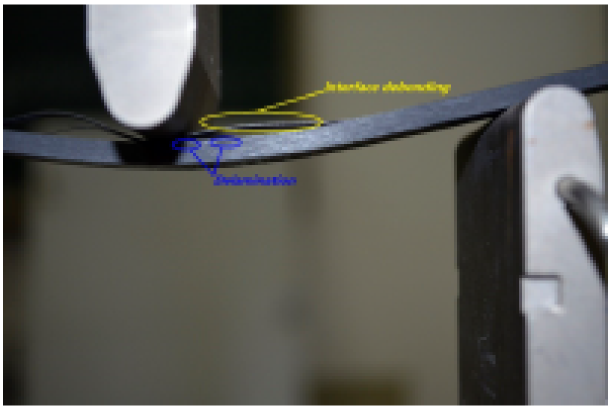


Figure 6. Interface debonding and delamination of the composite materials during loading.

The final stage (the third stage), the stiffness sharply decreased and the deflection sharply increased until the eventual material failure. At this stage, the fibers bore most of the load and apparently broke after the cumulative damage of the material had reached a certain degree. Material failure occurred after a small number of loading cycles and the duration of this stage is relatively short. Furthermore, the results reveal that the duration of the three stages of the material fatigue damage process changes with the loading stress level. For a stress level of 75%, the specimen entered the third stage after reaching approx 60% of its overall fatigue life, i.e., the third stage accounted for 40% of the sample's fatigue life. In comparison, for a stress level of 80 and 85%, the third stage accounted for only 20 or 10% of the whole fatigue life, respectively. In summary we can conclude that, the lower the stress level, the earlier the composite laminates enter into the third stage of the fatigue damage process, the more flat the stiffness and deflection curves during the third stage, and the higher the percentage of the whole fatigue life the third stage accounts for. At the same time, the higher the stress level, the faster the fatigue damage accumulation rate of the composite, the shorter the fatigue life and the more prone the materials will be to sudden damage.

3.3 Results of the Three-point bending fatigue test for different load frequencies

For a loading frequency of 5, 10, 15 and 20 Hz, failure occurred after 1380, 59290, 24359 and 15645 cycles, respectively. Because the failure cycles number for a loading frequency of 5 Hz was very small, we assumed that the fracture did not occurred due to fatigue damage. Therefore, we focused on the fatigue properties of the samples for the higher frequencies of 10, 15 and 20Hz. As shown in Figure 7 and Figure 8, the laws of the stiffness decrease and deflection increase of the specimens with the fatigue damage accumulation are accord with the three stage characteristics of the three-point bending fatigue damage of the carbon fiber composites.

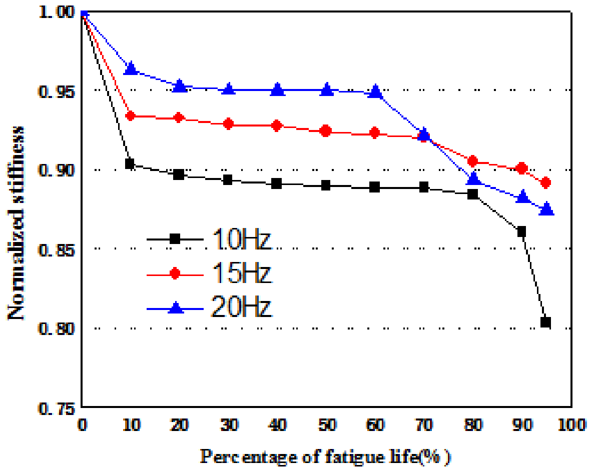


Figure 7. Stiffness degradation curves of the composite materials under three loading frequencies.

The comparison of the results of the three-point bending fatigue tests for different loading frequencies revealed first that, the decrease in stiffness was different for the three different loading frequencies during the first stage. For the loading frequencies of 20, 15 and 10 Hz, the stiffness decreased by 3.71%, 6.63% and 9.65%, respectively. Therefore, at the same stress level, the higher the fatigue loading frequency, the lower the decrease of the stiffness during the initial stage, the higher the stiffness during the second stage, and the smaller the deflection.

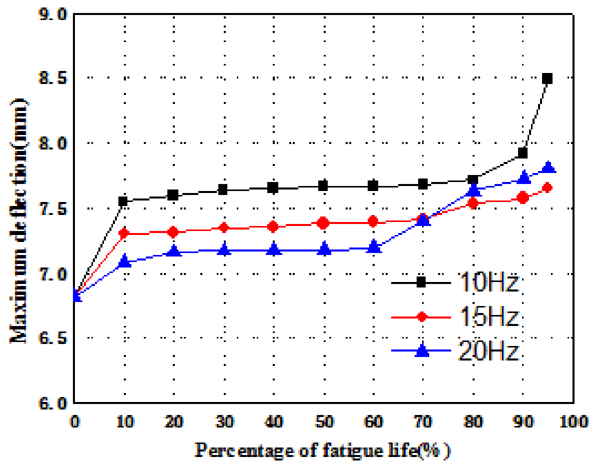
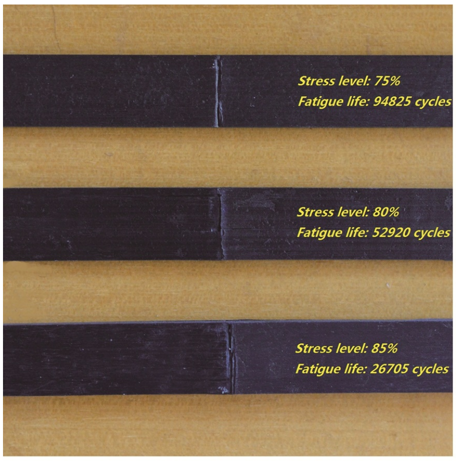


Figure 8. The deflection curves of the composite materials under three loading frequencies.

Further more, the results have shown that the duration of the three stages of the material fatigue damage process depends on the loading frequency. At a loading frequency of 20 Hz, the specimen entered the third stage after 60% of its overall fatigue life, i.e., the third stage accounted for 40% of the sample's fatigue life. In comparison, at a loading frequency of 15 and 10 Hz, the third stage accounted for 30% or 10% of the whole fatigue life respectively. In summary, when keeping the loading stress level constant, the higher

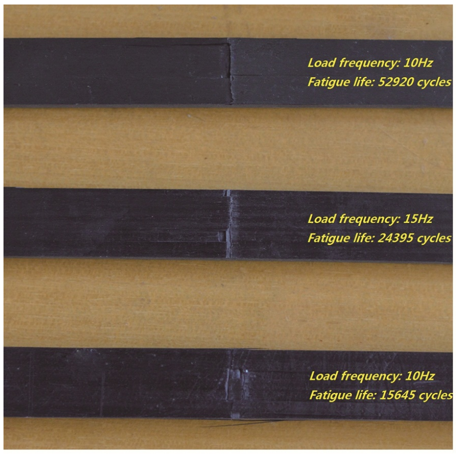


(a) Front surfaces

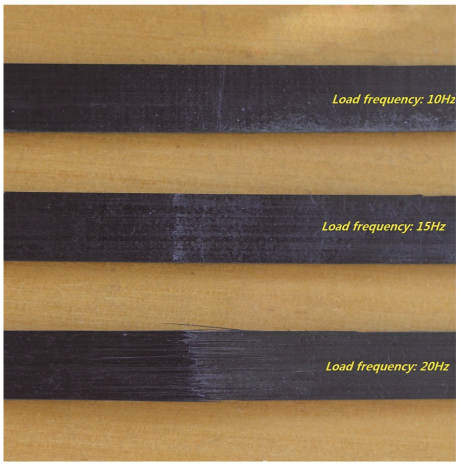
(b) Back surfaces

(c) Cross-sections

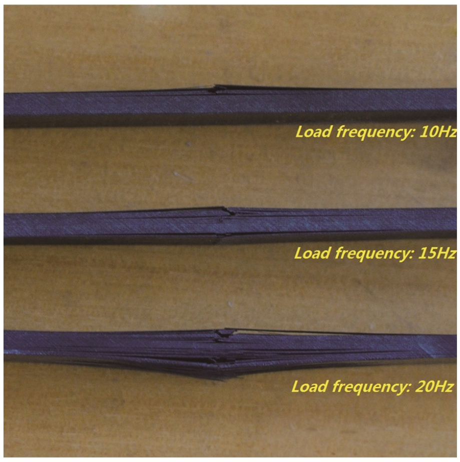
Figure 9. The fatigue failure morphologies of specimens under Three stress levels.



(a) Front surfaces



(b) Back surfaces



(c) Cross-sections

Figure 10. The fatigue failure morphologies of specimens under Three loading frequencies.

the loading frequency, the earlier the composite laminates enter into the third stage of the fatigue damage process, the more flat relatively the stiffness and deflection curves during the third stage, the third stage accounts for the higher percentage of the whole fatigue life. At the same time, the higher the frequency, the faster the material get damaged, and the shorter the fatigue life will be.

3.4 Fatigue failure modes

In order to further study the fatigue damage properties of the composites, the effects of the different loading stress levels and the different loading frequencies on the fatigue failure morphologies of the materials were compared and analyzed. Figure 9 compares the front surfaces, the back surfaces, and the cross-sections of the carbon fiber composite laminate specimens after the bending tests at the three different loading stress levels (85, 80, 75%). The fatigue damage is mainly concentrated in the center part of the specimen, and fiber breaking, matrix cracking, interfacial debonding as well as delamination are the main damage modes occurring in the carbon fiber composite laminates when subjected to bending fatigue loading. As the stress level increased, the failure of the specimen became more serious, and the fiber breaking and delamination phenomenon became more obvious, and even a fracture of the specimen could occur. When comparing the images of the different surfaces obtained for the same stress level, the front surface was more prone to damage. Taking the stress level of 80% as an example, the fiber breaking, matrix cracking phenomena can be easily observed on the front surface of the damaged specimen, and delamination was obviously found on the cross-section images, but the back surface did not show signs of damage. This is because the layers close to the front surface of the specimen were mainly subjected to compression loading, whereas those close to the back surface were mainly subjected to the tensile loading under the bending test conditions.

The front surfaces, back surfaces, and cross-sections of the carbon fiber composite laminate specimens damaged at the three different loading frequencies (10, 15, 20 Hz) are compared in Figure 10. Again, the fatigue damage is mainly concentrated in the center part of the specimens, and the higher the loading frequency, the more serious the specimen damage, and the more obvious fiber breaking and delamination phenomena. When comparing the images of the different surfaces obtained for the same loading frequency, the front surface was again more prone to damage, and fiber breaking, matrix cracking, and interfacial cracking damage occurred due to the continuous extrusion, whereas the back surface was more prone to zigzag fiber breaking and interface debonding due to the tensile stress. The cross-section images show that the layers close to the front and back surface of the specimen were prone to delamination damage. However in the center part of the sample along the thickness direction, damage phenomena did occur last because the stress was relatively small.

4 Conclusions

(1) The three-point bending fatigue damage process of the carbon fiber composites could be clearly divided into three distinct stages according to the stiffness degradation cure and the deflection cure: the stiffness decreased obviously and the degradation increased obviously during the first stage and the third stage, whereas the stiffness slowly decreased and the deflection slowly increased during the second stage. This is because the different damage mechanisms occurring in the carbon fiber composite materials under the alternating cyclic loading. (2) For different fatigue loading stress levels, the three-point bending fatigue lives of the carbon fiber composites and the duration of the three stages of the composite material's fatigue damage accumulation process were different. When the fatigue loading stress level was decreased from 85 to 75%, the fatigue life increased from 26705 to 94825 cycles. At the same time, the duration of the third stage increased from 10 to 40% of the overall fatigue life. The higher the stress level is, the shorter the three-point bending fatigue life of the carbon fiber composites, and the easier an abrupt failure of the material will occur. (3) For different fatigue loading frequencies, the three-point bending fatigue lives of the carbon fiber composites and the duration of the three stages of the composite material's fatigue damage accumulation process were different as well. When the fatigue loading stress level was kept constant, and the fatigue loading frequency was increased from 10 to 20 Hz, the fatigue life decreased from 59290 to 15645 cycles. At the same time, the duration of the third stage increased from 20 to 40% of the overall fatigue life fatigue. The higher the loading frequency, the shorter the three-point bending fatigue life of the carbon fiber composites. In comparison, the sample subjected to a low loading frequency of 10Hz was prone to abrupt failure. (4) Comparison of the damage morphologies of the samples investigate after the bending tests at different bending fatigue loading stress levels and different bending fatigue loading frequencies revealed that the fatigue failure mainly occurred in the center part of the material, and that fiber breaking, matrix cracking, interfacial debonding as well as delamination are the main damage modes in the carbon fiber composite laminates under bending fatigue loading. Furthermore, the higher the bending fatigue loading stress level and the bending fatigue loading frequency, the more serious the damage of the specimen, and the more obvious the fiber breaking and the delamination phenomena.

Acknowledgments

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