Effects of the Maximum Stress Level on Flexural Fatigue Behaviour of a Cross-Ply Laminated C/C Composite

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Abstract

Flexural fatigue behavior of a cross-ply laminated carbon/carbon composite had been studied. The results showed that fatigue behavior and residual strengths of the composite had a close relationship with the maximum applied stress level applied in the fatigue test. In the case of the stress level higher than the fatigue limit, specimens were serious delaminated after fatigue. In the fatigue limit stress level, different kinds of interfaces inside the composite were weakened after fatigue, and the residual flexural and interlaminar shear strength slightly increased and decreased, respectively. When the stress level was lower than the fatigue limit, only interfaces between carbon fibers inside one bundle were evidently weakened, and both of the residual flexural and residual interlaminar shear strengths were significantly improved.

Keyword: Carbon/carbon composites; Fatigue; Fiber/matrix interface

1. Introduction

Carbon fiber reinforced carbon composites, often known as carbon/carbon composites (C/Cs), exhibit many superior properties [1,2]. Their unique combination of mechanical and thermal properties makes them as an ideal choice for aerospace structural applications [3,4]. C/C composites are composed of carbon fibers, carbon matrix and various kinds of interface between the two phases. Mechanical properties and fatigue behavior of C/C composites are closely related to interfacial bonding condition [5-7], so fatigue behavior of C/C composites is really complicated [8,9], and there is no systematic theory that had been widely accepted.

In this work, a cross-ply laminated C/C composite were loaded using three-point flexural fatigue mode, under three different maximum applied stresses level respectively. This work focused attentions on obtaining changing regularity of different interfaces inside C/C composites during cyclic loading, and also paid concerns to the relationship between fatigue stress level and the residual strengths.

2. Experimental

The cross-ply carbon fiber preforms were densified in the process of isothermal chemical vapor infiltration (ICVI). The cross-ply C/Cs have densities of 1.60 (±0.01) g/cm3. Static flexural strength of the as-prepared composite was measured by three-point flexural test. The interlaminar shear strength test mode used in this work was three-point bending method. In this study, fatigue limit of the composites was determined as the value where the specimen was not failure even though the stress was repeated 106 times.

3. Results and discussion

The SEM micro-graphs of the as-prepared composite were presented in Fig. 1. Two different carbon fiber bundle layers existed in the composite, namely longitudinal and vertical carbon fiber bundle layers. There were three main kinds of interfaces inside the composites. The first one was interfaces between each carbon fiber bundle layers (I1). The second kind was interfaces between each carbon fiber bundles (I2).

The last one was interfaces between carbon fiber filaments inside one bundle (I3). As indicated in Fig. 1, that there were no micro-cracks and pores could be observed in the interfaces of the specimen.

Static three-point flexural strengths and fatigue test results of the cross-ply C/C composite were presented in Fig. 2. The ratio of the fatigue limit to the average static flexural strength was approximate 65%. Then, specimens were loaded on cyclic flexural loading under three different maximum applied stresses. The ratios of these three stresses to the average flexural strength were 70%, 65% and 60%, respectively.

The specimens who were loaded under 70% stress level failed ultimately. The specimens who were loaded under the other two stress levels could survive beyond 106 repeated loading. The average residual flexural strength and interlaminar shear strength of the specimens under the two stress levels after 106 repeated loading were measured, and the results were shown in Fig. 3. In the case of the 65% stress level, both of average residual flexural strength and interlaminar shear strength nearly equal to the static strengths. However, in the case of 60% fatigue stress level, the average residual strengths of the specimens were considerably improved. The results showed that the residual strengths of C/C composites after fatigue tests had a close relationship with the maximum stress level of the fatigue tests.

The SEM micro-graphs of the fatigue specimens were shown in Fig. 4. As indicated in Fig. 4a, when specimens were loaded under 70% stress level, the specimens were serious delaminated after fatigue test. As proposed by many scholars [10,11], delamination is the main failure mode of 2D-C/C composites. It was obviously observed in Fig. 4b that a large number of carbon fibers in longitudinal carbon fiber bundle layers were badly fractured. The photo also indicated that interfacial bonding conditions of I2 and I3 in vertical carbon fiber bundle layers were significantly decreased after repeated loading. To summarise, interfacial bonding of I1, I2 and I3 had been seriously weakened under the stress level higher than the fatigue limit of the composite (70% stress level).

In the case of 65% stress level, there were very few micro-cracks that could be observed in I1 region, as indicated in Fig. 4c. However, as showed in Fig. 4d, interfacial bonding of I2 had been weakened since lots of obvious micro-cracks generated in the carbon matrix between carbon fiber bundles. As a result, interfacial bonding strength of I3 had been decreased. In short, interfacial bonding strength of I2 and I3 declined remarkably, but I1 interface only had been gradually weakened, under the stress level of the fatigue limit (65% stress level).

As indicated in Fig. 4e, when specimens were loaded under 60% stress level, interfacial bonding of I1 was in good condition and no obviously micro-cracks and pores could be observed after 106 cyclic loading. As shown in Fig. 4f, there were not penetrating cracks developed in I2 interfaces. Since brittle carbon matrix broke and shed during cyclic loading, a number of semi-circular micro-cracks appeared inside fiber bundles and interfacial bonding strength of I3 decreased. To sum up, only interfacial bonding of I3 had been weakened evidently under the stress level lower than the fatigue limit (60% stress level).

As discussed above, in the case of 60% stress level , cyclic loading mainly lead interfacial bonding of I3 to be weakened, but the repeated loading does not produce an effect on I1 and I2. Since the weakening of I3 bonding strength, stress concentration at the tip of micro-cracks appeared during fatigue test can be released, and propagation speed of these micro-cracks decelerate [12]. As a result, both of residual flexural and interlamination shear strengths of the specimens are improved significantly. When specimens are loaded under the 65% stress level, the cyclic loading not only lead interfacial bonding of I2 and I3 to be weakened, but also bring about developing of micro-cracks in I1 region. The interfacial bonding weakening of I2 and I3 can release partial internal stresses inside the specimen and lead the residual flexural strength to increase. In the case of 70% stress level, the cyclic loading causes interfacial bonding of all interfaces inside the specimen evidently decrease. With the accumulating deformation inside the specimen, micro-cracks that developed along I1 region interconnect and form long and broad cracks. These cracks are parallel to the interfaces between carbon fiber bundle layers and lead the layers to be delaminated. As a consequence, the delamination of carbon fiber bundle layers causes the specimens fall ultimately.

4. Conclusion

Flexural fatigue behavior of cross-ply laminated C/C composites has a close relationship with the maximum applied stress level used in fatigue test.

Acknowledgements

This work has been supported by the Fundamental Research Foundation of Northwestern Polytechnical University under Grant No. GBKY1021 and the Research Fund of State Key Laboratory of Solidification Processing (NWPU), China (Grant No.12-BZ-2014).

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(a)

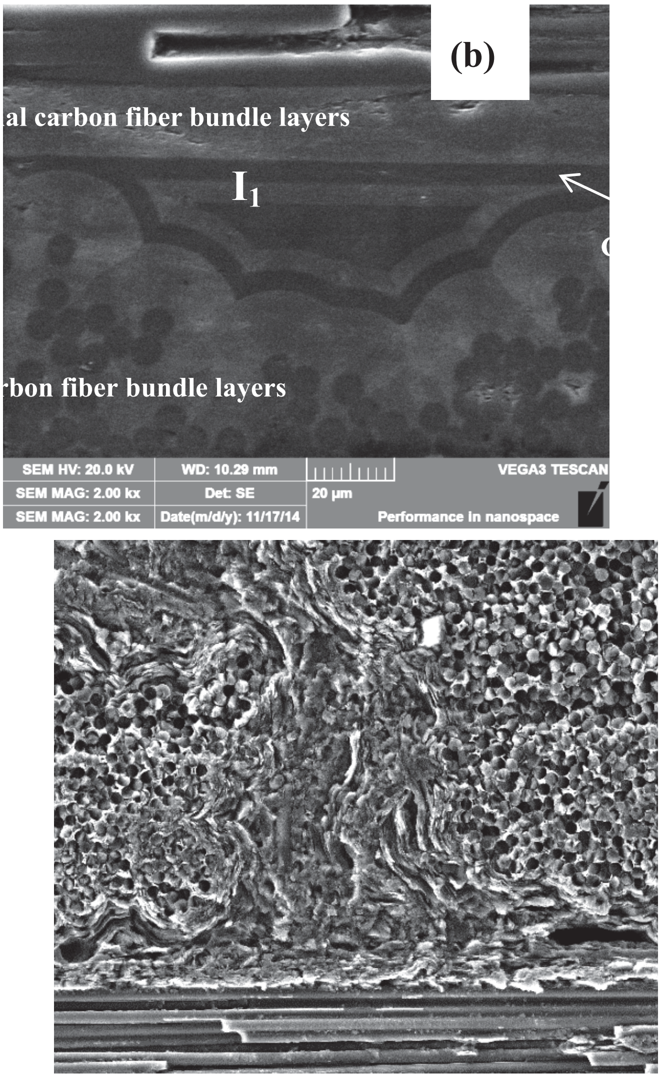


Fig. 1 SEM micro-graphs of the as-prepared composites,

(a) at ×2000 magnification, (b) at ×500 magnification.

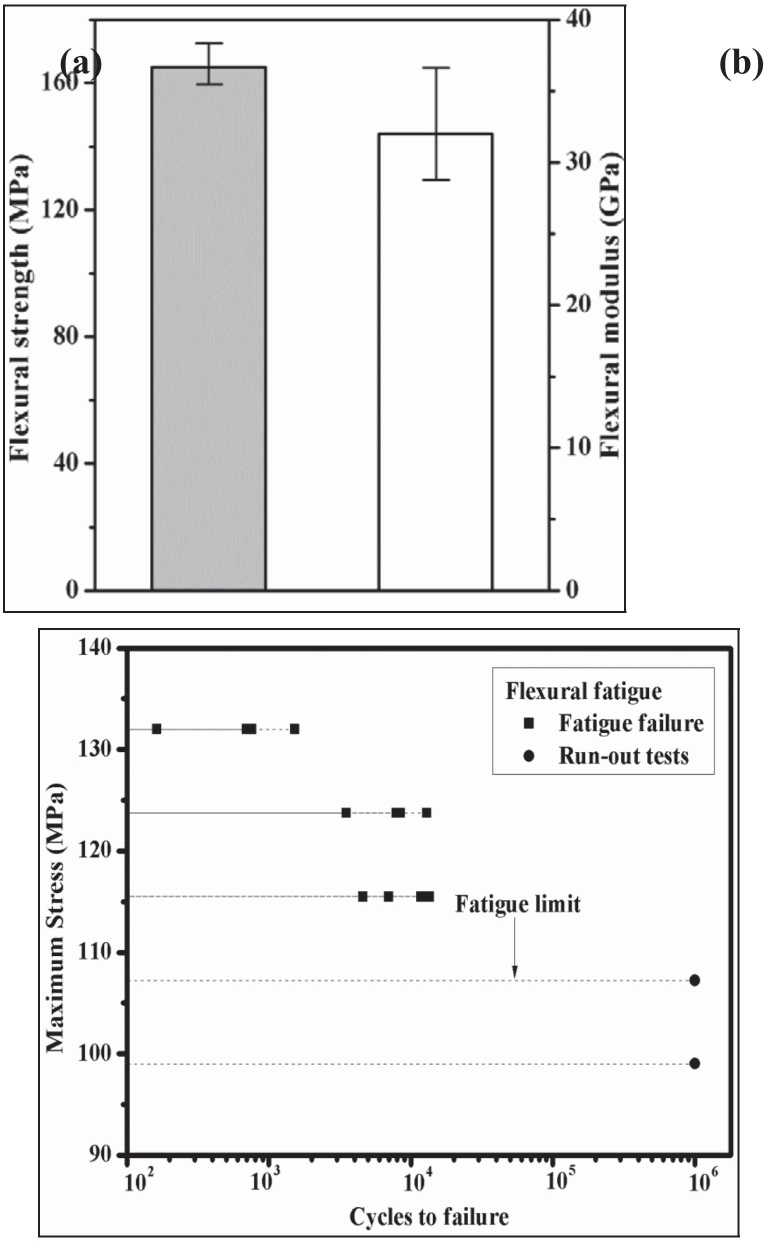
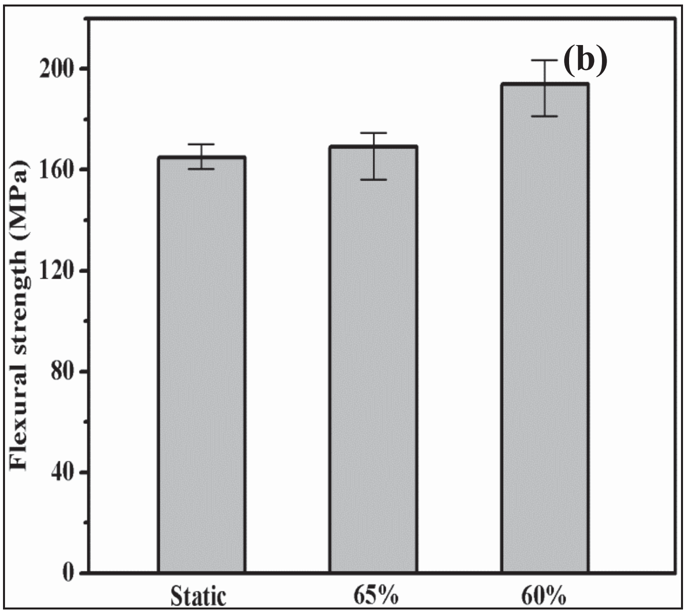


Fig. 2 Three-point bending test results of as-prepared C/C composites:

(a) static flexural test results, (b) flexural fatigue test results.

(a)



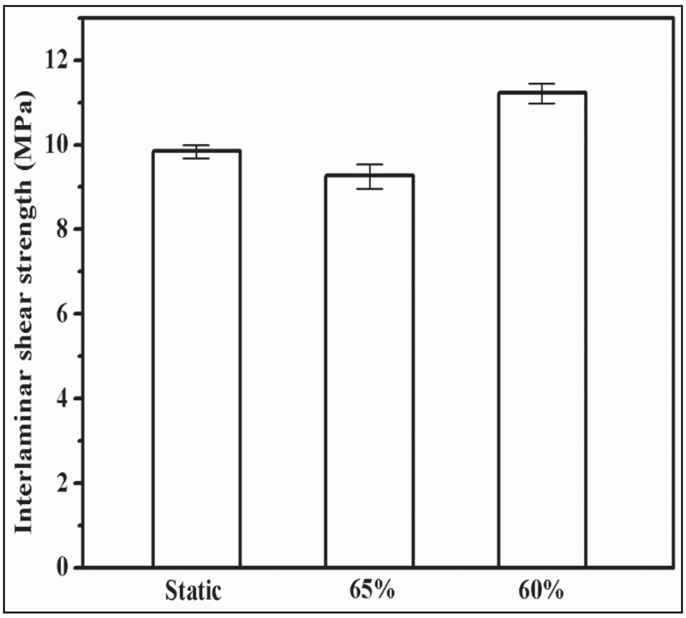
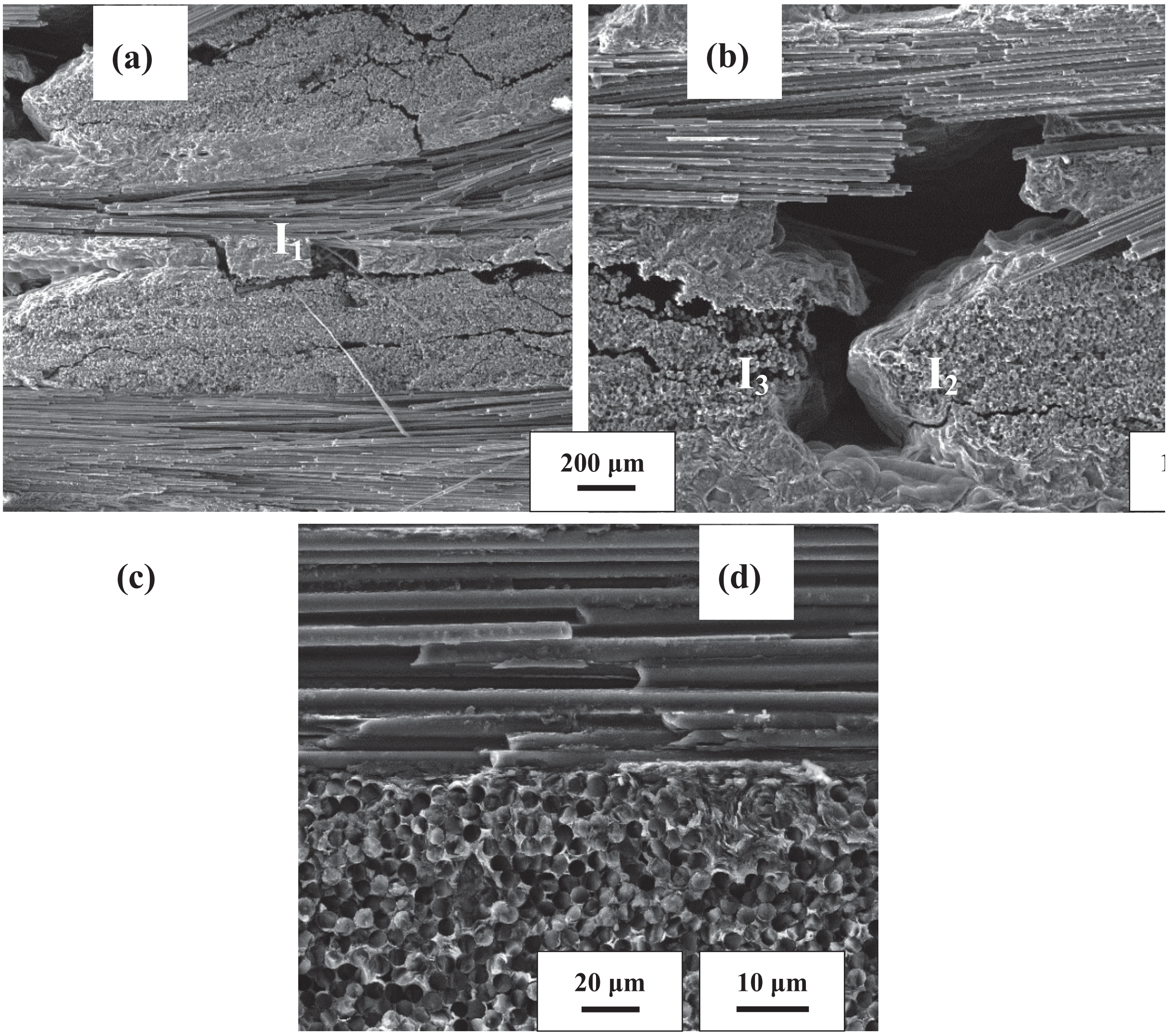
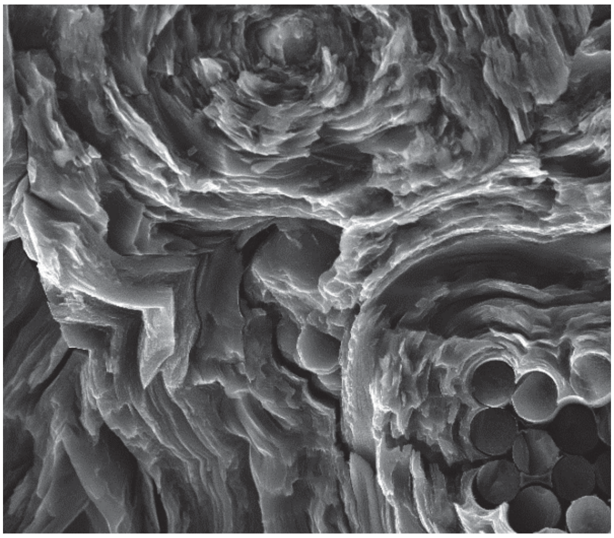


Fig. 3 Mechanical test results of specimens after 10^6 fatigue cycles under

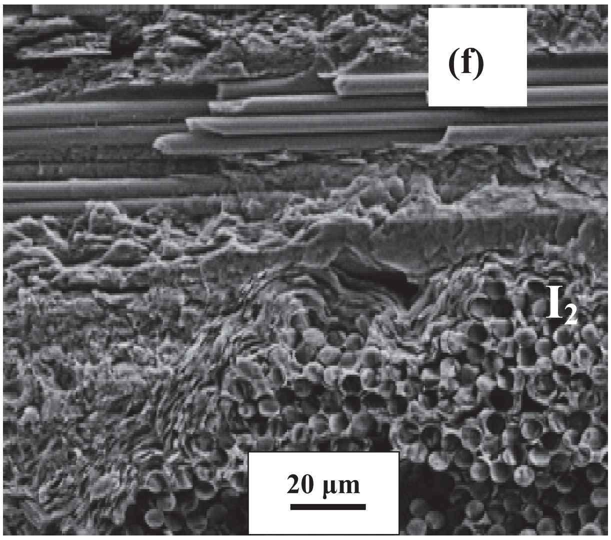
different maximum applied stress level: (a) flexural strength, (b) interlaminar

shear strength.





(e)



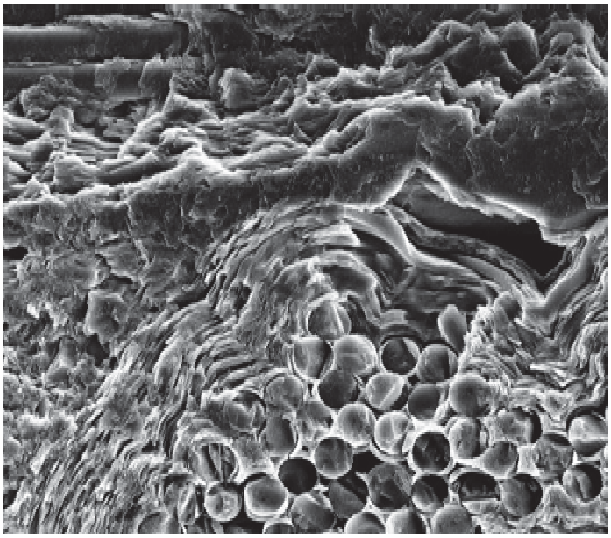


Fig. 4 SEM micro-graphs of specimens: (a), (b) failure morphologies of specimens under 70% stress level, (c), (d) survived specimens under 65% stress level, (e), (f) survived specimens under 60% stress level.