Failure Mechanism of Basalt Fiber-reinforced Polymer under Cyclic Load

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Abstract—This paper studies the fatigue behavior of basalt fiber reinforced epoxy polymer (BFRP) composites and reveals the degradation mechanism of BFRP under different stress levels of cyclic loadings. The BFRP composites were tested under tension–tension fatigue load with different stress levels by an advanced fatigue loading equipment combined with in-situ scanning electron microscopy (SEM). The specimens were under long-term cyclic loads up to $1 \times 10^7$ cycles. The stiffness degradation, S–N curves and the residual strength of run-out specimens were recorded during the test. The fatigue strength was predicted with the testing results using reliability methods. Meanwhile, the damage propagation and fracture surface of all specimens were observed and tracked during fatigue loading by in-situ SEM, based on which damage mechanism under different stress levels was studied. The results show the prediction of fatigue strength by fitting S–N data up to $2 \times 10^6$ cycles is lower than that of the data by $1 \times 10^7$ cycles. It reveals the fatigue strength perdition is highly associated with the long-term run-out cycles and traditional two million run-out cycles cannot accurately predict fatigue behavior. The SEM images reveal that under high level of stress, the critical fiber breaking failure is the dominant damage, while the matrix cracking and interfacial debonding are main damage patterns at the low and middle fatigue stress level for BFRP. Based on the above fatigue behavior and damage pattern, a three stage fracture mechanism model under fatigue loading is developed.

Index Terms—Basalt fiber; SEM; Fatigue; Damage mechanism

I. INTRODUCTION

Basalt fibers are environmentally friendly and nonhazardous fibers that are produced by drawing fibers from the melt basalt rock. Basalt fiber reinforced polymer (BFRP) is a promising fiber reinforced polymer (FRP) composite in the field of civil infrastructures. BFRP composites possess more desirable characteristics like high strength/weight ratio, ease of handling, and superior resistance to corrosion compared to steel material[1-3]. Furthermore, BFRP shows higher strength than traditional E-glass FRP (GFRP) as well as higher impact resistance and lower cost than traditional carbon FRP (CFRP)[2-4]. Other superiority of BFRP lies in its excellent creep behavior; or with a creep rupture stress of 54% of its tensile strength [5], which allows it to be used more sufficiently in prestressing and cable applications compared to GFRP. Prestressing tendons or cables in long-span bridges not only sustain the dead load of the bridges but also suffer from fatigue load induced by traffic and wind. The fatigue behavior of the bridge cables becomes a critical design consideration[5-8]. In order to introduce BFRP in those fatigue sensitive structures components, it is essential to investigate fatigue behaviors and develop new fatigue design methodology for BFRP composites.

This paper will focus on the fatigue behavior and fatigue life of BFRP by addressing the long-term ($1 \times 10^7$) fatigue behavior considering engineering applications of bridge cables. Furthermore, it will clarify the degradation mechanism of the composites under different stress levels of cyclic loadings by an advanced fatigue test equipment with in-situ scanning electron microscopy (SEM). It worth noting that the whole test system can simultaneously perform the fatigue loading test and SEM observation, which allows the fatigue damage propagation observed by SEM during the fatigue loading without unloading the specimens. In most previous studies[9-16], the damage patterns were only observed and compared after specimen fracture.

II. EXPERIMENTAL

As the restriction of the testing system, the tests were carried out on small specimens which were about 70 mm long and 3 mm wide with 20 mm gage length, as shown in Fig. 1. A specimen was manufactured by winding a preimpregnated continuous 1200 tex basalt fibers bundle onto a mold to control the width and gage length of the specimens. 2 layers of basalt fiber sheets serving as an end tab were preimpregnated and anchored onto each side of the specimen. The end tab consists of one outside layer and one inside layer stretched out about 10 mm from outside layer, to smooth the stiffness change in the tab and minimize the risk of tab failure during fatigue testing. After post-curing for 2 h at 200 °C, the specimens were cooled and cut to the shape as shown in Fig. 1. Prior to the tests, the specimen surfaces were cleaned with ethanol, and then were coated with a thin platinum layer in a JEOL JFC-1600 sputter coater.
The small specimens were tested in an advanced fatigue loading equipment combined with in-situ SEM (the Shimadzu SEM Servopulser) as shown in Fig. 2(a) and set up at a gripping device designed by the authors as shown in Fig. 2(b). The SEM Servopulser consists of two part: a fatigue devices and an in-situ SEM (JEOL 6510). This whole system can simultaneously perform the fatigue loading test and SEM observation. It should be noted that the SEM can only work in a vacuum chamber. For transferring the fatigue load to the specimens, a pair of steel wedges was fixed to the fatigue servo system and pretightened with the specimen. Between the wedges and specimens, aluminum shims were used to smooth the stiffness change between and minimize the risk of grip failure during fatigue testing.

III. RESULTS AND DISCUSSION

Low coefficient of variation (CV) was observed, which demonstrates that the mechanical properties of the specimens were stable. Representative stress–displacement curves obtained from the static tensile tests are shown in Fig. 3. All specimens exhibited a typical approximately linear load–displacement behavior with a sudden drop before failure.

The typical macro and micro failure pattern in static tests is shown in Fig. 4. It can be seen in Fig. 4(a) that the macro static fracture of specimens appeared broom-like with fibers totally and massively ruptured. From SEM image in Fig. 4(b), it can be drawn that the main damage mechanics in static tests is fiber breaking, followed by interface debonding along the interface between the broken fibers and unbroken ones. It is a desirable fracture mode for static tests.

Data of the specimens without failure in the fatigue test are not included in the curve fitting. The prediction equation is as shown in Fig. 5. The slope of the \( S–N \) fatigue curve (i.e. the parameter \( A \)) characterizes the degradation rate of the expected fatigue life. Note that parameter \( B > 1.0 \), which indicates that the extrapolation of the linear \( S–N \) curve to 1 cycle is above the quasi-static strength studied. The accuracy of the prediction represented by \( R^2 = 0.8888 \) is acceptable.

Fig. 6 shows the result of fatigue stress level prediction in \( 2 \times 10^6 \) cycles and \( 1 \times 10^7 \) cycles from the two models. The most conservative prediction was obtained from Whitney model with data up to \( 2 \times 10^6 \) cycles, which is 73.98% to achieve \( 2 \times 10^6 \) cycles fatigue life and 69.60% to achieve \( 1 \times 10^7 \) cycles fatigue life. That is the BFRP composites can carry a sustained stress of 73.98% and 69.60% of its tensile strength without fatigue failure within \( 2 \times 10^6 \) cycles and \( 1 \times 10^7 \) cycles with a reliability of 95%, respectively. Moreover, the prediction with data up to \( 2 \times 10^6 \) cycles is lower than that with all data, which indicated that the degradation rate of the BFRP specimens under fatigue load slow down after \( 2 \times 10^6 \) cycles. Similar phenomenon is also observed in GFRP and CFRP composites under low-cycle and high-cycle fatigue load even up to \( 10^8 \) cycles.
Fig. 6. S–N curves of different perdition models. (a) Models with data up to 2 million; (b) models with data up to 10 million.

Fig. 7 shows changes of the stiffness of BFRP composites depending upon the normalized fatigue cycles. The damage represented by the reduced stiffness was permanent. The fatigue failure of tested specimens occurred when the total accumulated damage reached a critical limit. Although there were notable scatters in the stiffness reduction for three specimens at each stress level, the critical limit was approximately 70–80% of the initial stiffness for all stress levels. For the specimens under different level of stress, the increase pattern also varied. For stress levels more than 87%, stiffness decrease can be found throughout fatigue cycles until the sudden failure of the specimen. This is due to the initial creep of composite and massive fiber breaking in a short time under those stress level. For stress levels less than 85%, an initial rapid decrease of stiffness can be observed, and then the rate gradually decreases with respect to time, and finally goes into a stable and slow rate of decrement. This steady trend is maintained without a further rapid rapture for the low stress levels like 75%. For the specimens under higher stress level (e.g. 85%), a sudden decrease of stiffness takes place up to failure. This reveals the same pattern with the three stage creep behavior in the creep tests on BFRP bars [5], which indicate that there are creep deformation occurred during the fatigue loading.

The typical failure pattern at stress level of 87% and 90% is as shown in Fig. 8. The fiber breaking was observed in the SEM image. Massive matrix debris were adhered to fibers, which reveals the interfaces remained in good bonding properties before failure.

Divergent damage patterns were found at knee point of S–N curve (the stress level of 85%) according to the SEM observation as shown in Figs. 9 and 10. Fig. 9 shows the SEM images of the damage observed under different number of fatigue cycles in the specimen failed at 102,642 cycles at 85% stress level. It is shown that numerous matrix cracks and fiber breaking occur at the beginning of the fatigue loading as seen in Fig. 9(a). The number of microcracks increases with the increase of number of cycles as shown in Fig. 9(b) and (c). Eventually, the fiber breaking points were linked together and cause catastrophic failure similar to the static tensile fracture. The massive matrix debris remaining on the fibers is observed in the failure surface as shown in Fig. 9(f).
This damage pattern is similar to that of specimens at stress level of 87% and 90%. However, a typical mode of matrix cracking is found in the specimen with 380,699 cycles fatigue life at the stress level of 85% as shown in Fig. 10. The matrix cracks exhibit short length at the beginning but propagate to longer cracks with the increasing of cycles, as seen in Fig. 10(a)–(c). Interface debonding is found at failure as shown in Fig. 10(d), which reveals that the interfacial degradation controls the fatigue life under this level of stress.

The damage pattern under the stress level of 83%, as shown in Fig. 11, exhibits similar matrix cracking propagation pattern to the specimen under 85% stress level shown in Fig. 10. In Fig. 11(a) and (b), the number and width of the matrix cracks became larger at $7 \times 10^5$ cycles than that at 521 cycles. Then the transverse propagation rate slowed down with increasing number of cycles whereas the cracking propagate along the fiber and form interface debonding as shown in Fig. 11(b) and (c). The failure pattern at 83% stress level was similar to that at 85% stress level which was dominant by interface debonding and wearing out in Fig. 11(d).

Fig. 12 presents SEM images of typical damage observed for different number of fatigue cycles at 75% stress level. It is shown that little short matrix cracks can be observed from the beginning of the fatigue loading shown in Fig. 12(a). The accumulation of the microcracks developed very slowly and only formed discontinuous interfacial debondings when they reached the interface of fibers and matrix, as shown in Fig. 12(b) and (c).

The SEM images (Fig. 8; Fig. 12) and $S$–$N$ curves (Fig. 5) indicate that three types of damage propagation patterns occur during fatigue loading under different stress levels. This speculation allows the creation of a fracture diagram for BFRP composites under fatigue loading as shown in Fig. 13. In region I of Fig. 13, i.e., high stress region like above 85% stress level in this test, the fracture of the specimens takes place in the fashion of progressive fiber breaking like the static tensile fracture.
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