Fatigue behavior and failure mechanism of basalt FRP composites under long-term cyclic loads

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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 maximum 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 1×10^7 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 an in-situ SEM, based on which damage mechanism under different stress levels was studied. The results show that the prediction of fatigue strength by fitting S-N data up to 2×10^6 cycles is lower than that of the data by 1×10^7 cycles, which reveals that 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.

Keywords: Basalt fiber; SEM; Fatigue; Damage mechanism

1. 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 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 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.

Only a few studies have been found in the literature related to the macro-scale fatigue properties of BFRP and the related hybrid FRP [2-8]. They revealed BFRP is

1 relatively suitable to be used in fatigue sensitive structures. Wu et al. [2] compared the
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4 fatigue behavior of various epoxy composites reinforced with carbon, glass, basalt, and
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7 polyparaphenylen benzobisoxazole (PBO) fibers sheets. They found that the fatigue
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10 behavior of BFRP is comparable to that of the conventional GFRP, while the fatigue
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13 behavior of BFRP can be significantly enhanced by hybridization with carbon fibers.
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15 Wang et al. [3] studied fatigue behavior of BFRP and the related hybrid FRP tendons.
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17 They found that BFRP and hybrid BFRP composites have higher fatigue life than the
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20 steel wire and can achieve integrated high performance in long-span cable-stayed
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23 bridges. However, above studies mainly focus on evaluation of the fatigue behaviors of
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26 BFRP with little attempt to explain the fatigue damage propagation and control factors
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29 of failure under different levels of fatigue loading. It is essential to understand the
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32 fatigue damage mechanism and control factors of failure for developing suitable
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35 controlling and designing method of BFRP composites under fatigue load.

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37 Recognized the importance of fatigue damage pattern, many researches have been
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40 done on its mechanisms of CFRP and GFRP laminates [9-19]. It is found that fatigue
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43 damage patterns are varied from that under static loading. For instance, Reifsnider et al.
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46 [9] reported that damage of composite during the fatigue begin at a microscopic scale
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49 and develops into extensive internal delamination which is only shown for the specimen
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52 reaching ultimate state under quasi-static loading [10]. Boniface et al. [11] presented
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55 that the transverse crack density in cross-ply CFRP laminates during fatigue is much
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58 higher than that under quasi-static loading. Therefore, it is necessary to observe the
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1 damage growth during fatigue loading rather than predicting it using quasi-static statics.
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4 In addition, the fatigue damage modes in CFRPs and GFRPs have been recognized as
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6 combinations of matrix cracking, transverse cracking, interfacial debonding,
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8 delamination, fiber breaking, etc. The fatigue failure mechanisms are affected by many
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10 factors like the types of fibers [13-14] and resins [15-16], textile techniques [17],
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12 surface treatments [18] as well as the fatigue stress ratios [19] and stress levels. Thus, it
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14 is essential to investigate the fatigue behavior and mechanism of target material under
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16 suitable fatigue loads. The amplitude of fatigue loading in the previous studies was
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18 maximized based on the view of materials instead of engineering applications.
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20 Regarding the microscale fatigue damage mechanism of BFRP, only two studies can be
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22 referred in the literature to the best of authors' knowledge. Li et al. [20] observed and
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24 monitored microscopic behaviors like matrix cracking, interfacial debonding and fiber
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26 breaking in BFRP composites using SEM and acoustic emission techniques. However,
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28 the study mainly focused on the detection of fatigue damage without mentioning the
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30 fatigue damage mechanism. Authors' previous study [21] found that fatigue damage
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32 control factors differed with the stress levels. However, the degradation mechanism of
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34 the composites under different levels of cyclic loadings is still not clearly explained.
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51 Furthermore, for most of those fatigue experiments of FRP composites especially
52 BFRP, the run-out cycles were usually defined as 2×10^6 cycles, which are adopted from
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54 the experience of metal materials. However, the damage accumulation and the fatigue
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56 degradation mechanism of FRP and metal materials can be greatly different [22]. For
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instance, FRP composites exhibit several modes of damage, whereas the metals usually fail by crack initiation and growth [23]. Considering the complex failure mode of FRP under fatigue loading, fatigue behavior of FRP under more cycles are necessary to investigate. It was found that 1×10^7 cycles would be more suitable to analysis the long-term fatigue life of than 2×10^6 as the stiffness and fatigue damage of FRPs become stable between 5×10^6 and 1×10^7 cycles [24-25].

This paper will focus on the fatigue behavior and fatigue life of BFRP by addressing the long-term (1×10^7) 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.

2. Experimental procedure

2.1 Materials and specimens

A system of continuous longitudinal basalt fibers reinforced epoxy composite has been investigated in the present tests. The basalt fibers were CBF13-1200 (1200 tex) from Zhejiang GBF Basalt Fiber Co., which were treated with silane sizing. The matrix used was an epoxy 9804 A/B from Bluestar Wuxi Petrochemical Co. The mechanical

properties of each component provided by the manufacturer are shown in Table 1. The system is suitable for manufacturing protruded BFRP cables.

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.

2.2 Static and cyclic loading procedure

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.

The specimens were tested under the quasi-static loading and the fatigue loading in the SEM Servopulser. For the quasi-static tests, a stroke rate of 2 mm/min was adopted to control test. The fatigue tests were performed under constant amplitude cyclic load with different stress levels and a frequency of 10 Hz. To simulate the actual cyclic loading condition of a bridge cable, the stress ratio R was determined to be 0.8 according to the mean value of the ratios of minimum to maximum load in cables by traffic and other live loads in a cable-stayed bridge [26-27]. For each stress level condition, three repeats were tested according to the test standard JSCE-535-1995 [28]. The run-out cycles were set as 1×10^7 cycles. The residual strength was tested for the run-out specimens. The stiffness of the specimens which were defined as (maximum load - minimum load)/(maximum deformation - minimum deformation) of each cycle were monitored during fatigue loading. All tests were performed at room temperature. The damage propagations and fracture surfaces of two randomly selected spots on each specimen were studied in the SEM during the fatigue loading.

3. Results and discussion

3.1. Static tensile properties

Five specimens were tested subjected to quasi-static loading. The test result is

listed in Table 2. The guaranteed tensile strength with a 95% confidence interval ($\sigma_{ult} - 1.645\sigma_s$) of the specimens was 2497 MPa, which was larger than that of the manufacturers' guaranteed design strength in Table 1. Low coefficient of variation (CV) was observed, which demonstrates that the mechanical properties of the specimens is 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.

3.2 *S-N curves*

The summary of the fatigue results is reported in Table 3. The data show a relatively low scattering according to fatigue testing results in the literature [3]. A linear fitting is calculated from the data using the least-square method according to Eq.(1) [29].

$$r_{\max} = \frac{\sigma_{\max}}{\sigma_{ult}} = A \ln(N_f) + B \quad (1)$$

Data of the specimens without failure in the fatigue test are not included in the curve fitting. The prediction equation calculated by Eq.(1) and the data in Table 3 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. However, it is clearly seen that the fatigue data can be divided into two groups by the deviation of data from the linear S–N relation. That is data above 0.85 stress level (less than 2 million cycles) have a different trend compared to those below. This phenomenon is similar to the different degradation rates of low-cycle fatigues and high-cycle fatigue loads observed in unidirectional GFRP composites [30]. Therefore, a bi-linear phenomenological fatigue model [30] is adopted to describe the effect of different property degradation rates, as shown in Fig.5. It should be noted that the knee points of the bi-linear S–N curve of GFRP in [30] and BFRP in this paper is different because the property difference between the glass fiber and basalt fiber in the composite. This knee point shifting of S–N curves of BFRP and GFRP can be verified according to the fatigue data of different FRP laminates in the reference [2]. It can be seen that the slopes of the linear and bi-linear lines are not consistent, which indicted different failure mechanics under different period of cycles. The changes of fatigue damage patterns and their mechanisms will be discussed in the section 3.5.

3.3 Prediction of fatigue life based on reliability analysis

In order to avoid the fatigue rupture of the FRP composites under cyclic loading, the allowable stress level should be analyzed based on S–N curves and reliability analysis. Statistically meaningful S–N curves were derived to predict the fatigue life of

the BFRP composites and fatigue limits. Two methods from the literature, normal lifetime distribution (NLD) [29] and Whitney's method [31-32], were adopted in this paper. The NLD method [29] is a simplified method that is based on the assumptions that the probability distribution function of the cycles to failure per stress level is normal. The S–N curve for 95% reliability level can be derived based on the fitting of a characteristic number of cycles per stress level versus the corresponding stress level, considering the stress parameter as the independent variable. It will be given by:

$$\sigma = \sigma_o R_k^{\left(\frac{1}{k}\right)} \quad (2)$$

where σ denotes the cyclic stress parameter under which the material exhibits life that can be fitted by a normal distribution with characteristic value, R_k . The $1/k$ and σ_o are the model parameters that must be estimated by the fitting.

Whitney's method assumed that this set of data follows a two-parameter ($\bar{N}$ and α_f) Weibull distribution:

$$P_s(N) = \exp \left[- \left(\frac{N}{\bar{N}} \right)^{\alpha_f} \right] \quad (3)$$

The S–N curve at any specified level of reliability can be calculated by:

$$\sigma = \sigma_o \left\{ \left[-\ln(P_s(N)) \right]^{\left(\frac{1}{\alpha_f k}\right)} \right\} N^{\left(\frac{1}{k}\right)} \quad (4)$$

where α_f , $1/k$ and σ_o are model parameters which can be determined by solving the values of the maximum likelihood estimators and by the fitting.

Fig.6 and Table 4 show the result of fatigue stress level prediction in 2×10^6 cycles

1 and 1×10^7 cycles from the two models. The most conservative prediction was obtained
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4 from Whitney model with data up to 2×10^6 cycles, which is 73.98% to achieve 2×10^6
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7 cycles fatigue life and 69.60% to achieve 1×10^7 cycles fatigue life. That is the BFRP
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10 composites can carry a sustained stress of 73.98% and 69.60% of its tensile strength
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13 without fatigue failure within 2×10^6 cycles and 1×10^7 cycles with a reliability of 95%,
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16 respectively. Moreover, the prediction with data up to 2×10^6 cycles is lower than that
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19 with all data, which indicated that the degradation rate of the BFRP specimens under
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22 fatigue load slow down after 2×10^6 cycles. Similar phenomenon is also observed in
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25 GFRP and CFRP composites under low-cycle and high-cycle fatigue load even up to
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28 10^8 cycles [31,33].

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31 It should be mentioned that for the actual design and application, more fatigue data
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34 of BFRP tendons should be accumulated to obtain design value with sufficient safety
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37 factor. Meanwhile, the manufacturing process of the FRP, environmental conditions,
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40 size effect and the type of fatigue load being applied should also be investigated for
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43 specific use. The current study on the fatigue behavior of BFRP is a fundamental study
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46 and can be referred to the future study.

47 48 49 3.4 Stiffness degradation and residual strength after fatigue loading

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52 Fig. 7 shows a change of the stiffness of BFRP composites depending upon the
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55 normalized fatigue cycles. The damage represented by the reduced stiffness was
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58 permanent. The fatigue failure of tested specimens occurred when the total accumulated
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61 damage reached a critical limit. Although there were notable scatters in the stiffness
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1 reduction for three specimens at each stress level, the critical limit was approximately
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4 70%-80% of the initial stiffness for all stress levels. For the specimens under different
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7 level of stress, the increase pattern also varied. For stress levels more than 87%,
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10 stiffness decrease can be found throughout fatigue cycles until the sudden failure of the
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13 specimen. This is due to the initial creep of composite and massive fiber breaking in a
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16 short time under those stress level. For stress levels less than 85%, an initial rapid
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19 decrease of stiffness can be observed, and then the rate gradually decreases with respect
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22 to time, and finally goes into a stable and slow rate of decrement. This steady trend is
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25 maintained without a further rapid rupture for the low stress levels like 75%. For the
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28 specimens under higher stress level (e.g. $85\%\sigma_{ult}$), a sudden decrease of stiffness takes
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31 place up to failure. This reveals the same pattern with the three stage creep behavior in
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34 the creep tests on BFRP bars [5], which indicate that there are creep deformation
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37 occurred during the fatigue loading.

38 Run-out specimens were also tested to evaluate residual tensile strength. Results in
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41 terms of residual maximum load and residual strength are shown in Table 5. The
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44 residual static strength is increased by 9% compared with that of the non-cycled
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47 specimens. This strength enhancement is achieved due to micro discontinuous
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50 debondings and cracking at and/or near the fiber/matrix interface which will be further
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53 explained in Section 3.5 and 3.6. Weak interfaces allow fibers to overcome the fiber
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56 damage by wear and exhibit its intrinsic strength. This damage tolerance mechanism of
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59 weakened interface also occurred during fatigue loading in C/C composites [34]. The
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1 fibers straightening due to the constant fatigue loading can also be a reason of the
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4 strength enhancement for it allows fibers in the composite can more uniformly deform
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7 and support the load. The phenomenon is also found in BFRP under creep loading [5].
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10 3.5 SEM observation 11

12 The typical failure pattern at stress level of 87% and 90% is as shown in Fig.8. The
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14 fiber breaking was observed in the SEM image. Massive matrix debris were adhered to
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17 fibers, which reveals the interfaces remained in good bonding properties before failure.
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21 Divergent damage patterns were found at knee point of S-N curve (the stress level of
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23 85%) according to the SEM observation as shown in Fig.9 and Fig.10. Fig. 9 shows the
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26 SEM images of the damage observed under different number of fatigue cycles in the
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29 specimen failed at 102642 cycles at 85% of stress level. It is shown that numerous
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32 matrix cracks and fiber breaking occur at the beginning of the fatigue loading as seen in
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35 Fig.9(a). The number of microcracks increases with the increase of number of cycles as
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38 shown in Fig.9(b)-(c). Eventually, the fiber breaking points were linked together and
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41 cause catastrophic failure similar to the static tensile fracture. The massive matrix debris
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44 remaining on the fibers is observed in the failure surface as shown in Fig.9(d). This
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47 damage pattern is similar to that of specimens at stress level of 87% and 90%. However,
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50 a typical mode of matrix cracking is found in the specimen with 380699 cycles fatigue
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53 life at the stress level of 85% as shown in Fig. 10. The matrix cracks exhibit short length
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56 at the beginning but propagate to longer cracks with the increasing of cycles, as seen in
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59 Fig. 10(a)-(c). Interface debonding is found at failure as shown in Fig. 10(d), which
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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 Fig. 11(b), the number and width of the matrix cracks became larger at 7×10^5 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 Fig. 11(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 the short matrix cracks can be observed from the beginning of the fatigue loading shown in Fig. 12(a). However, 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)-(c).

3.6 Fatigue damage mechanism analysis

The SEM images (Fig. 8-12) show that the transverse matrix cracking occurs during fatigue loading for BFRP composites. Wu et al. also reported that the BFRP sheet composites exhibited macro transverse cracks under cyclical loading [2]. This damage pattern differs from its counterpart of unidirectional CFRP composites. In unidirectional CFRP composites fatigue tests, longitudinal matrix cracks are usually dominant under

1 the fatigue cycles [2]. This can be the result of the different tensile modulus of fibers.
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4 For BFRP composite, the relatively low modulus of the basalt fiber makes the fatigue
5 stresses spread to the epoxy adhesive, whereas the high modulus of the CFRP
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7 composites (usually around 230 GPa) effectively transferred the fatigue stresses along
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9 the fibers.
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15 The SEM images (Fig. 8-12) and S–N curves (Fig. 5) also indicate that three types
16 of damage propagation patterns occur during fatigue loading under different stress
17 levels. This speculation allows the creation of a fracture diagram under fatigue loading
18 as shown in Fig. 12. In region I of Fig. 12, i.e., high stress region like above 85% in this
19 test, the fracture of the specimens takes place in the fashion of progressive fiber
20 breaking like the static tensile fracture. The small matrix cracks occur and weakest
21 fibers break within the first a few cycles. Because of the small crack stress
22 concentration and fiber strength distribution, more fibers around degrade and fail with
23 the increasing numbers of fatigue cycles, eventually causing massive and progressive
24 composite failure. In region II like 80%-85% stress level in this test, the stress intensity
25 is not big enough to cause progressive fiber breaking because the stress level is
26 relatively low. The short matrix cracks propagate transversely over a few fibers or along
27 the interface of fiber and matrix resulting in the initiation of progressive interface
28 debonding. The fiber damage was induced and fibers strengths degrade due to wear
29 caused by the initiation of long matrix cracks and fiber/matrix interfacial debonding.
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1 with the fatigue loading. On the other hand, the residual strength increases or recovers
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4 to its original value in region III, i.e., below the fatigue limit. The discontinuous
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7 fiber/matrix interface debonding and fiber straightening during fatigue take place in
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10 region III, which allows fibers to exhibit its intrinsic strength.
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12 **4. Conclusions and discussions**

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15 In this paper, fatigue behavior of BFRP composites was comprehensively
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18 investigated from both of the micro- and macro-scales. The fatigue failure phenomenon
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21 and fatigue-life curves of BFRP have been studied through the tension-tension fatigue
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24 tests and the damage process was monitored by the in-situ SEM technique. The fatigue
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27 life of BFRP composites is conditioned by the applied maximum stress (fatigue stress
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30 levels) and the damage development of different fatigue cycles.
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32 The prediction of the fatigue life and stress levels for certain fatigue life cycles of
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35 BFRP based on the data less 2×10^6 cycles (at high and medium stress levels) is not
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38 identical with that based on the data up to 1×10^7 cycles. The stiffness degradation and
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41 fatigue damage propagation of BFRPs slow down and even do not develop at about
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44 1×10^7 cycles (at low and medium level). Residual strength of BFRP composites is
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47 enhanced due to interfacial damage and fiber straightening when the fatigue stress level
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50 is below the fatigue limit.

51 The SEM images confirm that three different damage patterns appear at different
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54 fatigue stress levels. At high stress level and static loading, the dominant damage is
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57 normally fiber breaking, while matrix cracking and interface debonding are main
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1 damage patterns at the low and medium fatigue stress level for BFRP. Numerous
2 experimental and modeling efforts in the literature have been devoted to understand the
3 process of fatigue damage and the relation of fiber breaking, interfacial debonding as
4 well as matrix cracking under fatigue loads[35-39]. In future study, quantitative models
5 which reflect the damage patterns at different stress level of BFRP composites should be
6 developed and verified referring to those previous studies. Furthermore, with the
7 knowledge of the controlling effect of the fatigue damage, targeted fatigue improvement
8 methods can be proposed.

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16 **References**

- 17 [1] Meier U. Composite materials in bridge repair. Applied Composite Materials
18 2000;7:75-94.
- 19 [2] Wu ZS, Wang X, Iwashita K, Sasaki T, Hamaguchi Y. Tensile fatigue behaviour of
20 FRP and hybrid FRP sheets. Composites Part B: Engineering 2010;41:396-402.
- 21 [3] Wang X, Wu ZS, Wu G, Zhu H, Zen FX. Enhancement of basalt FRP by

1 hybridization for long-span cable-stayed bridge. Composites Part B: Engineering
2
3
4 2013;44:184-192.
5
6

7 [4] Colombo C, Vergani L, Burman M. Static and fatigue characterisation of new basalt
8
9 fibre reinforced composites. Composite Structures 2012;94:1165-1174.
10

11 [5] Wang X, Shi J, Liu J, Yang L, Wu Z. Creep behavior of basalt fiber reinforced
12
13 polymer tendons for prestressing application. Materials and Design 2014;59: 558-564
14
15

16 [6] Stallings JM, Karl HF. Stay-cable fatigue behavior. Journal of Structural
17
18 Engineering 1991;117: 936-950.
19
20

21 [7] Wang X, Wu ZS. Integrated high-performance thousand-metre scale cable-stayed
22
23 bridge with hybrid FRP cables. Composites Part B: Engineering 2010;41:166-175.
24
25

26 [8] Meier U. Carbon fiber-reinforced polymers: modern materials in bridge engineering.
27
28 Structural Engineering International 1992; 2: 7-12.
29
30

31 [9] Reifsnider KL, Jamison RD. Fracture of fatigue-loaded composite laminates.
32
33 International Journal of Fatigue 1982;4: 187-197
34
35

36 [10] Lee JW, Daniel IM, Yaniv G. Composite Materials: Fatigue and Fracture. American
37
38 Society for Testing and Materials. P.A. Lagace (Ed.), Philadelphia, 1989(2): 19-28.
39
40

41 [11] Boniface L, Smith PA, Ogin SL, Bader MG. Proceedings of the 2nd European
42
43 Conference on Composite Materials, London 1987;3:156-165.
44
45

46 [13] Demers CE. Fatigue strength degradation of E-glass FRP composites and carbon
47
48 FRP composites. Construction and building materials 1998;12: 311-318.
49
50

51 [14] Shan Y, Kin L. Environmental fatigue behavior and life prediction of unidirectional
52
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64
65

1 glass-carbon/epoxy hybrid composites. International journal of fatigue 2002;24: 847-
2
3
4 859.
5

6
7 [15] Curtis PT. The fatigue behaviour of fibrous composite materials. Journal of Strain
8
9 Analysis for Engineering Design 1989;24:235-244.
10

11
12 [16] Hartwig G, Hubner R, Knaak S, Pannkoke C. Fatigue behaviour of composites.
13
14 Cryogenics 1998;38(1):75-8.
15

16
17 [17] Shao YZ, Okubo K, Fujii T, Shibata O, Fujita Y. Effect of matrix properties on the
18
19 fatigue damage initiation and its growth in plain woven carbon fabric vinylester
20
21 composites. Composites Science and Technology 2014;104:125-135.
22
23

24
25 [18] Yudhanto A, Watanabe N, Iwahori Y, Hoshi H. Effect of stitch density on fatigue
26
27 characteristics and damage mechanisms of stitched carbon/epoxy composite.
28
29 Composites Part A 2014;60:52-65.
30
31

32
33 [19] Deng S, Ye L. Influence of fiber-matrix adhesion on mechanical properties of
34
35 graphite/epoxy composites: I. Tensile, flexure, and fatigue properties. J Reinf Plast
36
37 Comp 1999;18:1021-1040.
38
39

40
41 [19] Maier, G., et al. Damage development in carbon fibre-reinforced polyimides in
42
43 fatigue loading as a function of stress ratio. Composites 1986;17: 111-120.
44
45

46
47 [20] Li H, Wang WT, Zhou WS. Fatigue damage monitoring and evolution for basalt
48
49 fiber reinforced polymer materials. Smart Structures And Systems 2014;14: 307-325.
50
51

52
53 [21] Zhao X, Wang X, Wu ZS. Micro-macro investigations on fatigue behavior of basalt
54
55 fiber reinforced polymer composites, CICE Conference, Vancouver, August 2014, 20-
56
57
58
59
60
61
62
63
64
65

1
2 22.
3

4 [22] Nevadunsky JJ, Lucas JJ, Salkind MJ. Early fatigue damage detection in composite
5 materials. Journal of composite materials 1975;9: 394-408
6
7

8
9
10 [23] Salkind MJ. Fatigue of composites. Composite Materials Testing and Design (2nd
11 Conf) ASTM STP; 1972.
12
13

14
15 [24]Irving PE, Thiagarajan C. Fatigue damage characterization in carbon fibre
16 composite materials using an electrical potential technique. Smart materials and
17 structures 1998,7:456-466.
18
19
20
21

22
23 [25]Schütz D, Gerharz JJ. Fatigue strength of a fibre-reinforced material. Composites
24 1977;8: 245-250.
25
26
27

28
29 [26] Sih GC, et al. Fatigue crack growth behavior of cables and steel wires for the cable-
30 stayed portion of Runyang bridge: disproportionate loosening and/or tightening of
31 cables. Theoretical and Applied Fracture Mechanics 2008;49: 1-25.
32
33
34
35

36
37 [27] Lan CM, Li H, Ju Y. Fatigue Cumulative Damage Evaluation Based On Smart Stay
38 Cables. Intelligent Automation & Soft Computing 2010;16 : 715-727.
39
40
41

42
43 [28] JSCE-535-1995. Test method for tensile fatigue of continuous fiber reinforcing
44 materials (1995)
45
46
47

48
49 [29] Vassilopoulos AP, Keller T. Fatigue of Fiber reinforced Composites. Springer-
50 Verlag London Limited, 2011
51
52

53
54 [30] Harik VM, Klinger JR, Bogetti TA. Low-cycle fatigue of unidirectional
55 composites: Bi-linear S-N curves. International Journal of Fatigue 2002;20:455-462
56
57
58
59
60
61
62
63
64
65

- [31] Whitney JM, Fatigue characterization of composite materials. in Fatigue of Fibrous, Composite Materials, ASTM STP 723, American Society for Testing and Materials 1981:133-151
- [32] Whitney JM, Daniel IM, Pipes RB, Experimental Mechanics of Fiber Reinforced, Composite Materials. Prentice-Hall, Englewood Cliffs, 1984
- [33] Hosoi A, Sato N, Kusumoto Y, Fujiwara K, Kawada H. High-cycle fatigue characteristics of quasi-isotropic CFRP laminates over 10⁸ cycles (initiation and propagation of delamination considering interaction with transverse cracks). Int J Fatigue 2010;32:29-36.
- [34] Goto K, Furukawa Y, Hatta H, Kogo Y. Fatigue behavior of 2D laminate C/C composites at room temperature. Composites Science and Technology 2005;65:1044-1051.
- [35] Highsmith, A.L. and K.L. Reifsnider. Internal load distribution effects during fatigue loading of composite laminates. in Composite Materials: Fatigue and Fracture. 1986. Dallas, TX, USA: ASTM.
- [36] O'Brien, T.K. Composite interlaminar shear fracture toughness, G_{IIC} : Shear measurement or sheer myth? in Proceedings of the 1997 7th Symposium on Composite Materials: Fatigue and Fracture, May 7, 1997 - May 8, 1997. 1999. St. Louis, MO, USA: ASTM.
- [37] O'Brien, T.K. and K.L. Reifsnider, Fatigue damage evaluation through stiffness measurements in boron-epoxy laminates. Journal of Composite Materials 1981;15(1):

1
2 55-70.
3

4 [38] Reifsnider, K.L. and A. Highsmith. Characteristic damage states: a new approach to
5
6
7 representing fatigue damage in composite laminates. in Materials, Experimentation and
8
9 Design in Fatigue, Proceedings of Fatigue '81. 1981. Coventry, Engl.
10

11
12 [39] Subramanian, S., K.L. Reifsnider, and W.W. Stinchcomb, Cumulative damage
13
14 model to predict the fatigue life of composite laminates including the effect of a fibre-
15
16 matrix interphase. International Journal of Fatigue 1995;17(5): 343-351.
17
18
19
20
21
22
23
24
25
26
27
28
29
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Figure captions:

Fig. 1 The fatigue test specimens (unit: mm).

Fig. 2 Test setup. (a) SEM Servopulser; (b) Layout diagram of gripping device

Fig. 3 Stress-displacement curves in the static tensile tests.

Fig. 4 The typical micro and macro failure pattern. (a) Macro failure pattern; (b) Micro damage

Fig. 5 Stress level- $\log N_f$ curves.

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 Stiffness degradation of BFRP composites. (a) $r_{max}=0.9$; (b) $r_{max}=0.87$; (c) $r_{max}=0.85$; (d) $r_{max}=0.83$; (e) $r_{max}=0.8$; (f) $r_{max}=0.75$.

Fig. 8 Typical fiber breaking failure pattern at stress level of 87% and 90%

Fig. 9 A typical example of fiber breaking damage observed for different number of fatigue cycles at 85% stress level. (a) 519 cycles; (b) 50007 cycles; (c) 75000 cycles; (d) Failure at 102642 cycles.

Fig. 10 A typical example of matrix cracking damage observed for different number of fatigue cycles at 85% stress level. (a) 549 cycles; (b) 10000 cycles; (c) 300000 cycles; (d) Failure at 380699 cycles.

Fig. 11 Typical example of matrix cracking damage observed for different number of fatigue cycles at 83% stress level. (a) 521 cycles; (b) 700000 cycles; (c) 3500000 cycles; (d) Failure at 4000000 cycles

Fig. 12 Typical example of damage observed for different number of fatigue cycles at 75% stress level. (a) 508 cycles; (b) 5000000 cycles; (c) 10000000 cycles.

Fig.13 Schematic drawing of the S–N curve of the BFRPs with damage patterns.

Nomenclature

Roman symbols

A	slope of the linear fitting S–N curve (-)
B	y-intercept of the linear fitting S–N curve (-)
BFRP	basalt fiber reinforced epoxy polymer(-)
FRP	fiber reinforced polymer
CV	coefficient of variation (%)
CFRP	carbon FRP(carbon fiber reinforced polymer) (-)
GFRP	E-glass FRP(glass fiber reinforced polymer) (-)
N	number of cycles (-)
N_f	fatigue life, i.e. number of cycles to fracture (-)
NLD	normal lifetime distribution (-)
R	stress ratio (minimum stress/maximum stress; for load controlled fatigue tests) (-)
SEM	scanning electron microscopy (-)
S-N	stress level verse number of cycles to fracture
$r_{\max}$	stress level (maximum stresses/ultimate strength; for load controlled fatigue tests) (-)
R_k	characteristic value for a normal distribution(-)
$1/k$	model parameter determined by fitting (-)
$\bar{N}$	one of the characteristic value for a two-parameter Weibull distribution (-)

Greek symbols

σ	cyclic stress parameter (MPa)
σ_0	model parameter determined by fitting (MPa)
$\sigma_{\max}$	maximum stresses for load controlled fatigue tests (MPa)
σ_s	standard deviation of the tensile strength (MPa)
σ_{ult}	ultimate tensile strength (MPa)
α_f	one of the characteristic value for a two-parameter Weibull distribution (-)

Table 1 - Comparison of tensile properties of basalt fiber and epoxy

Type	Tensile strength, σ_{ult} (MPa)	Elastic modulus, E (GPa)	Failure elongation, ε_u (%)
Epoxy	85	3.5	5.0
Basalt fibers	2400	90	2.2

Table 2 Summary of the statics FRP tests

Specimen	Loading(kN)	Tensile Strength σ_{ult} (MPa)
1	1.19	2582
2	1.16	2522
3	1.19	2594
4	1.21	2640
5	1.26	2739
Mean	1.20	2615
Standard deviation (σ_s)	0.03	72
Coefficient of variation (CV)(%)	2.77	2.77

Table 3 Summary of the fatigue-failed BFRP specimens

Specimens	Stress level	Failure cycles	Avg. num. of cycles	CV (%)
BFRP-90-1	90%	51256		
BFRP-90-2	90%	27711	51963	47.4
BFRP-90-3	90%	76923		
BFRP-87-1	87%	54260		
BFRP-87-2	87%	196893	139584	54.0
BFRP-87-3	87%	167599		
BFRP-85-1	85%	102642		
BFRP-85-2	85%	220683	234675	59.5
BFRP-85-3	85%	380699		
BFRP-83-1	83%	931975		
BFRP-83-2	83%	3889667	2940547	59.2
BFRP-83-3	83%	4000000		
BFRP-80-1	80%	1949519		
BFRP-80-2	80%	2825178	3287365	49.3
BFRP-80-3	80%	5087398		
BFRP-75-1	75%	10000000		
BFRP-75-2	75%	10000000	Run-out	Run-out
BFRP-75-3	75%	10000000		

Table 4 Fatigue life prediction based on reliability analysis

Prediction of design stress level		Exp fitting	NLD	Whitney
With data up to 2 million	To achieve 2×10^6 cycles	77.91%	76.88%	73.98%
	To achieve 1×10^7 cycles	72.55%	72.29%	69.60%
With data up to 10 million	To achieve 2×10^6 cycles	82.10%	80.69%	79.59%
	To achieve 1×10^7 cycles	79.01%	77.45%	76.71%

Table 5 Results of the tensile static tests on run-out specimens.

Specimen	Residual maximum load (kN)	Residual strength (MPa)
BFRP-75-1	1.32	2867
BFRP-75-2	1.30	2817
BFRP-75-3	1.38	2995
Mean	1.33	2893
Standard deviation	0.42	91
CV (%)	3.18	3.18

Fig.1

Fig. 2

Fig.3 Stress-displacement curves in the static tensile tests

Fig.4

Fig. 5 Stress level- $\log N_f$ curves

(a) Models with data up to 2 million

(b) Models with data up to 10 million

Fig. 6 S-N curves of different perdition models

(a) $r_{max} = 0.9$

(b) $r_{max} = 0.87$

(c) $r_{max} = 0.85$

(d) $r_{max} = 0.83$

(e) $r_{max} = 0.8$

(f) $r_{max} = 0.75$

Fig. 7 Stiffness degradation of BFRP composites.

Fig.8

Fig.9

Fig.10

Fig.11

Fig.12

Fig.13 Schematic drawing of the S–N curve of the BFRPs with damage patterns.