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Thermal treatment influences the fatigue response of basalt-fiber-reinforced polymer

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Exposure to elevated temperatures causes the degradation of the resin matrix and a reduction of bonding strength in composite samples, and thus accelerates the propagation of fatigue damage.

Fiber-reinforced polymer (FRP) composites are used extensively for civil engineering purposes because of their excellent resistance to corrosion and high strength-to-weight ratio. In recent years, basalt fibers have been developed—as an alternative to traditional glass or carbon fibers—for use in FRP composites and have found many applications.[1] Such basalt fibers are produced directly from volcanic rocks, by using a single-component raw material (i.e., molten rocks) without additives, and are thus an environmentally friendly and nonhazardous material. Furthermore, basalt fibers provide many advantages over traditional glass or carbon fibers, e.g., in their mechanical behavior, chemical resistance, and high performance-to-cost ratio. For instance, the cost of basalt-fiber-reinforced polymer (BFRP) bars is comparable with that of glass-fiber-based FRP (GFRP) bars, but the tensile strength and modulus of the former are about 25% higher. With the application of BFRP in civil engineering, it is necessary to study the fatigue properties of these composites after exposure to elevated temperatures (e.g., because BFRP plates can be used to repair or strengthen a bridge, which could later be subject to a fire caused by an oil truck accident),[2,3] but there has so far been only a limited amount of work conducted on this topic.

In general, the typical fatigue damage that occurs in traditional FRP composites includes matrix cracking, fiber debonding, delamination, and fiber fracture.[4] In addition, the stiffness degradation in composites is commonly considered as a measure of accumulated damage during fatigue tests. It has also been reported that void content plays an important role in the fatigue behavior of composite materials.[5] It is thought, therefore, that exposing BFRP to high temperatures will cause degradations to the fiber bonding and lead to decomposition of the resin matrix and to an even higher void content. It is also thought that these changes will adversely affect the fatigue performance. Furthermore, BFRP composites are heterogeneous and anisotropic, so they are likely to have more complicated fatigue damage mechanisms than metals. Indeed, limited studies on sheet/laminate and bar forms[6–8] have shown that the tensile fatigue resistance of BFRP is close to that of GFRP, but much less than that of carbon-fiber-based polymer (CFRP). Other experimental results also indicate that the short-beam shear strength of a unidirectional BFRP plate is reduced (in an approximately linear fashion), from 70 to about 5MPa, as the temperature is increased from room temperature to 200°C (caused by softening of the matrix).[9]

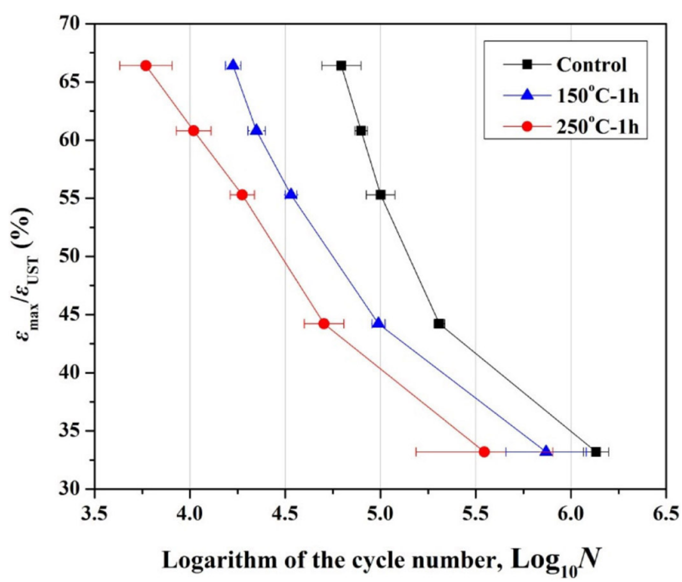

Figure 1. *The change in the fatigue lifetime (expressed in terms of N, the number of fatigue cycles before failure) of a control sample and basalt-fiber-reinforced polymer (BFRP) plates that were subjected to elevated temperatures (150 and 250°C) for 1 hour, under different strain (ε) ratios. ε_{max}: Maximum strain. ε_{UST}: Ultimate static tensile strain.*

To extend the understanding of BFRP behavior at high temperatures, we have investigated how an elevated temperature treatment affects the

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Table 1. *Void ratios (average and standard deviation values) of BFRP plates subjected to different thermal treatments.*

Treatment	Void ratio V_v (%)	
	Average	Standard deviation
Control	0.37	0.12
150°C (0.5h)	0.37	0.25
150°C (1h)	0.39	0.14
150°C (2h)	0.33	0.10
250°C (0.5h)	0.69	0.25
250°C (1h)	0.84	0.27
250°C (2h)	0.91	0.21

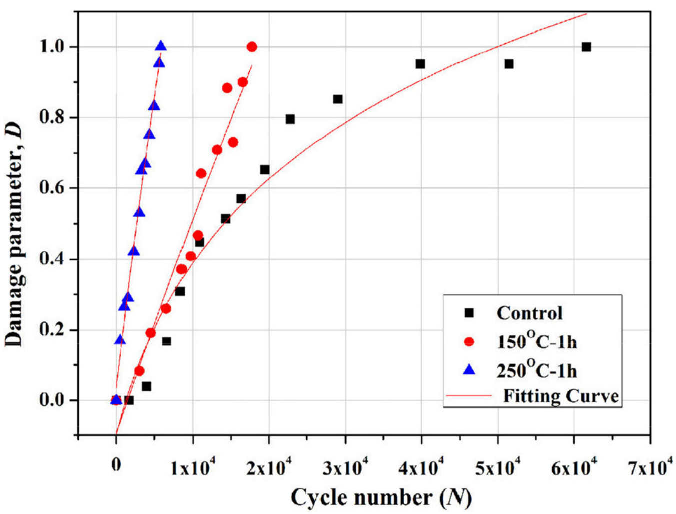

Figure 2. *Evolution of the damage in the BFRP as a function of the number of fatigue cycles for three BFRP samples (at a strain ratio of 66.4%). Both the experimental results and fitting curves are shown.*

flexural fatigue behavior of a pultruded BFRP plate.[10] We used a pultrusion machine (NLL-5TL from Nanjing Loyalty Composite Equipment Manufacture Co., Ltd, China) in our laboratory—with a pulling speed of 30cm/min—to produce a continuous BFRP plate (with a cross-sectional area of 15 × 1.4mm). Before we conducted the fatigue testing, we exposed six pieces of this BFRP plate to temperatures of 150 and 250°C in an oven for 0.5, 1, and 2 hours. In addition, we fabricated a control sample, which was also cut directly from the continuous plate, but was not exposed to elevated temperatures. We then examined—in a flexural mode—the fatigue evolution and the development of the fatigue damage in our samples.

We performed dynamic fatigue tests on our BFRP samples in three-point-bending mode under a displacement control, following an International Organization for Standardization protocol (13003-2003). We set the test frequency as 4.0Hz and the strain ratio (i.e., the minimum displacement/maximum displacement) as 0.1. For these displacement-control tests, the failure is defined as a reduction in test specimen stiffness (i.e., 20%). The strain–number of cycles before failure (S–N) curves for our control sample and BFRP plates are shown in Figure 1. For these tests, the samples had been treated at 150 and 250°C for 1 hour. Although the shape of the S–N curves for all the samples is similar, the results indicate that the treatment at elevated temperatures caused a dramatic reduction in the fatigue lifetime of the BFRP plates in flexural mode. Moreover, exposure to the higher temperature (i.e., 250°C) caused a greater reduction in fatigue lifetime.

The damage sustained during our fatigue tests is defined by the damage parameter (D), which is equal to zero in the first fatigue cycle and is 1 at the failure condition (N_0). We thus calculate the damage after a certain number of fatigue cycles (N) in terms of the initial stiffness (E_0), the stiffness when failure occurs (EN_0), and the stiffness after N fatigue cycles (E_N), i.e., as (E_0–E_N/E_0–EN_0). We illustrate the relationship between N and D for the same three samples, for a strain ratio of 66.4%, in Figure 2. We note that the growth of damage is fast during the initial cycles. This means that the specimens suffered initial defects, without being subjected to fatigue in the initial stage of the tests.[11] After this rapid propagation of damage in the early stages of the fatigue lifetime, we observe a slower progression of the damage mechanism. In addition, our fitting results show that the initial values of the slope are 0.48, 0.69, and 3.59 for the control, 150°C, and 250°C samples, respectively. This indicates that either the flaws inside the specimens developed during the thermal exposure in the oven, or that the heat engenders new defects.

We also measured (through optical microscopy) the void ratio (V_v) inside our BFRP plate samples (see Table 1) and found that the void ratios become larger after the 250°C thermal treatment. Such increases in V_v generally cause weakening of regions within composites, and thus they are considered to be the source of the fatigue damage cracks (especially during the initial stages of fatigue).[11] This means that the higher the V_v, the higher the stiffness deterioration velocity and the shorter the fatigue lifetime of the BFRP. This can explain the large decrease in fatigue lifetime, and the obvious increase in stiffness degradation, for the 250°C samples, which we observe. With the 150°C treatment, however, we find that the V_v does not change. The decrease of fatigue lifetime and increase of stiffness degradation for those samples is therefore mainly caused by a reduced bonding strength between the fibers and resin.

In summary, we have investigated the effect of thermal treatment on the flexural fatigue lifetime of pultruded BFRP plates. We have also made preliminary analyses of the development of microcracks in the

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samples during the fatigue tests. In general, we find that the thermal treatment causes a reduction in the fatigue lifetime of our samples and that damage in the samples occurs rapidly during the initial stages of the fatigue tests. In the next stages of our work, we plan to further study the mechanism of fatigue during the exposure of BFRP to thermal treatment and to compare these results with those obtained on traditional FRPs (i.e., GFRP and CFRP).

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