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Combined effects of sustained tensile loading and elevated temperatures on the mechanical properties of pultruded BFRP plates

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HIGHLIGHTS

- Elevated temperature and sustained tensile loading caused irreversible interface damage.
- Stress redistribution resulted in serious degradation in the tensile properties.
- A design method considered exposure temperatures and sustained loading levels was proposed.

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ABSTRACT

Fiber reinforced polymer (FRP) composites have to face harsh environments and service loading conditions during practical use, causing their mechanical properties to degrade. Mitigating this degradation is critical for the safe design and application of FRP composites. In the present paper, the combined effects of sustained tensile loading and elevated temperatures on the mechanical properties of a pultruded basalt FRP (BFRP) plate were studied. The examined tensile stresses were set at 35%, 50% and 65% of its ultimate tensile strength (f_u), and the exposure temperatures were room temperature, 80 °C, 120 °C and 160 °C. Strain was recorded during testing, and variations of the tensile and interlaminar shear (ILSS) properties were studied. The tensile strain evolution of BFRP specimens during sustained tensile loading depended largely on the exposure temperature due to the temperature sensitivity of the epoxy resin. As the exposure temperature increased above the glass transition temperature (T_g) of the composites (123.7 °C), a remarkable increase in strain was observed. Meanwhile, the residual tensile strength and tensile modulus decreased with the exposure temperature and sustained tensile loading level. The tensile strength and tensile modulus decreased by 41.8% and 30%, respectively, for the specimens exposed at 160 °C and 50% f_u. Sustained tensile loading led to stress redistribution in BFRP specimens especially at elevated temperatures, leading to serious degradation of the interlaminar shear strength (ILSS). Dynamic mechanical thermal analysis was performed to investigate the interface damage. An equation for predicting the tensile strength retention of BFRP plates under elevated temperatures was also proposed.

1. Introduction

Fiber reinforced polymers (FRPs) are widely-used materials for repair and rehabilitation of existing structures. The growing use of FRPs for strengthening and retrofitting can be attributed to the advantages offered by these materials, including light weight, high specific strength and specific stiffness, corrosion resistance and low maintenance costs [1,2]; it is expected that FRP composites will expand their usage in the near future [3,4]. In most civil engineering applications, FRPs are likely to be subjected to relatively high in-service temperatures [5], and these elevated temperatures are a primary concern threatening the wider applications of FRPs. Many previous studies have been conducted on the performance degradation of FRP composites or FRP reinforced structures at elevated temperatures [6–9].

In one such study, fire endurance of FRP-strengthened or reinforced concrete members were in excess of 4 h when the structures were well protected, and the glass transition temperature of the

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composite is a threshold value for its applications involving fire [10,11]. From our own previous study however [12], the tensile strength retention is approximately 98% for BFRP specimens exposed to 300 °C (much higher than T_g) for 4 h under normal atmosphere; similar test results can be found elsewhere in the literature [13,14] showing that FRP materials exhibit excellent resistance to elevated temperatures.

Understanding the performance degradation of FRPs and their reinforced structures at elevated temperatures is necessary for their expanded use. Previous studies have demonstrated that the most efficient application of FRP is as a prestressed component in structures, rather than as normal reinforcement in reinforced concrete (RC) structures, and FRPs in an external prestressed application exhibit prominent advantages compared to steel [15–17]. Considering the combined effects of both harsh environments and service loads is essential for determining the realistic serviceability of FRP for use in structures. Numerous studies were performed to investigate the combined effects of sustained loads and environmental attacks on FRP or FRP-reinforced concrete structures [2,9,18–21]. It should be noted that most structures must be designed to resist the effects of fire damage in order to ensure long-life safety and service [9].

Burke et al. [9] studied the effects of sustained load and elevated temperature on FRP-strengthened concrete systems at exposure temperatures of 100 °C and 200 °C. The mid-span tensile strain was sustained between 40% and 60% of the ultimate strain until failure occurred. These structures were able to maintain their structural effectiveness for several hours, even at exposure temperatures considerably exceeding T_g of the epoxy adhesives. Dutta [18] studied the creep rupture of a GFRP composite at 25 °C, 50 °C and 80 °C, with stress applied in the range of 60–80% of the room temperature failure stress. There was a significant loss in the failure time of the specimens when subjected to 50 °C and 80 °C conditions, and an empirical model was developed to predict the time-to-failure.

As mentioned previously, the existing literature provides only a limited understanding of the response of FRP composites under the combined effects of elevated temperature and sustained loading. Because of the variation in material parameters and different exposure temperatures, it is difficult to compare these different test results and draw general conclusions. Moreover, the glass transition temperature can be easily reached on structural surfaces directly exposed to sunlight in a typical summer climate or exposed to fire [12,22]. On the other hand, new high performance FRP composites have been developed, among which basalt fiber composites possess particular promise [16,20]. Basalt fibers have better tensile strength than E-glass fibers, greater failure strain than carbon fibers and burn with less poisonous fumes [23]. With these advantages, the applicability of basalt fibers for structural strengthening materials is highly expected [6,20,24]. As such, this study examines the combined effects of sustained tensile loading and elevated temperature on the behavior of basalt FRP (BFRP) plates. The residual mechanical properties of the treated BFRP plates were determined and a design method was proposed based on the test results, one which can be used to assess the serviceability of prestressed BFRP at elevated temperatures.

2. Experimental program

2.1. Raw materials

The BFRP plates used in this study were produced using a pultrusion process at the Laboratory for FRP Composites and Structures (LFCS), Harbin Institute of Technology (China). The fiber volume fraction of the pultruded plates was 68.7%, determined using a burning-off test method [25]. The widths and thicknesses of the plates were 15 mm and 1.3 mm, respectively. The density of a BFRP plate was 1.60 g/cm^3. The glass transition temperature (T_g) of the plate was 123.7 °C (determined by the storage modulus from dynamic mechanical thermal analysis, DMTA). The tensile strength, tensile modulus and elongation at break were 1492 MPa, 53.7 GPa and 2.8%, respectively.

The static tensile test results are listed in Table 1. Nine specimens were examined at room temperature, all of which failed by fiber fracturing in the middle region of the specimens. The variation of tensile strength, elastic modulus and fracture strain are all lower than 5%, indicating good stability in the BFRP specimens.

The continuous and untwisted basalt fibers roving (12 k) were provided by the TuoXin Aerospace Basalt Industrial Co., Ltd. (Chengdu, China). The average diameter of the basalt fibers was 15.5 μm, and the density was 2.6 g/cm^3. Based on single fiber tensile test, the tensile strength, modulus and elongation at break were 2.7 GPa, 85.4 GPa and 3.7%, respectively. The resin matrix was an epoxy polymer based on bisphenol-A (similar to EPON 828, provided by Xing Chen synthetic material Co., Ltd., Wuxi, China) and an anhydride-curing agent (MeHHPA, provided by Qing Yang Chemistry Co., Ltd., Jiaxing, China). The tensile strength, tensile modulus and elongation at break were 62.5 MPa, 3.1 GPa and 2.01%, respectively. T_g of the resin matrix was 107.5 °C, as determined by the storage modulus from DMTA.

2.2. Test setup and treatment procedure

A total of three ratios of sustained tensile stress were designed for testing, these being 35% f_u, 50% f_u and 65% f_u. The typical dimensions of the BFRP plate specimens were 400 mm × 15 mm × 1.3 mm, and aluminum sheets were used to anchor these systems at both sides. The load was controlled by an electronic universal testing machine (WDW-100D model, Hengyi Company, Shanghai, China) equipped with a 100 kN load cell, as shown in Fig. 1.

The loading rate was set to 5 mm/min, with control precision within ±0.05 kN. BFRP specimens underwent stress at 80 °C, 120 °C and 160 °C for up to 4 h. The testing temperature was controlled with an electric heating kiln (Fig. 1) at a rate of 12 °C/min, which was purpose-built at LFCS (control precision ±2 °C). After unloading, tensile testing was performed on a set of the treated specimens at the treatment temperatures. Testing of the thermal properties, interlaminar shear strength and tensile behavior were conducted on another set of treated specimens after being cooled down to room temperature. In addition, a set of control specimens were examined at room temperature for comparison. A summary of all the parameters, along with the number of specimens tested, is presented in Table 2.

Longitudinal strain was measured using a strain gauge. The strain gauges (Measurement type BA 350-3 AA) and the adhesive (Type H-610) were provided by ZhongHang Electronic Measuring Instruments Co., Ltd. (Shaanxi, China). Because of specimen expansion at elevated temperatures, the strain gauges will become detached at 160 °C and 120 °C with 65% f_u, the nominal tensile-creep strain was used according to ISO 899-1 [26].

2.3. Mechanical tests

Mechanical tests were performed using an electronic universal testing machine same as the load control machine. The tensile properties of the BFRP specimens were tested according to ASTM D 3039/D 3039 M-00 [27]. The dimensions of the BFRP specimens were set as 400 mm × 15 mm × 1.3 mm. Tensile tests were carried out at a loading rate of 5 mm/min. Specimen details for these tests are shown in Fig. 2(a).

Interlaminar shear strength (ILSS) tests were performed according to the ASTM D 2344/D 2344 M-00 standard [28], using an electronic universal testing machine. The specimen dimensions were 7.8 mm × 2.6 mm × 1.3 mm for these tests. ILSS was measured at a crosshead speed of 1 mm/min under displacement control. Further specimen details are shown in Fig. 2(b).

Five specimens were used for each test, and the average values of these five were reported.

2.4. Dynamic mechanical thermal analysis (DMTA)

Dynamic mechanical thermal analysis (DMTA) was carried out using a TA Instruments Q 800 with a single cantilever mode at 1 Hz, and the amplitude was set to 25 μm. The dimensions of the BFRP specimens were 35 mm × 15 mm × 1.3 mm, and were tested over a temperature range of 25–240 °C at a heating rate of 3 °C /min.

3. Results and discussion

3.1. Behavior of BFRP plates at elevated temperatures

Fig. 3 shows the variations of tensile strain under sustained tensile loading at different temperatures. The strain shows rapid initial growth, and then exhibits slower growth with time at the second stage at all temperatures and sustained load levels. Stress re-distribution occurred during the first stage [29], which can be explained by the viscoelastic theory of FRP composites due to the