

TENSILE PROPERTIES OF FRP COMPOSITES AT ELEVATED AND HIGH TEMPERATURES

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A series of tensile tests were conducted to investigate the tensile mechanical properties of carbon fiber, glass fiber and basalt fiber reinforced polymer sheets at temperatures ranging from 16°C to 200°C. Additionally, corresponding no-impregnated fiber sheets were tested at 16°C as a reference. The results show that the tensile strength of different fiber reinforced polymer (FRP) sheets is reduced significantly with an increase in temperature. However, the tensile strength of FRP sheets still remains a stable residual value after the polymer reaches its glass transition temperature (T_g), and this value is higher than the tensile strength of non-impregnated fiber sheets.

Key Words: FRP, High temperatures, Tensile testing

1. INTRODUCTION

Fiber reinforced polymer (FRP) composites are attractive for use in civil engineering applications due to their high strength-to-weight and stiffness-to-weight ratios, corrosion resistance, light weight, potentially high durability, and free design characteristics. In recent years, the usage of carbon fiber, glass fiber or hybrids of the two fibers reinforced polymer composites in shapes, such as FRP sheets, strips, grids, rods, and tendons for strengthening or reinforcing civil engineering structures, has increased substantially [1-3].

Although several investigations into the application of FRP composites have suggested their important role in future civil engineering projects, the increased use of FRP composites brings many challenges to material scientists and structural engineers. One of these challenges is the behavior of FRP composites at elevated and high temperatures. Researchers have observed that the performance of FRP composites is significantly influenced by environmental temperatures. At high temperatures, such as from fire or extremely hot climates, the mechanical properties of FRP composites can be adversely affected due to the degradation of the polymer materials.

It is well known that FRP composites are composed of a matrix of polymeric material that is reinforced by fibers or other materials. In general, the reinforcement

material is temperature-resistant and can retain much of its strength and stiffness at high temperatures. For example, carbon fibers can be used at 500°C in air due to its resistance to oxidation, while glass fiber can be used from -60 to 450°C and basalt fiber from -269 to 700°C. Unfortunately, most polymer matrices are susceptible to high temperature. At high temperatures, the polymer matrices are softened and modified, especially when the ambient temperature exceeds the glass transition temperature (T_g), wherein the polymer will rapidly lose strength and stiffness. Thus, increasing temperatures are expected to degrade the mechanical properties (especially the strength and the stiffness) of FRP composites, making their use in construction potentially unsafe. Currently, there have been few investigations into the application of FRP composites at high temperatures.

Using a supplemental, high temperature protection system (fire-retardant, self-extinguishing materials) applied to the exterior of a FRP-strengthening system, Brea Williams et al [4,5] investigated the performance of insulated, FRP-strengthened concrete slabs and T-Beams in fire. Similarly, Ershad U et al [6] investigated insulated, FRP-wrapped, and reinforced concrete columns in fire. The results of these investigations indicate that appropriately designed and insulated FRP-strengthened concrete systems have

satisfactory fire endurance. Unfortunately, these studies fail to provide useful information on the specific performance of the FRP wraps themselves. This information is fundamentally important in understanding the high temperature behavior of these materials [7]. S.K. Foster and L.A. Bisby [7] investigated the residual performance of CFRP and GFRP sheets after exposure to elevated temperatures. They observed a severe reduction in the residual tensile strength and stiffness at temperatures exceeding the thermal decomposition temperature of the epoxy polymer matrix, while exposure temperatures greater than the glass transition temperature of the epoxy polymer matrix did not appear to significantly impact the residual tensile strength or stiffness. Besides this, Thomas Keller et al [8,9] investigated the structural response of liquid-cooled GFRP slabs subjected to fire. Wu et al [10] investigated the tensile behavior of CFRP sheets with two different epoxy resins at different temperatures up to 70°C.

The above literature provides limited understanding of FRP composite performance at elevated and high temperatures. Furthermore, the constructional complexity of FRP composites need to be addressed, that is, their performance as a function of fiber type, fiber percentage, fiber orientation, type of polymer (resin), and manufacturing methodology. Therefore, there is a significant need to investigate the temperature dependent performance of FRP composites before they can be safely and reliably used as building materials.

Based on the aforementioned statements, this paper investigates the tensile properties of three different FRP composites subjected to temperatures ranging from 16 to 200°C. A series of tensile tests were carried out using specimens composed of carbon fiber, glass fiber and basalt fiber reinforced epoxy resin matrix sheets, and corresponding dry fiber sheets without resin impregnation as a reference. The purpose of this investigation is to evaluate the tensile strength and modulus of the three different FRP composites at high temperatures. Throughout the experimental studies presented herein, the results may provide fundamental information for the application of the carbon fiber, glass fiber and basalt fibers as a strengthening material.

2. Thermal Properties of Polymers

As mentioned before, the polymer matrices are susceptible to high temperature. To effectively study the temperature-dependent behavior of FRP composites, it is important to understand the thermal properties of polymers. Thermoplastics and thermosetting polymers are the two types of polymeric materials used in composite matrices, where thermosetting polymers are more popular for contemporary FRP structures [1]. Thermosetting

polymers are produced after a hardening or polymerization reaction (giving a cross-linked molecular structure) of lower molecular weight polymers. The cross-linked material can no longer be formed plastically and can not be welded together by heating. The most important thermosetting polymers used are epoxy resins, which can be produced as semi-products with partial interlinking, so-called prepreps, and are fully hardened only in the final production phase.

Thermosetting polymer matrices exhibit a viscoelastic stress-strain behavior, and can be characterized by a glassy, leathery, rubbery, or decomposed state at elevated temperatures. Among these different states, the transition from the glassy state to the leathery state is known as glass transition. The temperature at which this change occurs is known as the glass transition temperature (T_g). At this transition, the viscosity increases while the elastic modulus rapidly decreases, making the T_g a critical threshold that is specific to the kind of polymer used. In civil engineering, the T_g of the polymer resin is usually between 60 and 80°C [11].

The T_g can be estimated by using Dynamic mechanical analysis (DMA) technique, which can record the temperature-dependent viscoelastic properties of the polymer and determine the modulus of elasticity and the damping values by applying an oscillating force to the sample. In this study, a DMA experiment was performed in order to find out the glass transition temperature of the epoxy resin (aliphatic poly amide amine type) solidified polymers [10]. Cyclic dynamic loading was applied on a specimen with dimensions of 3 mm × 6 mm × 17.5 mm. The specimen was scanned by a dynamic oscillation frequency of 1 Hz, the strain was maintained at 0.1%, and the testing temperature was swept from 30°C to 120°C, at a heating rate of 3°C/min. The storage modulus E' (representing the elastic portion of Viscoelasticity of material), loss modulus E'' (representing the viscous portion of Viscoelasticity of material), and $\tan \delta$ (defined as the ratio of the loss modulus to the storage modulus) were obtained, as shown in Fig. 1.

Fig. 1 shows that T_g is approximately 38°C. E' was observed to be stable at a temperature range below 35°C. When the temperature was increased, E' decreased rapidly and plateaued at 60°C, which is about 10% of the value at 30°C. E'' increased as temperature was increased; however, it decreased rapidly when the temperature exceeded about 52°C, at which point it also plateaued before decomposition. The damping factor $\tan \delta$ behaved similarly to the loss modulus as a function of temperature.

3. EXPERIMENTAL PROCEDURE

3.1. Materials and specimens

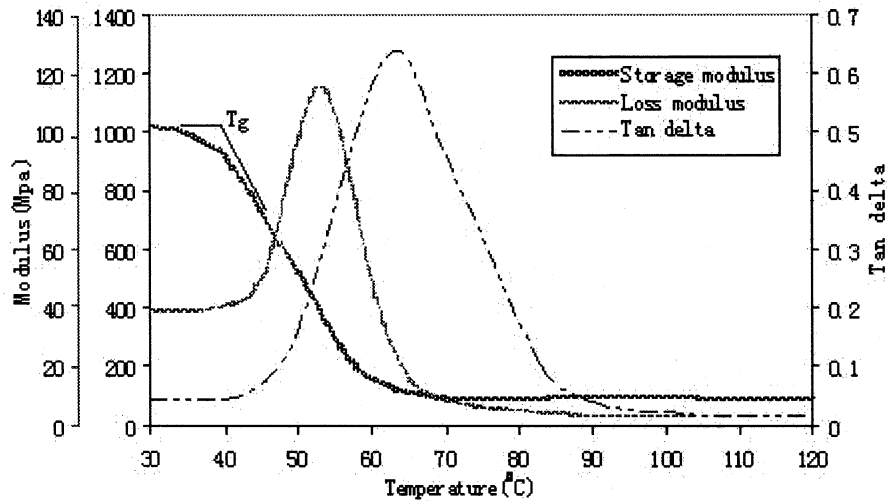


Fig.1 The DTA results of epoxy resin

Table 1 Typical material properties of fibers and epoxy resin [15,16,17]

	Carbon fiber (C1)	E-glass fiber (EG)	Basalt fiber	Epoxy resin
Guarantee tensile strength (MPa)	3400	1500	2100	51.9
Nominal elastic modulus (GPa)	230	80	91	3.43
Nominal ductility (%)	1.48	1.88	2.6	*
Nominal thickness (mm)	0.111	0.118	0.111	*
Glass transition temperature (°C)	*	*	*	38

Three different FRP systems were used in this study as representative systems that are currently in widespread use in industry. High-strength carbon fibers (C1), E-glass fibers (EG) and epoxy resin (aliphatic poly amide amine type) were obtained from Nippon Steel Composite Co. Ltd. Basalt fibers were obtained from Hengdian Group Shanghai Russia & Gold Basalt Fiber Co., Ltd. The material properties as the design values of different FRP composites for use in this investigation at room temperature are summarized in Table 1. These design values may be supplied by FRP system manufacturers or some valuable specifications.

The designed specimens were composed of CFRP, GFRP and BFRP sheets with impregnation of epoxy resin, and corresponding non-impregnated fiber sheets, and were 400 mm in length and 20 mm in width. With the exception of the dry fiber sheets without epoxy resin impregnation, specimens were impregnated with an epoxy resin adhesive and cured at 80°C for 3 hours [10,12]. The anchorage portions of all the sheets

were gripped GFRP tabs using an epoxy resin adhesive to ensure the failure of the testing specimen in the test specimen, not at the anchorage. After the specimens were prepared, tensile tests were performed. Fig. 2 depicts the schematics of specimen sizes.

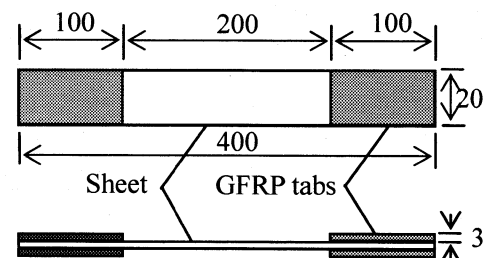


Fig.2 Depicts the schematics of specimen sizes

3.2. Testing method

The tensile tests were done in a universal hydraulic testing machine with an electric auto-controlling

heater that was self-designed. During each test, a constant rate of 2 mm/min was adopted to ensure all tests were performed at steady state. The tensile tests were repeated five times at each temperature. Table 2 summarizes all of the conducted tests.

Table 2 Details of the overall experimental program

Types of specimens		No. of specimen ⊗ Temperature (°C)
FRP sheets	CFRP	5⊗16, 5⊗30, 5⊗55, 5⊗120, 5⊗200
	GFRP	5⊗16, 5⊗30, 5⊗55, 5⊗120, 5⊗200
	BFRP	5⊗16, 5⊗30, 5⊗55, 5⊗120, 5⊗200
Fiber sheets	CF	5⊗16
	GF	5⊗16
	BF	5⊗16

(Notes: Laboratorial conditions:
home temperature 16°C; relative humidity 48%)

4. RESULTS AND DISCUSSION

According to Specifications of Concrete Engineering Series 41, JSCE (2001) [12], the average tensile strengths of FRP sheets can be calculated by the following expression:

$$\sigma = P / A, \quad (1)$$

where P is the maximum load shown in the recorded loading–displacement curves, and A is the nominal cross-sectional area of the specimen, that is, only the net cross-sectional area of fibers.

The results of the tests are shown in from Figs. 3 through 10. Figs. 3, 4 and 5 depict the typical stress-strain curves obtained from the loading-displacement results recorded for the three different fiber sheet specimens. It can be observed that the stress–strain relationships from 12°C up to 200°C are nearly linear until failure. Furthermore, from these plots it is evident that there is no obvious change in elastic modulus of FRP sheets with increasing temperatures. This result is attributed to the temperature-resistant characteristics of fibers. As mentioned before, carbon, basalt, or glass fibers can retain the whole strength and elastic modulus below 200°C, while the epoxy resin can not. Furthermore, the elastic modulus of epoxy resin is far less than the elastic modulus of any fiber. According to the rules of mixture of composites, fiber is in charge of elastic modulus of FRP composites. Therefore, it is obvious that there is no obvious change in elastic modulus of FRP sheets with increasing temperatures.

Figs. 6, 7 and 8 show the variation in the ultimate

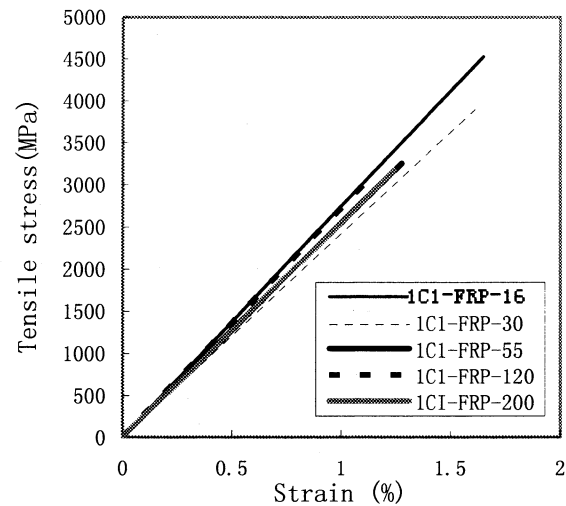


Fig.3 Tensile stress versus nominal strain curves for CFRP sheets at different temperatures

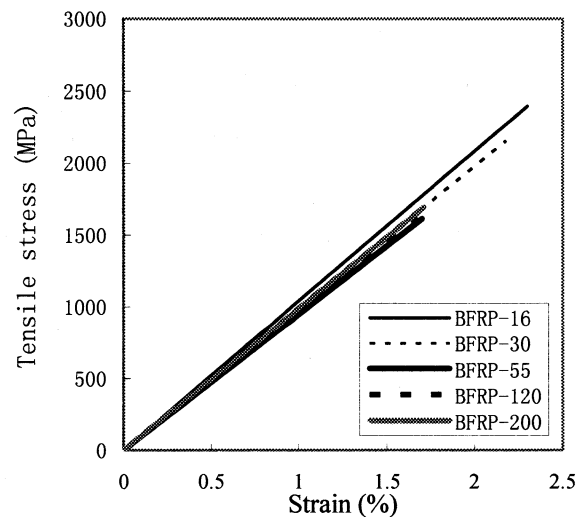


Fig.4 Tensile stress versus nominal strain curves for BFRP sheets at different temperatures

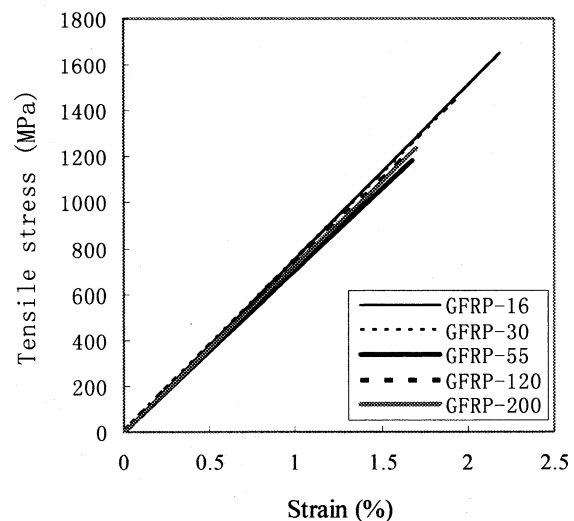


Fig.5 Tensile stress versus nominal strain curves for GFRP sheets at different temperatures

tensile strength of FRP sheets as a function of increasing temperature as well as the ratios of the average tensile strengths.

From these plots, a distinct temperature dependence of tensile strength in the fiber direction can be observed, although the values of the same type of specimens at the same temperature show some fluctuation. That is, at the temperatures below 55°C, all the examined FRP specimens experienced

significant reductions in the tensile strengths in the fiber direction at elevated temperatures. In contrast, at temperatures ranging from 55°C to 200°C, the tensile strengths were maintained. Through calculating, the average tensile strength of carbon, basalt, glass FRP sheets is 4527.03, 2450.45 and 1952.54 MPa at 16°C, respectively. Correspondingly, it is 3069.91, 1610.81 and 1176.52 MPa at 200°C, respectively.

To investigate the tensile strength of FRP

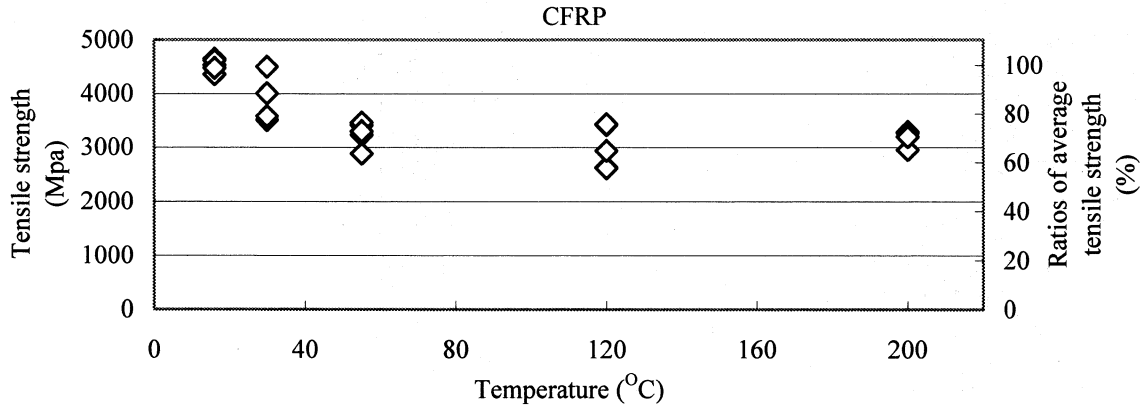


Fig.6 Variation in tensile strength of CFRP sheets with increasing temperatures

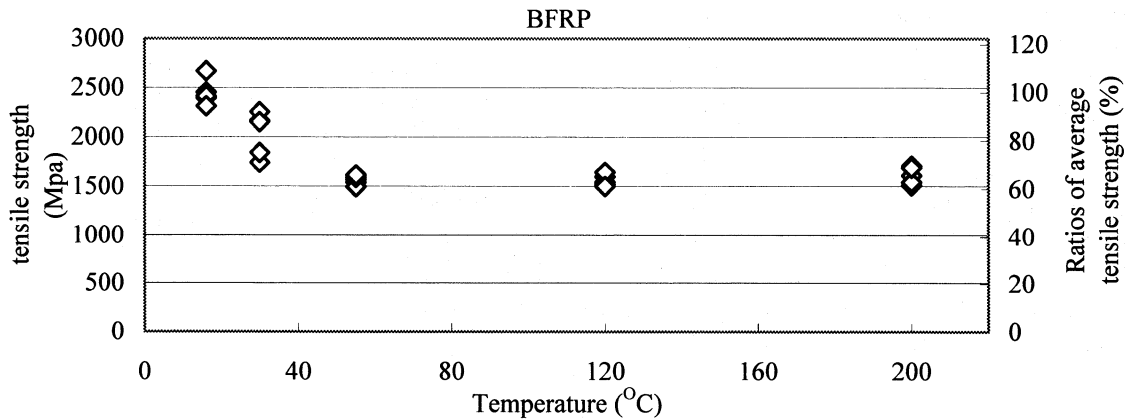


Fig.7 Variation in tensile strength of BFRP sheets with increasing temperatures

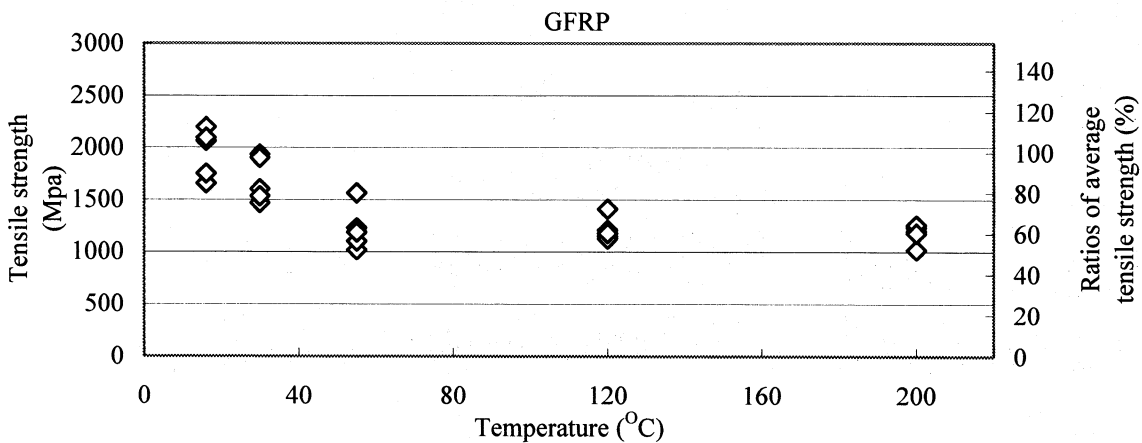


Fig.8 Variation in tensile strength of GFRP sheets with increasing temperatures

composites above the glass transition temperature of the epoxy resin, the three different fiber sheets (without impregnation of epoxy resin) were also test at 16°C. The results show that the average tensile strength of carbon, basalt, glass fiber sheets is 2178.68, 1406.31, 743.22 MPa, respectively.

Fig. 9 compares the ratio variation of the average strength of FRP sheets with the corresponding fiber sheets. This result indicates that at the high temperature of 200°C (far beyond the glass transition temperature of epoxy resin), the ultimate tensile strength of the three different FRP composites still remained a higher value, induces that at temperatures above the glass transition temperature, although the polymer resin softens and degrades, its action to protect and unify the carbon fibers is still significant.

It is well known that the epoxy resin is a typical viscoelastic material. At room temperature, the resin occurs in a glassy state, which can bring about good results in transferring stress between fibers, protecting and unifying the fibers; however, as the temperature is increased, the resin gradually softens and becomes malleable, and the material state transits from the glassy state to the leathery, rubbery, or decomposed state. The transition of the material state of the resin will reduce the effective ability of the matrix to protect and unify the fibers, making the overall structure of FRP composites weakened. Meanwhile, from Fig. 1, it can be found that the storage modulus of the epoxy resin decreases rapidly and then keep a stable value from 60°C to 120°C, which is about 10% of the value at 30°C. It is the stable residual storage modulus of the epoxy resin that makes it possible that the tensile strength of the FRP composites remained a relatively stable and higher value than simple fibers.

Fig. 10 shows specimen failure images at different temperatures, which indicate that increasing temperatures significantly affect the tensile failure

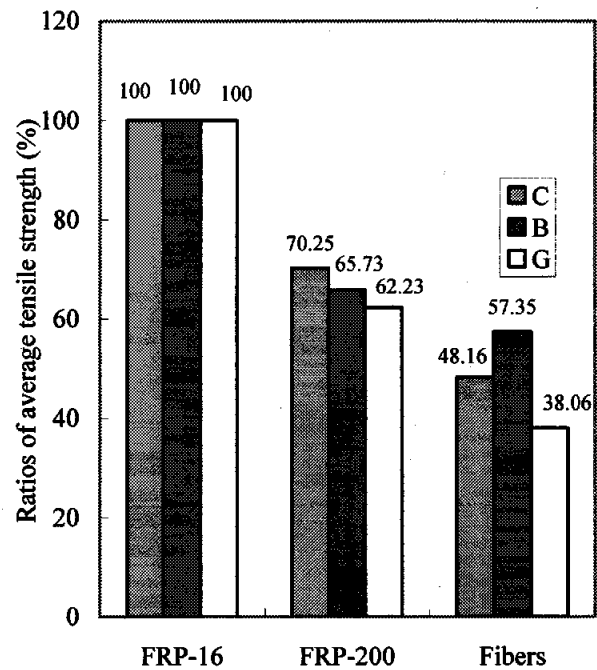


Fig.9 Comparison between a average tensile strength ratios of sheets

modes. At low temperatures, all CFRP sheets failed primarily at many cross sections by brittle fracture mode different from BFRP and GFRP sheets. From 55°C to 120°C, all the FRP sheets broke at a single fracture section. At 200°C, bond failure between the fibers and matrix is responsible for specimen failure.

The different failure modes of FRP sheets result from the two reasons: one hand, the fibers used in composites are not actually in perfect alignment, but are in a continually wavy state [13], making the loading on every fiber filament unequal [14]; On the other hand, the loss modulus of the epoxy resin changes with increasing temperatures.

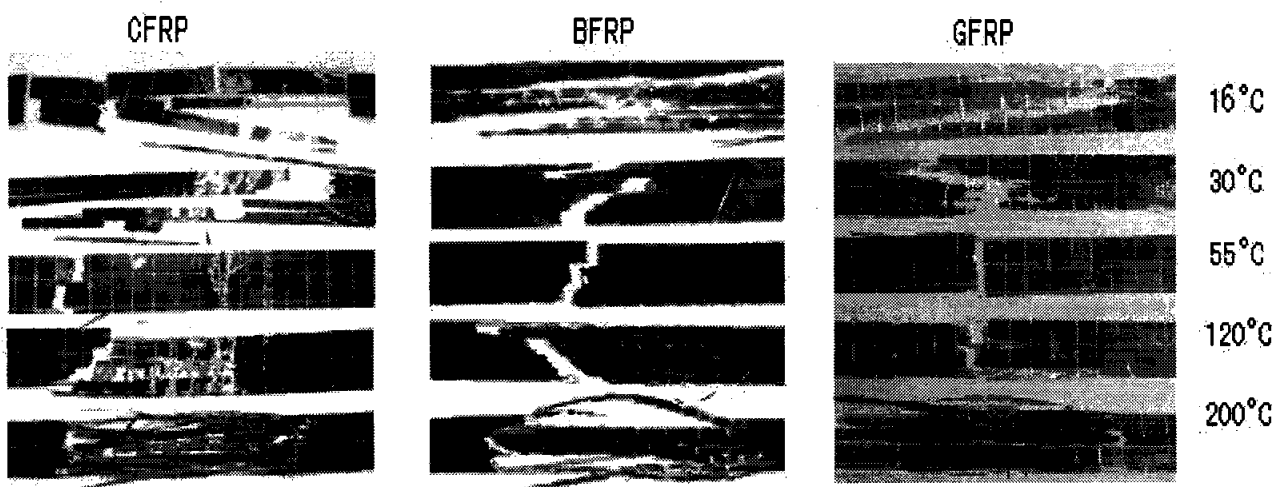


Fig.10 Failure modes of FRP sheets at different temperatures

5. CONCLUSIONS

This paper investigated the tensile properties of CFRP, GFRP and BFRP composites subjected to temperatures ranging from 16 to 200°C. A series of the tensile tests were conducted. Based on the results of the investigations conducted in this paper, the following conclusions can be drawn:

The tensile strengths of different FRP sheets are significantly reduced as the temperature increases, while the elastic modulus does not show a major reduction. After the polymer reaches its glass transition temperature (T_g), the tensile strength of different FRP sheets remains a stable residual value, and the residual strength is higher than corresponding no-impregnated fiber sheets.

APPENDIX

Basalt Fiber as a new kind of material of 21st century is a kind of high performance nonmetal inorganic fiber following carbon fiber, aramid fiber, UHMWPE, PPO, etc. It is known that the basalt fibers have better tensile strength than the E-glass fibers, greater failure strain than the carbon fibers as well as good resistance to chemical attack, impact load and fire with less poisonous fumes. Therefore, the applicability of the basalt fiber for a structural strengthening material is highly expected. More and more researchers over the world have come to show an interest in basalt continuous fibers and some useful investigations and applications have been done in the civil engineering field [19,20]. Some typical mechanics properties of basalt fibers and BFRP composites from Shanghai in China are listed in Tables 3, 4 [17].

Table 3 Basalt fiber technical index

Product No.	Area weight (g/m ²)	Diameter (μm)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation (%)	Thickness (mm)
BUF7-200	200	7	2100	91	2.6	0.111
BUF7-300	300	7	2100	91	2.6	0.170
BUF13-280	280	13	2100	91	2.6	0.111
BUF13-380	380	13	2100	91	2.6	0.170

Table 4 Basalt fiber sheet technical index

Product No.	Thickness (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)	Width (mm)
BCF7-50	1.2	≥2100	≥91	2.6	50
BCF13-50	1.4	≥2100	≥91	2.6	50
BCF7-100	1.2	≥2100	≥91	2.6	100
BCF13-100	1.4	≥2100	≥91	2.6	100

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