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FLEXURAL BEHAVIOUR OF GLASS FIBRE REINFORCED POLYMER (GFRP) BARS SUBJECTED TO ELEVATED TEMPERATURE

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ABSTRACT

The FRP reinforced concrete structures may be exposed to high temperatures that may reduce the structural integrity of the bars, and eventually of the entire structure. Therefore, the thermal stability of the FRP bars must be thoroughly investigated before they can be fully utilized in the construction industry. The flexural strength testing has long been a staple technique for measuring the uniaxial tensile strength of the brittle materials because it is inexpensive and convenient to run rather than the direct tension test. Although the results obtained were not the absolute tensile data, they can provide an indication about the relative tensile performance of the FRP bars. In this study, the flexural behaviour of the GFRP bars of varying nominal diameters (12.7 mm, 14.0 mm, 15.9 mm, 17.0 mm, and 20.5 mm) subjected to elevated temperatures (up to 150 °C) was investigated. The results showed that as the temperature increases, the flexural strength and stiffness of the GFRP bars decreases. As the temperature approaches the glass transition temperature (T_g) of the bars, a drastic strength and stiffness reduction was observed. These findings were also observed in the pure tension testing of the FRP bars done by other researchers. The bars with a larger nominal diameter showed a better flexural strength decay resistance than those with a smaller nominal diameter at elevated temperatures. However, a comparable flexural stiffness deterioration was observed at an increasing temperature.

KEYWORDS

FRP bar, thermal stability, flexural strength, tensile strength, glass transition temperature.

INTRODUCTION

The corrosion of the steel bars is the prime factor that causes the premature failure and/or shorter service life of reinforced concrete (RC) structures, especially those that are located in harsh environments, such as in marine and mining areas. One of the promising solutions is to utilize a corrosion resistant material called the fibre reinforced polymer (FRP) bars. Aside from being corrosion resistant, the FRP bars have high durability, high strength-to-weight ratio, and electromagnetic resistant (Gangarao et al. 2007). The FRP bars have been successfully used as internal reinforcement for concrete in the construction of roads and bridges. Many engineers and researchers are now extending the application of FRP reinforced concrete (FRP-RC) for the construction of multi-storey and industrial buildings. However, data regarding the fire resistance performance of FRP-RC structures (e.g. the time duration the structures can withstand high temperatures as well as fire exposures; the temperature at which the strength, stiffness, and bond between the materials decreased) must be gained for their wider acceptance and application in the construction industry.

The fire resistance of FRP-RC structures are dependent on its constituent materials, the concrete and the FRP bars. Between these two materials, the latter is more susceptible to degradation at higher temperatures. The strength and stiffness of the polymer are known to decrease significantly as the temperature approaches its glass transition temperature (T_g) (Fried 1995). The composite action between the fibres and the polymer diminishes and this would result into wider crack width in the concrete and consequently larger deflection of the structural element. The tensile behaviour of the FRP bar at elevated temperatures, therefore, must be thoroughly investigated. Many researchers (e.g. Kumahara et al. 1993; Abbasi and Hogg 2005; Wang et al. 2007; and Kashwani and Al-Tamimi 2014) studied the tensile performance of FRP bars at varying temperatures using a pure tension test. However, this test has several disadvantages such as the requirement for a longer test specimen, longer time duration and high costs of specimen fabrication and testing, and the difficulties of gripping. With the stated limitations, the bending test can be employed to roughly investigate the tensile performance of the FRP bars. The flexural strength testing has long been a staple technique for measuring the uniaxial tensile strength of the brittle materials such as ceramics and glasses (Quinn et al. 2009) and is relatively easy to run and inexpensive rather than direct tension test (Whitney and Knight 1980). Generally, the tensile stress obtained from the flexure test of the GFRP bars are higher than that obtained from the pure tension test (Whitney and Knight 1980; Tripathi 2003). In the present work, three-point bending tests were performed to investigate the tensile performance of the sand-coated GFRP bars subjected to elevated temperatures. The experimental results obtained from this study can provide an approximate interpretation of the tensile behaviour of the bars at elevated temperatures. Furthermore, the results can be used in the future for establishing a relationship between the tensile strength and the flexural strength of the GFRP bars at elevated temperatures such that the tensile response can be back-calculated from the bending behaviour. In this way, a large statistical-database can be obtained in a far more convenient and low cost approach.

EXPERIMENTAL PROGRAM

GFRP Bars

Five sand-coated GFRP bars with nominal diameters of 12.7 mm, 14.0 mm, 15.9 mm, 17.0 mm, and 20.7 mm were considered as shown in Figure 1. Three specimens were prepared for each bar diameter. The bars were provided by V-Rod® Australia (www.vrodaustralia.com.au) and were made by embedding E-glass fibres in a modified vinyl ester resin using a pultrusion process. The glass fibre content of the GFRP bars, determined by Burn-out test according to ISO 1172:1996(E), is 84.05 %.

Differential Scanning Calorimetry (DSC) Analysis

The average glass transition temperature (T_g) of the bars was obtained using a TA Instruments Q100 DSC machine following the ASTM D3418-12 standard. Approximately, 30-mg unconditioned samples were cut from the reference bars. After the samples were cleaned and dried, they were placed

in aluminium pans and sealed, as shown in Figure 2, using forceps. The samples were heated from 10 °C to 150 °C at a ramp rate of 3 °C/min for one hour duration. Based on the test, the mean T_g of the bars (117 °C) was found to be within the range of the T_g of a vinyl ester matrix system (110 °C to 120 °C) reported by Robert et al. (2009).

Flexural Test

The three-point bending test of the GFRP bars was presented in Figure 3. The test was conducted following the ASTM D4476 standard using full bars, instead of half bars. The simply supported specimens, with clear span of 180 mm, were loaded at midspan at the rate of 10 mm/min using the 100 kN capacity MTS testing machine. The test was conducted using a steady-state temperature (heat then load) regime. The temperature in the oven chamber was raised to the desired temperature. Then, the bars were placed inside the chamber for 15 minutes prior to testing to be sure that the temperature at the core of the bars reached the required temperature. The bars were subjected to temperatures ranging from room temperature (21°C) to 150 °C. The load and displacement were recorded using a data logger. Each specimen was identified in the following manner: nominal bar diameter (12.7mm, 14.0 mm, 15.9mm, 17.0 mm, and 20.5 mm) - temperature it was subjected to (21°C to 150 °C).

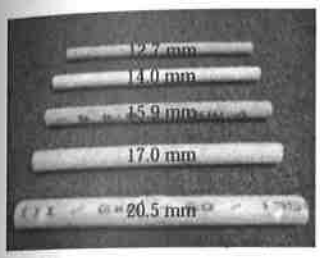

Figure 1. GFRP bars

Figure 2. Sample T_g specimen

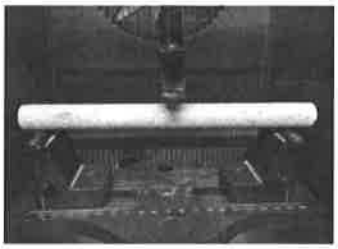

Figure 3. Three-point bending test

RESULTS AND DISCUSSION

Table 1 summarizes the experimental results such as the flexural load (F) and the corresponding standard deviation (SD), the flexural strength (f_b), and the flexural stiffness (E_b). The flexural strength and stiffness were calculated using Eq. 1 and Eq. 2, respectively, where L, d_b, and Δ are the clear span, the nominal diameter, and the midspan deflection, respectively. The ratio (F/Δ) was obtained from the slope of the linear portion of the load-deflection curves presented in Figure 4. In general, the strength and stiffness of the GFRP bars decrease as the bar diameter increases.

$$f_b = \frac{8FL}{\pi d_b^{\,3}} \qquad (1)$$

$$E_b = \frac{F}{\Delta}\frac{4L^3}{3\pi d_b^4} \qquad (2)$$

Load and Midspan Deflection Relationship at Elevated Temperatures

The typical relationship between the load and the midspan deflection of the GFRP bars (represented by 12.7 mm GFRP bars) subjected to elevated temperatures is shown in Figure 4. As can be seen from the figure, the load increases linearly with deflection up to failure for all subjected to temperatures ranging from 21 °C to 80 °C. The load drops observed, before reaching the peak load, were attributed to the debonding of the sand coating just beneath the point of load application. Generally, the bars failed in a brittle manner. The failure of the GFRP bars is dominated by the simultaneous crushing of the resin and fibre in the compression zone as depicted in Figure 5. In addition, the bars with larger diameters exhibited interlaminar shear failure in the tension zone as shown in Figure 6. On the other hand, it can be seen from Figure 7 that the mode of failure of the 12.7 mm and 15.9 mm GFRP bars was dominated by the fibre rupture and interlaminar shear failure at the tension zone of the bar that leads to the debonding of the sand coating.

The bars subjected to temperatures ranging from 100 °C to 150 °C exhibited a non-linear behaviour and stiffness degradation before reaching the maximum load because the T_g of the bars falls within this temperature range. The polymer behaves like a rubbery material and this has resulted in a ductile behaviour of the bars. Figure 8 shows the typical crushing failure of the GFRP bars exposed at these temperatures. White powder resins were formed. At a temperature of 150 °C, interlaminar shear failure was also observed in the tension zone of the bars with larger diameter. The bars with larger diameter exhibited more severe failure than those with smaller diameter.

Table 1. Flexural load, strength, and stiffness of the GFRP bars at elevated temperatures

Specimen	F (kN)	SD (kN)	f_b (MPa)	E_b (GPa)	Specimen	F (kN)	SD (kN)	f_b (MPa)	E_b (GPa)
12.7-21	7.6	0.1	999.8	77.3	15.9-21	7.6	0.1	869.7	41.9
12.7-35	3.6	0.2	815.0	77.1	15.9-35	7.1	0.1	811.6	41.4
12.7-50	2.2	0.3	495.1	74.1	15.9-50	5.2	0.3	598.1	41.7
12.7-65	2.2	0.5	495.4	72.0	15.9-65	5.3	0.4	603.3	38.5
12.7-80	2.4	0.5	534.6	68.3	15.9-80	4.6	0.6	520.8	36.8
12.7-100	2.1	0.1	473.8	53.9	15.9-100	3.2	0.2	370.4	31.6
12.7-120	0.9	0.1	191.5	28.5	15.9-120	1.6	0.2	184.9	15.8
12.7-150	0.3	0.1	60.5	24.5	15.9-150	0.9	0.1	102.0	11.4
14.0-21	6.6	0.4	1468.0	77.3	17.0-21	10.5	0.4	1201.3	63.1
14.0-35	5.6	0.0	1263.6	77.1	17.0-35	9.0	0.1	1031.7	62.2
14.0-50	3.7	0.3	820.0	74.1	17.0-50	7.3	0.4	828.0	58.1
14.0-65	3.6	0.3	815.8	72.0	17.0-65	7.0	0.4	796.0	57.4
14.0-80	3.5	0.4	792.9	68.3	17.0-80	4.5	0.3	510.1	53.2
14.0-100	1.7	0.1	385.3	53.9	17.0-100	3.5	0.1	396.9	40.9
14.0-120	1.0	0.1	222.6	28.5	17.0-120	2.3	0.3	261.5	29.6
14.0-150	0.5	0.1	122.6	24.5	17.0-150	1.0	0.0	118.3	15.4
20.5-21	15.5	0.2	1034.1	52.1	20.5-80	9.9	0.7	664.3	47.2
20.5-35	15.1	0.5	1012.1	52.2	20.5-100	7.5	1.5	501.2	39.4
20.5-50	12.6	0.8	838.9	50.9	20.5-120	3.8	1.3	254.6	23.2
20.5-65	12.1	0.6	811.8	50.1	20.5-150	2.0	0.2	132.1	10.8

Effect of Temperature on the Flexural Strength of the GFRP Bars

The relationship between the normalized flexural strength and the temperature is shown in Figure 9. The normalized values were calculated by finding the quotient between the flexural stress at t temperature, f_{bt}, and the flexural stress at room temperature (21 °C), f_{RT}. Generally, the flexural strength of the GFRP bars decreases as the temperature increases due to the decomposition of the resin. This trend was also observed in the pure tension test of FRP bars, conducted by Wang (2007), Abbasi (2005), and Robert and Benmokrane (2010). Furthermore, as the temperature approaches the T_g of the bars, a significant decreased of the flexural strength occurred because the polymer becomes soft and consequently looses its ability to hold the glass fibres together and to transfer stresses from one fibre to another. It can be seen that the bars with a larger nominal diameter experienced better flexural performance at higher temperature as compared to those with smaller diameter, which indicates that size effect (specifically the variation in the nominal diameters) should be considered in the investigation of the thermal stability of FRP bars.

Effect of Temperature on the Flexural Stiffness of the GFRP Bars

Figure 10 shows the correlation between the normalized flexural stiffness and the temperature. The normalized values were obtained by dividing the flexural stiffness at t temperature, E_{bt}, to the flexural

stiffness at room temperature (21 °C), E_{RT}. The same as the flexural strength, the flexural stiffness of the GFRP bars decrease as the temperature increases. However, the rate of deterioration of the flexural strength is faster than the flexural stiffness at temperature ranging from 21 °C to 100 °C. The same as the flexural strength, a drastic decrease in the flexural stiffness was also observed as the temperature approaches the T_g of the bars for the same reason. The composite action between the fibres and the polymer diminishes and this resulted in lower flexural stiffness (and strength) of the GFRP bars. On the other hand, a comparable rate of degradation of the flexural stiffness of the GFRP bars with varying diameter was observed at increasing temperatures.

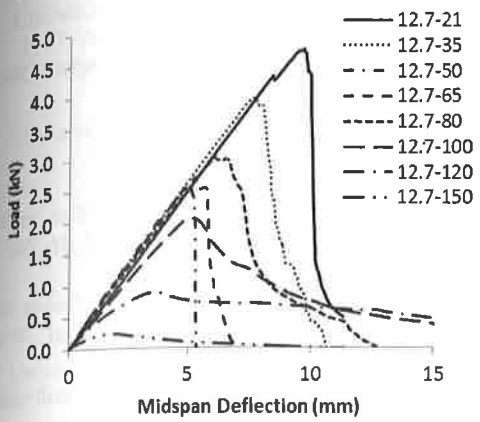

Figure 4. Typical load and midspan deflection relationships of the GFRP bars at elevated temperatures

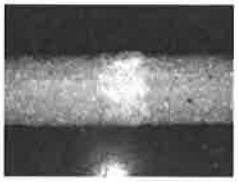

Figure 5. Crushing of the resin and fibre of GFRP bars (21 °C to 80 °C)

Figure 6. Interlaminar shear failure of GFRP bars (21 °C to 80 °C)

Figure 7. Interlaminar shear failure of the 12.7 mm and 15. 9mm GFRP bars (21 °C to 80 °C)

Figure 8. Crushing of the resin and fibres of GFRP bars (100°C to 150°C)

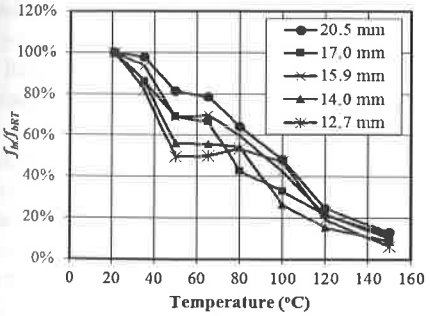

Figure 9. Flexural strength of the GFRP bars at elevated temperatures

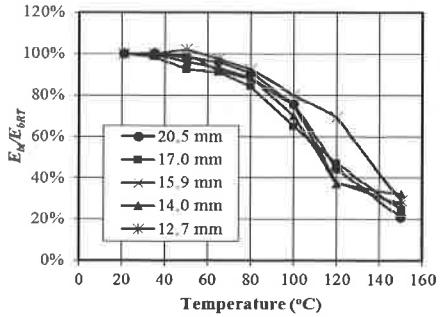

Figure 10. Flexural stiffness of the GFRP bars at elevated temperatures

CONCLUSIONS

The three-point bending test of the GFRP bars subjected to elevated temperatures was conducted. Based on the experimental results, the following conclusions were made:

- Generally, as the temperature increases, the flexural strength and stiffness of the GFRP bars decreases.
- A drastic decrease of the flexural strength and stiffness of the GFRP bars was observed as the temperature approaches the T_g of the bars because the polymer transition from a glassy (hard) material to a rubbery (soft) material, thereby losing its ability to hold the fibres together and to transfer stresses from one fibre to the other.

- The bars with a larger nominal diameter showed better flexural strength decay resistance than those with a smaller nominal diameter at elevated temperatures.
- The rate of degradation of the flexural stiffness of the GFRP bars with varying diameter was comparable with each other at increasing temperatures.
- Additional studies should be carried out to provide further information that can be used to establish a relationship that can predict the tensile response of the GFRP bars from the bending response at elevated temperatures.

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