BOND STRENGTH OF GLASS FIBRE REINFORCED POLYMER BARS IN CONCRETE AT HIGH TEMPERATURE

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Abstract: The polymer matrixes currently used for the fabrication of fibre reinforced polymer (FRP) reinforcing bars soften when the temperature rises to the glass transition temperature (T_g) resulting in reduction of mechanical strength. This paper discusses the effect of high temperature on the bond behaviour of commercially available glass fibre reinforced polymer (GFRP) reinforcing rebars through pullout tests. The results showed that the bond strength incurred a reduction of 84% at 200 °C comparing to the bond strength at room temperature. In the literature, pullout tests results on small sizes (12 mm diameter and less) were presented, while in many applications larger GFRP bars are used. In this paper, bond properties of #5 (16 mm nominal diameter) in a temperature range from 20 to 200 °C were studied. Test results showed a reduction between 14 and 84% in the bond strength as the temperature increased from 60 to 200 °C, respectively. At elevated temperatures, the bars showed reductions in bond strength since it relies mostly on the resin at the interface between the core of the bar and its coating.

1 INTRODUCTION

Application of FRP reinforcing bars in concrete construction has been widely growing because of the lessons learned from excessively deteriorated concrete structures. FRP bars are used as internal reinforcement because they provide superior properties such as corrosion resistance, magnetic transparency, and light weight. One of the obstacles to growing the FRP market is questionable performance of FRP reinforced concrete members in fire. Because of this uncertainty, design codes have suggested higher precautions such as increasing the concrete cover to ensure the required fire endurance. However, given the higher material price and unfamiliarity of the design engineers with the material, applying restrictions in the design in order to meet fire resistance requirements will create more barriers to accepting FRP bars as main reinforcing bars in concrete construction.

While the study of the tensile strength of GFRP bars at high temperature is underway by the authors, in this paper the results of an experimental program on the bond behaviour of GFRP bars at high temperature are presented. Full scale GFRP reinforced concrete slabs tested in fire showed that the bond behaviour of FRP bars is more critical than the deterioration of tensile strength[1, 2]. While bond strength of FRP bars has been studied widely, few studies have considered the bond behaviour of FRP bars at high temperature. Katz et al. [3] tested the bond behaviour of GFRP bars under pullout tests at high temperature, and they found drastic reductions in bond strength reduction at 180 °C. The amount of bond deterioration due to temperature was different depending upon the type of resin and the type of surface treatment. Given the fast-changing material properties of the FRP products in the market, conducting new series of tests on the currently produced material is essential. In one of the most recent studies, McIntyre et al. [4] tested pullout samples with #4 GFRP rods (12 mm) at high temperature. In the current paper, larger sizes of sand coated GFRP bars have been studied.

2 Experimental program

2.1 Material properties

The nominal diameter of the GFRP bars was 16 mm (#5) while the actual core diameter with and without sand coating was 17.8 and 19.0 mm, respectively. The ultimate tensile capacity was 340 kN and considering 199 mm^2 as the nominal cross sectional area, the nominal tensile strength was 1700 MPa. The glass transition temperature of the bars was 109 °C as provided by the manufacturer. Normal strength concrete with a 28 day compressive strength of 35 MPa was used. The concrete slump was 100 mm which allowed for good compaction around the rods without excess bleeding. The composition of the concrete is shown in Table 1.

Table 1 Concrete mix

MATERIAL	WEIGHT	UNIT
CEMENT	348	kg/m^3
WATER	195	kg/m^3
COARSE AGGREGATE	1059	kg/m^3
SAND	733	kg/m^3
TOTAL	2335	kg/m^3

2.2 Preparation of samples

According to CSA S806[5], the embedded length of the bars in 150 mm concrete cubes should be 4*d* where *d* is the nominal diameter of the bar. Thus, the bonded length in these tests was 68 mm. The rest of the length of the bar in the cube remained unbonded from the surrounding concrete. In the current experiments, high temperature resistant silicone was used which was flexible enough to deform easily on the interface of concrete and bar but ensured no bond contribution from the unbonded length.

As shown in Figure 1, one thermocouple was attached to each specimen on the debonded length of bars and deformed in the bonded area to touch the bar for each specimen. The thermocouples were not attached to the bar in the bonded area to avoid affecting the bond.

The next step was to place the bars vertically in the centre of the moulds. One hole on the bottom of each mould was drilled in advance to hold the bar in centre. For the cubes (150 mm), the concrete was placed in four layers of approximately equal thickness and each layer was tapped 25 times with a 16 mm diameter rod. After 24 hours, the specimens were removed from the forms and cured for 7 days. The samples were stored indoor for four months before the tests.

(a) (b) (c)

Figure 1 Construction of specimens: (a) Placement of thermocouples (b) Bond breaker (c) Concrete casting

2.3 Test setup

An Instron SATEC testing machine (Figure 2) was used for the pullout tests. According to CSA S806, the load shall be applied to the steel sleeve of the pullout samples with a displacement rate not greater than 1.27 mm/minute. In the current experiments, the displacement rate was set to 1.0 mm/minute. By the virtue of a parallel furnace with testing machine, loading and heating the samples were carried out simultaneously based on the type of test. Both steady-state and transient thermal tests were conducted. In the steady-state temperature tests, the specimens were heated to the specified temperature and then loaded to failure. For the transient temperature tests, a fixed load was applied and the temperature was increased until failure. To simulate a representative fire condition, the heating rate was chosen close to the rate of temperature rise during a real fire in concrete which was estimated 5 °C/min.

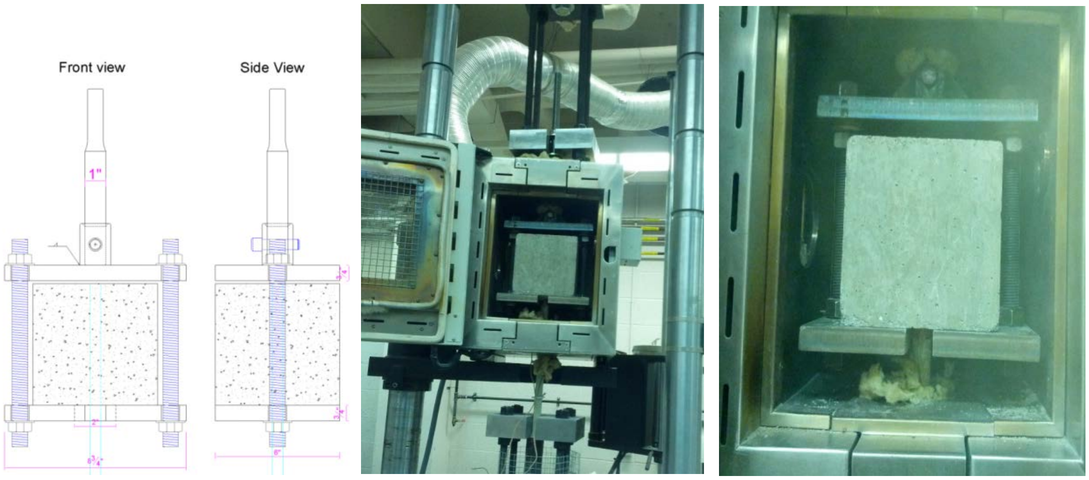


Figure 2 Pull-out sample placed in Instron furnace

To evaluate the thermal distribution around the concrete block, measurements of temperatures at various locations in the chamber were conducted before testing the pullout samples. Figure 3 shows measured temperatures on all sides of the cube (thermocouples TC2 to TC5 in Figure 3). The dashed-black curve shows temperature recorded by internal thermocouple placed on the bar surface during fabrication. To reach the desired temperature of tests in this case (120 ˚C), samples should remain in the furnace for 3 hours after furnace has reached its target temperature of 120 ˚C. As is shown in the graph, even after 3 hours, temperature of the bar was slightly lower than the furnace temperature. The differences between bar and furnace target temperatures increase at higher target temperatures.

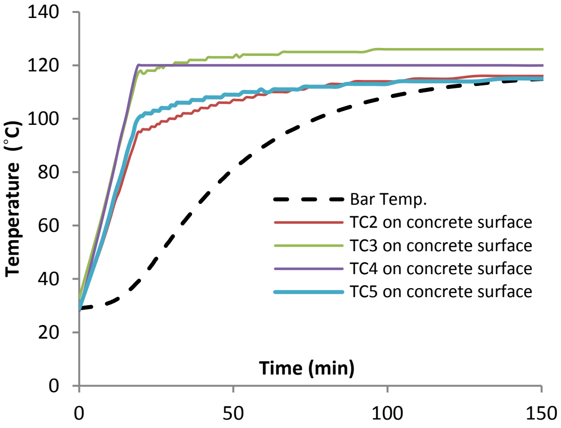


Figure 3 Thermal evaluation of concrete cube in the furnace

3 Results

A summary of the test results including bond strength at room temperature, at high temperature, and the bond strength reduction are listed in Table 2 and Table 3 for transient and steady-state temperature tests, respectively.

3.1 Steady-state tests

Table 2 summarizes the results for the steady-state temperature tests up to 200 °C. At 200 °C, most of the bond strength was lost. Load versus slip curves for some of tested samples are presented in Figure 4 and a plot of the strength degradation with temperature is given in Figure 5.

Table 2 Steady-state tests

Bar-Concrete interface Temp.(°C)	Furnace Target Temp.(°C)	Load (kN)	Embedded length (mm)	Effective Bar Dia. (mm)	Bond surface (mm2)	Bond Strength (MPa)	Average Load (kN)	Average Bond strength (MPa)	Bond Strength loss (%)
25	25	75	68	19	4060	19	67	17	0%
25	25	65	68	19	4060	16			
25	25	56	68	19	4060	14			
25	25	71	68	19	4060	18			
57	60	61	68	19	4060	15	58	14	14%
57	60	54	68	19	4060	13			
74	80	46	68	19	4060	11	48	12	28%
72	80	55	68	19	4060	14			
74	80	45	68	19	4060	11			
94	100	40	68	19	4060	10	46	11	31%
92	100	51	68	19	4060	13			
94	100	47	68	19	4060	12			
114	130	28	68	19	4060	6.8	28	7.0	58%
116	130	29	68	19	4060	7.1			
135	160	19	68	19	4060	4.7	18	4.5	73%
136	160	17	68	19	4060	4.3			
172	200	12	68	19	4060	3.0	11	2.7	84%
172	200	10	68	19	4060	2.4			
171	200	11	68	19	4060	2.7			

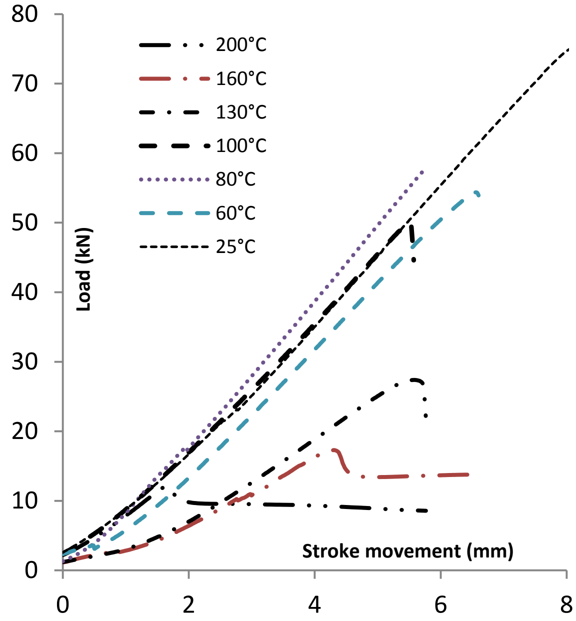


Figure 4 Load-stroke displacement curves

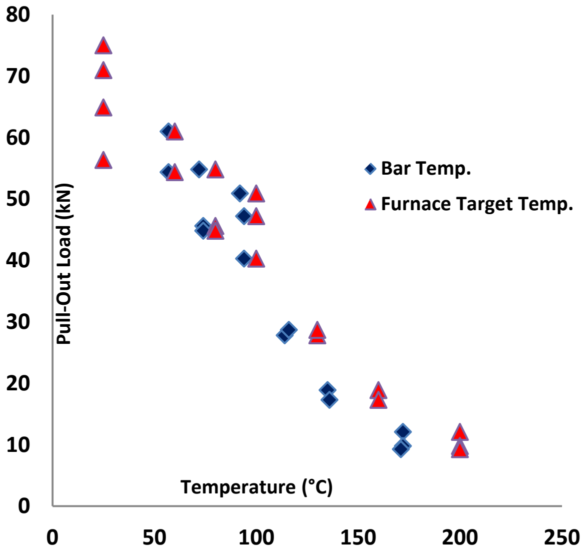


Figure 5 Steady-state pullout test results

3.2 Transient temperature tests

For the transient temperature tests, specified loads were applied to simulate the bond stress on the bar to concrete interface under service loads. The specimens were then exposed to increasing temperatures until failure occurred. A typical diagram of the transient test procedure is shown in Figure 6 for the tests under prescribed load of 20 kN before heating. The target temperature of the furnace was set to 300 °C with the rate of 5 C/min. The temperature at the interface between the reinforcing bar and the concrete increases until a sudden drop in the load occurred accompanied with a large slip. The failure temperature is the temperature at which the GFRP bar cannot carry the applied load, and starts to slip. As shown in Figure 6, the failure temperature for this sample is 86 C.

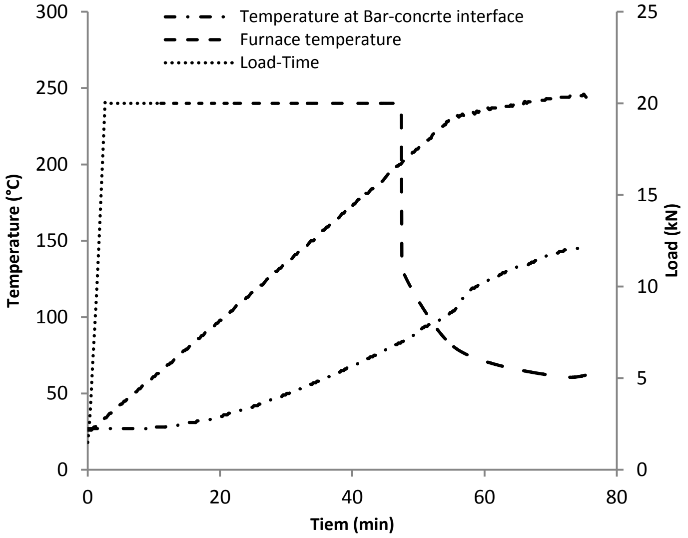


Figure 6 Typical transient temperature test results

In transient temperature tests, the failure temperature of the samples was observed to be lower than expected. One reason for this low strength could be attributed to moisture moving towards the bar during the heating process thus facilitating slippage of the bar. This issue has been previously observed in experiments conducted by Katz et.al [3]. To eliminate any such premature bond failure, transient temperature samples were placed in the oven before loading, and exposed to 100°C for 10 hours. After the samples were back to room temperature, the transient test was conducted. By preheating the samples, the possibility of premature failure due to moisture migration was eliminated from the tests. As an example for the sample shown in Figure 7, the premature failure temperature was 86 °C. However, for the dried sample, the failure temperature was 120 °C under the same load of 20 kN. The premature failure was not observed in the samples with lower specified initial loads. For the transient condition samples with the initial load of 10 kN, pre-drying did not cause any change in the failure temperature.

Table 3 transient condition tests

Prescribed Load (kN)	Bar-Concrete interface Temp.(°C)	Load (kN)	Embedded length (mm)	Effective Bar Dia. (mm)	Bond surface (mm^2)	Bond Strength (MPa)	Remarks
10	150	10	68	19	4060	2.5	Pre-dried
10	151	10	68	19	4060	2.5	-
20	86	20	68	19	4060	4.9	-
20	87	20	68	19	4060	4.9	-
20	120	20	68	19	4060	4.9	Pre-dried
30	104	30	68	19	4060	7.4	Pre-dried
30	111	30	68	19	4060	7.4	Pre-dried

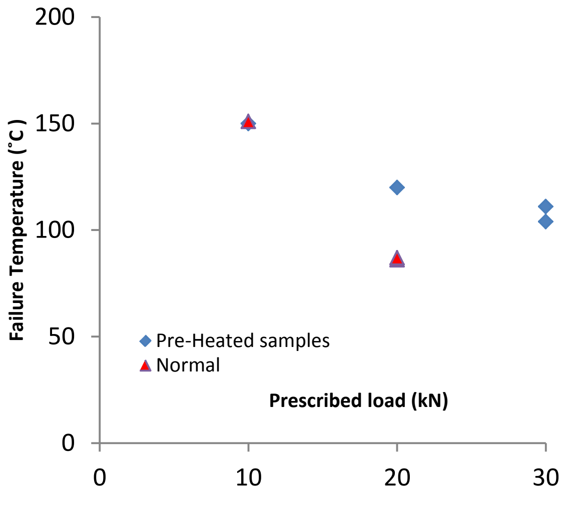
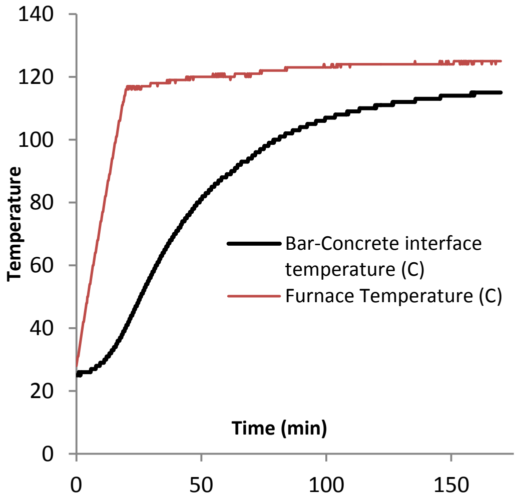


Figure 7 Transient temperature pullout test results

4 Residual (post-fire) bond strength tests

The residual pullout strength of GFRP bars after being subjected to elevated temperatures was also studied. These results were obtained by subjecting the specimens to different target temperatures for a soak period long enough to establish a constant increased temperature at the interface between the reinforcing bar and the concrete. A typical heating curve in the residual tensile strength tests is shown is Figure 8.



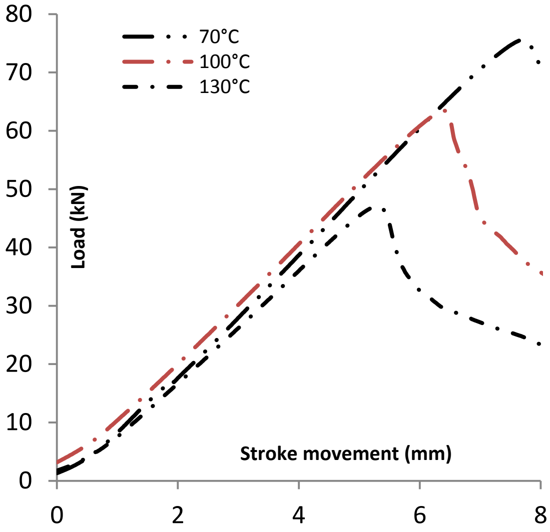


Figure 8 heating curve for 130 °C sample

Figure 9 Load-Slip curves (residual tests)

Figure 10 presents the bond strength of GFRP bars as a function of temperature. Increasing the temperature decreased the bond strength. In order to represent a real structural behaviour of GFRP reinforced concrete, samples were divided into two groups: in the first group, a 10 kN sustained load was applied during the heat exposure to simulate a loaded GFRP reinforced concrete member, while for the second group of samples, no sustained load was applied. In Figure 10, the rate of bond strength loss is greater when the sustained load is applied. Generally, bond strength losses are proportional to the exposed temperature.

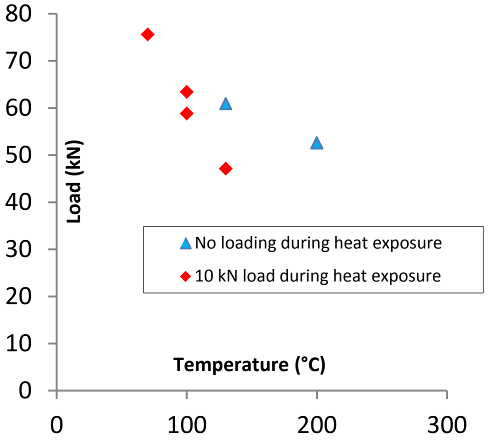


Figure 10 Residual strength (after fire) pullout test results

5 Discussion

After tests at elevated temperature, Figure 11 shows that a tube-shaped coating residue was left attached to the concrete. Thus, the coating layer was peeled off completely during the pullout test. The glass fibre core of the bars had no damage as shown in Figure 12.

Figure 11 Residue of coating layer after pull-out

Slight discoloration of the surface of the GFRP bars was observed at elevated temperatures especially for the samples tested at temperatures higher than 160 °C (Figure 12). The coating layer of the bars was damaged in different forms and levels based on the type of test as well as the temperature. In most of the steady-state temperature tests, the external coating layer was entirely peeled off. At temperatures above the glass transition of the resin, there was no sign of concrete residue on the surface of the reinforcing bars along the embedded length. However, residue of the coating from the surface of the rebar was left in the concrete cube after pullout test. The following pictures show the surface condition of the reinforcing bars after the pullout test.

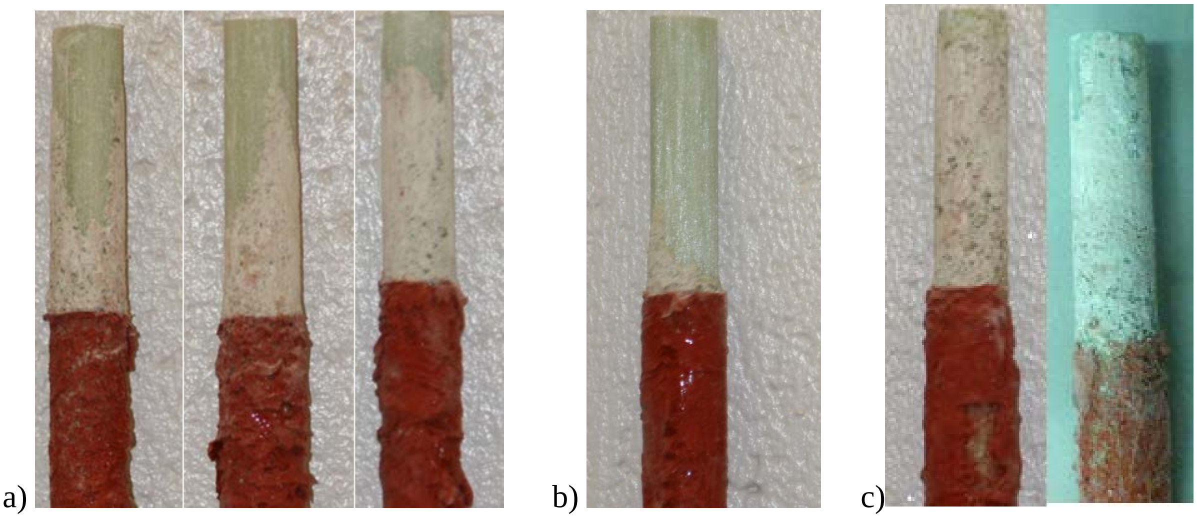


Figure 12 Bars after steady-state tests at (a) 25°C (b) 80 °C; (c) residual tests at 100 °C

6 Conclusion

Pullout test results showed high bond strength for the studied reinforcing bars at room temperature. Increasing temperature had a notable negative effect on the bond behaviour of the bars. The bond strength gradually reduced before the glass transition temperature (109 °C) of the bars. Between 100 °C and 130 °C, the bond strength dropped noticeably (60 to 70% loss) when the temperature passed the glass transition temperature. Then, the bond strength gradually diminished up to 200 °C where 84% of the bond strength was lost.

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