POST-FIRE RESIDUAL STRENGTH OF GLASS FIBRE REINFORCED POLYMER (GFRP) BARS

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ABSTRACT

Lack of reliable and adequate information on material characteristics of glass fibre reinforced polymer (GFRP) at elevated temperatures lowers the accuracy of analytical and design models developed to predict the behaviour of GFRP reinforced concrete members. There is an essential need to assess the remaining strength of bridge and building components after exposure to fire to determine if repair or replacement is required. This paper presents experimental results of a series of tensile tests on GFRP reinforcing bars after exposure to elevated temperatures. GFRP specimens with nominal diameter of 16 mm were exposed to different temperatures in an electric furnace. During the heat exposure, the samples were loaded with 25% of their ultimate tensile strength to simulate the sustained load that a reinforcing bar in a concrete member may carry in a fire incident. After the samples cooled to room temperature, they were loaded to failure. The same type of GFRP bars had been tested earlier by the authors under simultaneous effects of heat and load. At high temperature, the bars had considerable strength loss. However, the results presented in this paper show notable tensile strength recovery when the specimens were cooled before loading to failure. This information is essential for studying the post-fire evaluation of GFRP reinforced concrete members exposed to fires.

Keywords: Post-fire, residual tensile strength, GFRP, thermal degradation, fire, bridges, buildings

1. INTRODUCTION AND BACKGROUND

Not all fire incidents result in structural collapse. Assessment of the remaining strength of FRP reinforced concrete structures after fire is critical to decide on further use of the affected buildings and structures. The fibres in a composite material such as FRP reinforcing bars exhibit better thermal resistance than the matrix and can continue to support some load. The tensile properties of the overall composite, however, decrease due loss in transverse load sharing between fibres since the resin no longer binds the fibres together (Hajiloo et al. 2015). Extensive studies on fire behaviour of concrete (Lie 1992) have shown that the comparatively low thermal conductivity of concrete provides insulation to reinforcing bars, either steel or FRP, in concrete elements. CSA-S806 (CSA 2012) implements a prescriptive method, which is based on an assumed critical temperature for FRP reinforcement, to design FRP reinforced concrete members satisfying fire resistance requirements. At the critical temperature for the FRP reinforcing bar, the FRP reinforced structural member is assumed to have lost enough of its original strength such that the loads can no longer be supported. In CSA-S806, the critical temperature for the FRP is defined as the temperature at which the FRP bar has half of its room temperature strength. Critical temperatures for reinforcing and prestressing steel are established as 593 and 426°C, respectively. Wang et al. (2007) have suggested critical temperatures of 325°C for GFRP and 250°C for CFRP reinforcing bar. However, there is a very limited information available on the post-fire residual strength properties of FRP bars, and thus there is a need for more research in this area. In a recent experimental study, the residual tensile strength of GFRP bars after exposure to elevated temperatures and cooling was examined (Alsayed et al. 2012). The FRP bars were exposed to 100, 200, and 300°C for various periods of one, two, and three hours. Alsayed et al. showed that increasing the temperature level or heat-exposure period length caused the FRP bars to suffer more from heat effects. The losses ranged between 10 and 42% and the strength losses were almost linearly proportional to the exposed temperature.
2. EXPERIMENTAL PROGRAM

The objective of this material testing is to determine how much tensile strength remains in GFRP reinforcing bars after exposure to elevated temperatures. This information is essential to accurately evaluate the structural capacity of FRP reinforced concrete structures that have survived a fire incident. The procedure developed to conduct the tests in this study aims to represent realistic situations in a fire. To begin with, in a real fire scenario, generally, service loads consisting of permanent dead loads and a portion of the live loads are present while temperature increases in the structure. It is anticipated that the presence of stress in FRP bars during heat exposure accelerates degradation of FRP bars. Thus, to include the effect of sustained load, each reinforcing bar was loaded to 25% of its room temperature strength, and then exposed to the specific temperature. Second, the rate of temperature rise was set at 5 °C/min based upon the expected rate of heat increase of FRP bars embedded in concrete. Samples were held in the furnace for an additional 15 minutes after reaching the target temperature to ensure uniformity in heating. Then, the furnace was turned off, and the samples were left to cool before loading to failure. Finally, according to CSA-S806 (CSA 2012), the specimen was loaded in stroke control with a rate between 250-500 MPa/min. The loading rate was achieved by moving the actuator down at a rate of 8 mm/min until failure occurred.

None of the samples in this study failed under sustained load during heat exposure. Figure 1 shows the heating process at which the furnace target temperature was set to 400 °C while the thermocouple placed on the surface of the bar showed 370 °C at the end of heating process. There was always a slight difference between the bar’s surface temperature and the furnace air temperature. To monitor and record the temperatures in the furnace, in addition to the embedded thermocouple of furnace itself, two extra thermocouples were used. One thermocouple read the furnace air temperature, and the tip of the second thermocouple was placed on the surface of every bar specimen to record its temperature.

Two different GFRP reinforcing bars (Figure 2) from different manufacturers (called Rebar-A and Rebar-B in this paper) with a nominal diameter of 16 mm were tested in this study. Rebar-A has sand coating on the surface, which is applied on the hardened reinforcing bar following the pultrusion process. In addition to sand coating in Rebar-B, a helical braid of fibres is wound around the bar. These tightly doubly wrapped glass fibres create convex protrusions on the surface of Rebar-B.

![Figure 1: (a) Heating and cooling exposure curves; (b) Thermocouples on the reinforcing bar and in the furnace](image-url)
The reinforcing bars consist of continuous longitudinal E-glass fibres bonded together with vinylester resin. The ultimate tensile strength values were 1717 and 1287 MPa for Rebar-A, and Rebar-B, respectively. The nominal cross-sectional area and designated reinforcing bar diameter were in accordance with CSA-S807. Stress and modulus of elasticity are calculated based on these areas. Mechanical properties as reported by the manufacturers are shown in Table 1.

<table>
<thead>
<tr>
<th>Reinforcing bar Type</th>
<th>Rebar-A</th>
<th>Rebar-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Diameter (mm)</td>
<td>16</td>
<td>15</td>
</tr>
<tr>
<td>Diameter (including coating or ribs) (mm)</td>
<td>18.5</td>
<td>17.9</td>
</tr>
<tr>
<td>Nominal Cross Sectional Area (mm²)</td>
<td>198</td>
<td>199</td>
</tr>
<tr>
<td>Nominal Tensile Strength (MPa)</td>
<td>1717</td>
<td>1287</td>
</tr>
<tr>
<td>Nominal Modulus of Elasticity (MPa)</td>
<td>64145</td>
<td>62600</td>
</tr>
<tr>
<td>Ultimate Elongation (%)</td>
<td>2.7</td>
<td>2.1</td>
</tr>
<tr>
<td>Fibre content (By weight) (%)</td>
<td>80.7</td>
<td>82.9</td>
</tr>
<tr>
<td>Glass transition temperature °C</td>
<td>109.6</td>
<td>113.8</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION

Rebar-A specimens were loaded to 85 kN before starting the specific heat exposure, and the specimens sustained the load during entire heat exposure. The post-fire remaining tensile strength and normalized strength of tested samples is shown in Figure 3. The first elevated temperature was 150 °C. For these specimens, a minor strength loss was observed when tested, and the bars recovered 90 % of their room-temperature strength. The authors have extensively tested the same reinforcing bar’s characteristics at elevated temperatures under steady-state and transient temperatures (Hajiloo et al. 2015). It is worth to mention that in steady-state tests, the specimens were heated to a specific temperature and then loaded to failure. In transient tests, specified loads were applied to the bars, and the loaded bars were exposed to increasing temperatures until failure occurred. Rebar-A in steady-state temperature tests (Hajiloo et al. 2015) at 150 °C, retained on average 65 % of its room temperature strength. Since the specimens demonstrated only minor tensile strength degradation after exposure to 150 °C, the second temperature was selected to subject the reinforcing bar to a more severe exposure, 350 °C. After experiencing heat exposure at 350 °C, Rebar-A recovered 66 % of its original strength at room temperature. For exposure to 440 °C, the strength recovery was 51 %. Regardless of the loss in strength at very severe heat exposure, the recovered strengths of the reinforcing bars were all above 50 % of the strength at room temperature. Given that design codes allow the FRP reinforcing bars to be stressed only up to 25% of their ultimate strength, the experiments in this study showed that Rebar-A, even after experiencing a severe heat exposure, was still able to carry the design loads.
The extent of cracks on the reinforcing bar depends on several factors including the intensity of sustained load during heat exposure, duration of heat exposure, and the maximum temperature to which the reinforcing bar was exposed. For the specimens tested under steady-state temperature condition regardless of the heat intensity, there were no signs of cracking on the coating. However, presence of loads during heat exposure causes cracks to develop. In Figure 4(a), Rebar-A specimen was extensively cracked and had a charred appearance after heat exposure. However, the core of the reinforcing bar remained intact and no fibres ruptured. Heat exposure caused resin decomposition of the GFRP bars, and different levels of color change were observed in the heated specimens. The color change was minor in the specimens heated to 150 °C. Specimens exposed to 350 °C turned dark brown, and the ones that went above 400 °C became black. Because of the relatively slow heating rate followed in the experiments, there was quite a long time of heat exposure for the specimens heated to the temperatures above 400 °C. Not only the target temperature was high, but also the heat duration was increased in order to reach the target temperature leading to more severe effects on the specimens.

Figure 4(b) shows the sample after failure.

Rebar-B specimens were loaded to 64 kN while heated. Given that Rebar-A only had a minor tensile strength loss after experiencing heat exposure up to 150 °C, thus, Rebar-B specimens were tested for the range of elevated temperatures from 350 to 450 °C. When Rebar-B specimens were heated to 350 °C and cooled, they recovered on average 80% of their room temperature strength. Rebar-B has shown a transitional temperature between 350 and 400 °C with a sudden drop in tensile strength. This is in consistent with the steady-state temperature tests previously performed by authors. Even after this severe heat exposure, Rebar-B was able to recover 60% of its strength after cooling.
Figure 4: Rebar-A: (a) after exposure to 430 °C under 85 kN; and (b) after test and failure at 180 kN

Figure 5: Post-fire residual strength of Rebar-B

One of the Rebar-B samples caught fire at 420 °C (Figure 6(a)). Excessive fumes after 400 °C were a sign of fire initiation, and this established a combustion temperature for Rebar-B of 420 °C. To avoid such burning, special safety precautions should be taken in conducting tests on FRP materials at high temperatures. Figure 6(b) illustrates the same specimen, which failed at 128 kN.

The surface of the specimens were painted with high-temperature resistant paint to create a pattern for Digital Image Correlation (DIC) technique to calculate the modulus of elasticity. Wang et al. (2007) showed that modulus of elasticity of GFRP bars remain constant up to 400 °C, retaining about 90% of its value at room temperature, but at 500 °C, a drastic decrease occurred in tensile modulus falling below 30% of its original value. In the present study, Digital Image Correlation (DIC) method was used to measure the modulus of elasticity. This method was found useful in evaluation of modulus of elasticity in steady-state temperature tests conducted by the authors. For the samples presented in this paper, the modulus of elasticity of two specimens of Rebar-B, which experienced 350 and 420 °C, were assessed by DIC. The results showed that the modulus of elasticity remained unchanged (Figure 7(a)). Performing DIC method on Rebar-A to evaluate the modulus of elasticity was not feasible because the sand coated surface of the bars experienced dramatic changes during the heat exposure due to the thermal expansion and cracks on the surface. Figure 7(b) shows the load-displacement relationships for Rebar-A and Rebar-B. Substantial loss in tensile strength of Rebar-B with the increase of temperature from 350 to 420 °C can be observed. The load-stroke displacement relationships were linear for the samples exposed to 420 °C.

Figure 6: Rebar-B: (a) Catching fire at 420 °C and (b) After failure at 128 kN

Figure 7: Modulus of elasticity vs. Temperature
4. CONCLUSIONS

The post-fire residual tensile strength of two types of GFRP reinforcing bars was investigated through material testing. The sustained applied load during heat exposure was selected to be 25% of the bar’s room temperature strength. The remaining tensile strength after heat exposure up to 420 °C stayed above half of their original strength at room temperature. The results demonstrate that if a FRP reinforced member survives a fire scenario, there will be sufficient residual tensile strength in FRP bars to resist the service loads. The remaining post-fire bond strength of the FRP reinforcing bars has to be examined to evaluate the global residual strength of FRP reinforced concrete members. The results of this study are currently being used in numerical modelling work to predict such residual strength after survival from fire incidents.

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