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# Post-fire residual properties of GFRP reinforced concrete slabs: A holistic investigation

Hamzeh Hajiloo*, Mark F. Green

*Civil Engineering, Queen's University, 58 University Avenue, Kingston, ON K7L 3N6, Canada*

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ABSTRACT

This paper provides critical data regarding the post-fire residual strength of Glass Fibre Reinforced Polymer (GFRP) reinforced concrete slabs. The residual tensile and bond strength of three types of GFRP reinforcing bars and the post-fire residual strength of a GFRP reinforced concrete slab are examined. For residual tensile strength, GFRP bars with a nominal diameter of 16 mm are exposed to temperatures up to 450 °C and tested after 24 h at room temperature. After 24 h, the specimens are loaded to failure at room temperature. For residual bond strength, pullout specimens are heated under various sustained load values. Finally, a full-scale GFRP reinforced concrete slab is tested at room temperature to evaluate the post-fire residual capacity after exposure to three hours of a standard fire. The residual tensile test results show that the bars that were exposed to 400 °C recovered at least 45% of the original strength while the residual bond strength is approximately 40% for pullout specimens that had experienced 300 °C. The post-fire residual strength of the slab is 68% of its room temperature flexural design strength with the bond loss at the ends of the slab being the governing mode of failure.

## 1. Introduction

During the service life of a structure, fire is one the most severe hazards that may occur. In a specific study by Lee et al. [1] on fire incidents involving bridges, it was shown that 30 highway bridges collapsed due to fire in the United States between 1980 and 2012 while only 20 bridges failed due to earthquakes in the same time period. However, not all fire incidents result in structural collapse. If a structure survives a fire incident, the next question is whether or not the structure is safe to be used, and whether or not it needs repair. This question is often difficult for practitioners to answer quickly because the affected structure must be evaluated extensively to determine the extent of damage based on the severity of the fire and the effects on the critical members of the structure. For example, a truck collision caused a hydrocarbon fire under a Don Valley Parkway bridge on Highway 401 in Toronto that resulted in severe damage [2]. The composite concrete slab deck over prestressed girders suffered substantial spalling in the deck soffit area immediately above the crash location. The prestressed girders were also damaged in many locations, and concrete spalling left reinforcing bars exposed [2]. If a similar fire were to occur in a Glass Fibre Reinforced Polymer (GFRP) reinforced concrete structure, the uncertainties as to the remained strength would be higher because of the lack of knowledge on the performance of GFRP reinforcing bars at high temperatures. Specifically, assessment of the remaining strength of GFRP reinforced concrete structures after the fire is critical to decide on the further use of the affected buildings and structures.

In reinforced concrete structures, the reinforcing bars are protected from direct fire exposure, and the heat is transferred gradually to the bars through the concrete cover. Extensive studies on the behaviour of concrete in fire [3] have shown that the comparatively low thermal conductivity of concrete provides insulation to reinforcing bars, either steel or GFRP, in concrete elements. In a prescriptive and conservative method, CSA-S806 [4] recommends a relatively thick concrete cover to delay the heat-induced degradation of reinforcing bars. Although this might satisfy fire resistance requirements, it is less appealing to structural engineers because GFRP reinforcing bars are not used efficiently.

Recent experimental studies have revealed the dominant aspects of the behaviour of GFRP reinforced concrete in fire [5–7]. Bond strength loss was the main cause of failure when the ends of GFRP reinforcing bars were not sufficiently protected from heat.

## 2. Background and motivation

The study of tensile strength degradation of Fibre Reinforced Polymers (FRPs) has been of great interest ever since the material emerged [8,9]. The fibres in a composite material such as FRP reinforcing bars exhibit better thermal resistance than the matrix, and thus, the fibre can continue to support some load even if the matrix is

* Corresponding author.
*E-mail address:* Hajiloo.h@queensu.ca (H. Hajiloo).

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damaged. The tensile properties of the overall composite, however, decrease because of loss in transverse load sharing between fibres since the resin no longer binds the fibres together [10]. Wang et al. [11] defined critical temperatures of 325 °C for glass FRP (GFRP) and 250 °C for carbon FRP reinforcing bars. The critical temperature was defined as the temperature at which the bars lost half of their original tensile strength. Robert and Benmokrane [12] studied the variation of mechanical properties including tensile strength of sand coated GFRP reinforcing bars at high temperatures up to 315 °C. The breaking of molecular bonds at higher temperatures was stated as the cause of increased ductility leading to degradation of mechanical strength and stiffness of the material. At temperatures higher than 300 °C, strong degradation of the matrix reduced the load transfer between fibres. However, even less information is available on the post-fire residual strength properties of FRP bars. In experimental work conducted by Alsayed et al. [13], FRP reinforcing bars were exposed to 100, 200, and 300 °C for periods of one, two, and three hours. They showed that increasing the temperature level or the duration of the heat exposure caused higher losses in the residual tensile strength. The losses ranged from 10 to 42% in an almost linear relationship with temperature.

The second subject covered in the present study is the residual bond strength of GFRP to concrete. Early studies by Bank et al. [14] and Katz et al. [15] showed that the bond strength of GFRP reinforcing bars to concrete was completely lost at temperatures above 200 °C. More recent experiments by Hajiloo and Green [16,17] proved the severe loss of GFRP to concrete bond, and the bond degradation was identified as the reason for the failure of GFRP reinforced concrete slabs in fire tests [18,19]. Although the residual bond strength of steel to concrete is studied to an adequate extent, the lack of knowledge on the residual bond strength of GFRP bars is noticeable. Morley and Royles [20] conducted experiments on steel reinforced concrete pullout specimens where variables were the test procedure and the temperatures. The residual bond strength of the specimens (unstressed during heat exposure) at 250 and 400 °C were 100 and 70% of the original strength. At the temperatures below 250 °C, the residual bond strength was greater than the specimens tested at hot state. However, the situation reversed at higher temperatures, and this was associated with the lower concrete strength after cooling down when compared to the hot condition. The specimens retained 40% of the original bond strength when tested at 750 °C whereas the average residual value after exposure to the same temperature was 20%. Ergün et al. [21] examined the effects of concrete and steel material properties on the residual bond strength of concrete cylinders. Bond degradation occurred for all grades of steel reinforcing bars, but the degradation was largest for the lowest grade (220 MPa) wherein the residual bond was 10% of original strength. It was concluded that the residual bond strength correlates well to the residual strength of concrete after exposure to high temperature [21]. Unlike the residual bond strength of steel bars to concrete, the research on the residual bond strength of GFRP bars to concrete is insufficient. El-Gamal [22] studied the residual bond strength of GFRP bars and found 21 and 50% of bond losses for the specimens that experienced 200 and 350 °C for three hours. The loss in the residual bond strength was in part associated with the high transverse coefficient of thermal expansion of GFRP bars that caused cracks in the FRP to concrete interface when heated. The failure mode of all specimens was the concrete shear-off, and no damage was reported on the surface of the bars.

The third subject in the current study is the post-fire residual strength of GFRP reinforced concrete slabs. Nigro et al. [5] studied the post-fire residual strength of FRP reinforced slabs after three hours of exposure to a standard fire. The slabs were not loaded externally during the fire, and the bending moment caused by the weight of the slabs was equivalent to 10% of the design flexural strength of the slabs (65 kN.m). The first slab was 3500 mm long with 250 mm unexposed regions at the ends. The concrete cover was 32 mm and the temperature of the bars near midspan at the end of four hours of exposure was approximately 700 °C. The slab had deflected by 110 mm at the end of the fire exposure. The slab was left for 24 h to cool down before testing to failure when resisted to 55% of its original design flexural strength. The failure mode was determined as the pullout of bars. On the other hand, the second slab with 51 mm of concrete cover and 500 mm unexposed length at the ends recovered its full design strength when tested 24 h after 3.5 h exposure to a standard fire.

Gooranorimi et al. [23] exposed six small-scale 2000 mm long GFRP reinforced slabs to ASTM-E119 [24] standard fire. The slabs were similar to each other with the exception of the surface treatments of the reinforcing bars; three of the slabs were reinforced with sand coated GFRP reinforcing bars, and the other three slabs were reinforced with bars with surface deformations. The slabs were placed vertically and loaded to almost 25% of their theoretical flexural strength. The clear concrete cover to the bottom of the reinforcing bars was 19 mm, and after two hours of exposure, the temperature in the bars increased to 115 °C on average. The temperature increase was substantially lower than the anticipated values in a slab placed on top of a furnace [19]. With this low elevated temperature exposure, the reinforcing bars were not severely damaged from two hours of heat exposure, and even slight improvements were observed in the post-fire residual strength of the slabs when compared to the control slabs.

This paper studies the post-fire residual behaviour of GFRP reinforced concrete slabs from a holistic point of view. The scope of the present study was developed based upon the research need in quantifying the post-fire residual characteristics properties of GFRP reinforced concrete slabs. The variety of GFRP products demands a comprehensive and uniform study on the common types of products used in construction. Therefore, the material properties (tensile and bond strength) of three types of GFRP reinforcing bars were studied after exposure to elevated temperature. Finally, one GFRP reinforced concrete slab that survived three hours of the standard fire was tested to determine the post-fire residual strength. The slab was reinforced with the same GFRP bars that were tested for residual tensile and bond strengths. It should be mentioned that the fire test on the slab [18] was tested according to the provisions of ASTM E119 [24] at the National Research Council of Canada in Ottawa. Then, the slab that survived the test was transported to Queen's University for the residual test since it did not fail during the standard fire. Only the post-fire residual behaviour of the slab is presented in this paper; the results of the fire test on the GFRP reinforced concrete slabs are presented elsewhere [18].

## 3. Experimental program

The experimental work consisted of three distinct phases. First, 23 specimens were tested to determine the residual tensile strength of GFRP reinforcing bars after exposure to high temperatures. Second, 47 concrete cubes (150 mm) pullout specimens were fabricated and tested. Finally, one full-scale GFRP reinforced concrete slab was tested to assess its post-fire residual behaviour.

GFRP reinforcing bars with a nominal diameter of 16 mm (#5 bars) were received from three different manufacturers and denoted as GA, GB and GC (Fig. 1). Type GA reinforcing bars use an exterior sand-coated surface to create the bond with the concrete. On the surface of the GB bars, a helically wound braid of fibres is used in addition to a sand coated surface. These tightly wound glass braids create convex protrusions on the surface of the bars. The GC bars use a ribbed surface that is cut into the hardened bar after the pultrusion process. Therefore, the ribs do not contribute to the tensile strength of the GC bars. The bars all have continuous glass fibres in the longitudinal direction with vinyl ester used as the binding resin.

The material properties at room temperature were provided by the manufacturers (Table 1). The ultimate tensile capacity values were 340, 256, and 282 kN for GA, GB, and GC, respectively. These tensile load capacities of the bars were used in presenting the residual tensile strength test results. The glass transition ($T_g$) temperature value for GA and GB bars was determined (by the manufacturers) using the

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