Properties of GFRP Bars Subjected to High Temperature

Maan Hatam Saeed
College of Engineering, Department of Civil Engineering, University of Baghdad, Iraq
maan.hatem2101p@coeng.uobaghdad.edu.iq (corresponding author)

Ali Hussein Ali Al-Ahmed
College of Engineering, Department of Civil Engineering, University of Baghdad, Iraq
dr.ali-alahmed@coeng.uobaghdad.edu.iq

Received: 24 November 2024 | Revised: 9 December 2024 | Accepted: 19 December 2024

 DOI: https://doi.org/10.48084/etasr.9710

ABSTRACT

This study evaluates the properties of Glass Fiber Reinforced Polymer (GFRP) bars exposed to high temperatures. An experimental program was carried out, which investigated 30 samples burned at different temperatures, 300 °C, 500 °C, and 700 °C, and compared them with additional unburned samples. The chosen parameters in this study consist of the concrete cover thickness and the burning temperature. The experimental results demonstrated that at a temperature of 300 °C, burning did not significantly affect the tensile strength of the covered samples, as it exhibited a decrease between 0% and 7%. In contrast, at a temperature of 500 °C, burning significantly influenced the specific samples' tensile strength, as its decrease ranged between 0 and 30%. At 700 °C, burning substantially impacted the covered samples' tensile strength, causing a reduction ranging from 2% to 58%, contingent on the concrete cover thickness. It was generally observed that the samples' tensile strength decreased as the burning temperature increased, and that although significant alterations in the tensile characteristics of the uncoated GFRP bars were noted at 300 °C, the critical threshold for the coated GFRP bars was identified around 500 °C.

keywords-concrete cover; elevated temperature; fire; GFRP bars; burning

I. INTRODUCTION

In the past few years, there has been an increased interest in employing GFRP composites to enhance the concrete elements for infrastructure restoration. This trend has been consistently observed for around 40 years. GFRP reinforcement serves a wide variety of purposes, including constructing new buildings and rehabilitating existing ones [1-5]. Authors in [6] investigated the effects of exposing standard concrete to temperatures of 400 °C and 700 °C. Two scenarios of steel reinforcement combustion were tested alongside the exposure of 12 mm steel reinforcement bars. Some of them were subjected to elevated temperatures, 400 °C and 700 °C, while a 15 mm concrete barrier protected some of the other bars. The experimental results showed that after one hour of fire exposure at 400 °C and 700 °C, followed by gradual cooling, the residual average compressive strength of concrete was 85.3% and 41.4%, respectively. Similarly, the remaining average modulus of elasticity was 75% at 400 °C and 48% at 700 °C. Following combustion and subsequent cooling under identical conditions, the average tensile stress yield (Ø 12 mm) was recorded at 96.59% and 86.39% for the concrete-encased bars, and 93.39% and 81.29% for the exposed bars, respectively. Authors in [7] examined the residual tensile characteristics of freshly engineered GFRP bars following their exposure to extreme temperatures for several hours. This study examined a total of 120 GFRP samples, 50% of which were encased in concrete, while the remaining 50% constituted exposed bars. The samples were exposed to three distinct regulated temperatures, namely 100 °C, 200 °C, and 300 °C, for three varying time durations, 1, 2, and 3 hours. The test findings indicated that negligible losses in the tensile modulus were recorded across all exposure durations and temperatures. Decreases in tensile strength, correlated with the temperature levels and duration of exposure, were documented. The rebars with a concrete overlay exhibited greater residual tensile strength than those without coating. The cover of concrete demonstrated greater efficacy at the minimum temperature of 100 °C and the briefest duration, 1 hour. The Scanning Electron Microscopy (SEM) technique was employed to examine the impact of high temperature on the deterioration mechanism of GFRP rebars. The findings indicated that elevating the temperature influenced the resin matrix encasing the glass fibers, impacting the adhesion between the fibers and the matrix. Authors in [8] presented the experimental findings of an investigation examining the impact of increased temperatures on the binding characteristics of GFRP bars within concrete. A number of 39 pullout specimens incorporating GFRP bars were fabricated for bond strength assessments. Alongside the lab temperature, the samples underwent heating protocols of 100 °C, 200 °C, 300 °C, and 350 °C for durations of 1, 2, and 3 hours. The experiment's findings were reported in terms of the bond strength, bond–slip relationship, and failure mode. All instances failed owing to the shearing of the concrete corbel around the bars, with no damage seen in the GFRP bars. The findings indicated that the binding strength diminished with a rising temperature or prolonged exposure duration. Reductions of around 20% in the initial binding strength were observed following the exposure to 100 °C and 200 °C for 3 hours. Substantial decreases of around 50% in binding strength were noted subsequently to the exposure to 350 °C for 2 and 3 hours. A revision of the ACI and Comité Euro-International du Béton-Fédération Internationale de la Précontrain (CEB-FIP) equations was formulated to account for the impact of the increased temperatures, demonstrating a strong concordance with the experimental data.

Authors in [9] presented the experimental findings of a strength tensile testing performed on GFRP rebars at high temperatures. They examined five regularly utilized GFRP reinforcement rebars with a diameter of 16 mm to accurately reflect the actual building procedures. In addition to the traditional steady-state fire testing, tensile tests were performed under transient fire settings. In transient testing, the samples are subjected to loading before thermal exposure. The temperature range for the steady state testing is specified as 26 °C to 500 °C, depending on the bar kind, whereas for transient fire tests, rods are subjected to loads ranging from 26% to 71% of their strength at ambient temperature. The primary finding concerning the fire behavior of the GFRP-reinforced concrete components is that the three examined kinds of GFRP bars can sustain the expected service load at approximately 25% of their original strength in tension at a minimum of 400 °C. Authors in [10] examined the mechanical and bonding characteristics of GFRP and steel rebars under the influence of increased temperatures using a comparative analysis. Axial tensile and pull-out tests were conducted on these materials after they were subjected to increased temperatures ranging from 23 °C to 800 °C. Significant alterations in the tensile characteristics of bare steel bars were noted after exposure to 600 °C, whereas the critical threshold for bare GFRP bars was identified at 300 °C. Although the test results revealed that the bonding strength loss for both rebars was nearly linear, the critical temperature for noticeable concrete degradation was 600 °C. Authors in [11] investigated the residual adhesion between concrete and fiberglass reinforcement under fire conditions/exposure. The properties evaluated at elevated temperatures included the concrete's compressive strength, the ultimate tensile strength and elasticity modulus of the reinforcing bars, as well as the bonding strength and slippage. The suggested correlations at high temperatures were contrasted with the empirical findings. The findings indicated that the established bonding strength and slipping at/in/for peak bonding stress correlations at increased temperatures, ranging from 21 °C to 350 °C, are applicable for GFRP reinforcement bars, exhibiting ultimate tensile strengths ranging from 501 MPa to 1500 MPa. Authors in [12] conducted experimental and analytical studies on the bond behavior of GFRP bars and concrete at slightly increased temperatures. Steady-state tensile and pull-out tests were conducted on two ribbed GFRP rebars, characterized by distinct glass transition temperatures (Tg of 104 °C and 157 °C), ranging from an ambient temperature to 300 °C. The tensile strength and elasticity modulus of the struck GFRP rebars, particularly the strength and stiffness of the GFRP-concrete interface, were significantly diminished with an elevated temperature. Authors in [13] investigated the tensile performance of GFRP rods subjected to extreme temperatures reaching 717 °C. Tensile examinations were conducted at various increased temperatures within steady-state circumstances on 4 distinct kinds of GFRP rods supplied by separate suppliers. The reduction in tensile strength and modulus of elasticity with increasing temperatures was assessed and compared to the results reported in the existing literature. The findings were utilized to develop analytical models, characterizing the decline of the tensile characteristics of the GFRP rebars with burning. The findings demonstrated that the tensile strength deteriorated significantly more at elevated temperatures compared to the modulus of elasticity, particularly through the glass transition and after the resin's breakdown. At 714 °C, following the complete breakdown of the epoxy, the tensile capacity dropped to 4% of its worth at a normal temperature although the residual modulus of elasticity remained at 65%.

II. EXPERIMENTAL PROGRAM

The experimental program conducted in the current study explored the general effect of the concrete cover on the individual inherent GFRP bar, subjected to elevated temperatures and assigned the sensitivity of bars to such temperatures. Since GFRP bars exhibit a reduction in mechanical strength when exposed to high temperatures, this section examines their residual strength after such exposure to evaluate its impact on the performance of GFRP-reinforced concrete beams. The GFRP bars used in this study have a diameter of 12 mm and a length of 40 cm. The bar was embedded in a mold (prism), specifically designed to accommodate the bar and provide the required concrete cover for the study. Figure 1 shows the prisms of these parts. The cast prisms were exposed to elevated temperatures of 300 °C, 500 °C, and 700 °C, respectively. The concrete covers around each bar were taken as 1 cm, 2 cm, 2.5 cm, 3 cm, 4 cm, 5 cm, 6 cm, 7 cm, and 8 cm, respectively, from each side (Square section), as evidenced in Figure 2, in addition to the uncovered burned samples displayed in Figure 3. Each reading within the recorded response represents an average of three prisms. After an exposure to high temperature levels, the prisms were fractured to extract the GFRP levels to be subjected to tensile testing to inspect the residual strength, as illustrated in Figure 3. Table I depicts the details of the examined samples.

One size of GFRP bars with nominal diameters of 12 mm was employed. The results of the tensile test for the unburned uncovered bar are outlined in Table II. A photograph of the testing machine is portrayed in Figure 4. The testing was carried out according to the Standard Specification ISO 10406-1-(2015) standard specifications [14]. The GFRP bars were examined in the Structural Laboratory, Department of Civil Engineering / College of Engineering / University of Diyala.

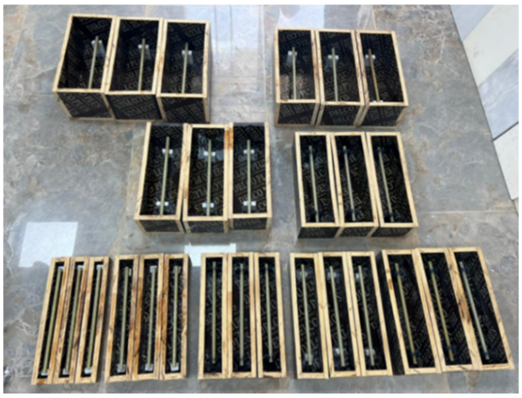

Fig. 1. The casted prism for the evaluation of the GFRP bars.

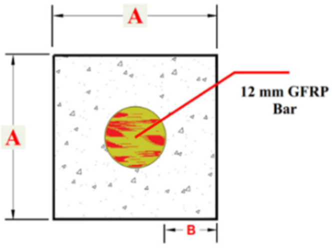

Fig. 2. A= 3.2 cm, 5.2 cm, 6.2 cm, 7.3 cm, 9.2 cm, 11.5 cm, 13.5 cm, 15.5 cm, and 17.5 cm. B= 1 cm, 2 cm, 2.5 cm, 3 cm, 4 cm, 5 cm, 6 cm, 7 cm, and 8 cm. The prism section of the GFRP bar.

TABLE I. DETAILS OF THE EXAMINED SAMPLES

No.	Temperature (°C)	Concrete cover (mm)
1	Ambient	without
2	300 °C	without
3	300 °C	10
4	300 °C	20
5	300 °C	25
6	300 °C	30
7	300 °C	40
8	300 °C	50
9	300 °C	60
10	300 °C	70
11	300 °C	80
12	500 °C	without
13	500 °C	10
14	500 °C	20
15	500 °C	25
16	500 °C	30
17	500 °C	40
18	500 °C	50
19	500 °C	60
20	500 °C	70
21	500 °C	80
22	700 °C	without
23	700 °C	10
24	700 °C	20
25	700 °C	25
26	700 °C	30
27	700 °C	40
28	700 °C	50
29	700 °C	60
30	700 °C	70
31	700 °C	80

Fig. 3. (a) GFRP bar extraction after burning from prism section, (b) GFRP bar preparation for the tensile test.

TABLE II. TENSILE PROPERTIES OF THE REFERENCE GFRP BARS

Diameter (mm)	Initial area (mm^2)	Max. force (N)	Elongation (%)	Tensile strength at break (MPa)
12	113.09	148147.9	3	1310

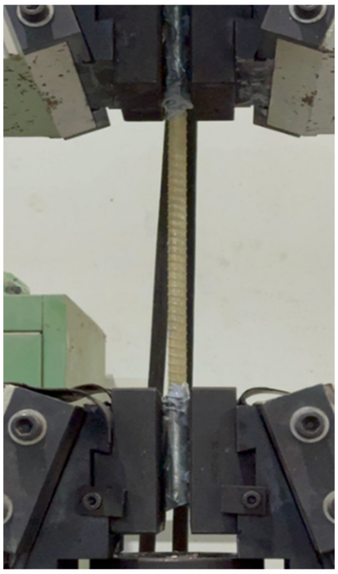

Fig. 4. GFRP bar tensile test.

Table III depicts the mix proportion that was used to cast the concrete cover of the GFRP bars. The unburned compressive strength of concrete (*f'c*) was 39.66 MPa.

TABLE III. MIX PROPORTION

w/c	Mix Proportion (kg/m^3)				
	Cement	Sand	Gravel	Water	Superplasticizer
0.3	470	827	945	147	6.22

The furnace was fabricated from a 5 mm thickness steel plate in a box configuration to facilitate the concurrent burning of many specimens. Figure 5 demonstrates that the dimensions of its interior space are 60 cm in height, 200 cm in width, and 300 cm in length. The furnace had 12 methane flame nozzles and 4 Air compressed-through nozzles, all set at the lowest level. Multiple small openings for ventilation and thermocouple wires were located on the upper layer of the furnace. Figure 6 illustrates the incinerated exposed samples.

Fig. 5. The furnace.

Fig. 6. The furnace.

III. TENSILE TEST POST-FIRE RESULTS AND DISCUSSION

A comparative analysis of the test results was performed, examining the behavior of the burned samples compared to the control sample.

A. Compressive Strength of Cylinder Concrete (f'c)

The remaining compressive strength data for the cylinders following the exposure to temperatures of 300 °C, 500 °C, and 700 °C are presented in Table III and Figure 7. The test findings are juxtaposed with the diminished estimated values derived from the formulae proposed in [15]. The experimental results align with the values provided by the particular equations, while it was observed that the disparity was minimal across all temperatures. Figure 7 exhibits a sharp decline in compressive strength as the temperature surpasses 500 °C. Figure 8 provides an illustration of the compressive strength test.

TABLE IV. EFFECT OF BURNING ON COMPRESSIVE STRENGTH

Temperature (°C)	*f′*c (MPa)	Average residual strength (%)	Residual strength (%)
ambient	39.66	100	100
300	35.11	88.5	95.5
500	31.79	80.2	72.6
700	21.81	55	41.4

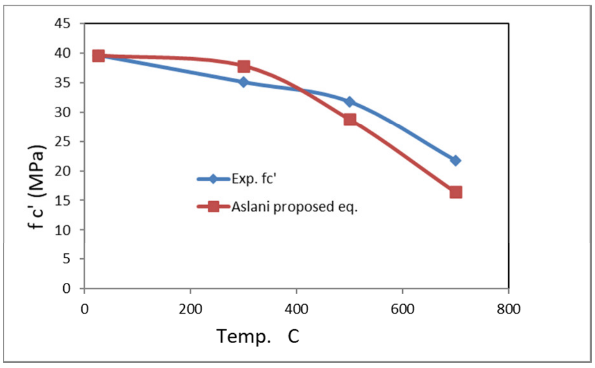

Fig. 7. Burning temperature versus compressive strength (fc').

Fig. 8. Compressive strength test.

B. Properties of Burned GFRP Bars

A total of 31 samples of GFRP bars, both uncovered and covered with concrete, were tested. These samples were subjected to high temperatures of 300°C, 500°C, and 700°C. Each temperature group included 9 samples, with varying concrete cover thicknesses: 10 mm, 20 mm, 25 mm, 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, and 80 mm. The uncovered group consisted of four samples. The impact of the high temperatures on the properties of the GFRP bars is summarized in Table V, where each value represents the average results of three samples. In general, the greater the concrete cover of the sample was, the less was the tensile strength decrease percentage of the burned GFRP bars. At 300 °C, burning did not significantly affect the tensile strength of the covered samples, as it decreased from 0% to 7% across all concrete cover values. However, at 500 °C, burning significantly affected the tensile strength, as the amount of its decrease for the covered samples ranged between 0% and 30% across all concrete cover values. At 700 °C, burning had a substantial impact on the tensile strength, with its reduction ranging from 2% to 58% for the covered samples across all concrete cover values. The tensile strength decreased progressively as the burning temperature increased. For the uncovered samples, the tensile strength decreased by 40%, 58%, and 85% at burning temperatures of 300 °C, 500 °C, and 700 °C, respectively, compared to the unburned reference sample. Hence, the uncovered samples were the most significantly affected. Figure 9 depicts the GFRP bars covered with concrete samples. As shown in Figure 10, the modulus of elasticity remained largely unaffected by the burning and cooling processes, as indicated by the consistent slope of the linear portions of the stress-strain curves. The shapes of stress-strain curves for the specimens exposed to and recovered from high temperatures were similar, which aligns with the findings from another research. Figure 11 displays the stress-strain relationship of the burned, uncovered GFRP bars [16, 17].

TABLE V. EFFECT OF FIRE FLAME ON THE PROPERTIES OF GFRP BARS- Ø 12MM

Temperature (°C)	Concrete cover (mm)	Tensile strength (MPa)	Decreasing percentage of tensile strength (%)
Ambient	without	1263	Ref.
300 °C	without	758	40
300 °C	10	1175	7
300 °C	20	1216	4
300 °C	25	1228	2.75
300 °C	30	1260	0.3
300 °C	40	1262	0
300 °C	50	1263	0
300 °C	60	1263	0
300 °C	70	1263	0
300 °C	80	1263	0
500 °C	without	530	58
500 °C	10	883	30
500 °C	20	922	27
500 °C	25	960	24
500 °C	30	972.5	23
500 °C	40	1011	20
500 °C	50	1126	11
500 °C	60	1215	4
500 °C	70	1226	3
500 °C	80	1263	0
700 °C	without	189	85
700 °C	10	530	58
700 °C	20	555.72	56
700 °C	25	627	50
700 °C	30	758	40
700 °C	40	812	38
700 °C	50	973	23
700 °C	60	1111	12
700 °C	70	1200	5
700 °C	80	1238	2

Fig. 9. GFRP bars covered with concrete samples.

(a)
(b)
(c)

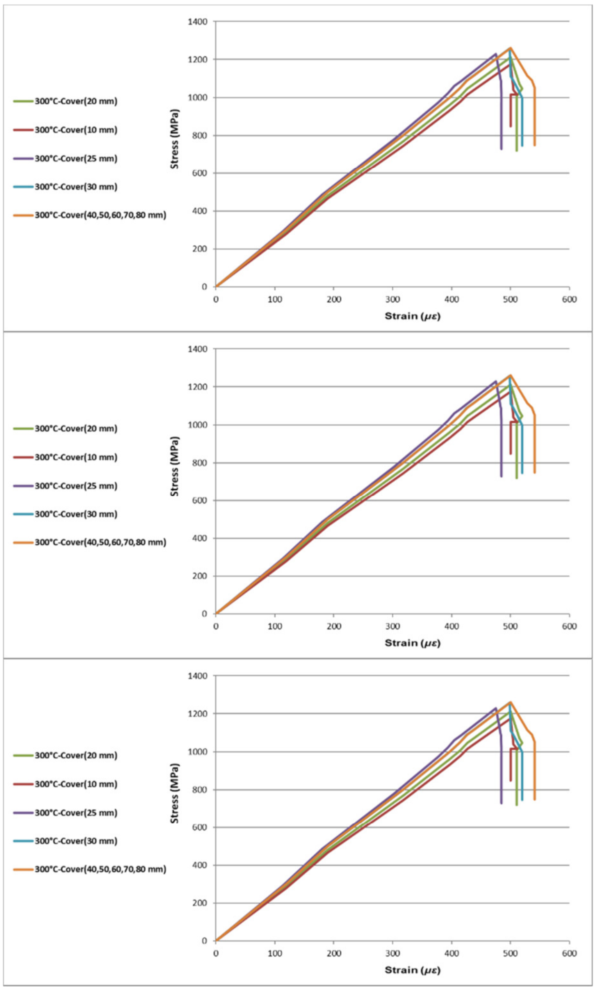

Fig. 10. Stress-strainss–strain relationship of burned-covered GFRP bars. (a) 300 °C, (b) 500 °C, (c) 700 °C.

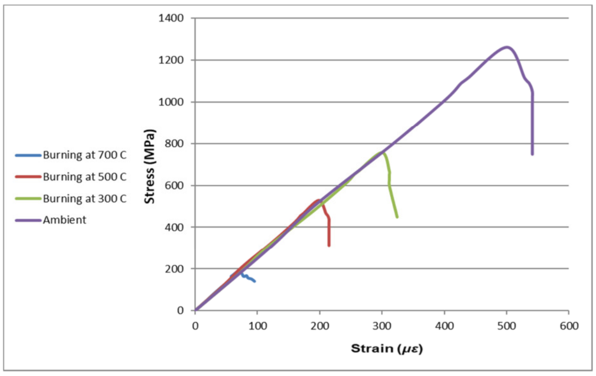

Fig. 11. Stress-strain relationship of burned uncovered GFRP bars.

IV. CONCLUSIONS

- The percentage of the residual concrete compressive strength was 95.5%, 72.6%, and 41.4% for burning temperatures of 300 °C, 500 °C, and 700 °C, respectively, according to the reference unburned sample. The residual concrete compressive strength was therefore inversely proportional to the burning temperature.

- At 300 °C, burning did not significantly impact the tensile strength of the covered samples, as its decrease ranged between 0% and 7%. On the contrary, at 500 °C, burning significantly affected the covered samples' tensile strength, as it decreased from 0% to 30%. At 700 °C, burning had a pronounced impact on the covered samples' tensile strength, with its reduction ranging from 2% to 58% across all concrete cover values. It was noted that the tensile strength consistently decreased as the burning temperature increased.
- The modulus of elasticity remained largely unchanged by the burning and chilling procedures since the linear segments exhibited identical slopes.
- The tensile strength decrease percentage of the burned Glass Fiber Reinforced Polymer (GFRP) bar was inversely proportional to the concrete cover thickness.
- Significant alterations in the tensile characteristics of the uncoated GFRP bars were noted at 300 °C, but the critical threshold for the coated GFRP bars was identified around 500 °C.

REFERENCES

[1] A. F. Hallawi and A. H. A. Al-Ahmed, "Enhancing the Behavior of One-Way Reinforced Concrete Slabs by Using Laced Reinforcement," *Civil Engineering Journal*, vol. 5, no. 3, pp. 718–728, Mar. 2019, https://doi.org/10.28991/cej-2019-03091282.

[2] A. H. A. Al-Ahmed, A. H. Al-Zuhairi, and A. M. Hasan, "Behavior of reinforced concrete tapered beams," *Structures*, vol. 37, pp. 1098–1118, Mar. 2022, https://doi.org/10.1016/j.istruc.2022.01.080.

[3] Z. K. Al-Mamory and A. H. A. Al-Ahmed, "Behavior of steel fiber reinforced concrete beams with CFRP wrapped lap splice bars," *Structures*, vol. 44, pp. 1995–2011, Oct. 2022, https://doi.org/10.1016/j.istruc.2022.08.096.

[4] B. F. Abdulkareem, A. F. Izzet, and N. Oukaili, "Post-Fire Behavior of Non-Prismatic Beams with Multiple Rectangular Openings Monotonically Loaded," *Engineering, Technology & Applied Science Research*, vol. 11, no. 6, pp. 7763–7769, Dec. 2021, https://doi.org/10.48084/etasr.4488.

[5] M. Abdulkhaliq and A. H. Al-Ahmed, "Behavior of GFRP Reinforced-Concrete Bubbled One-Way Slabs by Encased Composite Steel I-Sections," *Engineering, Technology & Applied Science Research*, vol. 14, no. 5, pp. 16701–16712, Oct. 2024, https://doi.org/10.48084/etasr.8123.

[6] B. F. Abdulkareem and A. F. Izzet, "Post Fire Residual Concrete and Steel Reinforcement Properties," *IOP Conference Series: Earth and Environmental Science*, vol. 856, no. 1, Jun. 2021, Art. no. 012058, https://doi.org/10.1088/1755-1315/856/1/012058.

[7] S. Alsayed, Y. Al-Salloum, T. Almusallam, S. El-Gamal, and M. Aqel, "Performance of glass fiber reinforced polymer bars under elevated temperatures," *Composites Part B: Engineering*, vol. 43, no. 5, pp. 2265–2271, Jul. 2012, https://doi.org/10.1016/j.compositesb.2012.01.034.

[8] S. El-Gamal, "Bond strength of glass fiber-reinforced polymer bars in concrete after exposure to elevated temperatures," *Journal of Reinforced Plastics and Composites*, vol. 33, no. 23, pp. 2151–2163, Dec. 2014, https://doi.org/10.1177/0731684414555408.

[9] H. Hajiloo, M. F. Green, and J. Gales, "Mechanical properties of GFRP reinforcing bars at high temperatures," *Construction and Building Materials*, vol. 162, pp. 142–154, Feb. 2018, https://doi.org/10.1016/j.conbuildmat.2017.12.025.

[10] F. M. Özkal, M. Polat, M. Yağan, and M. O. Öztürk, "Mechanical properties and bond strength degradation of GFRP and steel rebars at elevated temperatures," *Construction and Building Materials*, vol. 184, pp. 45–57, Sep. 2018, https://doi.org/10.1016/j.conbuildmat.2018.06.203.

[11] F. Aslani, "Residual bond between concrete and reinforcing GFRP rebars at elevated temperatures," *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, vol. 172, no. 2, pp. 127–140, Feb. 2019, https://doi.org/10.1680/jstbu.17.00126.

[12] I. C. Rosa, J. P. Firmo, J. R. Correia, and P. Mazzuca, "Influence of elevated temperatures on the bond behaviour of ribbed GFRP bars in concrete," *Cement and Concrete Composites*, vol. 122, Sep. 2021, Art. no. 104119, https://doi.org/10.1016/j.cemconcomp.2021.104119.

[13] I. C. Rosa, J. P. Firmo, and J. R. Correia, "Experimental study of the tensile behaviour of GFRP reinforcing bars at elevated temperatures," *Construction and Building Materials*, vol. 324, Mar. 2022, Art. no. 126676, https://doi.org/10.1016/j.conbuildmat.2022.126676.

[14] *Fibre-reinforced polymer (FRP) reinforcement of concrete — Test methods — Part 1: FRP bars and grids*, 2nd ed. ISO, 2015.

[15] F. Aslani, "Prestressed concrete thermal behaviour," *Magazine of Concrete Research*, vol. 65, no. 3, pp. 158–171, Feb. 2013, https://doi.org/10.1680/macr.12.00037.

[16] F. Yang and P. Yao, "Effect of temperature on tensile mechanical properties of GFRP bars with different diameters," *IOP Conference Series: Earth and Environmental Science*, vol. 189, no. 3, Aug. 2018, Art. no. 032068, https://doi.org/10.1088/1755-1315/189/3/032068.

[17] C. Zhou, J. Pan, Z. Zhang, and Y. Zhu, "Comparative study on the tensile mechanical behavior of GFRP bars under and after high temperature exposure," *Case Studies in Construction Materials*, vol. 16, Jun. 2022, Art. no e00905, https://doi.org/10.1016/j.cscm.2022.e00905.