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An Experimental Research Into the Bonding Strength of GFRP Bars in Concrete Under Elevated Temperatures

Ahmed Yahya Gaeeb [1] , Muayad Mohammed Kassim [2]
[1,2] Civil Engineering Department, University of Kirkuk, Kirkuk, Iraq
Email : [1] ahmedyahyagaeeb@gmail.com , [2]moayadmk@uokirkuk.edu.iq

Abstract *This study investigates the bond strength of Glass Fiber Reinforced Polymer (GFRP) bars in concrete at high temperatures. Twenty-four specimens were tested at 600°C to replicate fire conditions and analyze performance consequences in structural applications, with variables such as bar diameter and position within the concrete taken into account. The results show a considerable drop in binding strength, notably in edge-positioned bars with thinner covers, which is related to thermal degradation of the epoxy resin. The stress-slip relationship revealed significant increases in slippage, particularly for bigger diameter bars, as well as the vulnerability of GFRP bars to high temperatures. Failure modes shifted mostly to splitting following exposure, emphasizing the importance of design concerns in fire-prone structures. These findings improve our understanding of GFRP performance in harsh situations, influencing material selection for greater fire resilience.*

Keywords: *Bar Slippage, Bond Strength, Elevated Temperatures, GFRP Bars, And Thermal Degradation.*

1. INTRODUCTION

GFRP bars have great corrosion resistance, are light in weight, and have a high tensile strength, making them suitable reinforcement materials in concrete frameworks. The inquiry of the performance of GFRP bars at high temperatures remains a very relevant topic of interest, especially when considering fire threats in multi-story structures and other structural applications. In reality, the link between the GFRP bars and the concrete is critical to structural and functional performance under severe loads.

The impacts of elevated temperature might appear in numerous ways, including explosive bursting, surface bursting, aggregate bursting, angular bursting, and bursting that occurs during the cooling process of concrete Allah, S.J.S et al.

Many studies have looked into the effect of temperature on the binding strength between GFRP bars and concretes. Solyom et al. found that high temperatures had a significant impact on bond strength in GFRP bars; unexpected deteriorations were observed even at temperatures as low as 200°C. This was consistent with a similar finding by Aydin, who investigated the effect of thermal expansion on the bond performance of GFRP bars implanted in concrete and discovered that high temperatures significantly reduce bond strength. According to Masmou, bond strength decreases at high temperatures, highlighting the importance of a thorough understanding of GFRP bond performance in fire conditions.

In reality, experimental research have always focused on how warmth affects the bonding properties of GFRP bars. Rosa et al. discovered that increasing the temperature significantly affects the bond strength and rigidity of ribbed GFRP bars, highlighting the need for further research into the variation of GFRP-reinforced concrete behavior in different

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thermal settings. Özkal et al explained that increased temperature and time of exposure weakens the link between GFRP bars and concrete, highlighting the importance of including fire-resistance aspects in structural design.

Temperature has an impact on the GFRP bars that work in the concrete matrix, as well as their bonding behavior. In a 2020 study, Albu-Hassan et al. investigated the bond characteristics of hybrid concrete beams reinforced with GFRP bars.

They emphasized that bar position has a crucial role in determining total bond strength. This conclusion was supported by Hajiolo et al. in 2018, who found that the position of GFRP bars, whether centrally or at an edge, had a substantial impact on their performance when exposed to high temperatures.

As a result, the thermal stress response of GFRP bars is of major relevance to structural engineers as well as materials scientists working to improve the performance of composites. Aslani studied the residual bond strength of GFRP bars after high-temperature exposure, which hinted at maintaining bond strength but showed significant losses. It identifies new GFRP formula advancements that can enhance bond performance under thermal stress.

Other research into the mechanism of bond action between GFRP bars and concrete has focused on interface properties and stress transfer processes. Examples include Najafabadi et al.'s work on the tensile behavior of FRP bars embedded in concrete [10]. This demonstrated that there are highly complicated interactions at the interface that vary with temperature.

The findings from their contributions, among others, emphasize the importance of conducting detailed investigations into the mechanism that controls bond strength decline at high temperatures.

Given the significant effects that temperature can have on the performance of bonds in concretes, current research investigates the bond strength of GFRP bars under simulated fire circumstances in depth. This study will attempt to understand how temperature and exposure time effect bond behavior in the case of GFRP bars bonded within concretes while also enriching the database.

2. EXPERIMENTAL PART

Overview

This study looks at how elevated temperatures affect the bond strength formed between GFRP bars and concrete, as well as the effects of bar diameter and concrete cover. The systematic framework for the research included a variety of tests that model worst-case fire scenarios generated in multi-story structures, with the goal of assessing and investigating the behavior of GFRP bars in concrete in varied temperature settings.

Specimen Preparation

A total of twenty-four concrete cube specimens (150x150x150 mm) were prepared for the pull-out experiment, using normal-weight concrete with a compressive strength (fc') of 30 MPa. The concrete mix design intended for maximum performance and used standard Portland cement, coarse aggregates, sand, and water. The mix was adjusted to provide the desired mechanical characteristics. Following casting, the specimens were cured in a water basin for 28 days.

Mechanical Property Testing

Compressive Strength Testing

The concrete's mechanical properties, including compressive and tensile strength, were evaluated both before and after the elevated temperature program. Standard (150x150x150 mm) cubes were tested for (fc') on a universal testing machine. The average compressive strength observed was 31.5 MPa, but the average tensile strength (f_t) tested using cylindrical specimens was 4.65 MPa.

Specimen Configuration

The study used three different diameters of GFRP bars (10 mm, 12 mm, and 16 mm) that were embedded in concrete specimens in two ways: at the center of specimens (C group) and at the edge of specimens with a 40 mm clear cover (E group). Each test location was designed to investigate the effect of bar position on bond strength during thermal exposure; the embedment length of GFRP bars in concrete was 100 mm, as illustrated in Figure 1.

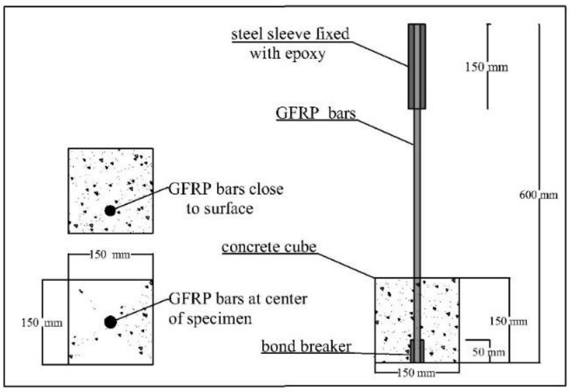


Figure 1. GFRP Bar positions and specimen dimensions.

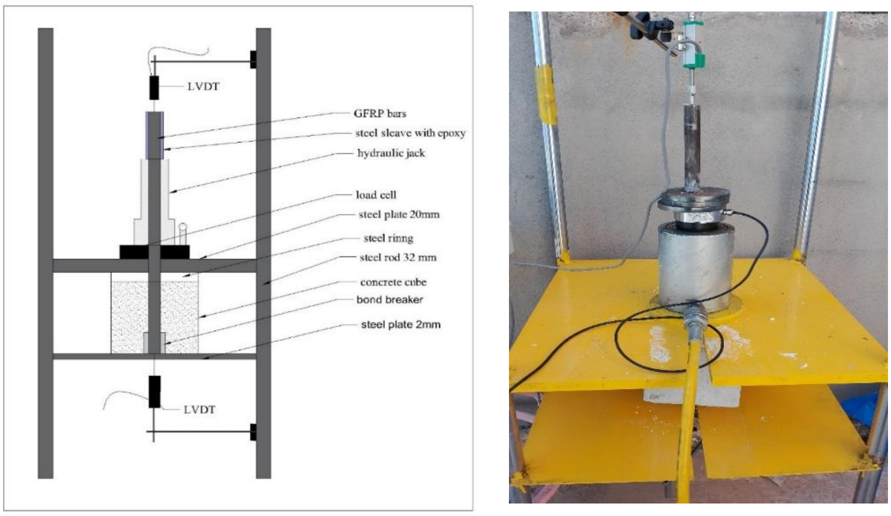
Thermal Exposure Procedure

The specimens underwent a controlled heating process in a furnace designed to replicate fire conditions. The furnace was warmed to a target temperature of 600 degrees Celsius. The temperature was measured with a thermometer and translated using a type K thermocouple.

Where the temperatures of the furnace, concrete core, and GFRP bars were measured at regular intervals to create a time-temperature relationship. As a result, each specimen was exposed to high temperatures for 90 minutes, which was chosen to simulate emergency reaction circumstances and meet ASTM E119 requirements .

Pullout Testing

Pullout tests were done after thermal exposure to assess the bond strength between the GFRP bars and the concrete. These tests were carried out using a customized frame, as indicated in Figure 2. Each specimen was exposed to increased loads until failure occurred. Linear Variable Differential Transformer) sensors (LVDT) were utilized to measure slippage during loading at the loaded and free ends of the bar, with data loggers recording 80 values per second. The bars' maximum load capacity and the load values that caused initial slippage were recorded, and load-slip curves were created to investigate bond behavior.



(a) (b)

Figure 2. Test loading frame setup (a) sketching schematic (b) Photo.

Data Analysis

The data that obtained from the concrete mechanical properties tests and pullout tests before and after elevated temperature, were analyzed statistically:

Bond Strength: Calculated using the maximum load (P_{max}) and the effective embedment length of the GFRP bars as shown in **Equation (1)** with values expressed in MPa.

$$\tau = \frac{P_{max}}{\pi dl} \text{ ....(1)}$$

Where,

- τ is the nominal bond strength,
- P_{max} is the peak load applied,
- d is the diameter of the bar,
- l is the embedment length.

Stress Ratio: Defined as the ratio of the actual applied force to the 75% of maximum tensile force capacity of the GFRP bars, providing insights into their performance under load before and after elevated temperature.

K value: Defined as nominal bond strength per unit embedment length (l) which is represented by (K) and is ruled by the square root of f_c' as given in the Equation (2).

$$K = \frac{p_{max}}{l\sqrt{f_c'}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

Failure Modes: The modes of failure were classified (e.g., pullout, splitting and pullout coincides with splitting) based on the specimens observable behavior of the during testing.

Residual Compressive strength: Effect of elevated temperature on compressive strength of concrete and its relationship to bond strength developed at GFRP bars.

3. RESULTS

The aim of this section is to expound on the thorough analysis of the test results obtained from the 24 specimens tested, with a particular emphasis on the temperature impacts on bond strength and characteristics.

Mechanical Properties of Normal Weight Concrete

In this paper, the bond performance of GFRP bars in concrete is addressed using the mechanical properties of normal weight concrete as a reference. The average compressive strength of the tested cubes was 31.5 MPa, whereas the average tensile strength of the cylinders was 4.65 MPa.

The significance of this strength is that it provides a benchmark against which the bond-slip performance of the GFRP bars can be evaluated.

Temperature Growth Diagrams for Furnace, Concrete, and GFRP Bars

The effect of elevated temperature on the specimens was investigated, indicate that temperature rapidly increased within the furnace during the initial 15 minutes of exposure, while the temperature at the of center specimens and in the GFRP bars increased gradually until reaches constant value with very little change during the test. The evaporation of moisture within the concrete pores and the inherent thermal properties of concrete contributed to the overall temperature distribution.

Figure 3. explains the time-temperature relationship, where it was observed during 90 minutes at 600°C, the temperature in core of concrete and GFRP bars reached to 303°C when GFRP bars at the center of specimens, while GFRP bars attained a temperature of 385°C when GFRP at the edge of specimens, the result also found by Hussien, N et al. [12] indicating substantial heat transfer..

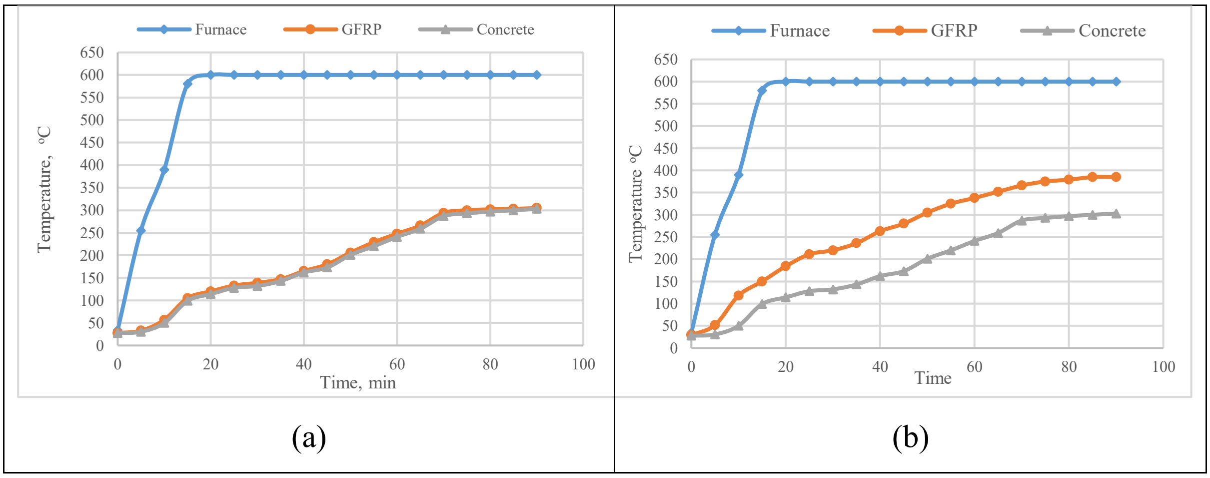


Figure 3 Thermal reactions when specimens exposed to a 600 ºC**.** (a)GFRP bar at the Edge with clear cover 40 mm.(b) GFRP bar at center of specimens.

The effect of elevated temperature on the specimens was tested, and the results are shown in Figure 3. During the first 15 minutes of exposure, the temperature in the furnace rises quickly, but the temperature in the center specimens and GFRP bars rises gradually until it reaches a constant value with very little fluctuation during the test. The overall temperature distribution was influenced by moisture evaporation within the concrete pores as well as the thermal characteristics of the concrete itself.

Figure 3 depicts the time-temperature relationship, which was measured over 90 minutes at 600 °C. The temperature in the core of concrete and GFRP bars reached 303°C when GFRP bars were in the center of specimens, and 385°C when GFRP bars were at the edge of specimens, as found by Hussien, N et al. [12], showing significant heat transfer. The considerable temperature rise within the GFRP bars indicates how thermal exposure affects their structural integrity.

Pullout Test Results

Table 1 shows the pullout test findings; there is diversity in the maximum pullout force applied among the examined specimens, ranging from a maximum of 38.33 kN to a low of 3.2 kN. This variance in results is related to the influence of GFRP diameter, concrete cover effect, and elevated temperatures, which all have a major impact on GFRP bars and concrete characteristics, principally due to the softening of epoxy resin.

The stress ratio of the GFRP bars was significantly reduced, with values ranging from 0.03 to 0.44 at 75% of the ultimate tensile strength of GFRP bars. Because GFRP is a brittle material, it prevents rapid failure in concrete structures, indicating a large loss of bond strength and overall performance capacity of the bars under high-temperature circumstances, as found by Rosa .

The nominal bond strength per unit embedment length (l) is represented by (K), with a maximum value of 69.96 for specimen G3 C T1-2 and a lowest value of 5.84 for specimen G2 E T3-2. This fluctuation is due to the maximum pullout load used during testing, as both the embedment length and(f_c') are kept constant.

Table 1: Pullout test results

Specimens ID	l/d_b	Pmax (kN)	P at First Slippage (kN)	P/P_{max}	Stress Ratio fs/0.75 fu	K Value	Failure Mode
D10 C T1-1	10	29.97	25.94	0.88	0.42	54.04	Pullout + Splitting
D10 C T1-2	10	331.12	29.1	0.95	0.44	56.82	Pullout + Splitting
D10 C T2-1	10	14.25	14.07	0.99	0.20	26.02	Splitting
D10 C T2-2	10	13.69	13.7	1.00	0.19	24.99	Splitting
D10 E T1-1	10	26.9	4.06	0.15	0.38	49.11	Splitting
D10 E T1-2	10	28.34	4.1	0.14	0.40	51.74	Splitting
D10 E T2-1	10	14.9	4.9	0.33	0.21	27.20	Splitting
D10 E T2-2	10	16.7	4.35	0.26	0.24	30.49	Splitting
D12 C T1-1	8.3	26.1	18.74	0.72	0.23	47.65	Pullout + Splitting
D12 C T1-2	8.3	28.02	18.18	0.65	0.25	51.16	Pullout + Splitting
D12 C T2-1	8.3	13.25	9.25	0.70	0.12	24.19	Splitting
D12 C T2-2	8.3	11.95	8.28	0.69	0.11	21.82	Splitting
D12 E T1-1	8.3	22.3	15.47	0.69	0.20	40.71	Splitting

D12 E T1-2	8.3	20.64	16.26	0.79	0.19	37.68	Splitting
D12 E T2-1	8.3	3.2	2.85	0.56	0.03	5.84	Splitting
D12 E T2-2	8.3	6.8	3.98	1.24	0.06	12.42	Splitting
D16 C T1-1	6.25	35	17.93	0.54	0.20	61.16	Splitting
D16 C T1-2	6.25	38.33	18.2	0.47	0.23	69.96	Splitting
D16 C T2-1	6.25	9.3	5.7	0.61	0.06	16.98	Splitting
D16 C T2-2	6.25	10	5.8	0.58	0.06	18.26	Splitting
D16 E T1-1	6.25	30.28	16.12	0.53	0.18	55.28	Splitting
D16 E T1-2	6.25	32.2	16.79	0.52	0.19	58.79	Splitting
D16 E T2-1	6.25	16.3	7.43	0.46	0.10	29.76	Splitting
D16 E T2-2	6.25	15.4	8.43	0.58	0.09	28.12	Splitting

--- Means no data recorded.

Residual Bond Strength after Fire Exposure*

The experimental program also studied the residual bond strength after the specimens were exposed to increased temperatures, which revealed that GFRP bar located in the center of the specimens had much stronger bond strength than those placed at the edge with a 40 mm clear cover.

This is due to the various stress distribution patterns around the bars. The ultimate bond strengths measured were 9.7, 7.2, and 7.1 MPa for 10, 12, and 16 mm diameter bars, respectively, demonstrating the effect of diameter on bond strength. The findings are consistent with McIntyre et al. [13] and Solyom et al. [2].

These statistics (see Table 2) demonstrate the considerable loss of bond strength in GFRP bars due to exposure to high temperatures. GFRP bars with a diameter of 16 mm experience a 73.13% reduction in bond strength after being heated at 600°C for 90 minutes. This loss is mostly caused by the weakening of the epoxy glue binding the glass fibers at high temperatures, which results in the loss of the bond between the GFRP bars and concrete. Such findings are consistent with other investigations, including Katz et al [14]. 2018 attained a 30-38% bond strength loss at 250°C though El-Gamal [15] attained a 50% bond strength loss at 350°C. The studies conducted by Özkal et al [6] confirm that losses in bond strength occur even at relatively low temperatures, such as 100°C, indicative of significant susceptibility of GFRP bars to thermal degradations.

Table 2. Average bond strength and slip of GFRP bars before and after fire exposure

GROUP ID	Ultimate Force (kN)	% Force Reduction	Slip (mm)			Bond Strength (MPa)
D10 C T1	30.36	--	0.314			9.7
D10 C T2	13.97	54	0.95			4.4
D10 E T1	27.62	--	0.616			8.8
D10 E T2	15.8	42.80	1.27			5.0
D12 C T1	27.06	--	0.467			7.2
D12 C T2	12.6	53.44	1.05			3.3
D12 E T1	21.47	--	0.714			5.7
D12 E T2	5.0	76.71	0.435			1.3
D16 C T1	35.91	--	1.12			7.1
D16 C T2	9.65	73.13	--			1.9
D16 E T1	31.24	--	0.827			6.2
D16 E T3	15.85	49.26	1.28			3.2

Effect of Bonding Area on Strength Capacity

Figure 4 depicts the relationship between bond strength capacity and diameter of GFRP bars. Notably, bond strength decreased as the diameter increased, with reductions of 26% and 27% when the diameter increased from 10 mm to 12 mm and 16 mm, respectively, due to the effect of stress distribution around the bar, and the same percent of reduction with a slight variation when exposed to elevated temperature 600 ºC for GFRP bars placed in the center of specimens.

While 35% and 30% were reduced when GFRP sat on the edge of specimens at room temperature, the reduction in bond strength after exposure to elevated temperature 600 ºC for GFRP bars 12 mm increased to 70% and 36% for 16 mm.

This large difference in effect of elevated temperature in GFRP with 12 mm is related to a lack of control in the manufacturing of the GFRP bars and the ribs surrounding the bras are not equal in spacing and height, these findings coincide with Mohammed, Djamaluddin et al. and Maranan et al.

farther more the increasing in bond strength reduction as the diameter of GFRP bars increased is related to the fact that larger-diameter bars have a larger surface area that is more susceptible to thermal dilation during a fire, resulting in a greater deterioration effect on bonding contacts. These findings are consistent with Granadeiro, L.M.R et al. , who said that increasing rib height around the rebar increases bond strength losses.

This trend underscores the need of considering bar diameter when designing and constructing GFRP-reinforced concrete structures.

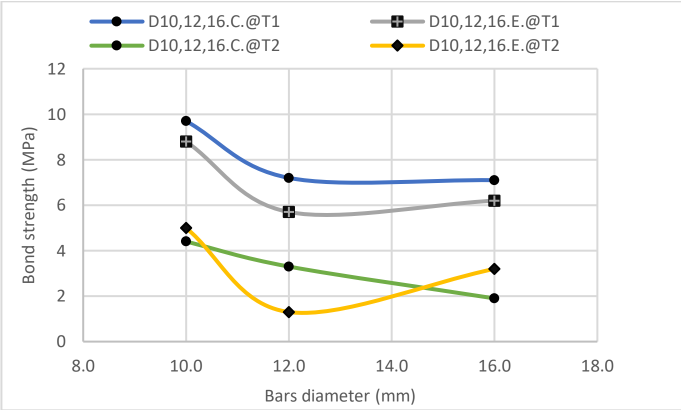


Figure 4. Relationship between bar diameter and bond strength capacity**.**

Bonding Stress-Slip Relationship

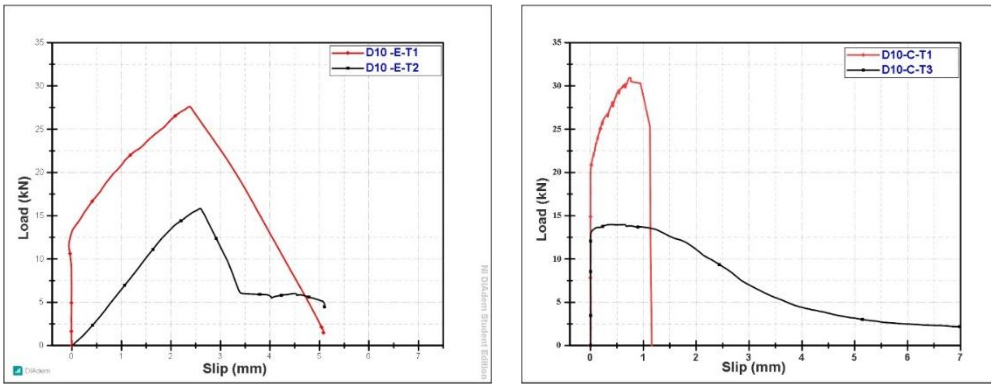
The bond-slip relationships for various diameters of GFRP bars were investigated, and considerable increases in slippage were seen after the specimens were exposed to high temperatures. For example, slippage for 10 mm GFRP bars at the specimen center increased drastically from 0.173 mm at ambient temperature to 1.04 mm at 600°C, indicating a 500% increase, and maximum pullout loads dropped from 30.36 to 13.97 kN, when GFRP bar is fitted with a 40 mm clear cover, the applied load decreases when subjected to elevated temperatures, and slippage increases from 1.55 mm to 1.93 mm at 600 °C, representing a 24% increase.

This finding is due to the influence of the concrete cover, which reduces the stress distribution surrounding the bar, and the applied pullout load decreased from 27.62 kN to 15.8 kN (see **Figure 5**).

For GFRP bars with 12 mm diameter at the center of specimens, slippage was observed as 0.238 mm at ambient temperature, and 1.03 mm at 600 °C. Slippage increased by 332% once the temperature was raised and the applied pullout load decreased from 27.06 kN to 12.6 kN. Meanwhile, for GFRP bars with a 40 mm clear cover, slippage increased from 0.741 mm to 1.15 mm with increases of 55% and the pullout load dropped from 21.47 kN to 5 kN due to effect of concrete cover on the GFRP bars (see **Figure 6**).

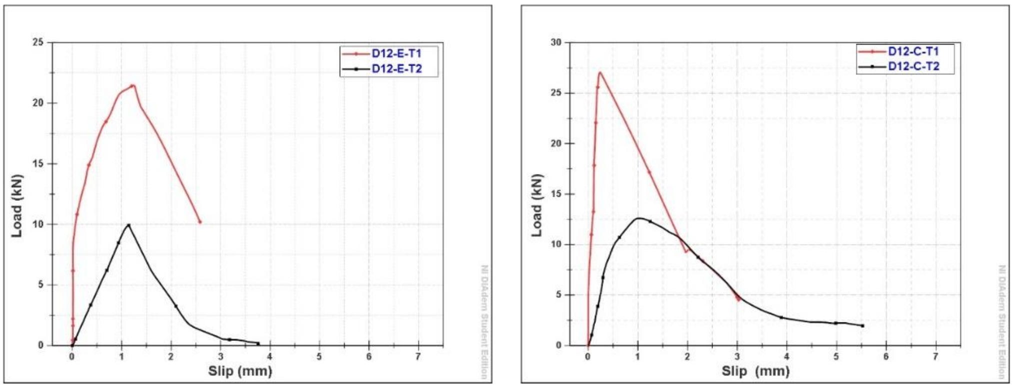
For GFRP bars with a diameter of 16 mm, as shown in Figure 6, when the GFRP bars were placed in the center of the specimens, the slippage increased from 0.811 mm to 1.14 mm and the maximum applied pullout load decreased from 35.91 kN to 9.65 kN. Whereas when the GFRP bars were placed at the edge of the specimens, the slippage increased from 0.247

mm to 1.28 mm and the maximum applied pullout load decreased from 31.24 kN to 15.85 KN. The results were consistent with Fava, G Fava [20] and Ozkal [6] (see **Figure 7**).



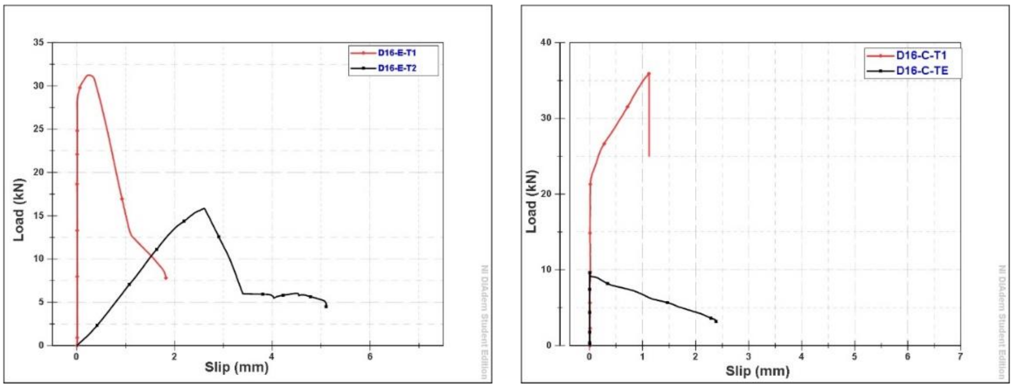
(a) (b)

Figure 5 Bond-slip relationship before and after fire exposure for 10 mm GFRP bars (a) at specimen edge, (b) at specimen center.



(a) (b)

Figure 6 Bond-slip relationship before and after fire exposure for 12 mm GFRP bars (a) at specimen edge, (b) at specimen center.



(a) (b)

Figure 7 Bond-slip relationship before and after fire exposure for 16 mm GFRP bars (a) at specimen edge, (b) at specimen center.

Failure Modes of Tested Specimens

The failure mechanisms for the test specimens were determined by the diameter and position of the GFRP bars. At room temperature, splitting and pullout failures predominated for GFRP bars with diameters of (10, 12) mm, particularly those positioned in the center of the specimens, whereas the rest of the specimens split due to stress distribution around the GFRP bars.

Figures 8 and 9 show that after being exposed to 600 °C, the major mode of failure for both central and edge-placed GFRP bars was splitting. These findings are consistent with previous study, demonstrating that temperature exposure exacerbates splitting failure modes; the failure also corresponds to Zhao, J.et al.

The detected failure modes from the test program illustrate the implications caused by temperature exposure. At ambient temperature, both forms of failure—splitting and pullout—are identified, but they are frequently restricted to the middle of the specimen bars. In direct contrast, post-exposure at 600 °C resulted in a majority of the splitting mode of failure, regardless of bar position.

This transition is notable because it demonstrates that when the temperature rises, not only does the bond strength drop, but the mechanism of failure in the GFRP bars begins to change. Hajiloo et al. [8] confirmed similar findings, stating that high temperatures are mostly responsible for splitting failures in specimens reinforced with GFRP bars.

Furthermore, residual bond strength observations show that even under high-temperature conditions, GFRP bars can retain some bonding capability, although significantly decreased. Residual strength would provide some structural redundancy during fire incidents. However, these advantages should not be considered in safety-critical applications.

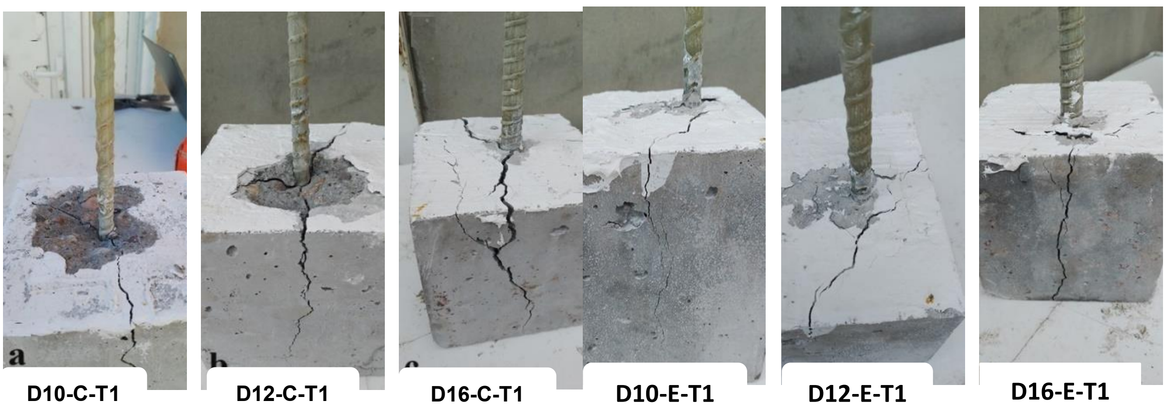


Figure 8 Failure modes at room temperature.

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Figure 9 Failure modes after exposure to 600 ºC.

Residual compressive strength after fire exposure

Tables 3 illustrate the compression test results for specimens before and after exposure to extreme temperatures. In addition, Jomaa'h, M. M. et al. [22] discovered an inverse relationship between compressive strength and rising temperature, independent of exposure length. This study also discovered that increased exposure temperatures were associated with a decrease in compressive strength. Concrete's compressive strength decreased when exposed to high temperatures; at 600 °C, it decreased by 39.3%.

Visual analysis of the heated samples revealed slight cracking at temperatures as high as 600°C, and changes in the color of GFRP and concrete after heating were also investigated.

Table 3. Residual compressive strength of the used concrete

No.	Temperature (°C)	Heating time (Min)	f_c' (MPa)	Average (MPa)	Average Fall (%)
1	30	0	31.3	31.33	0.00
2	30	0	31.9		
3	30	0	30.8		
4	600	90	21.15	20.90	33.30
5	600	90	21.45		
6	600	90	20.1		

Compressive strength and Residual bond strength

The examination of high temperature impacts suggests that concrete is essential in reinforced concrete structural components. In circumstances of high temperatures, concrete has a substantial indirect effect on the mechanical properties of the embedded reinforcement bars. This indirect effect can be characterized as thermal conduction to the rebar via the concrete and reduced bonding efficacy due to concrete degradation. Improved concrete performance would protect the rebar from external temperatures while also allowing for more effective load transfer to it.

Figure 10 depicts the relationship between concrete compressive strength and the bond strength of deformed GFRP bars. The bond strength results of the test specimens after 28 days are compared to those exposed to severe temperatures. The bond strength of GFRP decreased as compressive strength decreased, as did slippage, which will be explored later.

At 600 °C, concrete's compressive strength decreases by 33.3%. This reduction has a negative impact on GFRP bond strength, with bond strength dropping by 53% to 76% for GFRP bars placed in the center of specimens and by 42% and 76% for GFRP bars placed on the edges of specimens with a 40 mm clear cover. These findings are congruent with those of Kim, J., Jeong et al.

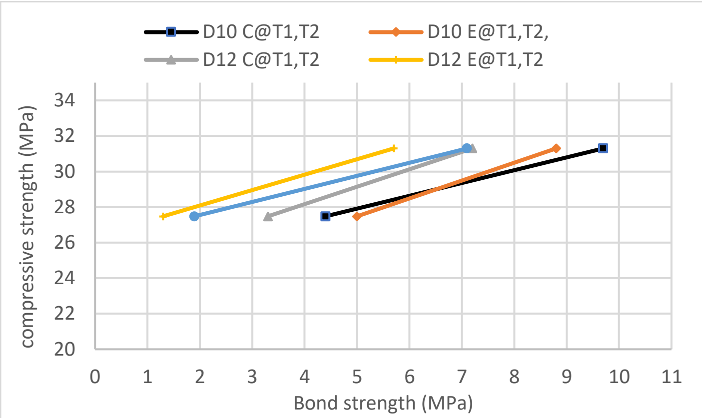

Figure 10. Relationship between compressive strength and bond strength capability.

4. CONCLUSIONS

Finally, this study highlighted the negative influence of high temperatures on the binding behavior of GFRP bars in concrete, emphasizing the importance of careful material selection and design in applications with a high risk of fire. The findings of this study were consistent with previous studies, emphasizing that, while GFRP bars are useful in many respects, they are extremely prone to deterioration in the event of a fire. Future research will focus on developing more effective fire-resistant materials and protection to improve the performance of GFRP-reinforced concrete structures in harsh situations.

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