

# Lessons learnt during experimental study of Bond Slip behavior of GFRP bars MS rebars

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**Abstract.** Bond strength of concrete-rebar composite directly influences load carrying capacity of reinforced concrete structures. It becomes more crucial when the structure is exposed to harsh environmental conditions including elevated temperatures, chemical, or mechanical loading. A research program was designed to evaluate the bond slip behavior of mild steel rebars and glass fiber reinforced polymer bars GFRP when subjected to above three conditions. In this investigation a total of 18 specimens were prepared. Six specimens, three of both categories were directly subjected to pullout test. A further six specimens, three of each category were first exposed to acidic solution (HNO<sub>3</sub> solution) of 2 pH then subjected to pullout test. Then six specimens, three of each category were first exposed to elevated temperature of 800 °C in an electric furnace then subjected to pullout test. However in this paper discusses pull out test of bars only. This study concluded that GFRP bars lost their integrity at high temperature due to resin damage. Further while performing pullout tests ends of GFRP bars are crushed. It was noticed that if bond between concrete and steel is intact failure initiates with split type crack in concrete cubes.

**Keywords:** Bond strength, pullout test, acid exposure, elevated temperature, GFRP bar

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## 1. Introduction

In The bond strength between reinforcing bars (rebar) and concrete is a critical aspect of reinforced concrete structures as it directly influences their overall performance and load-carrying capacity. However, in practical scenarios, concrete structures are often subjected to harsh environmental conditions and extreme events that can lead to concrete degradation and damage. These conditions may include exposure to elevated temperatures, chemical attack, or mechanical loading. As a result, the bond strength between the rebar and concrete can be significantly affected, leading to potential structural concerns.

Additionally, use of glass fiber reinforced polymer (GFRP) as rebars is also becoming popular. The study of response of MS bars and GFRP bars under various environmental challenges is important for durable designs. Present study aims to contribute to the body of

knowledge by evaluating the residual bond strength of concrete and rebar after exposure to chemical and elevated temperatures. The findings from this study will be useful in understanding the durability and performance of reinforced concrete structures in adverse environmental conditions and may aid in formulating guidelines for structural maintenance and rehabilitation.

The need to evaluate the residual bond strength of concrete and rebar under such adverse conditions is vital for ensuring the safety and longevity of structures in the industry. This research program aims to address above mentioned issues focusing on two types of bars that is Steel and GFRP only.

However only and only limited findings have been discussing in this paper. A comparison of two types of reinforcements i.e., which are diversely being used in construction these days have been explained.

## **2. Literature Review**

(Sayed Ahmad et al., 2011) evaluated the bond strength between GFRP bars and ultra-high performance concrete UHPC using a pull-out test. They found that "the bond strength increased with increasing embedded length and decreased with increasing bar diameter," and that "the use of sandblasting on the surface of the GFRP bars significantly improved the bond strength". (Qasem et al., 2020a) investigated the bond behavior between UHPC and GFRP bars with different surface treatments. They found that "the surface roughness of the GFRP bars had a significant influence on the bond strength, with sandblasting and acid etching producing the highest bond strength values". They also observed that "the bond behavior between UHPC and GFRP bars was affected by the curing age of the concrete, with the bond strength increasing with increasing curing time". Bond strength is a crucial factor in the performance of reinforced concrete structures. (Pan et al., 2022) found that the bond strength between UHPC and GFRP bars is affected by various factors, including the surface preparation of the concrete, the curing conditions, and the types of fibers used in the GFRP bars. (Amini Pishro et al., 2021) has shown that the bond strength between UHPC and GFRP bars can be improved by using a hybrid system that combines GFRP bars with steel reinforcement. The researchers found that steel reinforcement can provide additional mechanical interlock with the concrete, leading to improved bond strength. The roughness of the GFRP bar surface can also affect the bond strength with UHPC.

Performance of concrete at elevated temperature has been investigated by various researchers. (Özkal et al., 2018) investigated the bond performance of UHPC and GFRP bars after high-temperature exposure up to 600°C. The study found that the bond strength decreased with increasing temperature, and the reduction in bond strength was more significant for GFRP bars compared to

steel bars. The authors attributed this behavior to the degradation of the GFRP bar's resin matrix and the corresponding reduction in the interfacial bond strength between the bar and the UHPC. (Yu & Kodur, 2014) investigated the bond behavior of GFRP bars in UHPC under different high-temperature exposure scenarios. The study found that exposure to elevated temperatures significantly reduced the bond strength between the GFRP bar and UHPC. However, the study also found that the bond strength recovered partially after cooling down, indicating that the bond between the GFRP bar and UHPC was not entirely destroyed by high-temperature exposure. (Amin et al., 2022) investigated the bond behavior of GFRP bars in UHPC after exposure to high temperatures up to 800°C. The study found that the bond strength of GFRP bars in UHPC decreased significantly after exposure to high temperatures. The authors attributed this behavior to the degradation of the GFRP bar's fibers and resin matrix, which caused a reduction in the interfacial bond strength between the GFRP bar and UHPC.

Various chemicals can deteriorate the bond between UHPC and GFRP bars, leading to a potential loss in strength and serviceability. Researchers like (Guo et al., 2020) investigated the bond behavior of GFRP bars in UHPC after exposure to different chemical environments, including seawater, hydrochloric acid, and sodium sulfate solutions. The results showed that the bond strength between the GFRP bars and UHPC decreased significantly after exposure to chemical attack. The authors recommended using a protective coating on the GFRP bars to improve their resistance to chemical attack. (Hadigheh et al., 2017) evaluated the bond behavior of UHPC and GFRP bars after exposure to various chemical solutions, including sodium chloride, sulfuric acid, and sodium hydroxide. The results showed that the bond strength between the GFRP bars and UHPC decreased

with increasing exposure time and concentration of the chemical solution. The authors concluded that the durability of UHPC and GFRP-reinforced concrete structures can be improved by using high-performance GFRP bars and by taking appropriate measures to protect them from chemical attack. (J. Zhou et al., 2011) investigated the bond behavior of GFRP bars in UHPC after exposure to a sulfate attack environment. The results showed that the bond strength between the GFRP bars and UHPC decreased significantly after exposure to sulfate attack, which was attributed to the degradation of the UHPC matrix. The authors recommended using a protective coating on the GFRP bars and selecting appropriate sulfate-resistant UHPC mixtures to improve the durability of GFRP-reinforced UHPC structures.

The addition of special additives to UHPC can significantly alter the bond behavior of GFRP bars. The addition of special additives in UHPC can have a positive impact on its bond behavior with GFRP bars. These additives can enhance the properties of UHPC and increase its bond strength, which is crucial for the effective use of UHPC-GFRP bar composites in various applications.

(D. Y. Yoo & You, 2021) investigated the bond behavior between UHPC and GFRP bars with the addition of different percentages of silica fume. The results showed that the bond strength increased with increasing percentages of silica fume, and the maximum bond strength was achieved at 15% silica fume content. (Qasem et al., 2020a) investigated the effect of silica fume on the bond behavior between GFRP bars and UHPC. The researchers used different percentages of silica fume ranging from 0% to 15% and found that the addition of silica fume increased the bond strength between GFRP bars and UHPC. The results showed that the increase in bond strength was more significant at higher levels of silica fumes. The authors suggested that

the improvement in bond strength was due to the densification of the UHPC matrix, which resulted in a better transfer of stresses between the GFRP bars and UHPC matrix.

Apart from above studies numerous studies are available on the bond strength of rebars and GFRP (Aiello et al., n.d.). Tested bond performance under different conditions such as surface treatment, kind of fibers, and tests. Two types of tests were performed: the pull-out test and the modified pull-out test, in which the compressive stresses were not applied. Different types of coating were used, like fine and coarse coated CFRP and GFRP rebars, ribbed GFRP rebars, and conventional smooth and ribbed steel rebars were used to check the phenomenon. The tests conclude that the bond performance greatly depends upon the surface treatments.

(Cosenza et al., n.d.) a test was conducted to check FRP bars and concrete phenomena. After that, they were compared with deformed steel bars. The mechanical mechanism of the FRP bars and concrete was studied under various factors such as type of matrix, shapes, diameter of bars, and the compressive strength of concrete. Moreover, the analytical method was also considered, and different models were trained for that purpose. The effect of embedment lengths, temperature, and environmental changes was also examined in it.

(Achillides & Pilakoutas, 2004) tested total 130 specimens in the direct pullout. FRP and steel's failure mode was different in that case because of the resins. The bond strength of CFRP and GFRP was similar to or just below the steel. For concrete having the power of 30 MPa, failure occurred on the surface of the bars, while for concrete having the strength of 15 MPa, the concrete was crushed in front of bars deformation. The studies conclude that round-shaped bars have 25 percent less bond strength than square-shaped rebars.

(Baena et al., 2009) performed eighty-eight pull-out tests according to the respective standards. The CFRP, GFRP, and steel rebars were tested, and the embedment length was kept at 5 times the diameter of the bars. Different diameters of bars coated with sand, surface textures, and other coatings were used to examine the effect on the slip curves. The influence of the diameter of the rebar, concrete strength, and the surface of bars were analyzed on the bond-slip behavior. The studies concluded that the bars with larger diameters have less bond strength than the others. The values of slips were greater in GFRP than in the CFRP bars, and if we compared the steel bars with FRP bars, the steel bars showed maximum stiffness. (Zhu et al., 2022) proposed an innovative concept of using the additional aluminum alloy ribs (Ars for brevity) anchorage to enhance the bond of pretensioned CFRP bars in PPC members. (Kazemi et al. 2022) this paper focuses on the durability of steel bars and GFRP polymer embedded in seawater concrete in four different environments. Normal concrete specimens were also prepared for comparison. A total of 46 cubic samples were prepared, conditioned, and tested under direct pull-out Tests. It was found that during exposure to aggressive environments, the surface of FRP will be the most vulnerable part as the bond durability is dependent on it. In the present study locally available aggregates and other materials were used to prepare specimens except GFPR rebars. The specimens were than subjected to various exposure conditions.

### **3. Research Methodology**

A total of 18 specimens were cast and these were divided into six groups' three specimens in each group. Three groups were cast with MS rebars and in other three groups GFRP bars were used. Three specimens of each group were exposed to acid and elevated temperature, remaining three specimens of each group were directly

tested for Pull out test. In this paper only few findings have been discussed.

#### **3.1 Mix Design Preparation**

Concrete was prepared using ratio of 1: 1.02: 1.85, C: S: A, and W/C ratio was taken equal to 0.34. Additionally, Silica fume (10% by weight of cement) and Chemrite 530 superplasticizer (1.8% by weight of cement) were used. Silica fume is a very fine nanocrystalline silica produced in electric arc furnaces as a byproduct of the production of elemental silicon or a by-product of the ferrosilicon industry, is a highly pozzolanic material that is used to enhance the mechanical and durability properties of concrete. It may be added directly to concrete as an individual ingredient or in a blend of Portland cement and silica fume. Chemrite 530 (SP) is a highly effective superplasticizer to produce free-flowing concrete with substantial water reduction. It imparts excellent slump retention for prolonged periods. It increases the water tightness, substantially improves the workability without increased water or the risk of segregation, early strengths are significantly increased, and no adverse shrinkage. It also improves surface finish. Two type of Rebars were used in this investigation as explained below.

#### **3.2 Steel Bars**

15 in (375 mm) long steel bars of 0.75 in (19 mm) diameter were used in the process with herringbone (round) shape rings on them. This design helps to enhance the bond between the steel bars and the surrounding concrete, providing improved tensile strength and reinforcing the concrete against cracking and structural failure. The primary purpose of using herringbone-shaped steel bars in concrete structures is to increase the load-carrying capacity of the concrete and improve its overall mechanical properties. The bars are typically placed in specific locations where tensile forces are expected to occur, such as in beams, columns, slabs, and other critical areas of the structure.

### 3.3 GFRP Bars

15 in (375 mm) GFRP bars of 0.75 in (19 mm) diameter were used in the process. The spiral shape GFRP bars are typically used as an alternative to conventional steel bars in reinforced concrete structures. They come in the form of helical or spiral-shaped bars, providing axial reinforcement to concrete members like beams, columns, and piles. The helical shape offers increased surface area for bonding with the surrounding concrete, ensuring good load transfer and enhancing the structural performance of the concrete element. Both steel and GFRP bars are shown in Figure 1.



Figure 1 Ms and GFRP rebars used in the investigation.

### 4. Test Program

In this investigation 18Nos (150 mm × 150 mm) specimens were cast to investigate the bond strength of concrete and rebars. As shown in Table 1. Nine specimens containing steel bar of 0.75 in (19 mm) diameter and 9 specimens containing GFRP bar of 0.75 in (19 mm) diameter. Three control specimens were also cast to determine the compressive strength of the concrete used in sample preparation.

Table 1 Test Program.

Specimen	Direct Pullout	Acid Exposure	Elevated Temperature
Steel bar	3	3	3
GFRP bar	3	3	3

### 5. Development Length

A development length (within 6in cube) equivalent to three times the diameter of the bars that is equal to 2.25 in (56.25 mm) is provided in the concrete cube while the remaining 3.75 in (93.75 mm) of the bar was covered with duct tape. Both steel and GFRP bars are shown in Figure 2.



Figure 2 Development Length

### 6. Casting of Specimens

All bars were placed 2 in (50 mm) outside from the bottom of the cube and 7 in (175 mm) outside from the top of the cube ensuring proper 2.25in (56.25mm) embedment. Then the concrete was poured into the molds in 3 layers with the proper use of a vibrator for adequate compaction. After 48 hours specimens were de-molded, then the specimens were cured for 28 days. Figure 3 illustrates the dimensions of the specimen, and figure 4 explains the arrangement of mould and rebars.

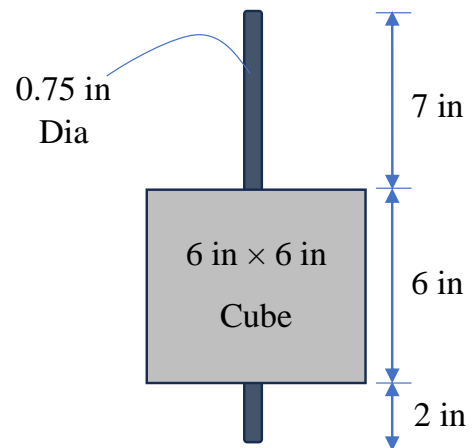


Figure 3. Specimen Dimensions.



Figure 4. Rebar being placed in the mold.



Figure 5. Specimens after removal of moulds

### 7. Nomenclature

For the identification the specimens were named. The first alphabet in the nomenclature (S) denotes ‘Specimen’. The second alphabet (A, F, D, or C) denotes ‘Type of Test’; {“A” stands for Acid Exposure, “F” stands for Fire Exposure, “D” stands for Direct Pullout, or “C” stands for Compressive Strength}. The third alphabet (F or S) denotes ‘Type of Bar’; {“F” stands for FRP, or “S” stands for Steel}. Identification name was written on each specimen as shown in figure 6. Detail of specimens is shown in Table 2.



Figure 6 Specimens ready for testing

Table 2 Nomenclature against corresponding test

Bar Type	Direct Pullout	Acid Exposure	Elevated Temperature	Compressive Strength
Steel	SD-S-1	SA-S-1	SF-S-1	SC-1
	SD-S-2	SA-S-2	SF-S-2	
	SD-S-3	SA-S-3	SF-S-3	SC-2
GFRP	SD-F-1	SA-F-1	SF-F-1	SC-3
	SD-F-2	SA-F-2	SF-F-2	
	SD-F-3	SA-F-3	SF-F-3	

### 8. Experimental Setup

#### 8.1. Setup For Pull-out Test

Assembly/Frame of iron was prepared for pullout test. This assembly consists of two 1-in (25 mm) thick 10 in × 10 in (250mm × 250mm) solid iron plates at the top and bottom. The upper plate has four 0.75 in (19 mm) diameter holes at the corners and one 1 in (25 mm) diameter hole in the center. While the lower plate has one 0.75 in (19 mm) diameter bar 6 in (150 mm) long connected at the center through welding. Four 0.75 in (19 mm) iron rods of 16 in (400 mm) length bolted from both

sides to support plates. Fig 3.9 illustrates the dimensions of assembly for the pull-out test. Pull-out test was performed in the UTM machine as illustrated in Figure 8. Dial gauges were fixed at suitable locations to record the slip of the bars.



**Figure 7** Assembly for pull-out test



**Figure 8** Pull Out test assembly fitted in UTM Machine.

### **8.2 Set up for Temperature exposure.**

An electric furnace as shown in figure 9 was used to expose specimens to elevated temperatures. The heating capacity of the furnace was 900 °C. It can accommodate

three specimens at a time. It took 1 hour to attain the desired temperature of 800 °C.



**Figure 9** Electric Furnace

### **8.3. Experimental setup for Acid Exposure**

A circular plastic container shown in figure 10. was used for exposure of specimen to the acidic solution. Nitric acid (HNO<sub>3</sub>) of 65% purity was used. The pH of the water was maintained at 2 and checked using electric pH meter.



**Figure 10.** Plastic container for acid exposure of the specimens.

## **9. Testing**

### **9.1 Direct Pull-out Test**

Rebars embedded within a concrete cube were pulled out by applying a tension force at a static loading rate and with a confined test setup. The applied force values and corresponding relative displacement between rebar and

concrete known as bond-slip are continuously measured and recorded by the UTM Machine and the deflection gauges. GFRP specimen SDS-1, 2 and 3 and SDF-1, 2 and 3 were tested after 28 days. These specimens were not subjected to any external exposure. Figure 11 and 12 illustrates specimens before testing and after testing respectively.



Figure 11 Specimen SDS3 Before Pull-out Test



Figure 12 Specimen SDS3 after Pull-out Test

## 10. Elevated Temperature

Samples numbers SF-S-1, 2, 3 and SF-F-1, 2, 3 were exposed to an elevated temperature in an Electric Furnace

with a capacity to hold three specimens at a Time. The samples were exposed to high temperatures for About 2 hours and the readings were properly noted to obtain the time versus temperature curve. The Furnace took about one hour to reach the required temperature of 800 °C and then the same temperature is maintained for an hour.



Figure 13 Specimens before temperature exposure



Figure 14 Specimens after temperature exposure

## 11. Acid Exposure

Specimens SA-S-1, 2, 3 and SA-F-1, 2, 3 were exposed to the acidic condition and then tested. However, in this paper due to limitation of space only few results have been discussed.

## 12. Results and Discussions

Average compressive strength of these specimens was found as 39.4 MPa. Table 3 presents the strength of individual specimens.

**Table 3 Compressive strength test results**

Specimen	Compressive Strength
SC-1	41.1
SC-2	38.9
SC-3	38.3

Specimens with GFRP bars and subjected to elevated temperature are shown in figures 15, 16 and 17.



**Figure 15 Specimen SF-F-1 after exposure.**



**Figure 16 Specimen SF-F-2 after exposure.**

Cracks appeared on the surface of concrete and along rebar at few locations. Resin of GFRP bar was burnt and the fibres were separated leaving brush like structure.



**Figure 17 Specimen SF-F-3 after exposure.**

Direct Pullout test was performed on SD-S-1, 2 and 3 and SD-F-1, 2, 3. As shown in figure 18 due to limitation of the equipment it was not possible to pull out GFRP bars to its full capacity. It was due to the reason that the bars were crushed in the jaws of UTM.



**Figure 18 Specimen SD-F-3 after Pull out test.**

### 12.1. Direct Pull-out Test on Steel Specimens

Three specimens SD-S-1, SD-S-2, and SD-S-3 with MS rebars were subjected to direct pull-out test. Results of these are shown and discussed below individually. The

SD-S-1 specimens after testing are shown in the figure below.



Figure 19 . SD-S-1 tested specimen.

The SD-S-2 specimens after testing are shown in the figure 20 below.



Figure 20 SD-S-2 tested specimen.

The SD-S-3 specimens after testing are shown in the figure 21 below. This specimen was broken from the center parallel to rebar. It was divided into two pieces and rebar remained attached with one piece



Figure 21 SD-S-3 tested specimen.

### 12.1 Summary of Results

Table 4 Summary of Results

Specimens	Diameter of Bars (mm)	Embedment Length (mm)	Concrete Age (Days)	Maximum Bond Stress (MPa)	Max. loaded End bar slip (mm)	Max. free End bar slip (mm)
SD-S-1	19.05	57.15	28	7.52	6.59	4.95
SD-S-2	19.05	57.15	28	8.6	9.65	3.31
SD-S-3	19.05	57.15	28	6.45	7.7	6.18

Greater slip on the loaded side of bars indicates proper bond between the steel bars and concrete. When load was increased slip of the free end of the bars started.

### 13 Conclusions

Present research work was conducted with limited resources to evaluate the bar slip behavior of GFRP bars and MS bars when subjected elevated temperatures and acid attack. Conclusions have been drawn on the bases on initial testing. the conclusions and lessons learnt and recommendations have been presented here for future studies.

- I. GFRP exposure to high temperatures up to 800 °C leads to the deterioration of the resin and GFRP bars turns into the raw fibers, leaving these bars ineffective and compromising the structural integrity.

A fire coating should be provided to GFRP bars or covers should be greater than normal concrete.

- II. GFRP is a very delicate material as compared to steel and can be compressed easily with UTM jaw tightening, leading to the unreliable results of pullout test. A special assembly is required to perform pull out test on GFRP bars.
- III. The bond slip behavior analyzed by the deformation gauges shows higher deformation in the free end bond side slip and smaller deformation in the loaded end bond slip.

### 13. Limitation

- I. This study is limited to laboratory-controlled conditions, and the actual field conditions may vary, affecting the generalization of the results to real-world applications. The exposure to chemical and elevated temperature was simulated in the laboratory, and the actual exposure conditions in the field may differ, which could impact the accuracy of the findings.
- II. This study was performed considering only 19mm diameter bars and only one type of concrete.
- III. Pullout testing is a simplified method to evaluate bond strength, and other factors that can influence the bond behavior, such as concrete cover, surface roughness, and curing conditions, were not fully accounted for in this study.
- IV. Duration of acid exposure can affect the overall performance concrete member; it is suggested that more specimens should be cast and subjected to various durations of acid exposure.
- V. The availability of specialized equipment and resources may constrain the scale and scope of the experiments, potentially limiting the statistical significance of the results.

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