Experimental and Theoretical Investigations on Bond Strength of GFRP Rebars in Normal and High Strength Concrete

P Eswanth and G Dhinakaran*
School of Civil Engineering, SASTRA University, Thanjavur 613401, India

*Email: gd@civil.sastra.edu

Abstract. Bond behavior between GFRP bars and concrete is the most important parameter for constructing corrosion free structures by implementing the material. Serviceability of reinforced concrete structures are controlled by bond behavior. GFRP materials behave differently from reinforcing steel in terms of bond. They are of non-homogeneous and anisotropic. Due to this outstanding behavior, there is a difference in transfer of loads between GFRP bars and concrete which made it as an idealized choice of a material. In the present work, the bond strength of GFRP bars in normal and high strength concrete was studied. In total, 12 specimens containing 12 mm, 16 mm diameter rebars which were embedded in 150 mm x 150 mm x 150 mm cubes were investigated. The specimens were subjected to direct tension pull out test in accordance with IS 2770 part 1. The comparison of bond properties of GFRP rebar in normal and high strength concrete showed that pull out load of non-metallic rebar fell well within the range.

1. Introduction
Fiber-reinforced polymer (FRP) reinforcement is used in structural construction as steel reinforcement is poor corrosion resistance. In structural members such as marine structures due to corrosion it leads to premature failure and serviceability of structures will be reduced. In case of corrosive conditions GFRP rebar are perfectly used as reinforcement in structures. It is important in case where design is mainly concentrated on durability of RC members.

Due to difference in properties of two materials steel and GFRP a direct substitution between these two materials is not possible. The major difference: Steel is having less tensile strength compared to that of GFRP bars and the elastic modulus is greater for steel compared to that of GFRP bars. Some FRP’s have low elastic modulus and yield point is not perfectly defined in their stress strain curves. Due to outstanding behavior, GFRP materials are referred as idealized choice of material. The use of GFRP as reinforcement has been reduced due to many reasons, as it includes high cost and lack of awareness about new technology. Currently, many issues are affecting the structural members with GFRP as reinforcement such as resistance to loading and aggressive environments.

Many research studies were done using GFRP bars as reinforcement and on bond performance in concrete. The bond strength was governed by number of parameters such as bar diameter, embedment length and environmental criteria. Numerous works were carried out on these areas using
GFRP rebars [1-6]. Conventional pullout tests were performed for low to moderate concrete strengths, with bond strength in the range of 2-14MPa. Larger diameter bars will give lesser bond strengths compared to that of small diameter bars. Many a times bond strength was governed by shear criteria. It was found that bond stress decreases are lesser for larger embedment lengths than that of smaller embedment lengths [7]. Also pullout test was conducted and bond strength was measured in the range of 14MPa with the cover of (5D_b) mobilizing the failure and absorbed ductile response [8]. Conventional and eccentric pullout test in the range of 5-22MPa with various parameters were conducted. Curves were ductile in nature [9].

In this paper, it focuses on bond strength of steel and GFRP reinforcing bars in normal and high strength concrete using direct tension pullout test. A total of 12 specimens were tested. The experimental results are presented in detail. This research benefit engineers, professionals and provide data for code writers since GFRP technology is an important aspect and has practical significance.

2. Experimental program

2.1 Materials

2.1.1 Concrete. According to IS standards, normal strength and high strength concrete was prepared, with the composition as given in table-1. OPC 53 grade cement was used. Coarse aggregate maximum size was 20mm, and fine aggregate size interval was in the range of 0-4.75mm. Around the rebar, plywood was used of required dimension to cast the concrete cube.

| Concrete mix | M40 | M60 |
|--------------|-----|-----|
| Water (kg/m³) | 147 | 190 |
| Cement (kg/m³) | 350 | 633.33 |
| Coarse aggregate(kg/m³) | 1102.5 | 1279.57 |
| Fine aggregate (kg/m³) | 787.5 | 352.986 |
| Superplastizer (%) | 0.5 | 0.5 |

2.1.2 Fiber reinforced polymer bars. In this study GFRP bars were used which were supplied by Go Green Products. Diameters of 12mm, 16mm were used. Properties of materials are mentioned in Table.2. These are of longitudinal fibers with a thermosetting vinyl ester resin manufactured by the process called pultrusion. Due to ribs and undulations bond improvement can be achieved. The GFRP bars behave linearly up to failure in stress-stain curve.

| Material | Elastic Modulus (MPa) | Poisson ratio | Yield strength (MPa) | Ultimate tensile strength (MPa) |
|----------|----------------------|--------------|---------------------|-------------------------------|
| GFRP     | 0.32 x 10^7          | 0.25         | 446                 | 446                           |

2.1.3 Apparatus. Size of the mould for bond test will be of 150 mm x 150 mm x 150 mm cubes as the diameter of bars are varying from 12mm to 20mm size of cube should be 150mm. Dial micrometer was used to measure the slip of the bar from the concrete cube. Dial micrometer mounted to read in 0.0025 mm at the unloaded end and having a range of greater than 2.5 mm shall be used. At loaded end, dial micrometers mounted in 0.025 mm will be used. Universal Testing Machine was used for testing the bond strength. Tamping rod which was round and straight of 0.6m in length and 15 mm in diameter was used.

2.1.4 Specimen. To determine local bond slip relation experimentally between rebar and concrete, rebar placed at center in concrete are used for direct pullout tests. This method was everywhere used
for comparing the relative bond between different materials. Pullout specimens depend upon different parameters such as concrete type, bar diameter, and bar type. The length was provided in such a way that the bond stresses should be uniformly distributed while loading is done. According to IS 2770.1.1967 direct tension test was conducted on 150 mm concrete cube, with a single rebar inserted vertically at the center of each cube specimen. The bar should extend 10mm outside the cube even after casting from the bottom face and shall provide 850mm at the top face for sufficient length of bar to extend through the blocks and to provide an adequate length to be gripped for application of load. According to IS 516-1959 three concrete were made and tested for the average compressive strength with the range of 200 to 300 kg/cm² at the time of making pullout tests. All the test specimens shall be cured for 28days.

2.1.5 Preparation of Test Specimen. Bars should be free from rust, grease, paint. Suitable solution must be applied so as to remove oil or grease. At the end of the bar, surface should be smooth normal to the axes of the bars. Mixing concrete and curing was done according to IS: 516-1959. After the top layer has been filled, extra quantity should be removed and it should be finished with a trowel. Bars of 12mm, 16mm were inserted in cube as shown in Figure 1. Each bar diameter of three specimens was tested. GFRP bars and steel bars were inserted in concrete as per IS standards and concrete was mixed properly, kept for curing for desired period and was kept in room temperature for dry curing to evaporate water from pores and specimens. Then pullout test was performed for that specimen.

2.1.6 Test procedure. Test was conducted in such a way that bar was subjected to axial pull from the cube in testing machine as shown in Figure 2. The distance between the loaded end of bar and concrete face in the testing apparatus was measured as slip. Load was applied at a rate not greater than 2250 kg/min or it should not greater than 1.25 mm/min. Slip was measured by using dial-micrometers. Calculation of bond strength was based on this load and results were to be recorded at maximum load at failure of the specimen as shown in Figure 3.
3. Results and Discussion

Experimental results of bond strength of GFRP bars in concrete are mentioned in table 3 and table 4 for normal and high strength concrete and theoretical results are also mentioned in detail. Slip was high for normal strength concrete compared to that of high strength concrete for both 12 mm and 16 mm diameter of bars. Bond stress was high for small diameter compared to that of larger diameter. Mode of failure was splitting as they are of high grade concrete.

| Diameter (mm) | Length (mm) | Embedment length (mm) | Load at bond failure (kN)* | Load @0.125 mm slip (kN) | Load @0.25 mm slip (kN) | Gauge length (mm) | Slip (mm) | Avg. bond strength at bond failure (N/mm²) |
|---------------|-------------|-----------------------|---------------------------|---------------------------|--------------------------|-------------------|----------|---------------------------------------|
| 12            | 850         | 150                   | 32.1                      | 0.9185                    | 150                      | 12.76             | 6.16     | 6.47                                  |
| 12            | 850         | 150                   | 34.85                     | 1.125                     | 150                      | 13.39             | 6.16     | 6.47                                  |
| 12            | 850         | 150                   | 36.59                     | 1.125                     | 150                      | 13.78             | 6.16     | 6.47                                  |
| 16            | 850         | 150                   | 39.05                     | 1.00                      | 150                      | 14.8              | 5.18     | 5.78                                  |
| 16            | 850         | 150                   | 43.62                     | 0.985                     | 150                      | 13.25             | 5.78     | 5.44                                  |
| 16            | 850         | 150                   | 41                        | 1.05                      | 150                      | 13.00             | 5.44     | 5.44                                  |

*mode of failure is splitting.

| Diameter (mm) | Length (mm) | Embedment length (mm) | Load at bond failure (kN)* | Load @0.125 mm slip (kN) | Load @0.25 mm slip (kN) | Gauge length (mm) | Slip (mm) | Avg. bond strength at bond failure (N/mm²) |
|---------------|-------------|-----------------------|---------------------------|--------------------------|------------------------|-------------------|----------|---------------------------------------|
| 12            | 850         | 150                   | 35.7                      | 1.025                    | 150                    | 14.26             | 6.31     | 6.29                                  |
| 12            | 850         | 150                   | 33.25                     | 1.275                    | 150                    | 13.72             | 5.88     | 5.88                                  |
| 12            | 850         | 150                   | 37.9                      | 1.145                    | 150                    | 14.9              | 6.75     | 6.75                                  |
| 16            | 850         | 150                   | 43.3                      | 0.925                    | 150                    | 13.01             | 5.74     | 5.74                                  |
| 16            | 850         | 150                   | 47.5                      | 1.025                    | 150                    | 13.85             | 6.30     | 6.30                                  |
| 16            | 850         | 150                   | 45.1                      | 1.105                    | 150                    | 12.96             | 5.98     | 5.98                                  |

*mode of failure is splitting.
Ultimate bond using the following formula: 
\[ \sigma_b = \frac{P_b}{\pi d l} \]  
(1)

where, \( \sigma \) = ultimate bond stress, \( P_b \) = Bond failure load, \( d \) = diameter of bar, \( l \) = gauge length.

Average bond strength at failure (N/mm²) = \( \frac{P_2}{\pi d l} \)  
(2)

4. Theoretical calculation

As per IS 456-2000, design bond stress can be calculated by using following formula:

\[ \tau_{bd} = \frac{\varnothing \sigma_s}{4 l_d} \]  
(3)

\( \sigma_s \) = Stress in bar at the section considered at design load (0.87fy), \( \tau_{bd} \) = design bond stress, \( \varnothing \) = diameter of the bar, \( l_d \) = development length.

As per code for bond stress in case of deformed bars conforming to IS 1786 the value will be increased by 60 percent.

So for deformed bars:

\[ \tau_{bd} = \frac{\varnothing \sigma_s}{4 \times 1.6 l_d} \]  
(4)

Results obtained based on theoretical calculations are tabulated in the table 5 for better understanding.
### Table 5: Results of theoretical calculations

| $\phi$ (mm) | $f_y$ (N/mm$^2$) | $l_d$ (mm) | $\sigma_s = 0.87f_y$ (N/mm$^2$) | $\tau_{bd} = \frac{\phi \cdot \sigma_s}{4 \cdot 1.6 \cdot l_d}$ (N/mm$^2$) |
|-------------|-----------------|------------|---------------------------------|-------------------------------------------------|
| 12          | 500             | 150        | 435                             | 5.44                                            |
| 16          | 500             | 150        | 435                             | 7.25                                            |

5. Conclusions
Following are the conclusions arrived from limited number of experiments conducted on bond performance GFRP in concrete. Average bond stress relationships and failure mode for each of the tested bars were experimentally determined. The results were explained as follows:
1. Failure of the bond was mostly due to length of embedment and bar surface.
2. Splitting failure occurs due to longer length of embedment. Increase in diameter reduced average bond strength.
3. Pullout load of normal strength concrete was found to be lower than that of high strength concrete. Bar diameter and embedment length are directly proportional to slip at peak bond stress.
4. Concrete strength is directly proportional to peak bond stress.

References
[1] Roman Okelo and Robert L Yuan 2005 Bond Strength of Fiber Reinforced Polymer Rebars in Normal Strength Concrete. *J. Compos. Constr.* 9 203-13.
[2] Tastani S P and Pantazopoulou S J 2006 Bond of GFRP Bars in Concrete: Experimental Study and Analytical Interpretation. *J. Compos. Constr.* 10 381-91.
[3] Breccolotti M and Materazzi A L 2010 Structural reliability of eccentrically-loaded sections in RC columns made of recycled aggregate concrete. *Eng. Struct.* 32 3704-12.
[4] Wambeke B W and Shield C K 2006 Development length of glass fibre-reinforced polymer bars in concrete. *ACI Str. J* 103 11-7.
[5] Ehsani M R, Saadatmanesh H and Tao S 1995 Bond of hooked glass fibre reinforced plastic (GFRP) reinforcing bars to concrete *ACI Mater. J.* 92(4) 391-400.
[6] Fei Yan and Zhibin lin 2016 Bond mechanism and bond strength of GFRP bars to concrete. *Compos. Part B* 98 56-69.
[7] Achillides Z and Pilakoutas K 2004 Bond behaviour of fiber reinforced polymer bars under direct pullout conditions. *J. Compos. Constr.* 82 173-81
[8] Cosenza E, Manfredi G, and Realfonzo R 1997 Behaviour and modelling of bond of FRP rebars to concrete. *J. Compos. Constr.* 1 40-51.
[9] Baena M, Torres L, Turon A and Barris C 2009 Experimental study of bond behaviour between concrete and FRP bars using a pull-out test. *Compos. Part B* 40 784-97.