Bond Behavior between helically wrapped FRP rebars and concrete

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Abstract. The bond behavior of FRP rebar embedded in concrete structures is influenced by many factors, such as fiber type, fiber content, the diameter of the rebar, and concrete strength. The bond behavior of FRP rebars is one of the major concerns in FRP applications as reinforcement in concrete structures. There are many studies in this area because there is no standardization for the surface treatment of these rebars. Besides the experimental analysis of the behavior of the rebars through pullout tests, numerical analyses are extremely necessary so that more of the parameters that influence bond behavior can be varied and their influence analyzed. The aim of this paper is to analyze the bond behavior of new FRP rebars developed. The numerical analysis will be carried out on the finite element analyses program ABAQUS. The material of both the concrete block and the FRP rebar was implemented as linear elastic until failure. For the interaction between the concrete block and the FRP rebars was used the cohesive surface solution and the results obtained by the simulation were compared with experimental results obtained by the authors.

Keywords: FRP rebars, FEM, Concrete, Abaqus, Bond behavior.

1 Introduction

The FRP rebars are made of fibers displaced in the longitudinal direction, which gives strength to the rebar, and a polymeric matrix that keeps these fibers together and transmits forces between fibers. The rebars can be made of glass, basalt, aramid, and carbon fibers and are referred to as glass fiber-reinforced polymer (GFRP), basalt fiber-reinforced polymer (BFRP), aramid fiber-reinforced polymer (AFRP) and carbon fiber-reinforced polymer (CFRP), respectively. Due to their high tensile strength, corrosion resistance, and electromagnetic neutrality, FRP bars have been efficiently used in structures exposed to marine environments, structures to store types of equipment affected by electromagnetic fields, water treatment plants, and structures exposed to de-icing salts [1].

For the proper use of FRP rebars as concrete reinforcement, it is necessary that the FRP rebars have a sufficient bond to the concrete so that the stresses are transmitted between the two materials. The bond behavior of FRP rebars embedded in concrete is influenced by many factors, such as the concrete strength, bar diameter, bar space, concrete cover [2], type of fiber and modulus of elasticity[3], embedment length, the shape of the cross-section, and surface deformation [4], [5]. The most common process of manufacturing FRP bars is the pultrusion process and it results in smooth bars that do not provide the necessary bond for the application of these rebars in concrete structures. Because of that, usually, after the manufacturing process, surface treatments are performed on these rebars to ensure proper bond behavior. As there is no standardization for this treatment as there is for steel rebars [6], the types and names of surface treatments vary widely in the literature and the most commonly found are helically wrapped, sand coated [7], grooved surface [8], indented and ribbed [3]. Also, because of the lack of standardization for the surface treatment the number of studies in the area analyzing the variation of bond characteristics over time [9], [10], the influence of the diameter on the bond strength [11], and different surface treatments [12] are very significant.

In addition to the experimental analysis of FRP rebars through pullout tests, the numerical simulation of this test is shown as a way to complement the bond behavior analysis. Several methodologies to simulate numerically in Abaqus the bond behavior of FRP rebars embedded in concrete structures and under pullout loading can be found in the literature among them the use of surface based cohesive behavior [13], Cohesive Zone Model (CZM) using cohesive elements placed in a row between the rebar and the concrete surface[14], [15] , and the use of translator elements [16], [17].

In this paper were described the experimental pullout test of three specimens named FRP1, FRP2 and FRP3 to analyze the bond behavior of the FRP rebar produced in concrete structures. The numerical simulations were developed to reproduce the experimental tests using the commercial FEA program ABAQUS to complement the analysis.

2 Experimental Program

2.1 Material Properties

FRP rebars with a combination of glass (70%), carbon (25%) and basalt (5%) fibers with 8 mm nominal diameter and helically wrapped surface treatment was used in this study-Figure 1. Pullout tests were made using high-strength concrete with an average compressive strength of 67.36 MPa. High-strength concrete was chosen for the pullout tests to ensure that the failure of the rebar-concrete bond occurred on the surface of the rebar and not on the surface of the concrete.

Figure 1. GFRP rebar analyzed

2.2 Test Specimens

Pullout specimens were prepared using 150 mm square wooden molds. The FRP rebar had 670 mm length, the embedded length adopted was 5 times the bar diameter and the anchorage system was 250 mm long as can be seen in Figure 2. The cast was made in the horizontal direction so that the positioning of the rebars inside the concrete block with the embedment length of five times the diameter was guaranteed. Plastic tubes were used as bond breakers at the bottom of the concrete block.

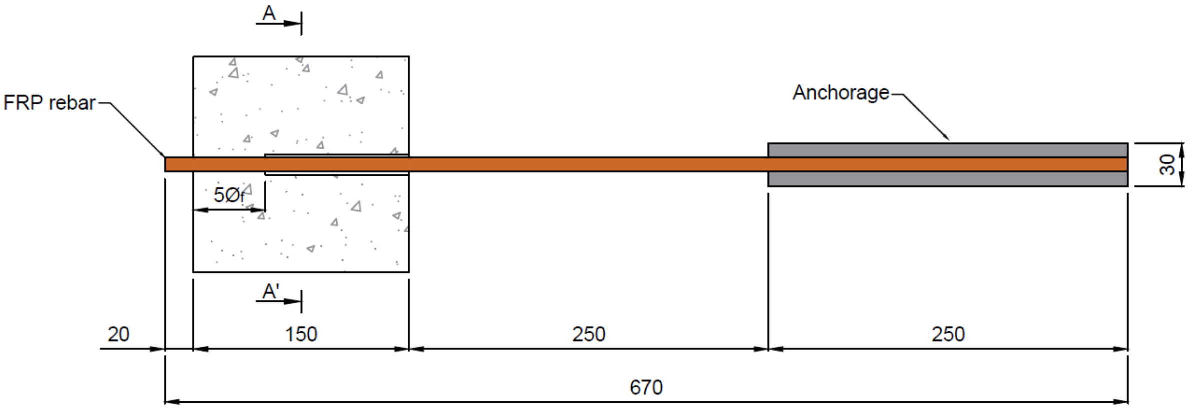

Figure 2. Pullout test specimen detail

2.3 Test Setup and Procedure

The experimental program was based on the recommendations of ACI.440.3R [18]. The relative displacement between the FRP bar and the concrete block was measure with three linear variable displacement transducers (LVDT) as presented in Figure 3. One LVDT was placed in the loaded end (end of the rebar where the load is applied) of the FRP rebar and two LVDTs in the unloaded end of the rebar and at the bottom of the concrete block.

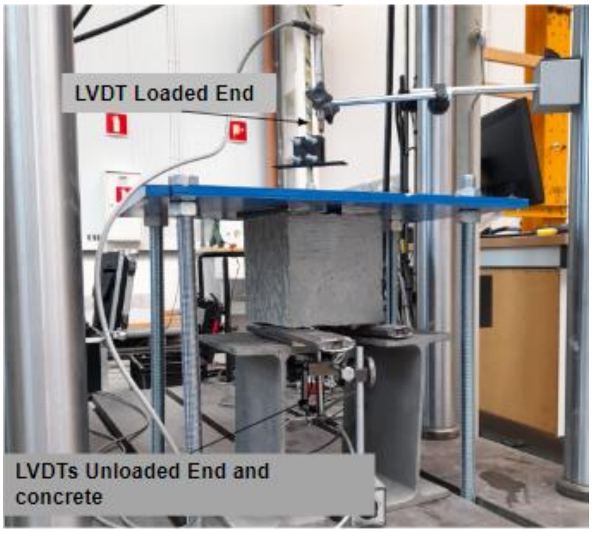

Figure 3. Layout of the pullout test

3 Experimental Results and Discussion

To obtain the bond stress results of the bars the force value was obtained using equation 1. To discount the bar elongation in the displacement measured by LVDTs equation 2 was used.

$$\tau = \frac{F}{\pi d L_d} \tag{1}$$

$$S_c = \frac{FL_c}{E_L A} \tag{2}$$

Where F is the tensile load, d is the diameter of the FRP rebar, and L_d is the embedment length, L_c is the distance between the top of the concrete block and the point where the measure device is attached E_L is the elastic modulus and A is the area of the FRP rebar.

The results of displacement measured by the LVDT placed on the loaded end are presented in Figure 4 and Table 1 as followed.

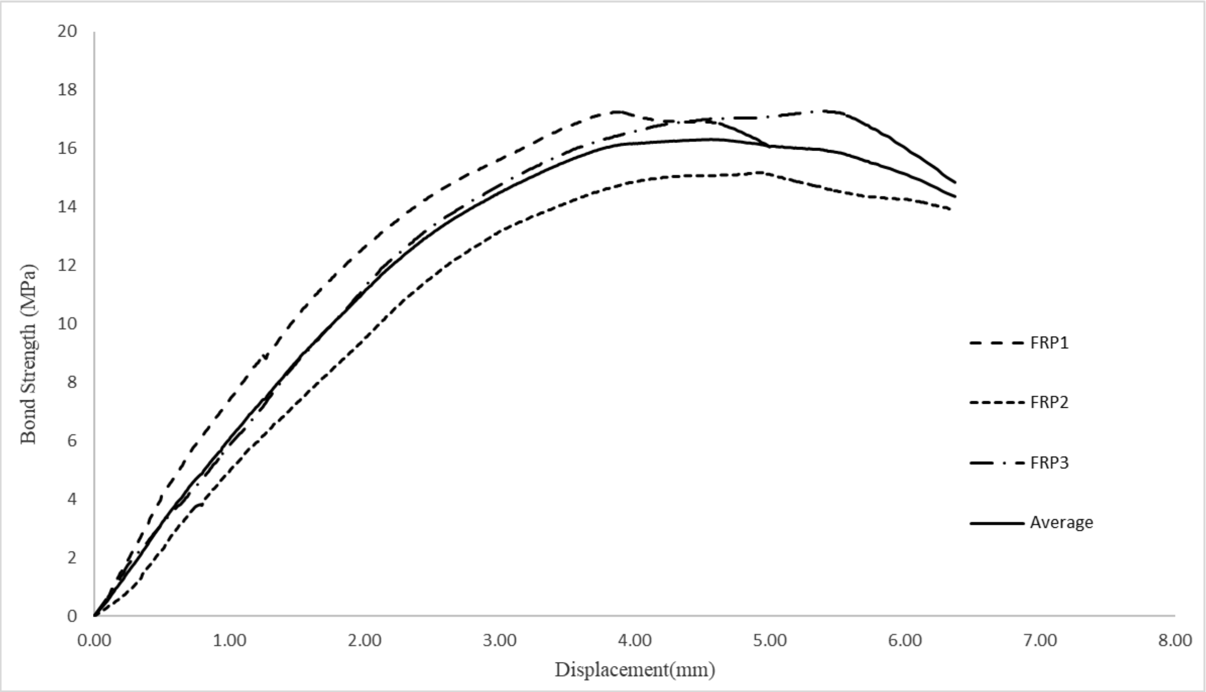

Figure 4. Pullout results

Table 1. Experimental pullout tests results

Type of rebars	Bond strength (MPa)
FRP1	16.75
FRP2	14.71
FRP3	16.75
Average:	16.07

4 Numerical Analysis

4.1 Model Geometry

Numerical simulations using finite element method (FEM) were carried out on Abaqus software. The concrete block and the FRP rebar were simulated in linear eight-node, three-dimensional, solid elements with reduced integration (C3D8R). The numerical model was developed considering only ¼ of the specimen taking advantage of its double symmetry as followed in Figure 5, symmetry boundary conditions were adopted to make it possible. A restriction on a node on the upper side of the concrete block to translate in z direction was also imposed, this point was connected to the entire upper face of the concrete block to simulate the steel plate that prevented the displacement of the concrete block in the direction of the force applied on the rebar. To ensure a better efficiency of the model a more refined mesh was adopted only in the region where the connection between the FRP bars and concrete takes place. The loading was applied as a displacement at the loaded end of the rebar.

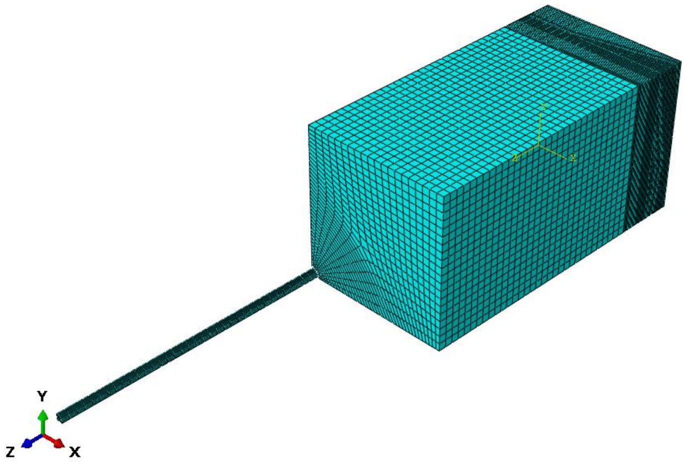

Figure 5. ¼ of Specimen simulated

4.2 Material properties

Since the concrete block did not present any crack during the pullout test it was simulated as linear elastic until failure as well as the FRP rebar. The elastic modulus adopted for concrete and the GFRP rebars is presented in Table 2 as followed.

Table 2. Material properties FRP rebar and concrete

Material	Elastic Modulus (GPa)	Poisson’s Ratio
FRP rebar	36	0.2
Concrete	42	0.3

4.3 Bond Behavior

The interaction between concrete and the FRP rebar was simulated using the surface-based cohesive behavior methodology. In this methodology the cohesive behavior is defined as an interaction property and the bond is described with a linear elastic traction-separation law until the damage initiate. To define the parameter of stiffness and damage for the contact many values were tested. The parameters that result in the closest approximation of the experimental results was adopted.

5 Numerical Results and Discussion

As can be seen from the comparison of the numerical and experimental results (Figure 6), there are a good agreement between experimental and numerical results, especially up to the maximum bond strength, where the value found in the numerical simulation was 16.53 MPa, presenting an error of 1% in relation to FRP1, 12% in relation to FRP2 , 1% in relation to FRP3 and 4% in relation to the Average of this results. However, in the post-peak section the results present a greater discrepancy when compared to the experimental results.

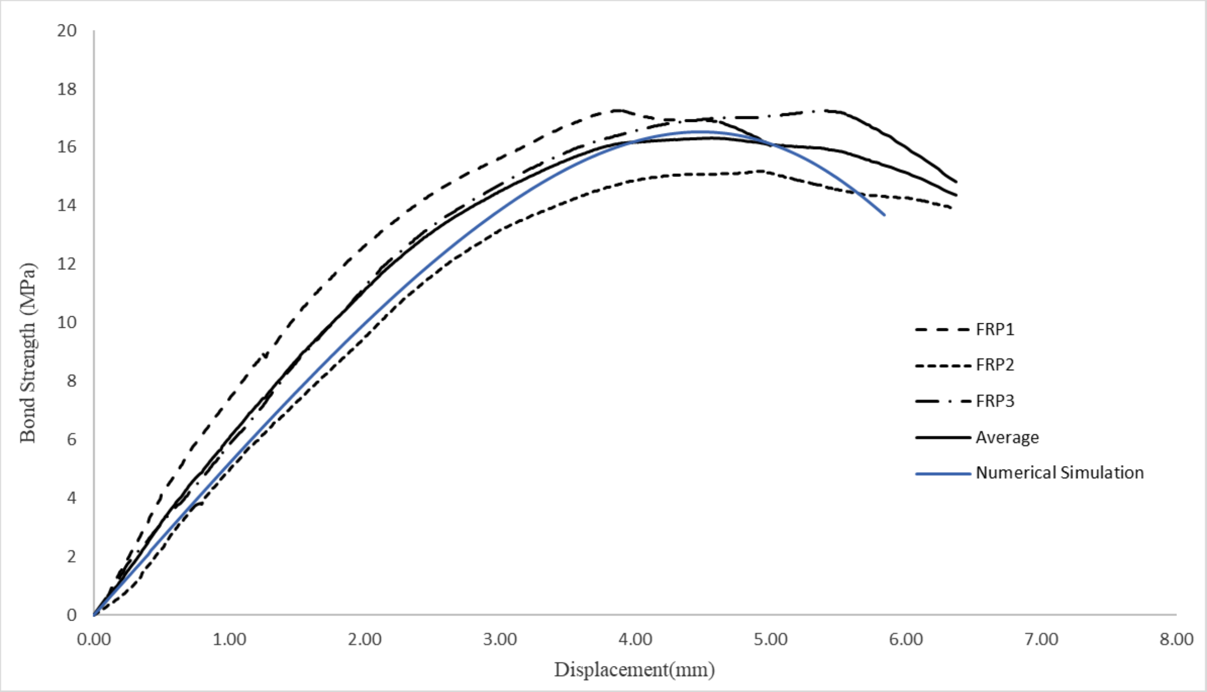

Figure 6. Pullout results compared to numerical simulation

6 Conclusions

The analysis of the bond behavior of FRP rebars used with concrete is a subject of extreme importance and relevance, because an adequate bond is necessary for the combined behavior between the bars and the concrete. Thus, the experimental analysis of these rebars through pullout tests combined of the analysis through numerical simulations is a recurring theme in the studies of FRP rebars. This study was able to prove the ability of a more simplified model using linear behavior for the materials and cohesive behavior in the interaction between both to represent the rebar *versus* concrete interaction. Although the results are promising, a deeper analysis of other forms of numerical simulation of bond behavior is an interesting topic for future studies.

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References

[1] J. Ramôa Correia, *Pultrusion of advanced fibre-reinforced polymer (FRP) composites*. 2013.

[2] Z. Achillides, "Bond behaviour of FRP bars in concrete," 1998.

[3] B. Başaran, İ. Kalkan, A. Beycioğlu, and I. Kasprzyk, "A Review on the Physical Parameters Affecting the Bond Behavior of FRP Bars Embedded in Concrete," *Polymers (Basel).*, vol. 14, no. 9, 2022, doi: 10.3390/polym14091796.

[4] Z. Achillides and K. Pilakoutas, "Bond behavior of FRP Bars under direct pullout conditions," *J. Compos. Constr.*, vol. 8, pp. 173–181, 2004.

[5] A. El Refai, M.-A. Ammar, and R. Masmoudi, "Bond Performance of Basalt Fiber-Reinforced Polymer Bars to Concrete," *J. Compos. Constr.*, vol. 19, no. 3, pp. 1–12, 2015, doi: 10.1061/(asce)cc.1943-5614.0000487.

[6] S. Reichenbach, P. Preinstorfer, M. Hammerl, and B. Kromoser, "A review on embedded fibre-reinforced polymer reinforcement in structural concrete in Europe," *Construction and Building Materials*, vol. 307. 2021, doi: 10.1016/j.conbuildmat.2021.124946.

[7] G. Fava, V. Carvelli, and M. A. Pisani, "Remarks on bond of GFRP rebars and concrete," *Composites Part B: Engineering*, vol. 93. pp. 210–220, 2016, doi: 10.1016/j.compositesb.2016.03.012.

[8] M. Baena, L. Torres, A. Turon, and C. Barris, "Experimental study of bond behaviour between concrete and FRP bars using a pull-out test," *Composites Part B: Engineering*, vol. 40, no. 8. pp. 784–797, 2009, doi: 10.1016/j.compositesb.2009.07.003.

[9] A. El Refai, F. Abed, and A. Altalmas, "Bond Durability of Basalt Fiber – Reinforced Polymer Bars Embedded in Concrete under Direct Pullout Conditions," vol. 19, no. 5, pp. 1–11, 2015, doi: 10.1061/(ASCE)CC.1943-5614.0000544.

[10] A. Altalmas, A. El Refai, and F. Abed, "Bond degradation of basalt fiber-reinforced polymer (BFRP) bars exposed to accelerated aging conditions," *Construction and Building Materials*, vol. 81. pp. 162–171, 2015, doi: 10.1016/j.conbuildmat.2015.02.036.

[11] W. Wei, F. Liu, Z. Xiong, Z. Lu, and L. Li, "Bond performance between fibre-reinforced polymer bars and concrete under pull-out tests," *Constr. Build. Mater.*, vol. 227, p. 116803, 2019, doi: 10.1016/j.conbuildmat.2019.116803.

[12] V. A. Rossetti, D. Galeota, and M. M. Giammatteo, "Local bond stress-slip relationships of glass fibre reinforced plastic bars embedded in concrete," *Mater. Struct.*, vol. 28, no. 6, pp. 340–344, 1995, doi: 10.1007/BF02473149.

[13] B. H. Tekle, A. Khennane, and O. Kayali, "Bond Properties of Sand-Coated GFRP Bars with Fly Ash–Based Geopolymer Concrete," *J. Compos. Constr.*, vol. 20, no. 5, pp. 1–13, 2016, doi: 10.1061/(asce)cc.1943-5614.0000685.

[14] J. Y. Lee *et al.*, "Interfacial bond strength of glass fiber reinforced polymer bars in high-strength concrete," *Compos. Part B Eng.*, vol. 39, no. 2, pp. 258–270, 2008, doi: 10.1016/j.compositesb.2007.03.008.

[15] A. Rolland, P. Argoul, K. Benzarti, M. Quiertant, S. Chataigner, and A. Khadour, "Analytical and numerical modeling of the bond behavior between FRP reinforcing bars and concrete," *Constr. Build. Mater.*, vol. 231, p. 117160, 2020, doi: 10.1016/j.conbuildmat.2019.117160.

[16] C. A. Issa and O. Masri, "Numerical simulation of the bond behavior between concrete and steel reinforcing bars in specialty concrete," *Int. J. Civil, Environ. Struct. Constr. Archit. Eng.*, vol. 9, no. 6, pp. 767–774, 2015.

[17] O. Gooranorimi, W. Suaris, and A. Nanni, "A model for the bond-slip of a GFRP bar in concrete," *Eng. Struct.*, vol. 146, pp. 34–42, 2017, doi: 10.1016/j.engstruct.2017.05.034.

[18] ACI Committee 440, "ACI 440.3R-12 Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures," *Tech. Doc.*, p. 440, 2012.