ANALYSIS OF THE BOND STRESS WHEN USING GFRP BARS

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Submetido 08/01/2019 - Aceito 21/09/2021

DOI: 10.15628/holos.2021.9386

ABSTRACT

For most of the structural solutions, the construction industry in Brazil is based on the use of conventional reinforced concrete elements composed of concrete and steel bars. However, problems related to this traditional structural system, such as the corrosion of metallic bars exposed to aggressiveness environments, motivate the study of new materials to be used as a replacement of conventional bars. In this context, FRP (Fiber Reinforced Polymers) bars can be viable due to their good mechanical properties and resistance to aggressive environmental agents. Thus, the main objective of this paper was the evaluation of the bond stress of GFRP bars using pullout tests. Thus, twenty specimens were analyzed with two concrete compressive strengths of 30 MPa and 60 MPa and two different GFRP bar diameters of 9.5 and 16.0 mm. According to the test results, it was verified a high variability of the adhesion between the GFRP bar and the concrete. Concerning the statistical analysis of pullout tests performed and considering the methodology proposed to analyze the quality control, the variation coefficient varied from 13.71% to 20.17%, classifying the pullout tests performed as medium or poor. These results demonstrate that the response of the GFRP bars obtained in the pullout tests was not reliable, demonstrating the need for new research to obtain adhesion coefficients and anchoring lengths for use in structural designs with such materials.

KEYWORDS: GFRP bars, bond, pullout test, variability.

ANÁLISE DA TENSÃO DE ADERÊNCIA COM O USO DE BARRAS DE GFRP

RESUMO

A indústria da construção civil no Brasil é baseada, na maior parte das soluções estruturais, no uso de elementos convencionais de concreto armado compostos de concreto e barras de aço. No entanto, problemas relacionados a este sistema estrutural tradicional, tal como a corrosão de barras metálicas em ambientes de elevada agressividade ambiental, motivam o estudo de novos materiais a serem utilizados como substitutos das barras convencionais. Neste contexto, as barras de FRP (Polímeros Reforçados com Fibras) são viáveis devido às suas boas propriedades mecânicas e resistência aos agentes agressivos. Assim, o objetivo principal deste trabalho foi avaliar a tensão de aderência de barras de fibra de vidro (GFRP, *Glass Fiber Polymed Polymer*, em língua inglesa) por meio de ensaios de arrancamento. Assim, vinte corpos de prova, com resistências à compressão de concreto de 30 MPa e 60 MPa e dois diferentes diâmetros de barra GFRP de 9,5 e 16.0 mm foram analisados. De acordo com os resultados obtidos, verificou-se a alta variabilidade da aderência entre a barra de GFRP e o concreto. Quanto à análise estatística dos testes de arrancamento realizados e levando em conta a metodologia para verificação do controle de qualidade, o coeficiente de variação apresentou valores entre 13,71% e 20,17%, classificando os ensaios realizados em níveis de qualidade médio ou ruim, demonstrando a necessidade de novas pesquisas para obtenção de coeficientes de aderência e comprimentos de ancoragem para uso em projetos estruturais com tais materiais.

PALAVRAS-CHAVE: Barras de GFRP, aderência, ensaio de arrancamento, variabilidade.

1 INTRODUCTION

For many years, it was believed that the metallic reinforcements of conventional concrete structures remained protected by the alkalinity of the concrete, and, in this way, the structures remained durable (MAZZÚ, 2020). However, corrosion of reinforcement has always been a significant problem when designing concrete structures. According to Mazzú (2020), when exposed to aggressive environments, such as industrial and marine environments with a significant variation of temperature, humidity, and water level, the structures present a reduction of the alkalinity of the concrete, followed by corrosion of the reinforcement, degradation and detachment of the concrete, exposing the reinforcement directly to the conditions of environmental aggression.

The corrosion of steel reinforcement can be induced by the carbonation of the concrete or by chloride penetration. In a lesser number of cases, corrosion may be caused by leakage currents or hydrogen embrittlement in high-strength steels used in prestressed concrete structures (BERTOLINI, 2010).

An effective approach to eliminating the corrosion problems in concrete structures would be corrosion-resistant fiber-reinforced bars instead of conventional steel bars. In this context, Glass Fiber Reinforced Polymer (GFRP) bars can be used to design reinforced concrete elements under conditions where conventional steel bars result in unacceptable serviceability problems (EHSANI *et al*., 1993; SPAGNUOLO *et al.,* 2021).

The Fiber Reinforced Polymers (FRP) materials are anisotropic and are characterized by high tensile strength only in the direction of the reinforcing fibers. This anisotropic behavior affects the shear strength and dowel action of FRP bars and the bond performance of FRP bars to concrete. Furthermore, FRP materials do not exhibit yielding. Thus, this material presents a linear-elastic behavior until failure. In this context, the design procedures should account for the lack of ductility in concrete elements reinforced with FRP bars (ACI 440.1R, 2015). The mechanical behavior of FRP reinforcement differs from the behavior of steel reinforcement. Therefore, changes in the design philosophy of concrete structures using FRP reinforcement are needed since it should consider ductility change in concrete reinforced with FRP bars (DALFRÉ, MAZZÚ E FERREIRA, 2021).

The GFRP bars have demonstrated better performance in tension behavior and moisture absorption under the different exposure conditions when using urethane-modified vinyl ester coating compared to the sand-coated surface layer (MESFER, 2007).

The properties of the FRP reinforcement control the bonding in FRP/concrete systems. Thus, the bond strength between GFRP bars and concrete is given by friction, unlike the ribbed steel bars, where this strength is given by the mechanical bond (BAKIS *et al*., 1998). Usually, there are two principal experimental test methods to be used to study the bond behavior of steel bars embedded in a concrete matrix: direct pullout tests of an embedded bar in a concrete cube or cylinder with distinct bond lengths and the pullout of a single bar placed in small beam specimen tested in bending (DOMONE, 2006). The beam test is more reliable; however, it is more complicated to be executed and, because of that, the pullout test was adopted in this research due to its simplicity.

Several analytic and numerical models in literature try to represent the bond stress response in the steel-concrete interface. In these models, most of them were based on experimental observation. Several parameters were studied, like concrete compressive strength, concrete cover, steel bar diameter, development length, and others, and these tests provided equations to calculate the average bond strength using linear or non-linear regressions from the experimental hypothesis. Thus, there are several ways to analyze the variability of a given factor, from simple methods such as the mean value, standard deviation, and coefficient of variation, to more complex methodologies such as the analysis of variance (ALMEIDA FILHO, 2006).

The application of statistical analysis has been the objective of several researchers. However, extra care must be taken not to fall into contradictions due to the bad use of the statistical tool or a small number of results used in the analysis. The usual drawback of the statistical procedures when applied to concrete is that the mean value and standard deviation need a great number of specimens to avoid a significant error in estimating such parameters (MELCHERS, 1987; ALMEIDA FILHO, 2006; DOMONE, 2006).

In this context, to attain a high level of quality control, it is necessary to establish variability limits for parameters such as the standard deviation and the coefficient of variation. Although the standard deviation is more commonly used, the coefficient of variation permits a better understanding and easy visualization of the actual variability since it will not depend on the magnitude of the measured properties (MELCHERS, 1987).

Due to the amount of variables that can interfere in the bond properties of GFRP reinforcing bars, the main objective of this work was to statistically evaluate the variability of the bond stress variability of GFRP bars in pullout tests with different concrete compressive strength and different GFRP bar diameters. The importance of the present research relies on the lack of published data on the variability of the bond stress of GFRP bars, which could be affected by its sensibility to minor modifications such as embedment length, GFRP bars roughness, and concrete compressive strength.

2 MATERIALS AND EXPERIMENTAL PROGRAM

2.1 Pullout tests

The main objective of this work was the evaluation of the variability of the bond stress between the GFRP bars and the concrete substrate using pullout tests. Due to the absence of a normative recommendation to analyze the bond stress, the pullout specimens were based on recommendations given by RILEM/CEB/FIP (Rilem, 1973) and on experimental programs described in other publications (PILAKOUTAS *et al.,* 1994; COOK *et al*., 1993; BAKIS *et al*., 1998; AHMED *et al.*, 2020; among others). The typical test specimen consisted of a concrete cubic block in which a steel anchor bar was embedded in its center. However, in this work, the given specimen was adapted to a cylindrical geometry with the diameter and the height equal to 10 times the diameter of the GFRP used in the pullout test (100 mm or 160mm, respectively). The embedment lengths considered in this work were equal to five times the GFRP bars (50mm or 80mm, respectively). To ensure the embedment lengths, a plastic tube was applied over the part of the bar to be unbounded length. The geometry of the specimens can be found in Figure 1.

The specimens were divided into two series, S1 and S2, in correspondence to a nominal diameter of the steel bar, 9.5 mm and 16 mm, respectively. Each series includes two groups, composed of two different concrete compressive strengths (30 MPa and 60 MPa), respectively. Table 1 shows the nomenclature used for the pullout specimens.

Table 1: Identification of the pullout specimens

Specimen	Concrete compressive strength	Nominal GFRP bar diameter	z (specimen identification)
C30B9-z	30	9.5	1 to 5
C30B16-z	30	9.5	1 to 5
C60B9-z	60	16.0	1 to 5
C60B16-z	60	16.0	1 to 5

(COUTO, 2007)

Each specimen was designated by a set of symbols and numbers to be uniquely identified. The notation adopted to identify the specimens is CxBy-z, where x is the concrete strength class (30 or 60 MPa); y is the nominal diameter, in mm (9.5 or 16.0mm); and z is the number of the specimen: 1 to 2. Therefore, C30B9-1 denotes a specimen with a concrete strength class of 30 MPa, GFRP bar with a diameter of 9.5 mm, and 1 denotes the first specimen out of the five replicates.

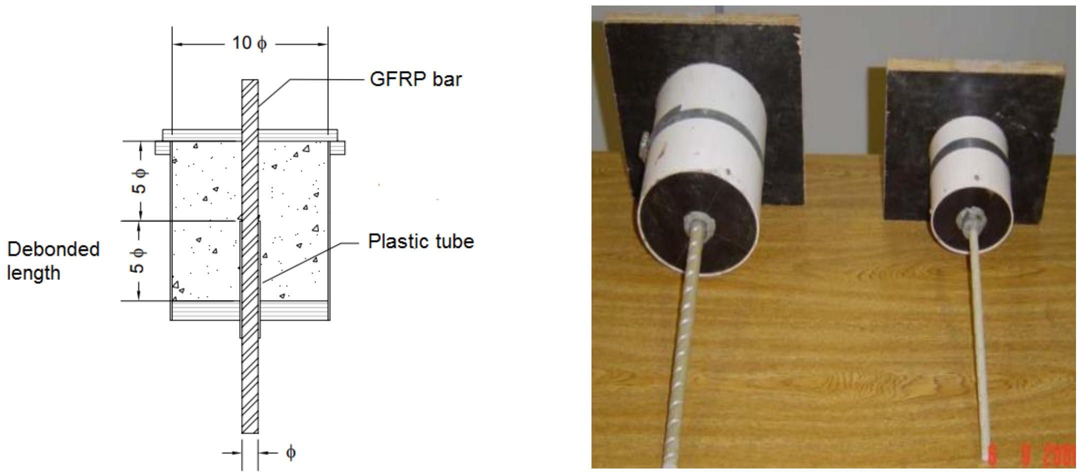


Figure 1: Geometry of the specimens (COUTO, 2007)

The tests were conducted, at the age of 28 days, by using an Instron testing machine, Model 8506, with a 2500 kN static load capacity, and under displacement control, with a rate of 0.010 mm/s or 0.016 mm/s in the case of specimens with bars of 9.5mm and 16mm, respectively (CASTRO, 2002; ALMEIDA FILHO, 2006; FERNANDES, 2000). The slip was measured using a Linear Variable Differential Transformer (LVDT) of KYOWA, model DTH-A-10, with a maximum core displacement of 10mm (accuracy of 0,001mm), positioned at the free-ended bar.

2.2 Determination of the mechanical properties of the GFRP bars

The GFRP bars used in the experimental program were manufactured using the pultrusion process, as shown in Figure 2, and are made up of continuous longitudinal type E-glass fibers embedded in thermoset vinyl ester resin. The surface configuration was obtained by using a helical winding of the same kind of fibers with a coating of sand particles of a specific grain-size distribution. The bars used in this work presented the nominal diameters of 9.5 or 16.0 mm (Figure 3). The mechanical properties, according to the manufacturer, and geometric parameters are given in Table 2.

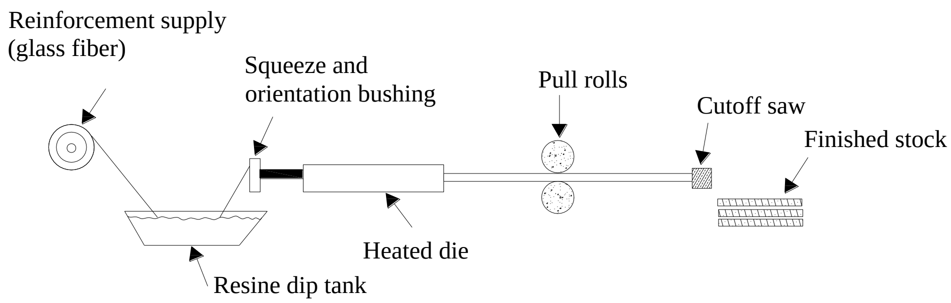


Figure 2: Pultrusion process to obtain the GFRP bars (TIGHIOUART *et al.,* 1998)

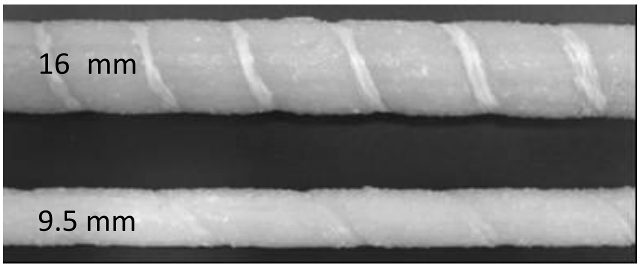


Figure 3: GFRP bars used in the experimental program (COUTO, 2007)

Table 2 - Properties of GFRP bars used in the experimental program (HUGHES BROTHERS, 2006)

Nominal diameter of the bar (mm)	Cross-section (mm^2)	Tensile strength (MPa)	Modulus of elasticity (GPa)
9.5	84.32	760	40.8
16.0	217.56	655	40.8

The effective diameter was obtained by immersing three specimens of each bar, with a length of 25 cm, in water. The displacement of water caused by the immersion of the specimens was measured, and then the effective diameter of the bar was calculated, considering them to be perfectly circular. Thus, effective diameters of 9.56 and 15.90 mm for the bars were obtained.

For each nominal bar diameter, five tensile tests were conducted by using an Instron testing machine, Model 8506, according to the standard procedures of the ASTM D3916 (ASTM, 2002) in order to determine the modulus of elasticity, the ultimate stress, and strain of the GFRP bars (Figure 4).

Figure 4: Tensile test of the GFRP bars

The determination of the GFRP bars' mechanical properties by testing is complicated due to the stress concentrations in and around anchorage points, leading to the premature failure of the specimen (TIGHIOUART *et al*., 1998). Then, to avoid premature failure, aluminum grips were used as an attempt to allow failure to occur in the middle of the test specimens (Figure 5).

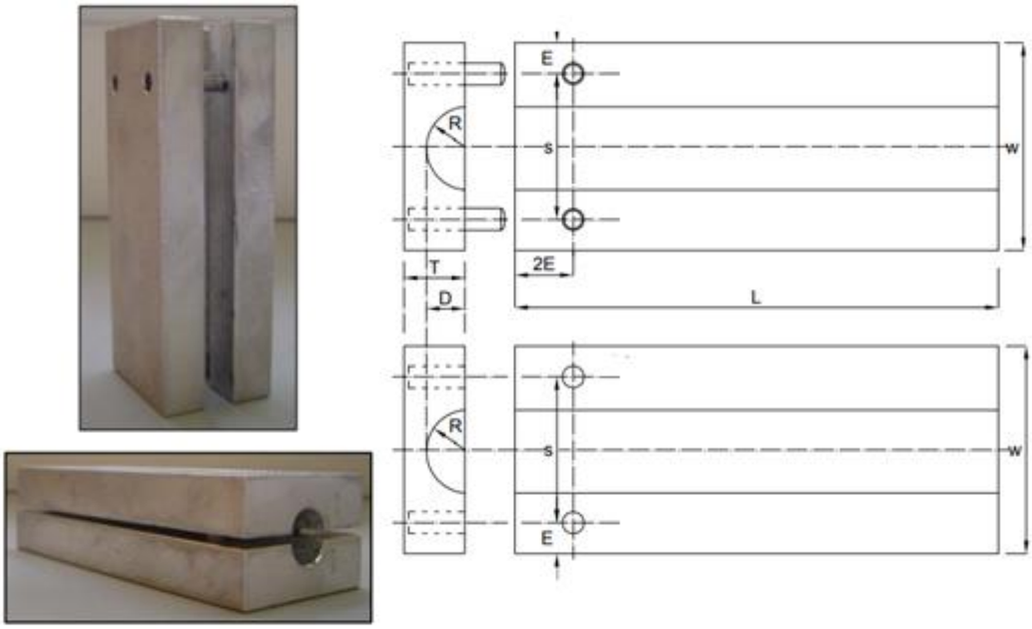


Figure 5: Aluminum grip (COUTO, 2007)

2.3 Determination of the mechanical properties of the concrete mixtures

Cylinder specimens, with a diameter of 100 mm and a height of 200 mm, were used to obtain the compressive strength, tensile strength, and the Young's modulus according to the recommendations NBR 5739 (ABNT, 2018), NBR 7222 (ABNT, 2011) and NBR 8522 (ABNT, 2017), respectively. The average compressive strength (fcm) and the static modulus of elasticity in compression (Ec) were determined at the age of 28 days. The two different concrete mixtures and their proportions and basic properties are shown in Table 3.

Table 3: Composition and properties of concrete (COUTO, 2007)

Components (kg/m³)	**30 MPa**	**60 MPa**
Cement (kg)	365	488
Sand (kg)	884	767
Aggregate (kg)	942	942
Water (kg)	256	227
Slump (mm)	21.0	13.0
Compressive strength (MPa)	34.6	55.2
Splitting tensile strength (MPa)	2.2	3.8
Modulus of elasticity (GPa)	32.53	39.93

2.4 Statistical analysis

The statistical parameters analyzed in this work include mean value (M), standard deviation (S.D.), and the coefficient of variation (C.V). It should be noticed that the mean value (M) is the average obtained by the relationship between the sum of the values (x) and the number of specimens (n), as presented in Equation 1.

$$M = \frac{\sum_{l}^{n} x_i}{n} \qquad (1)$$

The Standard Deviation (S.D.) is used to quantify the amount of variation or dispersion of a set of data values (x) and the value (M), and it is expressed according to Equation 2.

$$S.D. = \frac{\sum_{l}^{n} (x_i - M)^2}{(n-1)} \qquad (2)$$

The Coefficient of Variation (C.V.) consists of the relation between the Standard Deviation (S.D.) and the mean value (M), as presented in Equation 3.

$$C.V. = \frac{S.D}{M} \qquad (3)$$

Barbosa (2001) and França (2004) performed statistical analysis of pullout tests performed considering conventional steel bars and concrete and adopted a coefficient of variation equal to

25% as the limit. Thus, if the C.V. value is less than 25%, the set of specimens could be accepted due to their lower bond stress variability.

Almeida Filho (2006) adopted three limit values for the variation coefficient, aiming at greater quality control of the specimens analyzed. For the A-class (excellent), the accepted upper limit for the coefficient of variation was 10%; for the B-class (medium), the C.V. limit was 15%, and for the C-class (poor), the limit of C.V. was 20%.

Table 4 shows the quality control levels and limits adopted by Melchers (1987) for the compressive strength.

In this study, the variability measures have been calculated considering results obtained by carrying out the pullout test at least five specimens, and the quality criteria limit values presented by Almeida Filho (2006) were applied.

Table 4: Accepted limits of the variability of concrete compressive strength as a function of the quality control

Quality control	Accepted limits for the standard deviation (f_c > 27 MPa)	Accepted limits for the coefficient of variation
A (excellent)	2.7	10%
B (average)	4.0	15%
C (poor)	5.4	20%

MELCHERS (1987)

3 RESULTS AND DISCUSSION

3.1 Tensile tests

Table 5 shows the mechanical properties experimentally obtained for each nominal diameter bar and the ones presented for the manufacture. Figure 6 shows the relationship between stress versus strain for each bar experimentally tested, while Figure 7 shows the typical failure modes of the GFRP bars.

As expected, both GFRP bars presented a linear-elastic behavior until rupture. The analysis of the results experimentally obtained, and the ones presented by the manufacture are quite similar. The elastic modulus experimentally obtained was 5% and 10% higher when compared to the values provided by the manufacturer for the 9.5 and 16.0 mm diameters, respectively. The ultimate strengths vary -6% and -5% for the diameters of 9.5 and 16.0 mm, respectively.

Table 5: Mechanical properties of the GFRP bars (COUTO, 2007)

Nominal diameter (mm)	9.5 mm			16.0 mm		
	Experimental program	Manufacture	Experimental/ Manufacture	Experimental program	Manufacture	Experimental/ Manufacture

Modulus of elasticity (GPa)	42.7	40.8	1.05	44.9	40.8	1.10
Tensile strength (MPa)	714	760	0.94	624	655	0.95

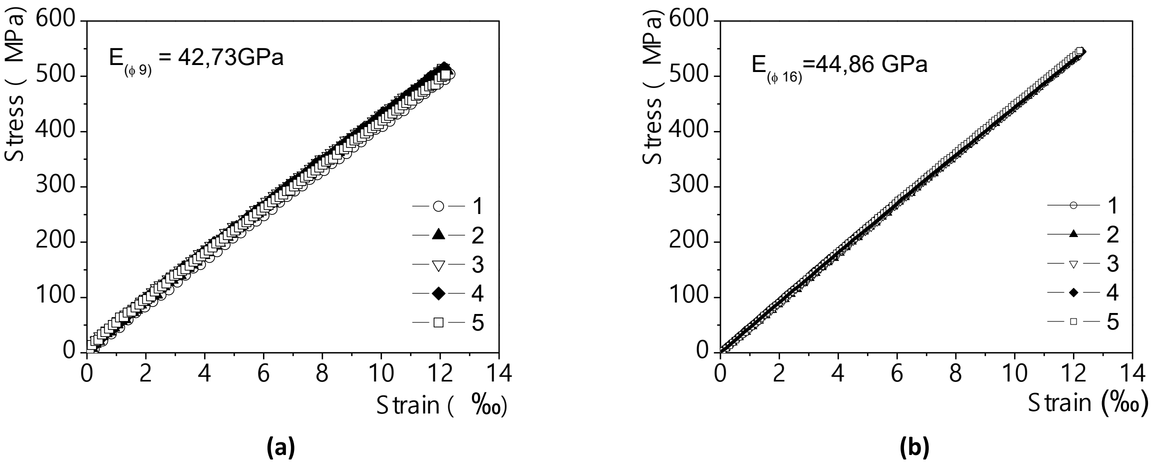


Figure 6: Relationship between stress versus strain of the GFRP bars with 9,5 mm diameter (a) and 16.0 mm diameter (b) (COUTO, 2007)

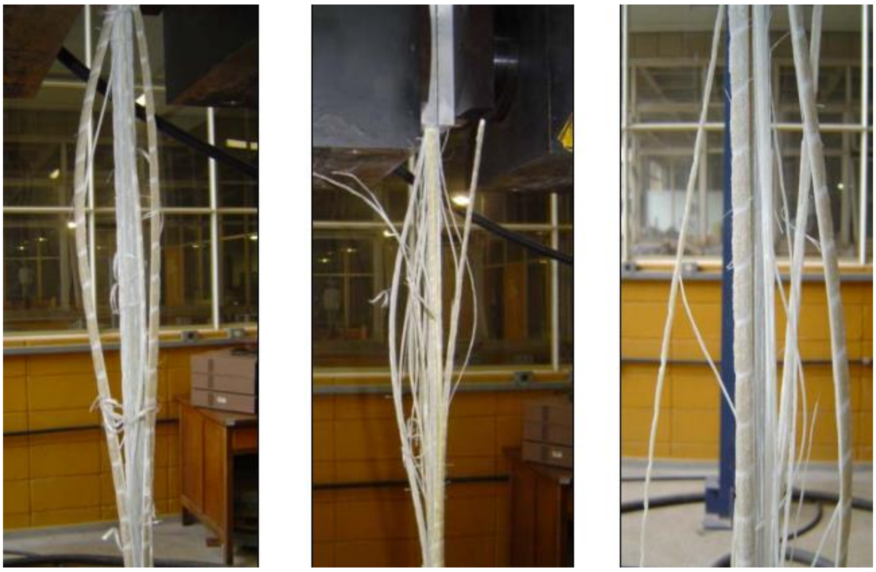


Figure 7: Typical failure modes of the GFRP bars (COUTO, 2007)

However, the aluminum device used to minimize stresses caused by the anchorage of the bar on the test machine improperly behaved since it was observed the defibration of the bars and failure close to the machine grips. It should be noticed that the recommendation ACI 440.1R (2015) reports the difficulty to perform this test and allows to consider the design the mechanical properties of the FRP bars reported by the manufacturer.

3.2 Pullout tests

During the pullout test, the bond stress profile changes along the embedment length, but the main focus of the present research was not to assess the local bond law but its dependence on the parameters investigated. To derive a practical design indicator, the influence of the parameters analyzed was restricted to the bond stress that can be obtained as presented in Equation 4, where F is the registered pullout load, l_d is the embedment length, and ϕ is the bar diameter.

$$\tau = \frac{F}{\pi \cdot \phi \cdot l_d} \tag{4}$$

The average bond stress (τ_m) was obtained by the sum of the three bond stresses of $\tau_{0,01}$, $\tau_{0,1}$ and $\tau_{1,0}$, being them the bond stress when the slippage reaches 0,01 mm, 0,1 mm and 1,0 mm, respectively, as shown in Equation 5.

$$\tau_m = \frac{\tau_{0.01} + \tau_{0.1} + \tau_{1.0}}{3} \tag{5}$$

The bond strength at three levels of slippage, namely 0,01 mm, 0,1 mm and 1,0 mm, the maximum bond strength and average bond strength with the corresponding diameter of bars and concrete compressive strength are shown in Table 6.

Table 6: Bond strength of GFRP bars from pull-out test (COUTO, 2007)

Specimen	$\tau_{0,01}$ (MPa)	$\tau_{0,1}$ (MPa)	$\tau_{0,1,0}$ (MPa)	τ_u (MPa)	τ_m (MPa)	Failure mode
C30B9-1	3.56	4.20	5.16	6.17	4.31	P[1]
C30B9-3	2.39	3.03	4.84	5.69	3.42	P
C30B9-4	2.13	2.29	4.04	4.46	2.82	P
C30B9-5	2.18	2.55	4.04	4.46	2.92	P
Average	2.56	3.02	4.52	5.20	3.37	-
D. P.	0.674	0.846	0.567	0.866	0.679	-
C.V.	26.29%	28.06%	12.56%	16.67%	20.17%	-
C60B9-1	2.71	4.36	7.44	8.08	4.84	P
C60B9-2	3.30	5.42	11.85	12.28	6.86	P
C60B9-4	2.87	4.09	8.72	10.42	5.23	P
C60B9-5	3.14	4.84	9.73	11.85	5.90	P
Average	3.00	4.68	9.43	10.66	5.70	-
D. P.	0.262	0.584	1.864	1.894	0.884	-
C.V.	8.73%	12.48%	19.76%	17.77%	15.50%	-
C30B16-1	3.69	4.61	7.46	7.90	5.25	P
C30B16-2	3.50	5.36	9.66	10.70	6.17	P
C30B16-4	2.98	3.57	6.97	10.11	4.51	P
C30B16-5	4.15	5.30	8.36	10.13	5.94	P
Average	3.58	4.71	8.11	9.71	5.47	-
D. P.	0.485	0.832	1.183	1.239	0.749	-
C.V.	13.56%	17.65%	14.58%	12.76%	13.71%	-
C60B16-2	3.44	5.73	13.28	16.04	7.48	C[2]

C60B16-3	4.05	6.65	14.35	16.04	8.35	C
C60B16-4	7.28	10.03	13.89	14.16	10.40	C
C60B16-5	5.44	9.40	-	14.95	7.42	S[3]
Average	5.05	7.95	13.84	15.30	8.41	-
S. D.	1.705	2.086	0.540	0.918	1.393	-
C.V.	33.74%	26.24%	3.90%	6.00%	16.56%	-

[1] Pullout; [2] combined failure; [3] splitting; Standard Deviation (S. D.); Coefficient of Variation (C.V.) = (Standard deviation/Average) x 100

Figure 8 presents the pullout test conducted in this work, and Figure 9 presents the relationship between bond stress versus slip registered in the experimental program.

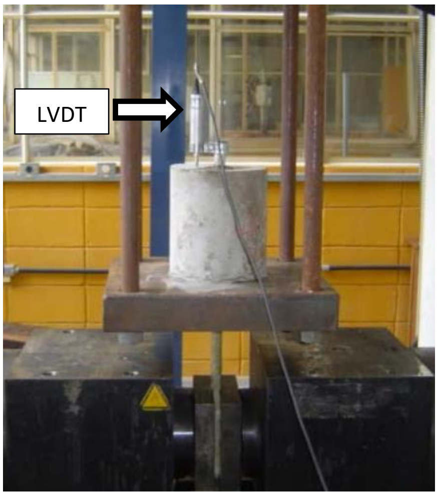
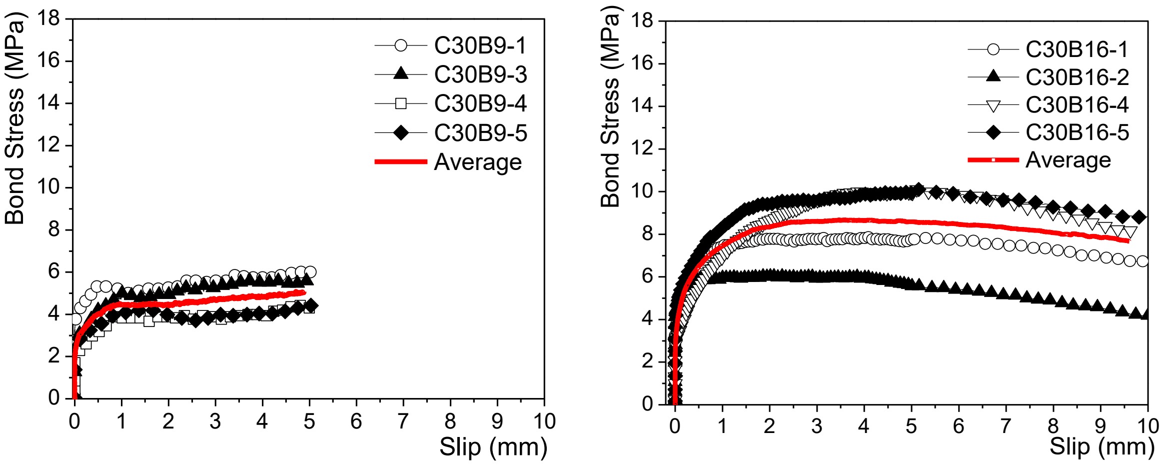
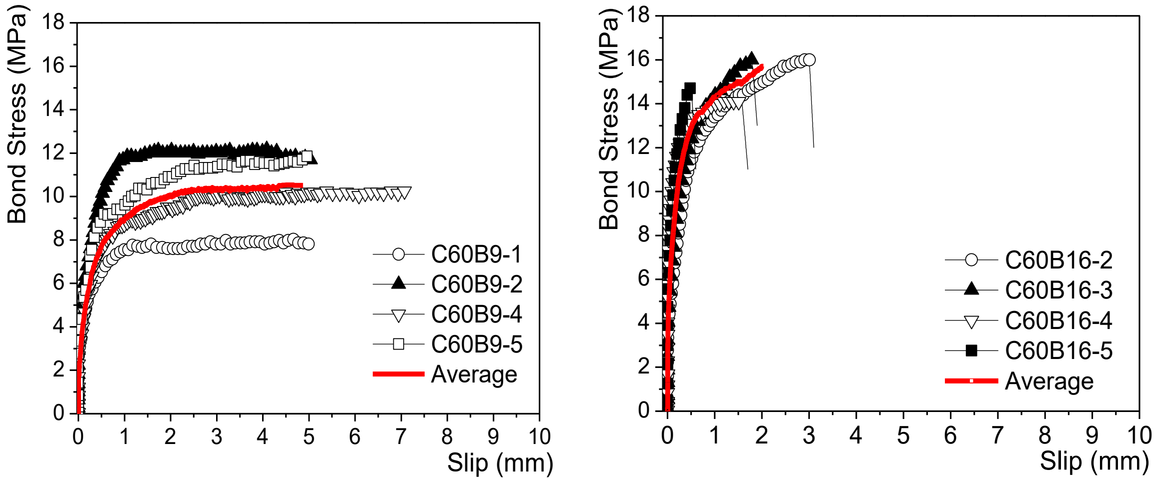


Figure 8: Pullout test (COUTO, 2007)



(a) (b)



(c) (d)

Figure 9: Relationship between Bond stress versus slip of GFRP bars with concrete of 30MPa and GFRP bar of (a) 9.5 mm and (b) 16.0 mm. concrete of 60MPa and GFRP bar of (c) 9.5 mm and (d) 16.0 mm (COUTO, 2007)

The C30B9-2 specimen presented atypical behavior due to a wrong positioning of the plastic tube used to define the bond length and, since a slight variation in anchorage length may compromise the results, it was not considered for the analysis (ALMEIDA FILHO, 2006). The C30B16-3 specimen (Figure 10) presented a crack opening at the beginning of the test, which compromises the bond between the GFRP bar and the surrounding concrete. Thus, this model was not adopted in the analysis of the results. Considering the specimens with concrete strength of 60 MPa, the specimens C60B9-3 and C60B16-1 were not analyzed since they presented a significantly lower adhesion strength or presented an unusual failure compared to the other samples. Thus, these specimens were not adopted in the analysis of the results.

Figure 10: Crack opening registered in the specimen (COUTO, 2007)

The bond mechanism is mainly dependent on three components: adhesion, friction, and mechanical bearing. For steel bars, the bearing component plays the most crucial role in the bond. However, when using GFRP bars, the surface conformation does not possess the characteristics of steel bars (i.e., higher shear strength and stiffness) that provide enough lateral confinement through rib bearing. Therefore, for GFRP bars, it is the adhesion and the friction that control the bond strength (BENMOKRANE *et al*., 1996).

Concerning the pullout tests performed, it can be concluded that the models were suitable for the measurement of the displacement of the GFRP bar about the concrete substrate.

Concerning the results presented in Table 6 and Figure 9, it can be seen that a significant variation was obtained for the bond stress of the GFRP bars, mainly concerning the bond stress registered at the 0.01 mm level of slippage.

For the concrete strength class of 30MPa, specimens with GFRP bars with 9.5 mm diameter presented a higher variation in results than the specimens with GFRP bars of 16 mm, presenting an average bond stress variation of 20.17% and 13.71%. The specimens with a concrete strength class of 60 MPa presented an average bond stress variation of 15.50% and 16.56%. It can be attributed to the smaller dimension of specimens and the embedment length, leading to a lower variation of the bond length (50 and 80 mm, for specimens with a bar diameter of 9.5 and 16 mm, respectively), that can lead to the significant variations observed in the results. The same behavior was observed in the experimental program carried out by Mesfer (2007). Thus, the bond stress is appreciably higher in the models where high-strength concretes were used compared to models with the concrete strength class of 30 MPa. Regarding the failure mode, the specimens of the C30B9, C60B9, and C30B16 series were based on the bar pullout, while the C60B16 were based on the combined (bar/concrete interface) and splitting of the concrete specimen.

Concerning the statistical analysis of pullout tests performed, taking into account the results presented in Table 6 and the methodology adopted by Almeida Filho (2006), the series C30B16 could be classified as B class (13.71%) and the other three series as C class (varying from 15.50% to 20.17%). Thus, the obtained results show that the response of the GFRP bars was not entirely reliable, demonstrating the need for further research for the correct use and design of these bars as reinforcement in concrete structures.

4 CONCLUSIONS

The main objective of this paper was to evaluate the variability of the bond stress of GFRP bars using pullout tests. Thus, twenty pullout tests were performed with two concrete compressive strengths (30 MPa and 60 MPa) and two different GFRP bar diameters (9.5 and 16mm).

Considering the GFRP bars tensile test, the aluminum device used to minimize stresses caused by the anchorage of the bar on the test machine improperly behaved since it was observed the defibration of the bars and failure close to the machine grips. Thus, another anchorage system should be adopted to obtain the tensile properties of the GFRP bars.

The test results obtained in the pullout tests verified a high variability of the adhesion between the GFRP bar and the adjacent concrete, showing that the bar diameter had a significant influence. Considering the quality control tests, the performed pullout tests could be classified as B-class (13.71%) for series C30B16 and C-class (varying from 15.50% to 20.17%) for the other three series. This behavior shows that the response of the GFRP bars was not entirely reliable, demonstrating the need for further research to obtain the bond stress parameters and the bond lengths for the structural design with this type of materials.

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COMO CITAR ESTE ARTIGO:

Dalfré, G. M., Almeida Filho, F. M. de, Couto, I., Giongo, S., Mazzú, A. D. E. (2021). Analysis of the bond stress when using GFRP bars. *Holos*. 37(5), 1-16.

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Editor(a) Responsável: Francinaide de Lima Silva Nascimento

Pareceristas *Ad Hoc*: IVAN DE SOUZA e GUSTAVO SAVARIS