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EXPERIMENTAL AND NUMERICAL STUDY OF THE STEEL-CONCRETE BOND PHENOMENON - PULL-OUT TEST ANALYSIS WITH AN ELASTO-PLASTIC MODEL

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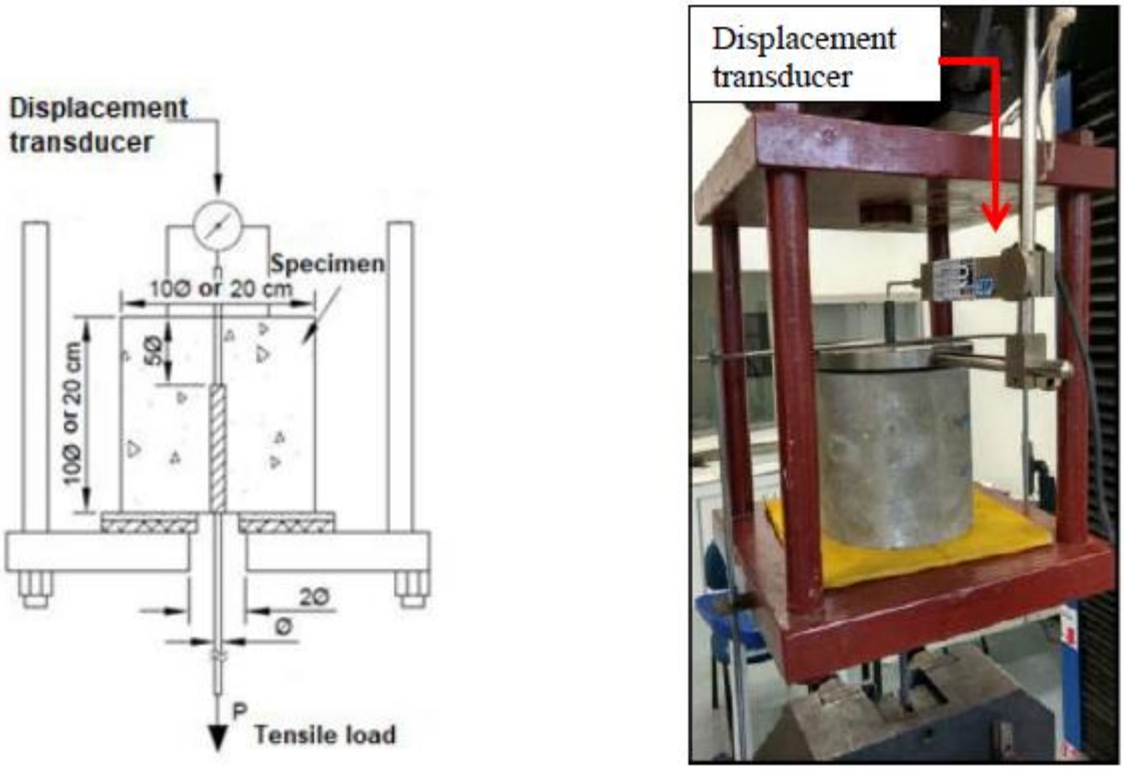
Abstract. Experimental and numerical analysis were performed to evaluate the bond behavior between steel and reinforced concrete with thin bars. The pull-out test is the most used mechanical test to study the bond phenomenon and the results of this test may adequately represent the interaction of the materials in reinforced concrete structures. Numerical analysis based in the finite element method may be used to better understand the bond behavior, but the numerical models need some specific parameters that can influence the stresses and the slip, which are important to understand the interface zone. However, the correct determination of these values is not an easy job, so in many cases the experimental data is necessary to develop a satisfactory model. In this study a modified pull-out test was applied with cylindrical specimens of 150x150 cm, composed by ribbed bars (CA-50) with 6.3, 8.0 and 10.0 mm, conventional concrete and bond length of 10 times the bar diameter. An elastic-plastic model was developed to study stress bond and the failures mechanisms, using parameters related to bar properties and the interact mechanisms between steel and concrete. The numerical model was adequately to represent the bond in pull-out test, with results able to represent the specimen behavior, especially for the 10.0 mm diameter bar.

Keywords: reinforced concrete structures, bond behavior, modified pull-out test, finite element method

1 Introduction

The feasibility of the reinforced concrete structures is assigned especially to bond phenomenon and because of this importance many researches advanced in this field [1–6]. Along the anchorage length, the transferring of the internal forces allows the materials to work together, however in the cracking regions the reinforced steel is responsible for support the loads effects. Many difficult are associated to study steel-concrete bond. The major difficult in the developing of the numerical models to evaluate the bond behavior in concrete structures are the models parameters and how to consider them [7].

In the experimental field, steel-concrete bond can be studied from different mechanical tests like confined bars tests, beam test and pull-out test. The beam test is prescribe in the RILEM RC5 [8] and is one the most accurate of these tests. This test is able to represent adequately the real reinforced concrete structure, but is of complicated execution. Associate with the facility and good results, the pull-out test (Fig. 1) is the most used in the experimental researches. In the other hand, no country has a specific standard for this test and the consequence is that many researchers make changes in this test without thinking about how the modifications can be influence the results. However Carvalho et al. [1] highlights that the EN10080 [9] standard makes reference to RILEM RC6 [10] that presents recommendations for the pull-out test.



(a) EN10080 [9] specifications (b) Modified pull-out test

Figure 1. Mechanical test details

The Fig. 1 (a) is an illustration of the pull-out test recommended and described by EN10080 [9]. A concrete cube with a steel concentric bar disposed in a machine with a load cell. The load is applied to one end of the bar while in another end is positioned a displacement transducer to measure the slips. The dimension of the concrete specimen is ten times the bar diameter (10ϕ) or at least (20x20) cm.

During the test run, a data acquisition system records the values of the applied load and slip. The applied load is used to calculate the bond stress by Eq. (1), in which P is the load apply, ϕ is rebar diameter, and l is the anchorage length ($l = 5\phi$).

$$\tau_m = \frac{P}{\pi \cdot \phi \cdot l} \tag{1}$$

Steel-concrete bond has two failure mechanisms that can be perfectly observed in the pull-out test: the pulled-out of the bar and the splitting failure. In the first one, the concrete confinement is adequately and the phenomenon is processed until damage occurs in the materials interface with the crushing of the concrete between the ribs permitting the pulled-out of the bar. In the second one (Fig.2), the specimen does not resist the stresses developed due to inadequate concrete confinement and a longitudinal cleavage divided the element in two.

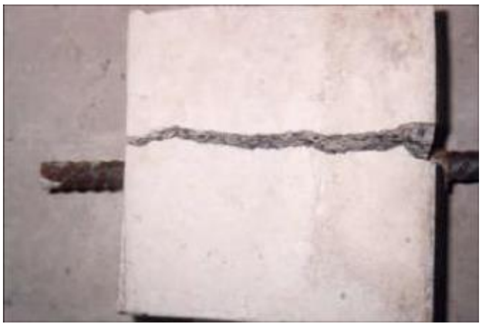


Figure 2. Splitting failure (BARBOSA [11]).

Nowadays many researchers are concerned about bond performance, use of the new materials and concrete quality, but the analysis only use the pull-out test with some differences, mainly in geometry and anchorage length [2,3,12–16]. One of the main issues of the experimental test changes is that the authors do not present analysis or information about the influences of these adjustments on the results. Thereby the conclusions about bond quality, stress, strength and performance with the better materials or innovative aggregates and additions could be influenced for the test methodology. When cylindrical concrete specimen are used [7,14,17–21], some authors [1,22] highlight specifics effects on results chiefly with respect the stress distribution.

In this reality, studies based on numerical models may contribute to better understand the bond phenomenon. In a numerical model it is possible to verify how the different parameters and variables can influence the steel-concrete bond behavior. In a finite elements models minimal factors and mechanisms can be evaluated, as the interface behavior, failures mechanism and plasticity conditions. The first developed models adopted the perfect bond in the materials interface ignoring the relative displacement of the bar, but currently the bond models presents the real conditions of the interface and the materials using mainly models of commercial softwares [7,23–27]. Cox and Herrmann [28] rate the numerical models in three scales: rib-scale, bar-scale and member scale, which differ basically with model accuracy.

Some authors evaluate the steel-concrete bond through specific theoretical models associating with finite elements approach which allow to study bond characteristics that the commercial softwares models do not evaluate properly [28,29]. Brisotto et al. [29] studied the bond through an elastic-plastic model developed following the Lundgren and Gylltoft [30] theory, but introducing some parameters to evaluated the failures mechanisms. Brisotto et al. [29] adopted two functions to reproduce the mainly damage modes: splitting and pull-out. These functions delimited the elastic bond behavior which results show the conditions of the interface stress and mechanical interlocking process. The results of the validating model showed that it can capture the damages mechanisms, but it is worth noting that this model is not calibrated with Brazilian experimental results, so some adjust can be necessary because of the distinct materials properties.

This research is a complementary investigation about the bond behavior in pull-out tests through of an experimental and numerical approaches aims to evaluated the stress of specimens in modified pull-out test presents in [1]. The experimental test was developed with conventional concrete and steel ribbed bars CA-50, with 6.3, 8.0, and 10.0 mm diameters whose results were compared and evaluated with the numerical model developed by [29].

2 Materials and methods

2.1 Experimental program: Pull-out tests

The Table 1 presents a brief of the experimental program whose casting was executed separately for each bar diameter with 6 specimens to each group. The specimens geometry was cylindrical with dimensions 150x150 mm, ilustrated in Fig.3. The anchorage length used was ten times of the bar diameter that is bigger than EN10080 [9] recommendation. This is based on the Carvalho et al.[6] conclusions that highlight the high dispersion of the test results and the possible relationship with the short anchorage length mainly with bars with diameter less than 10.0 mm. The remainder length of the bar was isolated with a PVC tube to avoid contact with concrete.

Table 1. Experimental program

Issue	Bar diameter (ϕ) mm	Anchorage length (10ϕ) mm	Repetitions
Bond stress	6.3	63	6
	8.0	80	
	10.0	100	

Some execution details of the test are showed in the Fig. 3. During the test a computer record the data of the applied load over the bar and the displacement measured by transducer. With the Eq. (1) are obtained the bond stress average to each specimen and with the displacement are plotted the stress displacement curves.

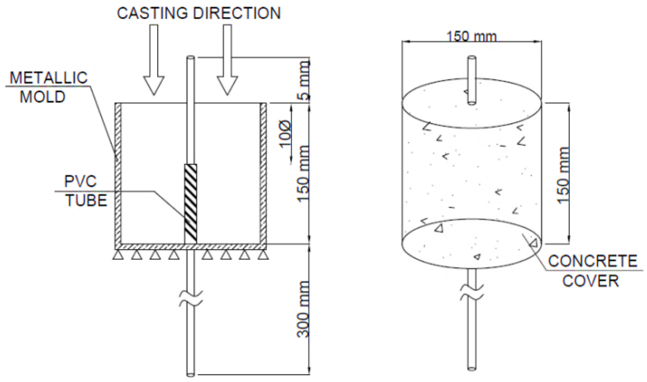


Figure 3. Specimens characteristics.

Cylindrical concrete specimens with 10x20 cm dimension was used to evaluated the concrete properties, compressive and tensile strength, in accordance with the normative prescription (ABNT NBR 5739 [31] and ABNT NBR 7222 [32] respectively). The both specimens: to pull-out test and to concrete mechanical properties determination, were keep on moist cure for 28 days, i.e. until date of the tests. The steel bars properties and the surface characteristics, presents in the Table 2, were determinate in accordance with ABNT NBR 7480 [33]. The average tensile strength was 674 MPa and

591 MPa for the yield strength.

Table 2. Steel bar surface characteristic

Ribs parameters	Bar diameter (ϕ)mm		
	6.3	8.0	10.0
High (mm)	0.3	0.3	0.6
Inclination (º)	64.4	65.2	64.8
Spacing (mm)	4.8	5.9	6.8

2.2 Numerical analysis: elasto-plastic model

Two components are responsible for the bond stress developed in the steel-concrete interface, a tangential component (τ_t) and a normal component (τ_n). The first one refers to adherence mechanism and the another is associated to splitting condition. These components determinate a tensile stress characteristic of the bond phenomenon, in accordance with Brisotto et. al. [29], and is related to elastic deformation through an elastic matrix (D_{ij}) explicit in the Eq.(2.b).

$$t_i = D_{ij} \cdot u_i^e \tag{2.a}$$

$$\begin{bmatrix} t_n \\ t_t \end{bmatrix} = E_c \begin{bmatrix} K_{11} & -\text{sgn}(u_t^e) K_{12} \\ sym & K_{22} \end{bmatrix} \cdot \begin{bmatrix} u_n^e \\ u_t^e \end{bmatrix} \tag{2.b}$$

The term D_{12} in Eq. (2.b) takes into account compressive stress resulting of the bar pulling process. To avoid an asymmetric elastic matrix, as used in Brisotto et. al. [29], the term D_{21} is considered equal to D_{12}. The effect on tangential component (τ_t) caused by the introduction of the term $D_{21} \cdot u_n^e$ is minimal because u_n^e is several orders of magnitude smaller than u_t^e. As a consequence, numerical results using Eq. (2.b) or an asymmetric version, where D_{21} = 0, are very similar.

The terms K_{11}, K_{12}, K_{22} are related with a considered spring strength developed in the interface, and E_c is the conventional elastic modulus of the concrete. The calculus of the K_{12}, K_{22} parameters are descripted in the Eq. (3) and Eq. (4), respectively, in which μ^* is a friction coefficient to the steel-concrete interface, $A' sen\alpha$ is the rib transversal area (Fig.4) to a rib inclination angle (α), ϕ diameter bar and l_k is the longitudinal rib distance.

According to Brisotto et. al. [29] the elastic tangential tensile is resist for the rib, represented in the component $E_c \cdot K_{22}$.

$$K_{12} > -\frac{K_{22}}{\mu^*} \, admitted \rightarrow K_{12} = -0,5\frac{K_{22}}{\mu^*} \tag{3}$$

$$K_{22} = \frac{t_t}{u_t^e} = E_c \cdot \frac{2A' sen\alpha}{\pi \phi l_k^2} \tag{4}$$

In conditions of negative normal deformation values (u_n^e) the component $E_c \cdot K_{11}$ assume a significative value, that can be considered a penalty factor, on the other hand, when u_n^e acquires positive values indicates interface opening, the material around the bar is responsible for the cohesion and K_{11} parameter assume a residual value.

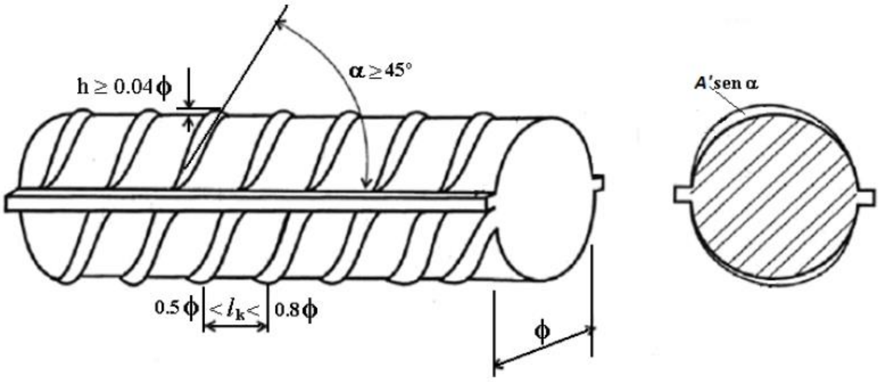


Figure 4. Bar geometry characteristics (ABNT NBR 7480 [33]).

Two functions, related to failure mechanisms, were determinate to limit elastic behavior of the tensile stress. These functions are presented in the Eq. (5) and Eq. (6) and illustrated in the Fig. 5.

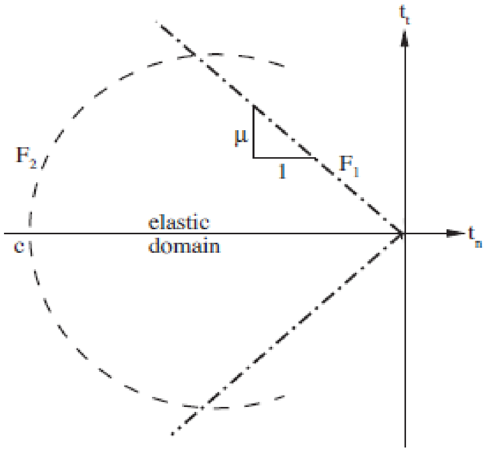


Figure 5. Representation of the limit functions in the elastic domain (Brisotto et al. [29])

$$F_1 = |t_t| + \mu . t_n = 0 \tag{5}$$

$F_1 = 0$: splitting failure

$$F_2 = t_t^2 + t_n^2 + c.t_{\tilde{n}} = 0 \tag{6}$$

$F_2 = 0$: pull-out failure

In these equations the function μ is related to the friction coefficient and the function c means the stress variation from de mechanical interlocking interaction, that be initially equivalent to concrete compressive strength (f_c). The determination of the μ and c parameters depend on the spacing rib of the bars and plastic deformation represented by d . This variable (d) theoretical express the mechanical interlocking dominance about the bond response and rib geometry influences, it can be defined, in a simplified way, as a minimal value and proportional to the interface plastic slip (Eq.7)

$$d = \min\left(\frac{u_t^p}{l_k}, 1\right) \tag{7}$$

in which l_k is the distance between two consecutive ribs and u_t^p is the plastic slip.

Firstly the calibrations were perform to conventional concrete and 16 mm rebar diameter, following the Lundgren and Gylltoft [30] research. In this context, the function $c(d)$, in Fig. 9(a), is related with the representative uniaxial compressive curve to concrete and $\mu(d)$ curve, Fig. 9(b) is obtained though experimental results of pull-out test with concrete confined specimens. The function $c(d)$ accord with the same descriptive compressive concrete function (stress *versus* slip) in an experimental test [29].

The experimental program performed was studied by the presented model in conditions of a monotonic crescent loading, like in the tests, and Newton-Rapson solution method was applied. The concrete was considered an elastic-linear material with non-linearity conditions. The reinforcement was considered a elastic-plastic model: von-Mises criterion with associated flow rule and isotropic hardening.

3 Results and discussions

3.1 Experimental: pull-out test results

The experimental results were calculated considering 95% confidence interval, materials properties and bond analysis. Concrete mechanical properties were evaluated to each concrete batch: mean compressive strength was 35± 3 MPa and mean tensile strength was 2.5± 0.7 MPa.

Table 3 presents the bond stress results, with mean specimens values, and Fig.6 present the mean and maximum values obtained to each diameter evaluated. All specimens presented pull-out failure.

Table 3. Bond stresses – Pull-out test

Bar diameter (ϕ)mm	Mean bond stress (MPa)	Standard deviation (MPa)	CoV(%)
6.3	11.6	1.9	16.5
8.0	10.9	0.9	8.2
10.0	11.3	0.9	7.7

The coefficient of variation (CoV) data is a statistical result about the dispersion and quality of the experiment. Conventionally in pull-out test studies, following exactly the recommendations about specimens (cubic geometry and anchorage length of 5ϕ), the dispersion and CoV are very high, mainly with thin bars, denoting the difficult with this test, but in this case the results show the good quality of the experimental results with low dispersion.

Influences about diameter and bond stresses results are controversial. Observing the Table 3, we can not conclude that there is a tendency about the results, but the bond stresses calculated were very close between bar diameters considering the experimental conditions of this research. The next figures present the stresses-slip graphs. Is important highlight that this mechanical experimental test, mainly with thin bars, is sensible to different factors which can affect the behavior results. In this case, such can be observed in the Fig. 1(b) a neoprene support, between specimen and metallic base, was necessary to avoid possible concentration stress damage in the concrete specimen. This can proportioned initials small slips in begin of the test earlier than expect, as can be viewed in the

Fig.7(c), but not affect the final results.

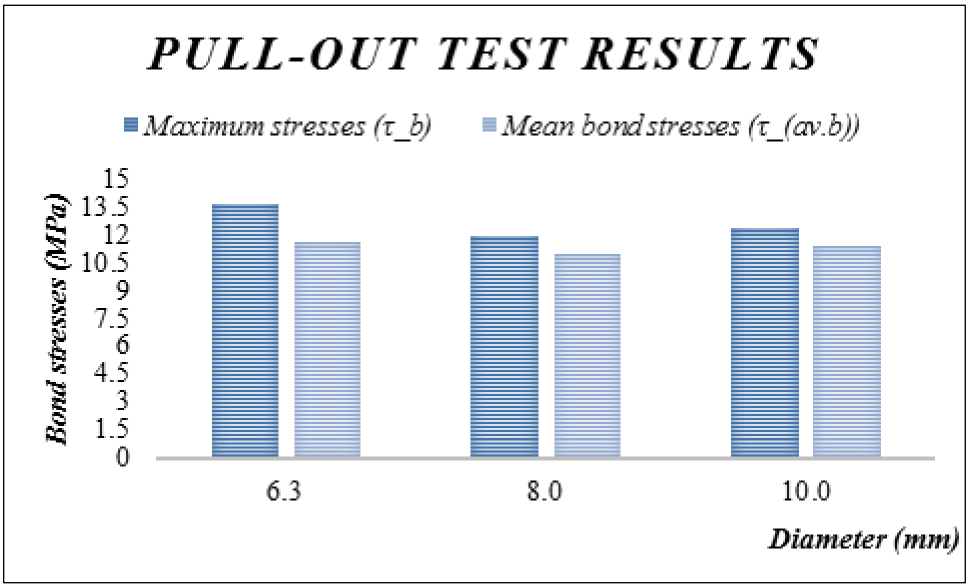
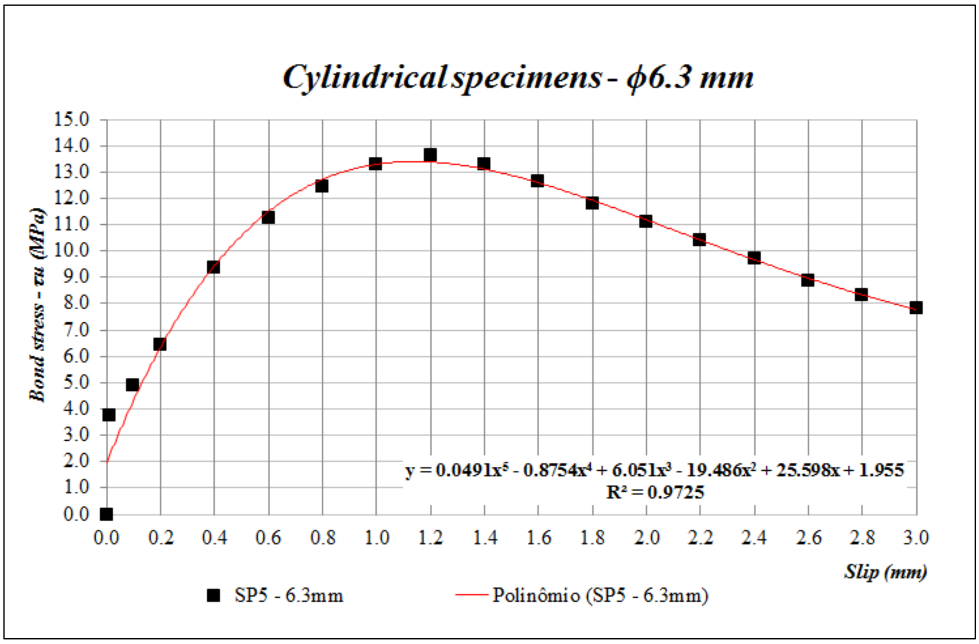
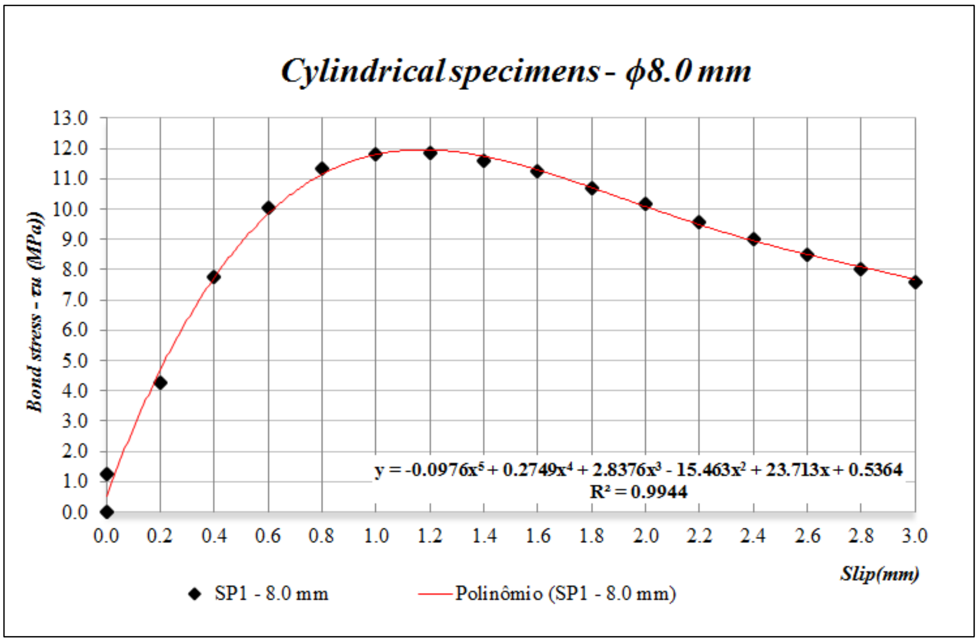


Figure 6. Maximum and mean bond stresses results

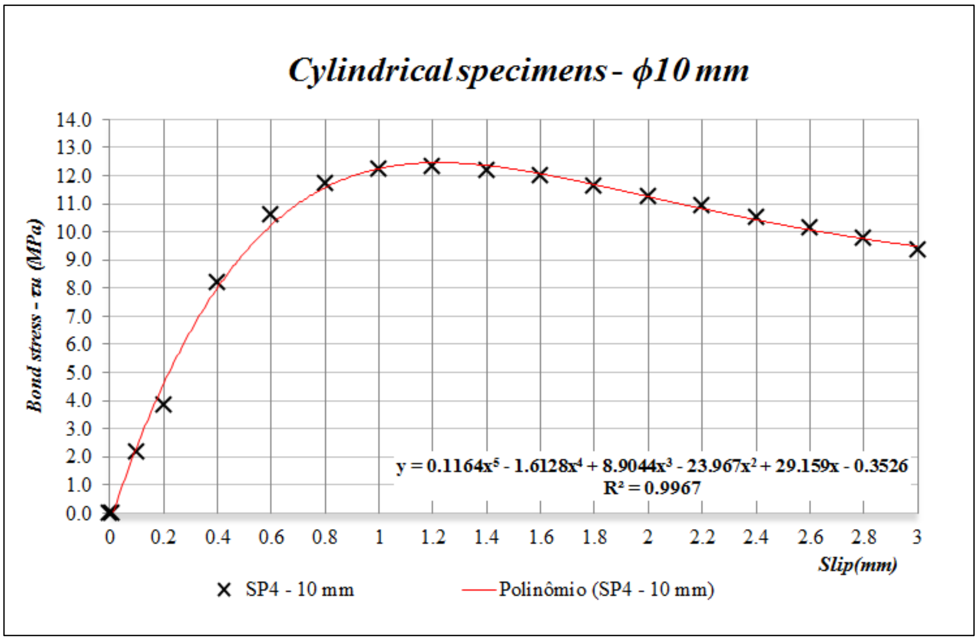
The stress *versus* slip complete graphs are presented with details in [1], this work presents the minimum and maximum samples results and for this last one a theoretical adjust equation (polynomial) (Fig.7 (a), (b), (c)). The consistency of the bond behavior between of the specimens, mainly with the 8.0 and 10.0 mm diameters and we can observe the maximum bond stress in these three cases occurred about 1.2 mm slip.



(a) Specimens (6.3 mm): theoretical adjust.



(b) Specimens (8.0 mm): theoretical adjust.

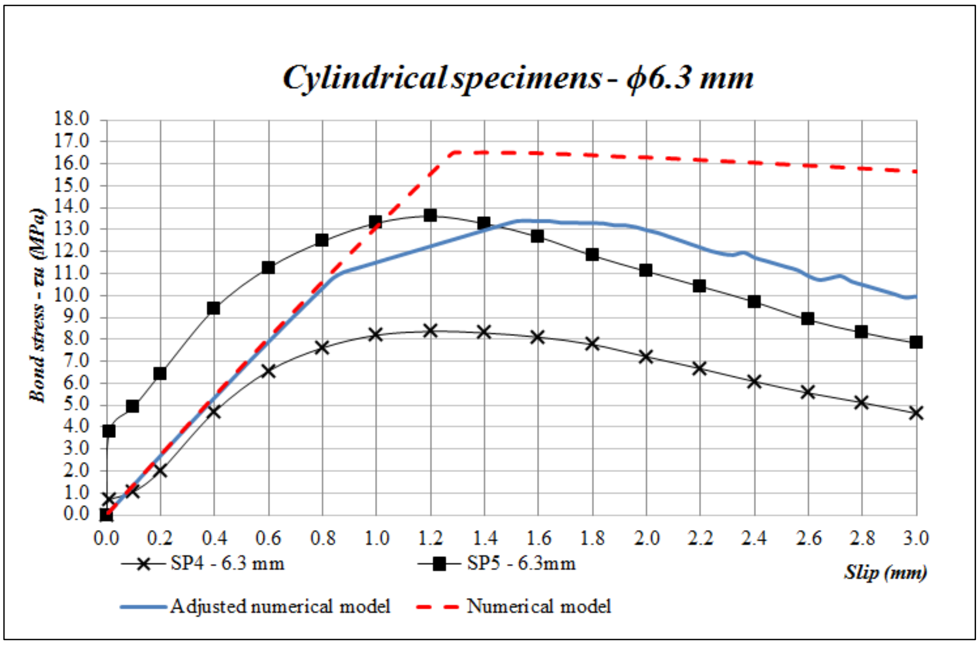


(c) Specimens (10.0 mm): theoretical adjust.

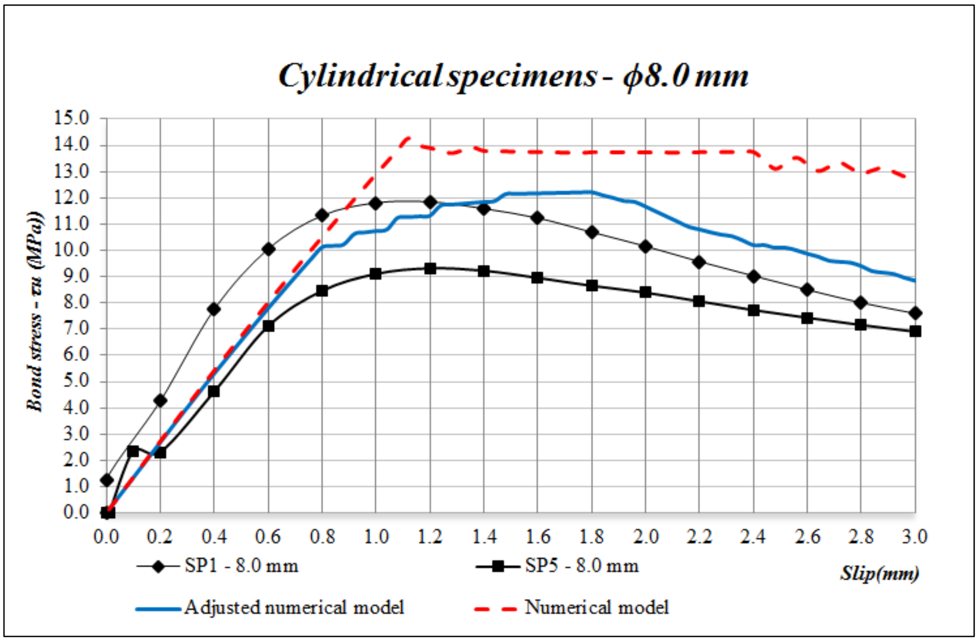
Figure 7. Theoretical adjusts for experimental data – Maximum specimens values.

3.2 Numerical: pull-out test simulation

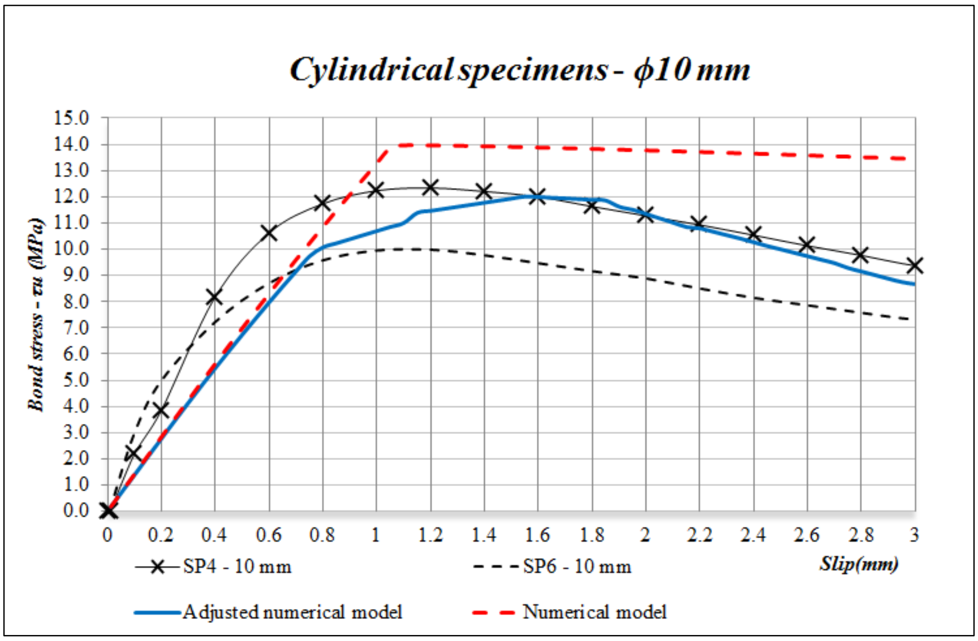
The experimental materials (concrete and steel bars) results were used to prepare the model and perform the pull-out test and finally confront numerical and experimental results. In a first approach, the model was analyzed used the same parameters values, considering the $c(d)$ and $\mu(d)$ functions, adopted in the initial calibrations and validation model. The results are present in the figures Fig.8(a), (b), (c).



(a) Specimens (6.3 mm): bond stress *x* slip



(b) Specimens (8.0 mm): bond stress *x* slip



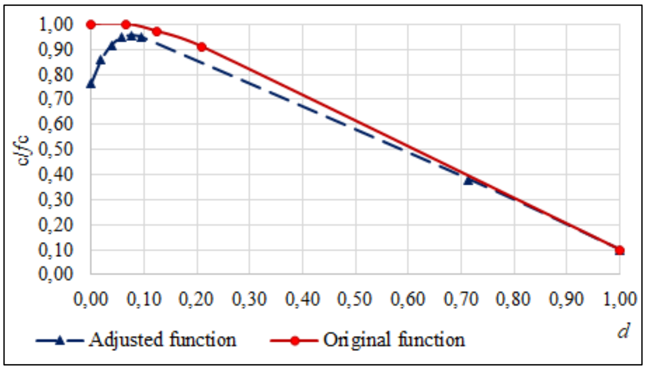
(c) Specimens (10.0 mm): bond stress *x* slip

Figure 8. Pull-out: bond stress x slip behavior – Experimental and numerical results

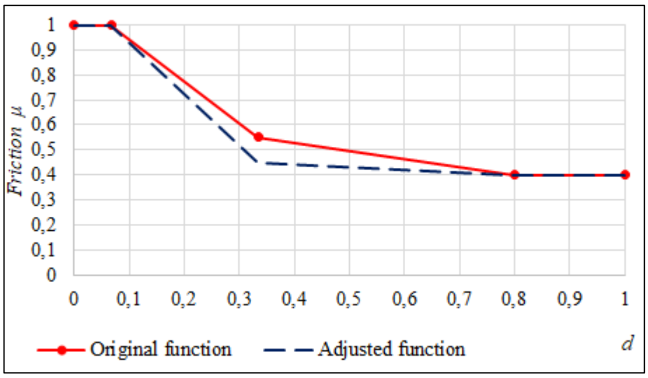
The first results (discontinued line, entitled *“numerical model”*) indicate an inadequate response between experimental and numerical approaches, mainly to smaller diameters (6.3 and 8.0 mm), to 10 mm diameter a better adjust can be observed but is not considered fitting. However, to these numerical curves, except to K_{11}, K_{12}, K_{22} elastic parameters (spring strength) and specific materials properties, the others factors (functions to friction ($\mu(d)$) and $c(d)$) were used considering the calibration following the Lundgren and Gylltoft [30] data information, only to 16 mm diameters bars, but the differences in the concrete-steel interface from the present experimental program and the authors data, especially the superficial rebars characteristics, can be influence the quality of the results.

Some analysis were performed to evaluated and adjusted the interface functions to experimental tests: adjust in the friction function and the $c(d)$ held constant (same the first case); friction function held constant and the $c(d)$ is adjusted; both function are adjusted. The variations following mainly the rebars diameters and properties variation, that were not consider in Brisotto et. al. [29] .

In the Figs.9 are present the best adjusts to the friction function and $c(d)$, considering the experimental conditions of this search and as from its were obtained the new numerical results for the pull-out test.



(a) Function *c(d)*



(b) Function $\mu(d)$

Figure 9. Better adjusts to interface functions.

Numerical model results, represented in the bond stresses curves, exhibit the adequate perform of the pull-out test program. In this point is important highlight the influence and importance of the properties of the interface in the bond result and demonstrated the necessity of the fitting curves to evaluated different experimental characteristics. However, were observed, in both analyses, that the first curve stage presents an elastic behavior with elevate slip values, higher than experimental ones. Elastic region in the damage model is influenced by elastic interface parameters which depends on concrete mechanical properties bars properties. Variations on these specific factors does not present significative effects on the curve fitting.

It may be noted, from the figures, that the maximum bond stress occurs about 1,6 mm slip but in each diameter case the stress values are close to the experimental results and the high slip can be related with the significative values observed in the begin of the curve. The model conclusions are an important result to analysis of pull-out test with cylindrical specimens using the proceedings of the standard recommendations on this account confirms the considerations present in Carvalho et al.[1], the geometry specimen influence on the experimental results occasioned highest bond stress results, that unconsidered by the researchers.

4 Conclusions

Steel-concrete bond behavior is a important research area and many papers are divulgated considering different aspects, influence parameters and studies approaches, but different factors can affect significantly the results and considerer all them can be a challenge. Many experimental researches use mainly mechanical test, the pull-out test, to analyze the phenomenon include modification in the test condition especially in the specimens without verify the possible effects.

An experimental program from modified pull-out test was realized and the results were confronted and studied with an elastic-plastic model. The numerical model is a representative of the bond damage and the stresses developed in steel-concrete interfaces which include an algorithmic to verify the conditions of elastic and plastic stresses and slips. From the results can be observed a specific influence of the interface parameters, represent by friction and function *c*, on the bond behavior and the importance of fitting these functions to different analysis that used this model. However, the elastic behavior of the numerical model is an inherent conditions of the materials properties and do not affect by the others parameters.

On the other hand, the results indicating that the stress behavior observed in the experimental test are correct and can be exist an important influence of the geometry specimen on bond stresses values and step up the necessity to more researches about the modified pull-out test and the importance of stablished a standard to the bond mechanical test.

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