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Bond steel-concrete: simulation analysis of the pull-out tests and APULOT using the program ATENA

Aderência aço-concreto: simulação numérica dosensaios de arranchamento pull-out e APULOT usando o programa ATENA

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Abstract

The bond between steel and concrete is essential for the existence of reinforced concrete structures, as both materials act together to absorb structural strain. The bond phenomenon is considered to be complex regarding many factors that affect it. Several types of bond tests have been proposed over years. One is the modified proposed of pull-out test, which was elaborated by Lorrain and Barbosa [1] called APULOT test (Appropriete pull-out-test). Based on experimental results obtained by Vale Silva[2] either by conventional pull-out tests, or by modified pull-out test, APULOT, seeks to know the numeric behavior of bond steel-concrete through a numerical simulation using a calculation code ATENA which is based on the Finite Element Method (FEM). The numerical simulation provided better evaluate the stress distribution and cracking that occurs during the test, thereby becoming a valuable tool to support the experimental project that aims to validation, validation partially or not recommend the modified bond test steel-concrete - APULOT test – as quality control test of structural concrete. The numerical results showed good representation compared to experimental results.

Keywords: bond steel-concrete, numerical analysis, pull-out, APULOT, pull-out test.

Resumo

A aderência entre o aço e o concreto é fundamental para a existência das estruturas de concreto armado, uma vez que os dois materiais atuam em conjunto para absorver os esforços solicitantes. O fenômeno da aderência é considerado complexo no que se refere aos vários fatores que o influenciam. Vários tipos de ensaios de aderência foram propostos ao longo dos anos. Um deles é a proposta modificada do ensaio de arrancamento pull-out-test, que foi elaborada por Lorrain e Barbosa [1] denominado de ensaio APULOT (Appropriete Pull-Out-Test). Com base nos resultados experimentais obtidos por Vale Silva [2] para os ensaios pull-out convencionais e para o ensaio pull-out modificado, APULOT, procura-se conhecer o comportamento numérico da aderência aço-concreto através de uma simulação numérica utilizando um código de cálculo chamado ATENA que é baseado no Método dos Elementos Finitos (MEF). A simulação numérica permitiu melhor avaliar a fissuração e a distribuição de tensões que ocorre durante o ensaio de arrancamento, tornando-se com isso, uma ferramenta de apoio preciosa ao projeto experimental que visa à validação, validação parcial, ou não recomendação do ensaio de aderência aço-concreto modificado – Ensaio APULOT – como ensaio de controle de qualidade do concreto armado. Os resultados numéricos obtidos apresentaram boa representatividade quando comparados aos resultados experimentais.

Palavras-chave: aderência aço-concreto, análise numérica, pull-out, APULOT, ensaio de arrancamento.

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1. Introduction

The steel-concrete bond has been investigated for a long time in many countries. These studies are closely linked with the evolution of reinforced concrete. The first scientific articles on the steel-concrete bond date back to the early twentieth century [Carl Von Bach (1905), Bach (1905), Koenen (1905), Kollbohm and Mautner (1907)], and today it's the subject of such scientific meetings as BIC2012 (Bond in Concrete 2012, Bresquia - Italy) supported by the ACI, RILEM and FIB. This interest is justified by its importance in reinforced concrete and prestressed concrete parts. In order to understand these part so that their behavior and the anchoring of the reinforcement is ensured, and, consequently, to ensure their safety, the bond phenomenon must be understood in detail.

One of the most popular and traditional bond tests is the direct pull-out test, called the pull-out test, normalized by RILEM / CEB / FIP RC6 [3] and ASTM [4]. It is a test of reinforced concrete composite materials to seeks to assess the strength of the bond between the concrete and the reinforcement.

Based on previous studies, Lorrain and Barbosa [1] and Lorrain et al. [5] presented a simplified alternative to the pull-out test, called the APULOT test, to be used *in situ*. The procedures of this new test are being studied, discussed and improved by some research groups located in Brazil, France, Spain, Tunisia and Paraguay. The validation of this new test could provide an alternative for the evaluation of reinforced concrete quality in civil constructions.

Vale Silva [2] investigated the proposal by Lorrain and Barbosa [1] of comparing two types of steel-concrete bond tests: the pull-out test and the APULOT test. The results showed on the pull-out tests that the type of rupture was observed the sliding for all diameters. However the results obtained for the APULOT test showed different behavior for bars with diameters of 8.0 mm, 10.0 mm and 12.5 mm. Vale Silva [2] believes that this behavior variation is related to the diameter of the specimen prepared with molds as PET bottles (Polyethylene Terephthalate), which did not have suitable dimensions suitable for withstanding the stresses induced with the enlargement of the diameter of the reinforcing steel bars, or the inadequate anchorage length used. This study evaluates the distribution of stresses occurring in these two cases through a detailed numerical analysis

The numerical simulation of the pull-out and APULOT tests is a tool to support an experimental project aimed at the overall validation, partial validation, or to establish the undesirability of the APULOT test for reinforced concrete quality control testing. These simulations, when compared with the experimental results, assist in the choice of some parameters that affect the behavior of the steel-concrete bond, such as the strength of the concrete, the diameter of the reinforcement and the variation in the anchorage length, among others.

2. Steel – concrete bond

The steel-concrete bond is one of the most important mechanisms in reinforced concrete structures, since both materials must act jointly to absorb internal forces. This bond is responsible for anchoring the reinforcement in the concrete and also serves to prevent slippage of the bar segments between cracks, thus limiting the opening of the cracks.

According to Tassios [6] and Ducati [7], the behavior on the limit between the bar and the concrete is of decisive importance for the load capacity and service of reinforced concrete parts. This knowledge is essential in order to reach the anchorages calculation rules and splices by transpassive of reinforcement bars, for the deflections calculation considering the effect of stiffening traction, for crack control and therefore the minimum amount of reinforcement. This can be extended to the durability of the structures.

According to Tassios [6] the efficiency of the steel-concrete connection can be quantified by the bond stress versus sliding ratio, which expresses the strain that arises in the concrete steel interface related to the relative displacement between the steel bar and the concrete that surrounds it. A little sliding suggests local damage or the interface accommodations. When these two actions occurred together, i.e., when the slide reaches the maximum value, indicate the destruction of the bond, which can be associated with a certain state of deformation and cracking. Some limits values of sliding and procedures of structural design were presented in

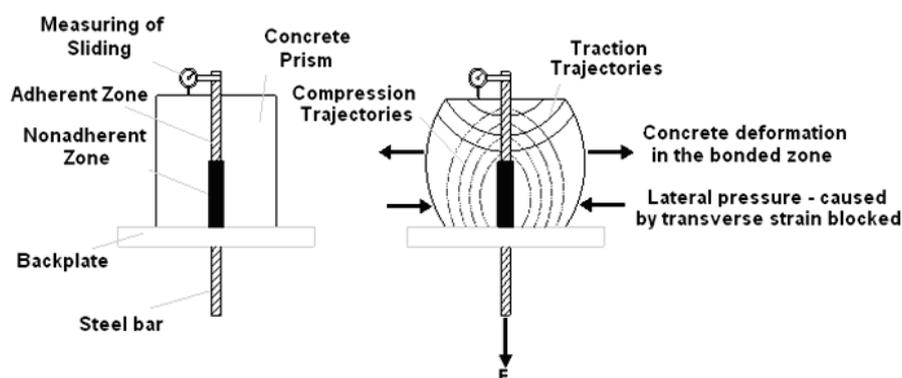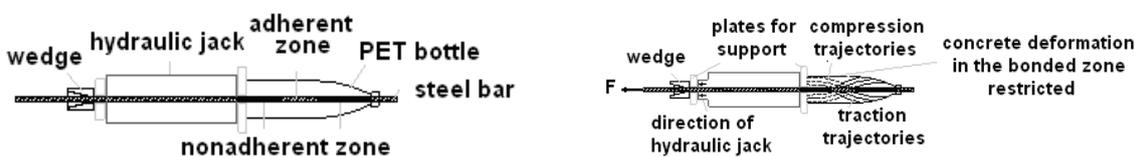**Figure 1 – Details of the direct pull-out test. P. (Leonhardt and Mönnig (11))**

Figure 2 – Schematic of APULOT test (Vale Silva (2))

the standards, which are usually associated with an unacceptable state of deformation and cracking (Caetano [8]).

The sliding at the beginning of loading is caused in part by the elastic deformation of the concrete. For higher loads, however, it is caused by crushing of the concrete on the bar ribs. In Bars without ribs the bond occurs because of the chemical bond between the cement paste and the bar. When the chemical bond is broken, there occurs a resistance to sliding due to friction. When this resistance is reached, the splitting is not complete, but the bar is pulled out, resulting in an almost intact hole inside the concrete (Goto [9]).

In ribbed bars, which were developed to produce a stronger bond than in bars without ribs, the bonding phenomenon occurs in a different way. Although these bars are developed adhesion and friction, the resistance to sliding in ribbed bars depends mainly on the mechanical action between the concrete and the ribs. The effect of chemical adhesion is small and no friction occurs until there is sliding between the bar and the concrete (Vale Silva [2]).

Figure 3 – Lorrain and Barbosa Correlation Curve (1)

Legend	
1	Points found by Lorrain and Barbosa [1]
2	Linear regression with the points suggested by Lorrain and Barbosa[1]
	$\tau_U = 0,33.f_C + 4,35 \ / \ R^2 = 0,96$

2.1 Bond tests

Among the various types of testing proposed (eccentric pull-out test; beam test; pull-out test with circumferential ring - ring test - out test , among others), which determine the bond stress values between the steel reinforcement and the concrete, the so-called pull-out test should be highlighted. This test consists of pulling a steel bar positioned in the center of a concrete prism. The two ends of the steel bar out of the concrete prism where the load is applied to one end and read the sliding at the other end.

In pull-out test occurs a longitudinal compression component, and to minimize this effect, a non- bonded zone after the backing plate is considered. This component does not exist in anchorage areas of tensile reinforcement of beams subjected to bending (Fusco [1]). Figure 1 shows the direct pull-out test, with the trajectories of tensile and compression stresses.

Once the steel-concrete connection is broken, the bar moves with more intensity inside of the concrete prism depending on the surface roughness involved (slick bar or ribbed bar). The maximum value of resistance allows us to calculate the connection ultimate stress (maximum) (τ_u) obtained by dividing the maximum force applied by the nominal anchoring surface.

2.2 APULOT test (modified Pull-out test)

Lorrain and Barbosa [1] and Lorrain et al. [5] proposed a modification of the pull-out test, which was named the APULOT test. This test uses cylindrical plastic bottles (PET) discarded in nature as a template, with a minimum diameter of 8 cm and, if possible, with a more homogeneous form in the bonded zone. Figure 2 shows the "APULOT" test with the bonded zone location and the traction and compression trajectories. A change made in this test is the fact that the specimen remains inside the plastic bottle (PET), which results in reduced lateral deformation. In the APULOT test, the anchorage length (bonded zone) will depend on the concrete compressive strength (f_{cm}) and the diameter of the steel bar (ϕ), based on the concept of balancing the stresses necessary to anchor a steel bar in concrete, according to Equation 1.

$$L = \frac{f_y \cdot \emptyset}{4 \cdot \tau_u} \tag{1}$$

where: = anchor length (mm); f_y = steel yield strength (MPa); ϕ = bar diameter (mm); τ_u = last Bond Strength (MPa);
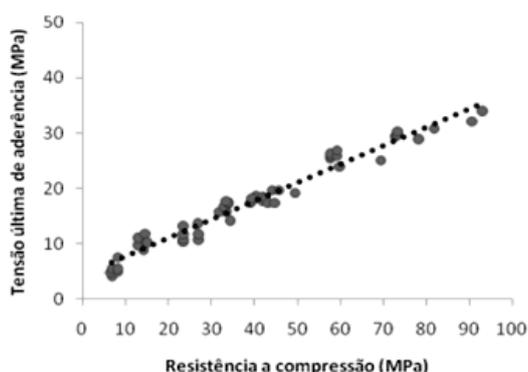
The L determination, ei, the value of the ultimate bond strength, it is obtained by the correlation curve adopted by Lorrain and Barbosa [1] (Figure 3).

In determining the anchorage length using Equation 1 adopts the materials resistance values used as the age provided of the tests. Vale Silva [2] used the value of L = 10 ϕ in his experimental tests as the average of concrete compressive strength (f_{cm}) of 27,8 MPa at 28 days and 6 ϕ as the average of concrete compressive strength (f_{cm}) 49,3 MPa at 28 days. These data are used for the numerical analysis of this test.

3. Numerical analysis

3.1 Calculation Code: ATENA

The calculation code ATHENA (Advanced Tool for Engineering Non-linear Analysis) has been used in structural engineering to simulate the behavior of concrete and reinforced concrete structures, as well as of concrete cracking. It uses the finite element method for the nonlinear analysis of structures, simulating the real behavior of structures either through linear or nonlinear analyses. The total action active was defined by the time integral of forces increments, with application of the Newton-Rhapson or Arc-Length Methods.

The materials were characterized through their properties and physical parameters and into groups according to their constituent features.

Among the properties of steel, are its stress-strain ratio in the elastic-linear or multilinear mode, with or without a defined flow level; the nonlinear model of loading and unloading cycles, and the criterion of von Mises flow.

Among the concrete properties are: the stress-strain law and the ruin plan of the structure, determined by criteria of Drucker-Prager plasticity (compression) and Rankine failure (traction). The software allows two models of the above described combination to simulate the breaking and cracking of concrete.

The constitutive models of each material were described in Cervenka [12].

In this paper, the Newton-Rhapson analysis method was used with increments of displacements of 0,06 mm in each step.

The Newton-Rhapson method adopts the concept of strength increments that were performed iterative calculations each step loading until there is a convergence between the differential function variables. The force was kept constant and the displacement was redefined until the tangent line of the force increment find the force versus deflection curve for each new iteration of a load step.

3.2 Interface constitutive model

The interface material model in ATENA can be used to simulate contact between two materials. The interface material is based on the Mohr-Coulomb criterion with the shear stress. The constitutive relation for a three-dimensional general case was given in terms of traction forces in the interface planes and relative displacements of running and opening (Equation 2).

$$\begin{Bmatrix} \tau_1 \\ \tau_2 \\ \sigma \end{Bmatrix} = \begin{bmatrix} K_{tt} & 0 & 0 \\ 0 & K_{tt} & 0 \\ 0 & 0 & K_{nn} \end{bmatrix} \begin{Bmatrix} \Delta v_1 \\ \Delta v_2 \\ \Delta u \end{Bmatrix} \qquad (2)$$

Where τ is the shear stress and σ is the normal stress. K_{nn}, K_{tt} denote the normal initial elastic stiffness and the normal initial elastic shear, respectively, and the shear relative displacement is represented by Δv and the normal displacement is represented by Δu.

The initial fracture surface corresponds to the Mohr-Coulomb condition (Equation 3) for a ellipsoid system under stress. Following stress violating this condition, the surface collapses into a residual surface corresponding to dry friction.

$$|\tau| \le c - \sigma \cdot \phi, \text{ if } \sigma \le 0$$
$$\tau = \tau_0 \sqrt{1 - \frac{(\sigma - \sigma_c)^2}{(f_t - \sigma_c)^2}}, \tau_0 = \frac{c}{\sqrt{1 - \frac{\sigma_c^2}{(f_t - \sigma_c)^2}}}; \sigma_c = -\frac{f_t^2 \phi}{c - 2f_t \phi}, \text{ if } 0 < \sigma < f_t$$
$$\tau = 0, \text{ if } \sigma > f_t \qquad (3)$$

The failure criterion is replaced by an ellipsoid, which intersects the axis of the normal stress value of f_t with the vertical tangent and the shear axis was trapped in the amount of c (cohesion) with the equivalent tangent -∅.

The limits of the stress were defined as "rupture areas" in Mohr space. Cox [13] defines those surfaces with only one function while Lundgren [14] applies two functions: F1 and F2.

According to Lundgren [14], it can be consider the problem as being controlled by friction approximately, although the bond process in ribbed bars was made by mechanical engagement. The F1 function describes the combinations of stress that define the start of slipping by friction, including the adherence f_a. This function (Equation 4) was defined by:

$$F_1 = |t_t| + \phi \cdot (t_n - f_a) = 0 \qquad (4)$$

Where: ∅ is a friction apparent coefficient, t_n is the normal stress, t_t is the bond stress and f_a adhesion. This surface was associated with the failure by cracking usually.
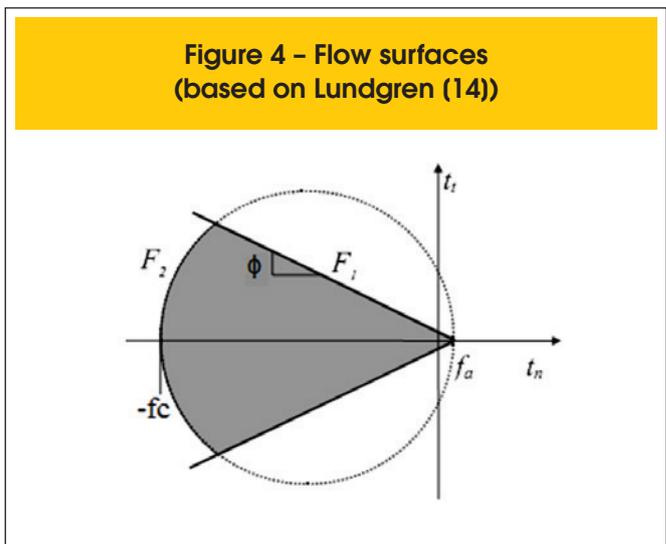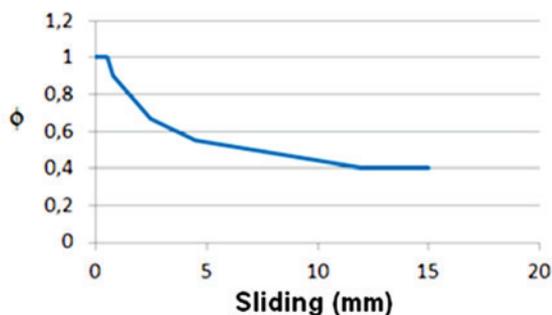

Figure 4 – Flow surfaces
(based on Lundgren (14))

Figure 5 – Friction coefficient variation as
a sliding function (based on Lundgren (14))

Figure 6 – Analyzed part demonstration
for the bar with 8 mm diameter

The other function, F2, describes the failure limit by pullout. This function is determined by the balance of forces resulting from the mechanical interaction between the steel-concrete, resulting in Equation 5:

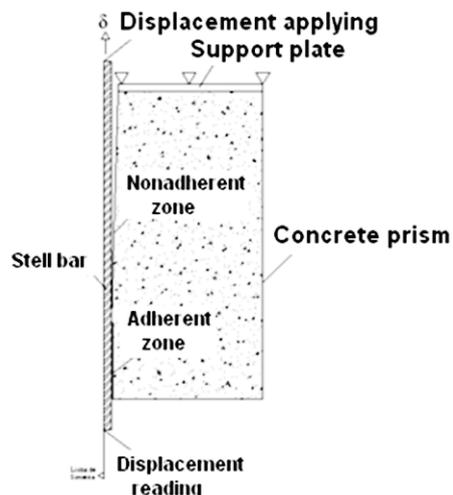$$F_2 = t_t^2 + (t_n + fc) \cdot (t_n - f_a) = 0 \qquad (5)$$

Where: f_c is the concrete compressive strength.

Figure 4 shows the rupture surfaces, which was defined by the F1 and F2 functions.

The friction coefficient (ϕ) is defined by Lundgren [14], as shown in Figure 5.

The rupture surface decreases with the deformation process, since this parameter also decreases. This corresponds with a "softening" of the constitutive ratio with the dissipative processes.

4. Numerical simulation

This paper conducted a numerical study of the pull-out and APULOT tests, comparing their behiavior with the experimentally results obtained by Vale Silva [2].

4.1 Pull-out test

An analysis was performed with the experimental data obtained by Valley Silva [2] to the concrete compressive strength of 27,8

Figure 7 – Comparison of numerical results with the range of experimental results produced by
Vale Silva (2) - concrete of 27,8 MPa and 8.0 mm, 10,0 mm and 12,5 mm bars. Pull-out test
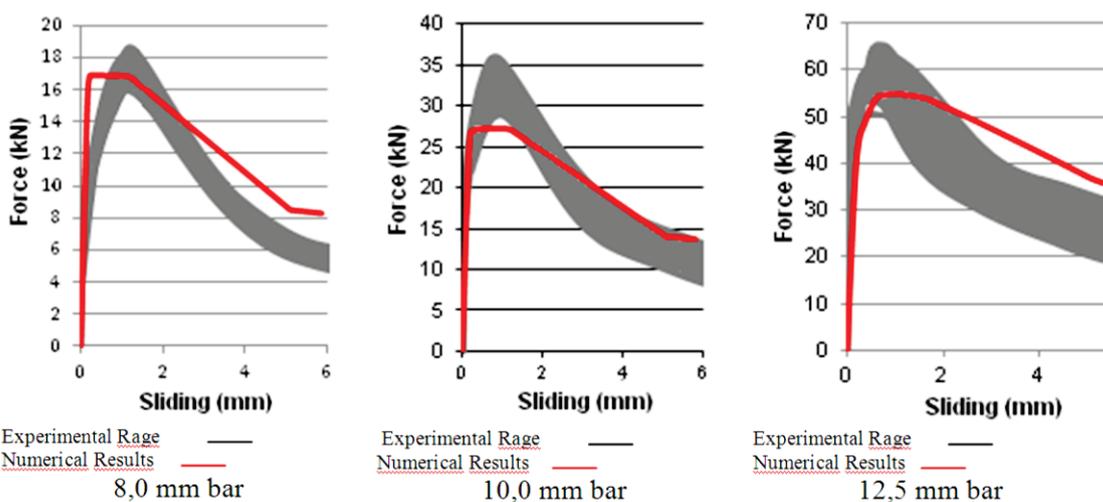
Figure 8 – Distribution of stresses and cracking. Concrete of 27,8 MPa - 8.0 mm, 10.0 mm and 12.5 mm bars. Pull-out test
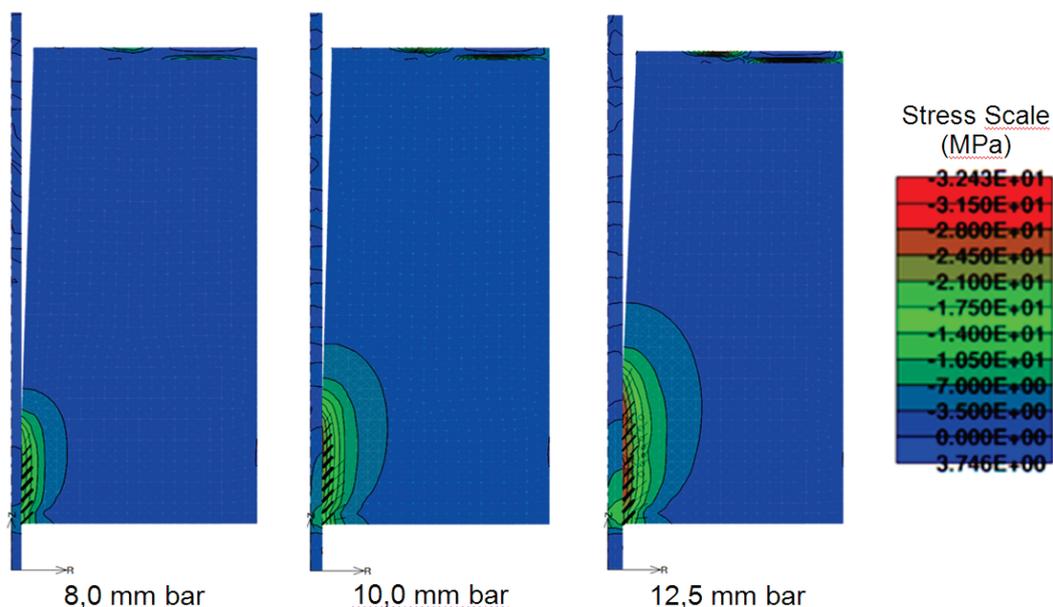
MPa (Concrete T1) and 49,3 MPa (concrete T2) at 28 days with the steel bars with 8.0 mm , 10.0 mm and 12.5 mm diameters and yield stress (f_y) equal to 625,0 MPa.

In order to reduce the number of elements, and consequently, the processing time, we used the "axial symmetry" analysis of the ATENA software considering the axisymmetric model, with the axial symmetry axis in the center of the concrete prism. Figure 6 shows

in detail the numerical scheme used in this case.

After analyzing the finite elements grids possible, we chose to use a grid with 943 elements and 1097 nodes.

The analysis of the grid and the parameters of the materials are shown in Tavares [15].

Figure 7 shows the force x sliding diagram comparing the experimental results with the numbers for the bars of 8.0 mm, 10.0 mm,

Figure 9 – Comparison of numerical results with experimental range from Vale Silva (2) – concrete with 49,3 MPa and 8.0 mm, 10.0 mm and 12.5 mm bars. Pull-out test
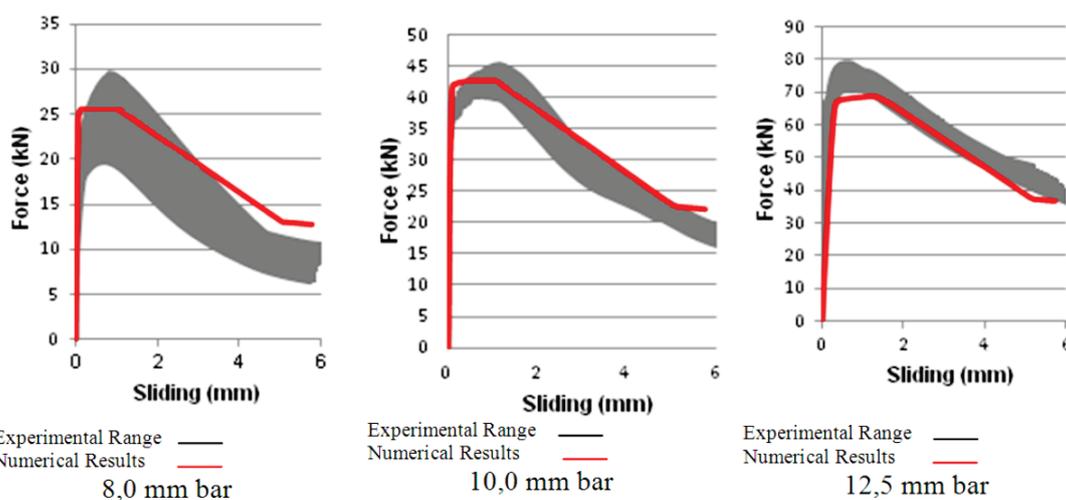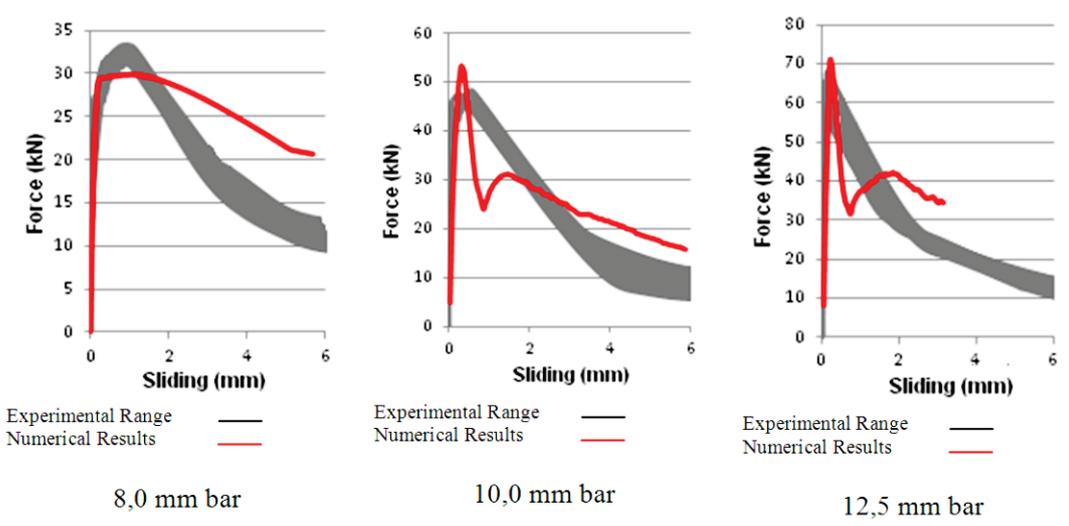
Figure 10 – Distribution of stresses and cracking. Concrete of 49,3 MPa - 8.0 mm, 10.0 mm and 12.5 mm bars. Pull-out test

8,0 mm bar   10,0 mm bar   12,5 mm bar
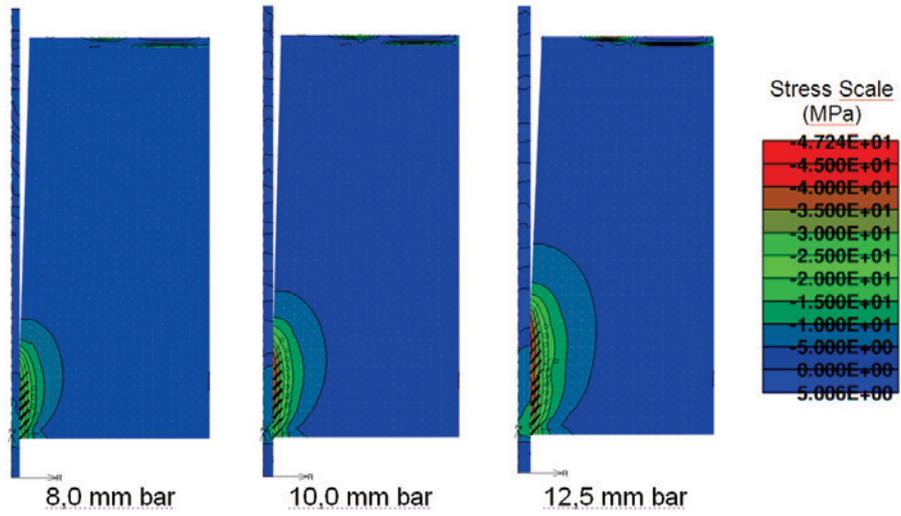
12.5 mm and the concrete compressive strength of 27,8 MPa.

Figure 7 reveals that the numerical results curves approach the range of experimental results. Figure 8 shows the distribution of stresses, cracking and the deformed structure for the 8.0 mm, 10.0 mm and 12.5 mm bars.

There is also an increase in the stress value and the cracking amount too, as well as the bar diameter increases from 8,0 mm to 12,5 mm, and the increase in the anchorage length. This can be explained by the fact that the stresses generated were supported by the concrete prism - with a larger contact area - there is a greater sliding resis-

tance and increasing the stress and cracking at peak load.

The pull-out tests results for the concrete compressive strength at 28 days of 49,3 MPa (Figure 9) shown in the force-sliding diagrams compares the range of experimental results with the numerical results for 8, 0 mm, 10.0 mm and 12.5 mm bars.

The numerical results curves are within the experimental results range for the maximum bond stress value, when there is the bar sliding, but the curve peak for the 12,5 mm bar was slightly under the experimental range, which reduces the bond final stress value of the numerical result than experimental results.

Figure 11 – Comparison of numerical range with the experimental results by Vale Silva (2) results –concrete with 27,8 MPa and 8,0 mm , 10,0 mm and 12,5 mm bars. APULOT Test

8,0 mm bar   10,0 mm bar   12,5 mm bar

Figure 12 – Stresses and cracking distribution. Concrete of 27,8 MPa – 8,0 mm, 10,0 mm and 12,5 mm bars. APULOT Test
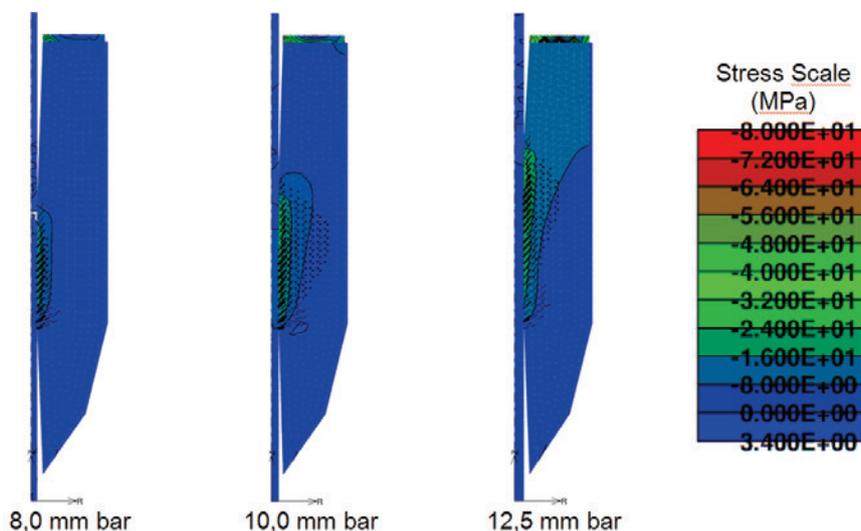
Figure 10 shows the stress distribution in the model with values presented in MPa in the description, together with the cracking and the deformed structure in the load step when it is reached the bond last stress value for the pull-out tests with concrete compressive strength equal to 49,3 MPa and 8,0 mm, 10,0 mm and 12,5 mm bars diameter.

In Figure 10 the same effect can be observed for the concrete called T1 (f_{c28} = 27,8 MPa), with an increase in the stress value and the number of cracks as the bar diameter increases and, consequently, an increase of anchorage length. Comparing Figures

8 and 10, we observed that with the increase of the compressive strength of the concrete there was an increase of cracking and a higher stress value of the concrete.

4.2 APULOT Test

In the APULOT tests simulations, the asymmetrical analysis with the same type of finite element and the same constituent models for the materials of pull-out test were also used.

Figure 11 shows the APULOT force-sliding diagrams for test with

Figure 13 – Comparison of numerical results with experimental results range from Vale Silva (2010) - concrete of 49,3 MPa and 8,0 mm, 10,0 mm and 12,5 mm bars. APULOT Test
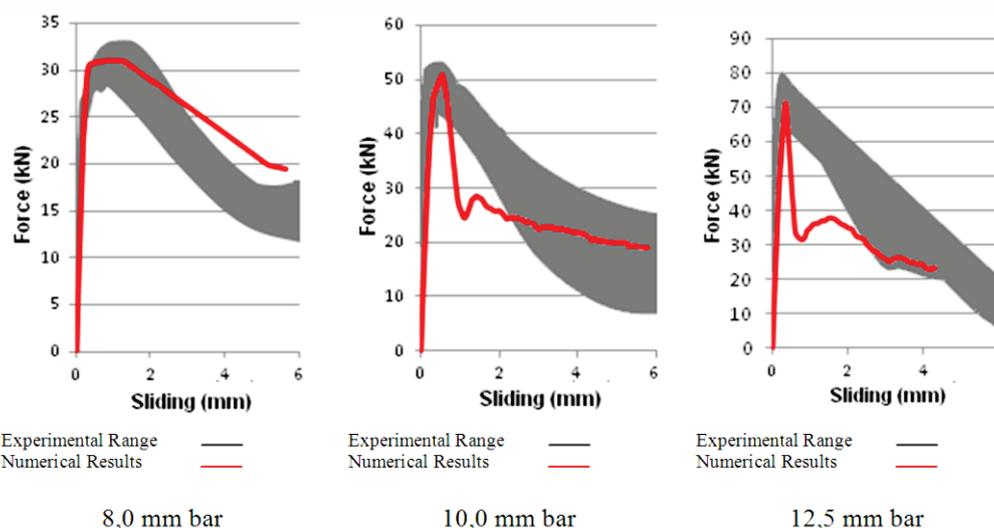
8,0 mm, 10,0 mm and 12,5 mm bars and the concrete compressive strength of 27,8 MPa.

In the simulation with the steel bar of 8,0 mm, the curve of the numerical result fell within the range of experimental results range – including the after-peak representation – showing the bar slide in comparing to concrete. However, the numerical results with the bars of 10,0 mm and 12,5 mm represent the typical behavior of a rupture by splitting, although they have reached values until higher than the experimental results for the maximum stress in the after-peak region, as well as this behavior was also obtained in most experimental results – Vale Silva [2] in this case. Thus, the constitutive model used to represent the concrete and the interface is capable of simulating different modes of bond failure, i.e., the constitutive model can capture pullout and splitting mechanisms. The stress and cracking distribution in the concrete in the load step that which was reached the bond stress is given in Figure 12.

Figure 12 reveals there was an increase in the stress value and also in the amount of cracks as the bar diameter increases from 8,0 mm to 12,5 mm, similar to the *pull-out test*.

Figure 13 shows the force-sliding diagrams comparing the numerical result with the experimental results range related to the 8,0 mm, 10,0 mm and 12,5 mm bars with a concrete compressive strength of 49,3 MPa.

The bond failure mode was similar to the results obtained for the concrete of 27,8 MPa looking for these particular examples relating to 49,3 MPa, i.e., there was ruptured by sliding for the 8,0 mm bar and a rupture by splitting in the 10,0 mm and 12,5 mm bars, which also occurred in the experimental results of Vale Silva [2] for the APULOT test with these bars. The maximum bond strength value of the numerical result reached the maximum level within the experimental results range for the three different diameters bars.

Figure 14 shows the distribution of stresses and cracks in the load step which was reached to the bond final stress.

According to Figure 14, the same effect occurs to the concrete

with 27,8 MPa (Figure 12): there was sliding of the 8,0 mm bar and splitting of the 10,0 mm and 12,5 mm bars.

5. Conclusions

By analyzing the force-sliding diagrams, we concluded that the numerical results have an equivalent behavior to the results of experimental tests, validating the use of this model. In the *pull-out* tests and APULOT tests, we observed that an increase in bar diameter resulted in the increase of stresses in the concrete at the region of the bonded zone, for concrete with the same mechanical strength. However, when bar samples with the same diameter and with different concrete strength were compared, there was an increase in concrete stress with increasing concrete compressive strength. In all *pull-out* tests the bond rupture occurred by sliding. In the APULOT tests, however, the bond rupture for the test with 8,0 mm bar occurred by sliding, whereas the bond failure mode occurred by splitting for the concrete mechanical strength used in the tests with 10,0 mm and 12,5 mm bars. This may be occurring because the concrete coverage around the bar is higher in the *pull-out* test than in the APULOT tests, thus contributing to a better distribution of the stresses generated during the test.

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Figure 14 – Distribution of stresses and cracking. Concrete of 49,3 MPa – 8,0 mm , 10,0 mm and 12,5 mm bars. APULOT Test
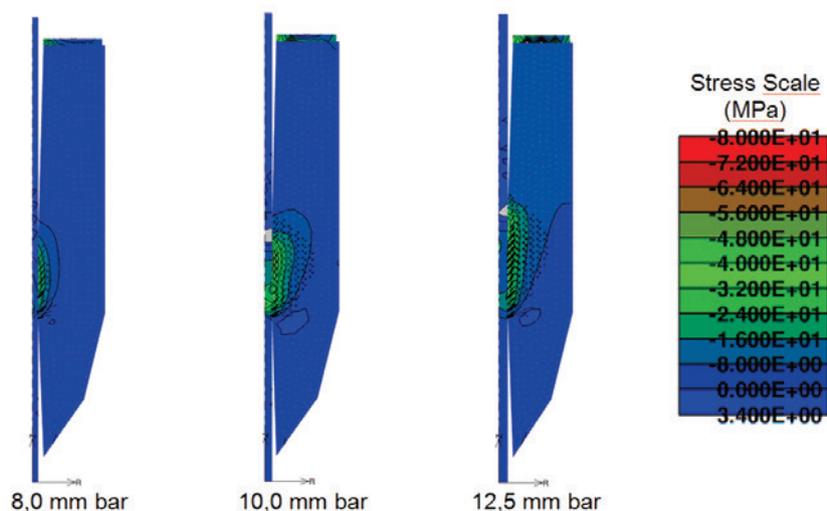
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