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Investigation of Bond Stress in Pull Out Specimens with High Strength Concrete

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Investigation of Bond Stress in Pull Out Specimens with High Strength Concrete

Maria Teresa Gomes Barbosa [α] & Souza Sánchez Filho [σ]

Abstract - Some international standard regulate the use of the high strength concrete, which may not be adopted generally without consideration of the differences that can exist among the materials in different countries. This paper relate the results of an experimental study consisting of pull out tests of Brazilian's steel, with five different concrete strength 20, 40, 60, 80 and 100 MPa, and three different steel bars diameter 16.0, 20.0 and 25.0 mm. The experimental results for the relationship bond stress *vs.* slipping were compared with CEB provisions and with some theoretical formulations found in literature. One statistical analysis is made and based on this approach four equations for predicting the bond stress was derived.

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I. Introduction

The designs of structural members are based on the fundamental assumption that exist the effective bond linking concrete and steel when the structural member is loaded. The behaviour of reinforced concrete elements depends on the steel-concrete bond, and the strength capacity of these elements is directly related with the bond. For a reinforced concrete member to act as designed there must be no slipping between concrete and the steel reinforcement. It is assumed that the steel resist the tension force, and the change in tension force in the bar is transmitted to the concrete by a surface stress, denominated bond stress.

Bond stress varies in magnitude along the length of reinforcing bar, and is function of several parameters. The large variation of bond stress is created by cracks. Several parameters for the structural design depend on the bond, for example: the bars anchorage length, the lap splices, tension stiffening between cracks, cracking control, and minimum reinforcement ratio.

The most important parameters in bond stress analysis are the bar anchorage length, and the tension stiffening. Bond study in general is made considering relationship between the bond stress τ (x) and slipping s(x) of steel bar in pull out specimens (Tassios, 1979). The first is identified by the shearing stress between the bar and surrounding concrete, and the second, by the relative displacement between the bar and the concrete.

The concrete compression strength, and consequently, the concrete tension strength are the main parameters that influence the anchorage length and the transmission of the tensions concentrated on the bar ribs. Other factors that influence the bond stress are: surface of the bars roughness and/or irregularities (increase the bond); diameter of the bars (one increase of the bar diameter reduces the maximum bond stress); type and disposition of the ribs.

Although a much better understanding of the structural behavior of bond stress to normal strength concrete, this phenomenon is not yet clarified, and limited research on pull out test of high strength concrete had been reported in the literature, and available data are scarce, and they still do not meet adequate level of the knowledge.

This paper examines the bond stress and slipping of steel bars in pull out specimens of high strength concrete, and is summarizing the results obtained with the concretes of different theoretical strength 20. 40. 60. 80 and 100 MP a, and rib bars of different diameters 16.0, 20.0 and 25.0 mm. A statistical analysis furnished the average and the maximum value for bond stress, and the expression to bond stress τ(x) *vs.* slipping s(x) for Brazilians' steel.

a) Bond Behavior

Three factors define the bond strength: chemical adhesion, friction, and bearing of bar deformation (ribs on bar). The adhesion is less important in magnitude and resists only small stress. Friction is a mechanical interlock between irregularities of steel surface and concrete, with magnitude superior than adhesion, and occurs after the adhesion is broken, and some small movement between steel and concrete take place. These two bond mechanisms are quickly lost, and the tension is transferred by bearing of bar deformation.

The mechanism that transfers forces between short concrete corbels surrounding the ribs of the bars is the most important type of bond.

For the plain bars the bond is formed by two parcels: the chemical and friction that depends of the deformed bar surface. The ultimate bond force is proportional to lateral bar area, where occur the adhesion effect, friction and deformed surface.

For deformed bar, the strength occurs mainly by the action of these ribs. The chemical adhesion is

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low, and friction not happen even when the slipping between the bar and concrete occurs. The loading origins an internal mechanical system on concrete, where the principal stresses need to be evaluate, and anchorage strength is limited by the smallest value of the principal tension stress or by principal compression stress. Bond failure is connected with these stresses. The stress transfer between the steel and the concrete happen mainly by the action of the bar ribs on the concrete between bar salience, and the crush of concrete surrounding to the one of these ribs not affect the bar anchorage. The stress of the one salience is transferred to others ribs. Therefore, there are two failure situations in the bond: micro-failure, which is a local bond failure and does not affect the anchorage, and a macro-failure, that is formed after the occurrence of several micro failures. The second type of failure does not allow a new stress distribution, and the bar anchorage is no more effective.

Bond failure on deformed bar happens by the followings modes: a) crush of the concrete surrounding to the ribs; b) shear of the concrete surrounding to the bar; c) or more frequently, by one longitudinal spalling of concrete cover; d) one combination of these three modes.

CEB 151 (1982) prescribes that in the deformed bars their tension force is transferred to concrete by the ribs, and the radial components of the ribs force on the concrete surrounding increase with the shear bond τ. This parameter is assumed as the longitudinal component of the rib resultant force that is inclined of an angle α with beams axis (Figure 1).

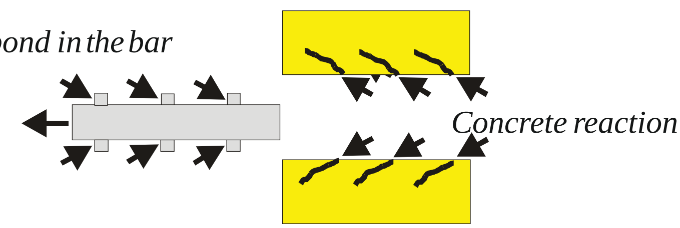

Figure 1 : [¥]Strength between reinforced and concrete (CEB 151, 1982; Barbosa and Sánchez, 2006)

On the rib bars the tension force on them is transferred to the concrete by the ribs. The radial components of the ribs forces that spread along the concrete perpendicular to the bar axis increases with the bond stress that can be regarded as longitudinal component of the ribs total force in the concrete. The radial component of the ribs force in the concrete generates internal pressure inducing tensions in the form of rings, that cause cracks along the anchored bar. When the rings are loaded to the failure point, longitudinal cracks appear. However, those can begin as longitudinal cracks that cannot be seen on the surface of the concrete before the maximum load is reached. As cracks appear, they increase the displacements between the bar and the concrete, and the bond stress is transferred along the anchorage length where the crack appears.

Bond can be described ideally as a shearing stress between the surface of reinforced concrete and the surrounding concrete. This mechanism is evaluated by means of the relative displacement between the concrete and the steel.

After concrete between the ribs was reach the shear strength, the bond strength will be do only by the friction between the rough concrete and the cylindrical surface of the, but in general this strength is smaller than the initial strength.

b) Bond stress $\tau(x)$ vs. slipping $s(x)$

Several concrete researches were developed during the past century to the standardized steel bars and normal concrete strength that are used today. In general these studies are focused simply for particular steel bar conformation and normal concrete strength. This study particularizes the bond analysis for Brazilian's steel bar and high strength concrete.

II. Research Significance

Some existing pull out test data do not satisfy current bond requirements for high strength concrete. This paper shows the experimental results obtained from 08 (eight) specimen test/ diameter of bar/ type of concrete on pull out specimens with conventional and high strength concrete. Also, the experimental results are used the suitability of several analytical approaches to estimate the behavior of bond stress and steel bar slipping. The main parameters affecting the bond response of different concrete strength are studied. The obtained results could contribute to the development for procedures of correct design of bond on structural concrete members.

The significance of this research is to investigate the applicability of CEB provisions in the prediction of bond between concrete and Brazilian's steel bar for high strength concrete.

III. Previous Research

CEB 151 (1982) prescribes that in the deformed bars the tension force is transferred to concrete by the ribs. The radial components of the ribs force on the concrete surrounding to the beam axis increase with the shear bond τ. This parameter is assumed as the longitudinal component of the rib resultant force transfers to the surrounding concrete, and is inclined of an angle α with beams axis (Figure 2).

On the rib bars the tension force on them is transferred to the concrete by the ribs. The radial components of the ribs forces that spread along the concrete perpendicular to the bar axis increases with the bond stress that can be regarded as longitudinal component of the ribs total force in the concrete. Figure 2 shows the angle between the total force and the bar axis. The radial component of the ribs force in the concrete generates internal pressure inducing tensions in the form of rings, that cause cracks along the anchored bar. When the rings are loaded to the failure point, longitudinal cracks appear. However, those can begin as longitudinal cracks that cannot be seen on the surface of the concrete before the maximum load is reached. As cracks appear, they increase the displacements between the bar and the concrete, and the bond stress is transferred along the anchorage length where the cracks appear. The radial components of the bond strength impose a load, and when those are loaded until its maximum value, they break suddenly.

The bond can be described ideally as a shearing stress between the surface of reinforced concrete and the concrete that surrounds it. That mechanism is determined by means of the relative displacement between the reinforced concrete and the concrete.

If the concrete between the ribs was reached the shear strength, the bond strength will be do only by the friction between the rough concrete and the bar cylindrical surface. In general this strength is smaller than the initial strength.

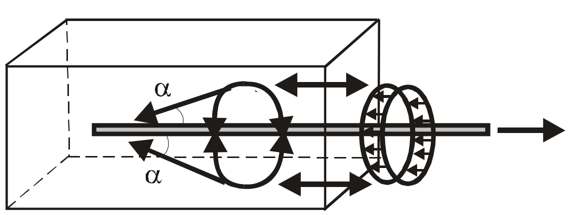

Figure 2 : 羊Radial component of the strength bond in the anchorage zone (Tepfers, 1979)

By the CEB (1997) provisions the bond stress (Figure 3) can be calculated as:

$$\tau = \tau_{max}\left(\frac{s}{s_1}\right)^{\alpha} \qquad 0 \leq s \leq s_1 \qquad (1)$$

$$\tau \quad \tau_{max} \qquad 0 < s < s_1 \qquad (2)$$

$$\tau = \tau_{max} - (\tau_{max} - \tau_r)\left(\frac{s - s_2}{s_3 - s_2}\right) \qquad s_2 < s \leq s_3 \qquad (3)$$

$$\tau = \tau_r \qquad s_3 < s \qquad (4)$$

Table 1 shows the bond conditions, good and poor, defined in CEB 235 (1997).

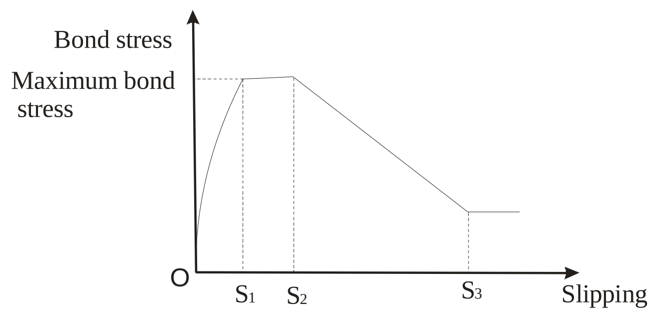

Figure 3 : Bond stress *vs.* slipping (CEB 235, 1997)

Table 1 : CEB parameters for deformed bars

Parameter	Not confined concrete		Confined concrete	
	Bond conditions		Bond conditions	
	Good	others	Good	Others
s_1	0.6 mm	0.6 mm	1.0 mm	
s_2	0.6 mm	0.6 mm	3.0 mm	
s_3	1.0 mm	2.5 mm	rib spacing	
α	0.4		0.4	
τ_{max}	$2.0f_c^{1/2}$	$1.0f_c^{1/2}$	$2.5f_c^{1/2}$	$1.25f_c^{1/2}$
τ_u	$0.15\tau_{max}$		$0.40\tau_{max}$	

Bond shear stress *vs.* slipping behavior was described by an analytical model in Martins (1989, 1991, and 1996). This model is developed considering some assumptions of CEB provisions, and their parameters are show in Figure 4.

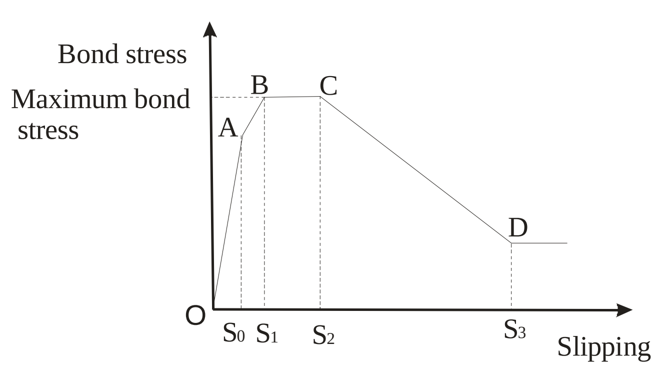

Figure 4 : 羊 Bondstress x slipping (Martins, 1989, 1991, 1996)

Data of bond studies of Huang *et al.* (1996a, 1996b) summarized on Table 2 and the comparison with CEB model showed that this Code need some change in its provisions.

Table 2 : Huang *et al.* (1996a and 1996b) Data

Parameter	Good Condiction			
	Normal strength concrete		High strength concrete	
	good	others	good	others
s_1	1.0 mm	1.0 mm	0.5 mm	0.5 mm
s_2	3.0 mm	3.0 mm	1.5 mm	1.5 mm
s_3	spacing ribs	spacing ribs	spacing ribs	spacing ribs
α	0.4	0.4	0.3	0.3
τ_{max}	$0.45f_{cm}$	$0.225f_{cm}$	$0.45f_{cm}$	$0.225f_{cm}$
τ_u	$0.40\tau_{max}$	$0.40\tau_{max}$	$0.40\tau_{max}$	$0.40\tau_{max}$

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IV. Experimental Investigation

Review of the literature on bond between-concrete and steel bar indicated that principal type o test is the pull out, but diverse researches employed several different approaches for this analysis.
The straightforward way to test the bond strength of bars is by mean of pull out test, which a concrete cube containing the bar is mounted on a stiff plate; the loading is applied by a jack used to pull the bar out the compressed concrete cylinder.

The pull out test is the most traditional of bond test and it consists of the extraction of a bar embedded longitudinally in a concrete prism with the free or unloaded end of the bar, which is usually positioned in the center of a cubic specimen. It is the method allowed to calculate, according to RILEM (CEB, 1983), the values of the average and maximum bond stress for each bar diameter used in different strength concrete, to compare them with the values given by some standards, as well as to draw curves characteristics of bond stress *vs.* slipping.

a) Materials Properties

Table 3 shows five mixture proportions, silica fume weight contents, proportion of plasticized and superplasticized, and five theoretical concrete strengths; the actual strength at 90 days were used in this study. Table 4 shows the concrete strength obtained in cylinder compression tests that were carried out in accordance with Brazilian standards.

The CEB 151 (1982) provisions gives the rib angle between 55^0 and 65^0, and some authors give the value 55^0. For the Brazilian steels with nominal diameters 16.0, 20.0 and 25.0 mm, was verified that this angle is, respectively, 46^0, 45^0 and 50^0 (Figure 5).

Table 3 : Concrete mixture proportions

f_c (MPa)	Mixture proportions (Kg)	Silica fume (kg)	Plasticized (%)	Superplasticized (%)	f_{c90} (MPa)
20	1: 2.927 : 3.933 : 0.786	0.3	0	0	33.63 MPa
40	1: 1.682 : 2.631 : 0.523	0.3	0	0	54.77 MPa
60	1: 1.219: 1.828: 0.392	0	0.3	0	63.31 MPa
80	1: 1.219: 1.828: 0.391	0.12	0.3	2.5	83.24 MPa
100	1: 0.884: 1.542: 0.348	0.12	0.3	2.5	105.44 MPa

Table 4 : Concrete Strength f_c (MPa)

f_c (MPa)	Concrete age (days)			
	3	7	28	90
20	19.32	26.78	33.44	33.63
40	28.23	43.50	51.71	54.77
60	33.01	57.00	61.46	63.31
80	39.85	59.87	79.98	83.24
100	48.41	68.15	100.89	105.44

The mechanical proprieties of the steel were determined by several specimens, tested in accordance with Brazilian standards. The yield stress and ultimate tension stress of the steel bars are given in Table 5.

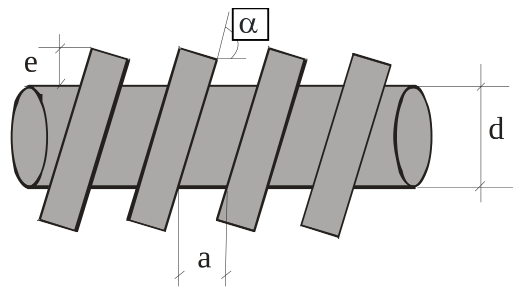

Figure 5 : Geometric characteristic of bar surface

Table 5 : Geometric and mechanical properties of the steel bars

Ø (mm)	α (°)	f_y (MPa)	f_{su} (MPa)	ε_{su} (%)	Rib heigth (cm)	a (cm)
16.0	46	627	745	16.67	0.16	0.92
20.0	45	529	842	8.00	0.18	1.17
25.0	50	619	722	11.59	0.25	1.57

b) Test Specimens

The bond strengths obtained by pull out test (cube with wide of 200mm), with concretes of different theoretical strengths: 20, 40, 60, 80 and 100 MPa; steel of diameter of 16.0, 20.0 and 25.0 mm. The actual concrete strengths considered in this study are 33.63, 54.77, 63.31, 83.24 and 105.44 MPa.

c) Experimental Procedures

In the average bond stress τ_m were calculated according to Equation (5), the values corresponding to the slipping 0.01 mm, 0.1 mm and 1.0 mm (rupture). If the maximum slipping is smaller than 1.0 mm in the τ_m, τ_u should be used in the $\tau_{1.0}$:

$$\tau_m = \frac{\tau_{0.01} + \tau_{0.1} + \tau_{1.0}}{3} \quad (5)$$

Figure 6 shows the test apparatus and a fractured specimen. All procedures were made in accordance with RILEM recommendations.

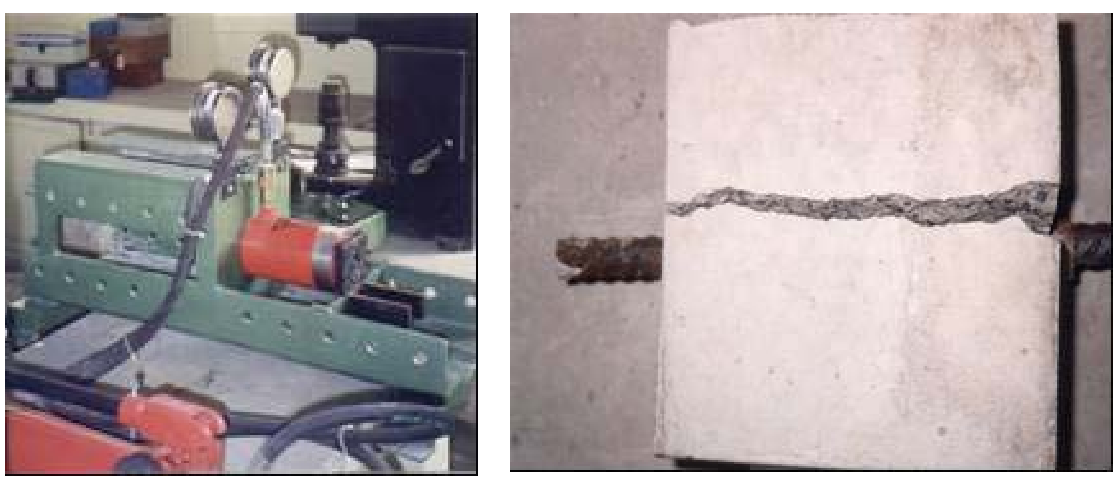

Figure 6 : Test apparatus and fractured specimen

V. Test Results

Pull out tests were conducted on concrete of different strengths and with three different steel bars diameters. As many as nine specimen test were made, for each diameter and different strength of concrete, which was evaluated at the 3, 7, 28 and 90 days of age (Tables 4).

Tables 6 shows for each bar diameter and actual concrete compressive strength at 90 days the followings experimental results: average bond stress for 12 slipping level, ultimate bond stress and maximum slipping.

Table 7 summarizes the test results of average bond stress, ultimate bond stress, and maximum slipping.

Table 6 : Average bond stress (MPa), ultimate bond stress (MPa) and maximum slipping (mm)

∅= 16.0 mm														
f_c (MPa)	s (mm)													
	0.01	0.1	0.2	0.4	0.6	0.8	1.0	1.20	1.40	1.60	1.80	2.00	τ_u	S_{max}
33.63	3.50	5.10	6.70	7.20	8.00	9.20	11.2	11.6	12.5	羊	羊	羊	12.9	1.57
54.77	4.24	5.20	6.80	9.05	11.6	14.5	16.5	17.5	18.2	19.4	羊	羊	19.9	1.66
63.31	5.17	9.70	11.2	14.1	17.0	19.7	21.3	22.2	23.7	24.4	羊	羊	26.6	1.63
83.24	5.50	10.1	12.8	14.6	17.5	19.9	21.8	23.2	25.5	26.5	29.0	羊	29.7	1.82
105.44	5.70	11.0	14.1	16.6	19.6	24.2	27.1	28.2	29.4	30.1	羊	羊	30.6	1.70
∅= 20.0 mm														
33.63	3.30	5.70	8.20	9.50	10.6	11.3	12.5	12.9	13.9	14.1	15.0	16.1	16.8	2.10
54.77	4.17	7.80	10.5	14.0	18.0	20.9	26.1	28.0	29.7	31.2	32.0	35.6	36.7	2.12
63.31	4.53	9.23	12.5	17.0	19.5	25.2	31.7	34.0	37.0	羊	羊	羊	40.0	1.55
83.24	4.67	11.3	14.7	19.9	25.0	31.5	37.0	40.0	40.1	44.1	羊	羊	46.0	1.80
105.44	5.87	13.7	19.7	22.5	27.0	33.0	38.6	41.0	43.5	46.5	羊	羊	48.5	1.70
∅= 25.0 mm														
33.63	7.50	8.00	10.6	12.8	14.4	18.3	24.0	26.1	27.6	28.9	30.1	30.9	32.0	2.21
54.77	7.65	8.30	15.5	17.0	20.9	31.7	39.8	40.8	42.3	44.7	46.3	48.4	52.5	2.32
63.31	8.30	9.20	18.9	24.3	32.4	36.3	41.2	45.6	49.9	54.6	5.77	60	羊	2.00
83.24	8.75	9.53	19.9	25.0	33.0	37.1	41.3	46.7	52.3	54.4	56.4	58.9	羊	2.01
105.44	9.02	9.90	21.4	27.1	36.5	38.0	45.5	47.3	49.1	52.7	55.3	57.8	羊	2.20

Table 7 : Average bond stress, failure bond stress (MPa), and maximum slipping (mm)

∅ (mm)	f_c (MPa)														
	33.63			54.77			63.31			83.24			105.44		
	τ_m	τ_u	s	τ_m	τ_u	s	τ_m	τ_u	s	τ_m	τ_u	s	τ_m	τ_u	s
16.0	6.59	12.9	1.57	8.65	19.9	1.66	12.0	26.6	1.63	12.5	29.7	1.82	14.6	30.6	1.70
20.0	7.17	16.8	2.10	12.7	36.7	2.12	15.5	40.0	1.55	17.6	46.0	1.80	19.4	48.5	1.70
25.0	13.2	32.0	2.21	18.6	52.5	2.32	19.6	60.0	2.00	19.9	60.0	2.01	21.5	60.0	2.20

VI. Comparasion of Experiemntal and Theoretical Models

Attempting to obtain an equation that represents the bond stress *vs.* slipping for Brazilians' steel and high strength concrete, it is search out a regression analysis that furnish the followings formulas 6 to 8 and figures 7 to 12:

1) normal strength concrete ($f_c \leq 50$ MPa):

$\tau = 19.36 s^{0.51}$ (erro=1.51 MPa) (6)

$s_{max} = 0.25 \varnothing 0.68$ (erro=1.07 MPa) (7)

2) high strength concrete ($f_c > 50$ MPa):

$\tau = 32.58 s^{0.48}$ (erro=1.32 MPa) (8)

$s_{max} = 0.52 \varnothing^{0.42}$ (erro=1.07 MPa) (9)

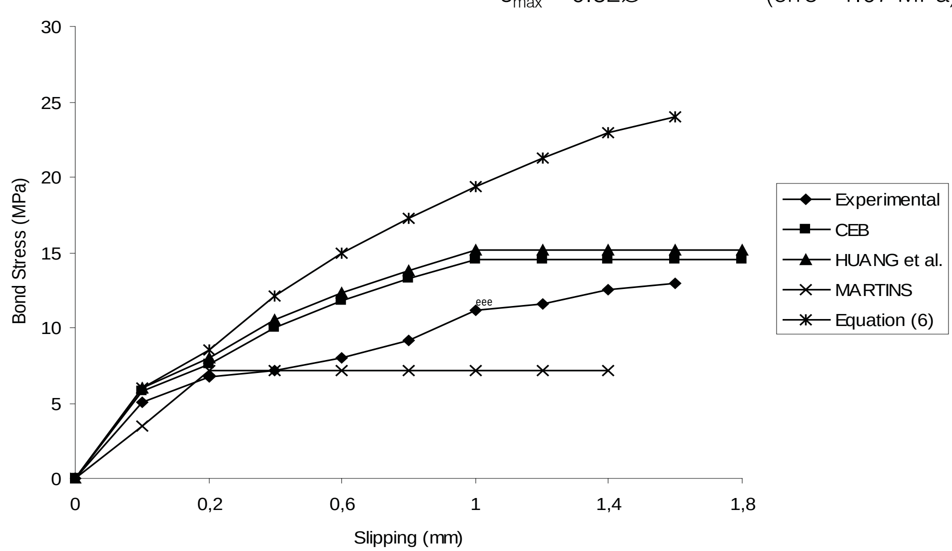

Figure 7 : Bond stress *vs.* slipping: ϕ=16.0 mm, f_c=33.63 MPa

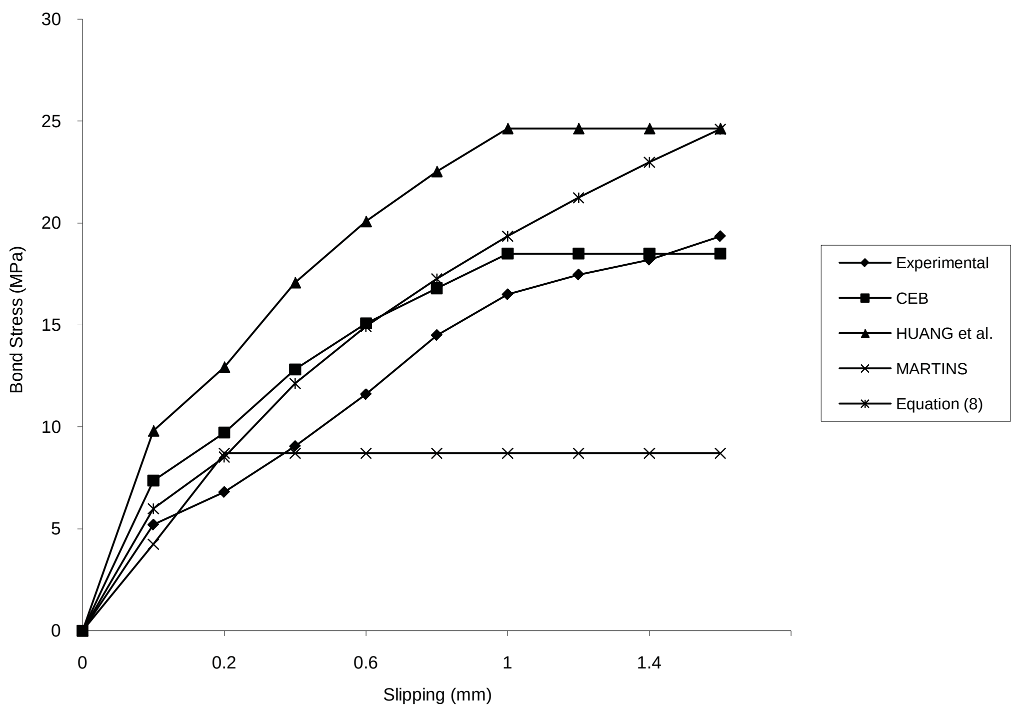

Figure 8 : Bond stress *vs.* slipping: ϕ=16.0 mm, f_c=63.31 MPa

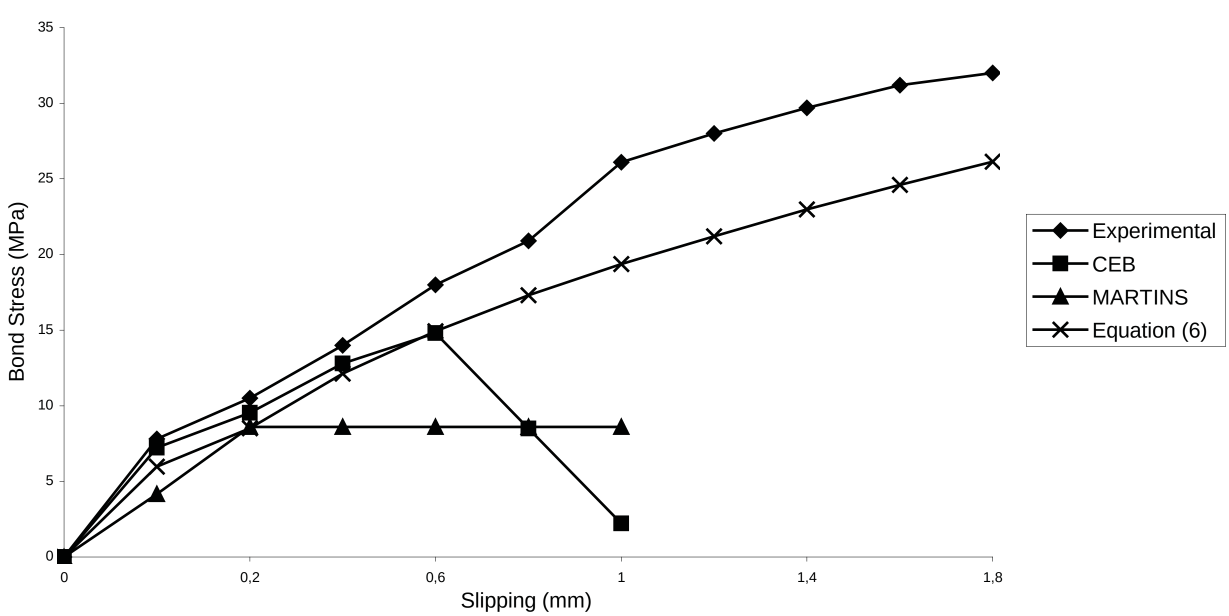

Figure 9 : Bond stress *vs.* slipping: ϕ=20.0 mm,

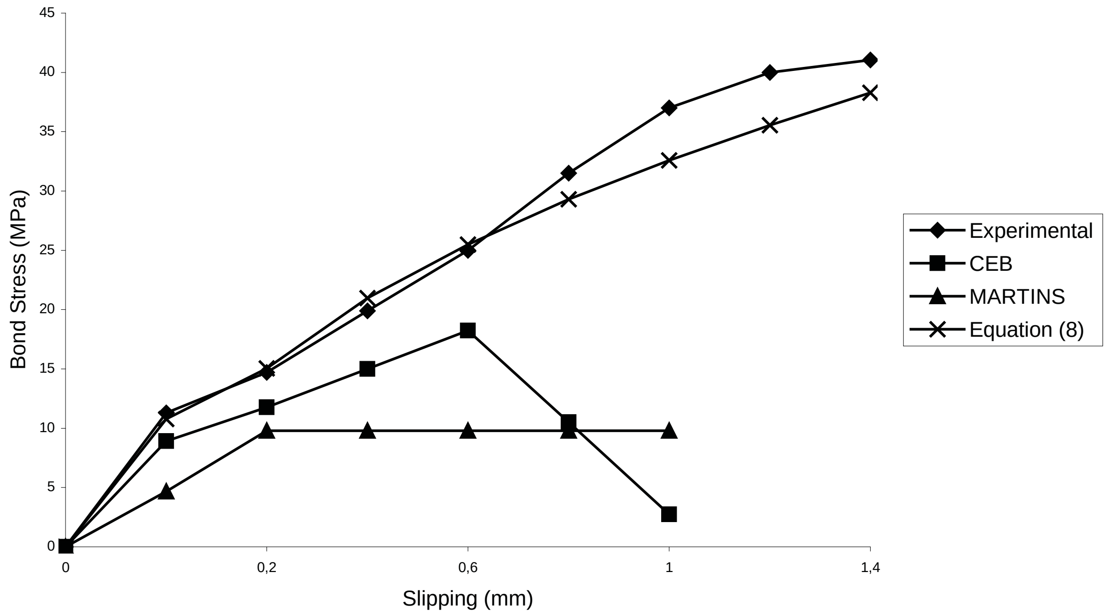

Figure 10 : Bond stress *vs.* slipping: ϕ=20.0 mm, f_c=83.24 MPa

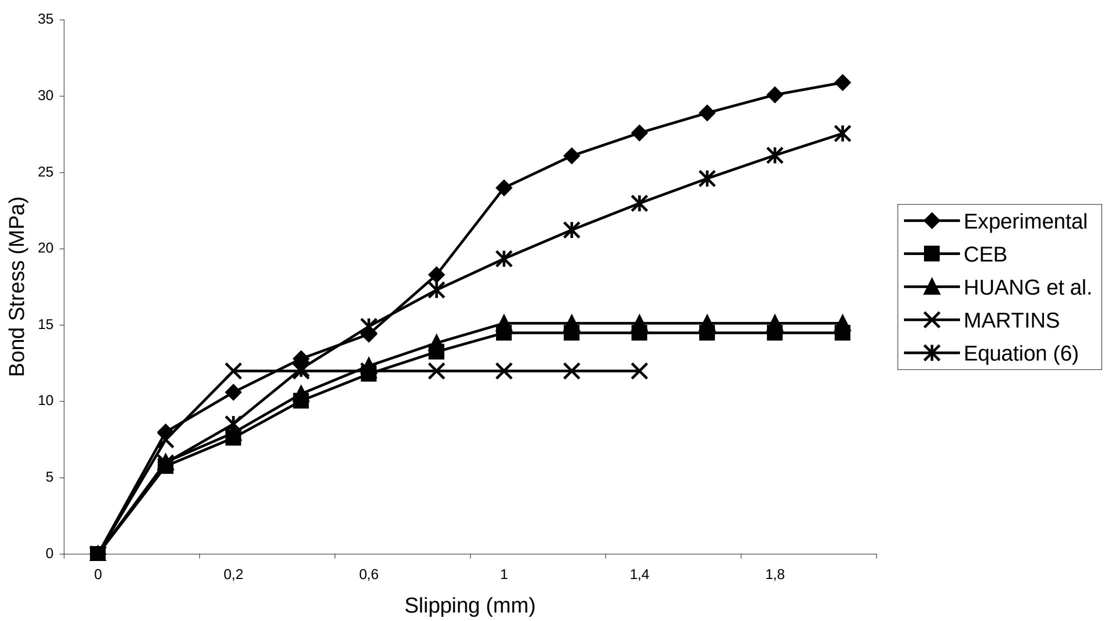

Figure 11 : Bond stress *vs.* slipping: ϕ=25.0 mm f_c=33.63 MPa

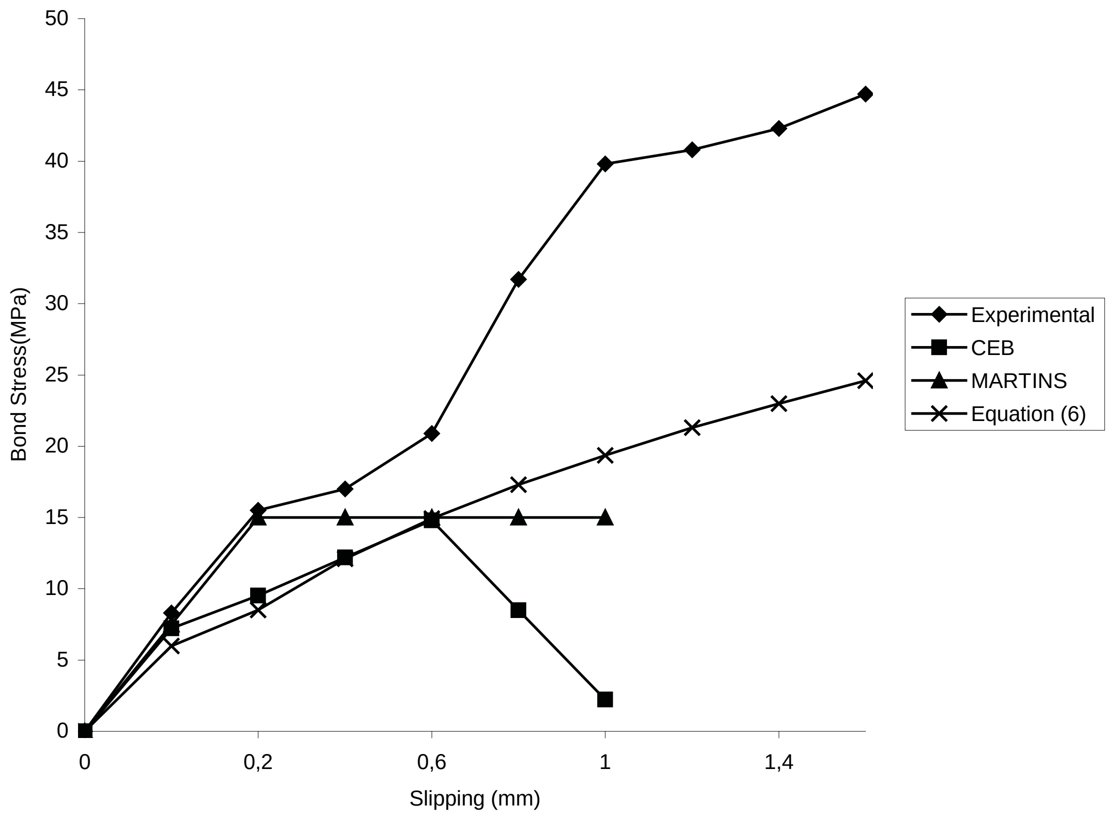

Figure 12 : Bond stress *vs.* slipping: $\phi = 25.0$ mm $f_c = 54.77$ MPa

VII. Conclusions

A review of bond between concrete a steel bar has been conducted. Experimental results from pull out test with Brazilian's steel were used to compare the bond behavior with results of some theoretical models found in the literature.

The study of the bond between the reinforcement and the concrete is not easy mainly due to the application of new materials as the fibers (Benmokrane *et al.*, 1996) and other components on concrete. There are none researches about the bond stress of high strength concrete with same characteristic than this study.

Based on review analysis, of experimental and analytical results into the bond between concrete and steel bar reported in this paper, the followings conclusions are presented:

1. The bond stress x slipping has the same aspect for the ordinary and the high strength concrete. If the concrete strength increases the bond stress increases, because the fly ash is better component to link the transition zone between concrete components. The expressions found for bond stress x slipping but are necessary more complementary studies to confirm these results.
2. If the bar diameter increases the bond stress increases. It's opposite the conclusions of Soroushian and Choi (1989), Reynolds and Beddy (1982). The pull out test placed the concrete surrounding the bar in compression and the bar in tension, but in practice both the bar and the concrete are in compression.
3. A regression was used to obtain an expression that represents the average and maximum bond stress in function of the concrete strength and bar diameter for Brazilian's steels:

   a) for $f_c \leq 50$ Mpa (10)

   $$\tau_m = e^{0.082\varnothing} + e^{0.019f_c} + 0.86 \text{ (error=1.09 MPa)}$$

   $$\tau_m = e^{0.104\varnothing} + e^{0.027f_c} + 0.93 \text{(error=1.13 MPa)} \quad (11)$$

   b) for $f_c > 50$ MPa

   $$\tau_m = e^{0.05\varnothing} + e^{0.004f_c} + 4.35 \text{(error=1.07 MPa)} \quad (12)$$

   $$\tau_{max} = e^{0.08\varnothing} + e^{0.003f_c} + 6.68 \text{(error=1.08MPa)} \quad (13)$$

4. The experimental results were compared with CEB provisions and with theoretical formulations proposed by several authors, considering the relationship bond stress *vs.* slipping.
5. Statistical analysis of the experimental results demonstrated that CEB provisions and the models showed for assessing bond stress of ordinary strength concrete and high strength concrete are inappropriate for Brazilian materials. The correlation

formulas obtained with experimental data demonstrate the poor applicability and limitations of three analytical models found in literature.

6. This study furnishes formulas for statistical correlations of bond stress between concrete and steel bar, which have acceptable errors.

Notation

f_c = concrete strength

f_{ck} = characteristic concrete strength

f_y = steel yield stress

f_{su} = steel ultimate tension stress

s = slipping (mm)

α = rib angle

ε_{su} = steel ultimate strain

$\varnothing$ = bar diameter (mm)

τ = bond stress (MPa)

τ_m = average bond stress

τ_{ma} = maximum bond stress

τ_u = ultimate bond stress

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