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The bond stress x slipping relationship

A relação tensão de aderência x deslizamento

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Abstract

A few international standards regulate the use of the high strength concrete, which may not be adopted generally without consideration of the differences that can be among the materials in different countries. This paper presents the results of an experimental study consisting of pull out tests of Brazilian steel, with five different concrete strengths, 20, 40, 60, 80 and 100 MPa, and three different steel bar diameters, 16.0, 20.0 and 25.0 mm. The experimental results for the bond stress vs. slipping relationship were compared with the provisions of the CEB and with some theoretical formulations found in literature. One statistical analysis is made and equations for predicting the bond stress were derived.

Keywords: reinforced concrete, bond, normal strength concrete, high strength concrete.

Resumo

Algumas normas estrangeiras regulamentam o uso do concreto de alto desempenho, as quais não podem ser adotadas nacionalmente sem considerar as diferenças que possam existir entre os materiais. Este artigo avalia o comportamento da aderência aço-concreto através do ensaio de arrancamento (Pull out test) para as barras de aço de fabricação nacional de seção circular: 16,0; 20,0 e 25,0 mm e cinco classes de resistência à compressão do concreto, a saber: 20, 40, 60, 80 e 100 MPa. Os resultados experimentais obtidos no estudo da relação entre tensão de aderência e deslizamento foram comparados com as prescrições do CEB e com algumas formulações teóricas encontradas na literatura. E, finalmente, efetuou-se uma análise estatística a fim de se estabelecer equações adequadas ao cálculo da tensão de aderência.

Palavras-chave: concreto armado, aderência, concreto convencional, concreto de alto desempenho.

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1. Introduction

The bond stress can be defined as being the strength of the adhesion between two bonded surfaces, being in this case the relationship between the strength of the reinforced concrete and the surface of the reinforced bond applied to the concrete. At first sight, this relationship seems quite simple to understand even though several factors can interfere in its quantification, being that these factors have a direct influence on the behaviour of the bond, in such aspects as the concrete compressive strength, the concrete cover, the rebar diameter and others [1].

This mechanism allows the materials to be deformed jointly and, as a consequence, allows the transference of the strength from one to the other, that is to say, whenever the stress in the bar varies, be it due to compression or tension, and supposing that the bond stress is carried out along the bar, there will be transfer of forces between the bar and the concrete.

In fact, that bond is composed of several portions, which went through different phenomena that intervene in the steel-concrete connection [2, 3]:

a) *Chemical adhesion*: It is the physical-chemical connection that arises from the interface of reinforced concrete during the reactions of the hydration of the cement. In other words, it is the action that comes from the adhesion or capillary forces.

b) *Attrition*: The attrition strength shows itself after the adhesion has been broken.

c) *Mechanical*: It is the mechanical interaction between the steel reinforcement and the concrete, due to the presence of ribs on the surface of the bar; being that those ribs act as support pieces, by mobilizing the compression tensions in the concrete. The mechanical bond is the most effective and reliable connection, since it contributes in a vital way to the solidification of the two materials.

Therefore, the behaviour of the reinforced concrete depends on the steel-concrete bond, and the strength capacity of these elements is directly related with the bond since the bond stress varies in magnitude along with the length of the reinforcing bar. This large variation of the bond stress is originated by cracks. Several parameters concerning to the structural design depend on the bond, for example: the anchorage length, the lap splices, to stiffen the tension between cracks, cracking control, and minimum reinforcement ratio [2, 4, 5, 6].

In the case of the smooth bars, wherein rupture caused by slipping occurs, the bond is mainly carried out by using the chemical adhesion between the cement paste and the rebar. When that connection is broken, the strength that leads to the slipping appears due to friction, being that its intensity depends on the type of the surface of the bar. In those bars, the mechanical bond between the concrete and the steel happens through the irregularities that exist on the surface of the bars. Therefore, the force capable of breaking the bond is proportional to the size of the area of the bar in contact with the concrete as regards the adhesion.

In what to the other bars (rib bars) is concerned, the resistance to slipping is mainly derived from the strength that the ribs offer to the pressures exercised on the concrete, that is to say, from the mechanical action between the concrete and the ribs. The effect of the chemical adhesion, in that case, is small and the friction does not happen until a displacement of the reinforced steel happens [2, 3].

In the case of the rib bars, the strength of tension applied on them is transferred to the concrete by the ribs. The radial components of the forces of the ribs, which spread along the concrete in a way perpendicular to the axis of the bar, increase with the bond stress, which can be regarded as a longitudinal component that results from the force exercised by the ribs in the concrete. The resulting force forms an angle in relation to the axis of the bar (see Figure 1 and 2). The radial component of the force exercised in the concrete generates an internal pressure that will induce traction tensions, in the form of rings, that cause bursting cracks along the anchored bar. When the rings are loaded to the point of rupture, longitudinal cracks appear. [3, 4]

As longitudinal cracks appear, they increase the displacements between the bar and the concrete and the bond stress is transferred all along the anchorage length of the areas where the cracks appear. The radial components of the strength of the bond induce a sort of load and when those loads are filled until its maximum capacity, they break suddenly [4].

In this context, the anchorage strength is limited by the smallest value of either the main tension stress or the main compression stress, being that the bond failure is connected with these stresses. The transfer of stress between the steel and the concrete happens mainly due to the action of the ribs of the bar, between its protuberances, that are present in the concrete.

The crush of concrete in the areas surrounding one of these ribs

Figure 1 – Strength between reinforced and concrete (adapted from (4))

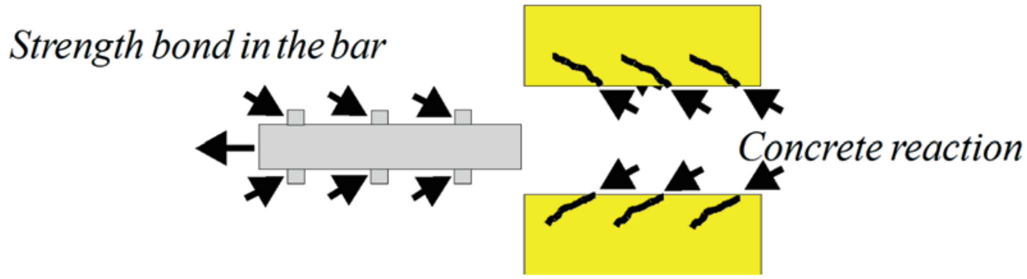
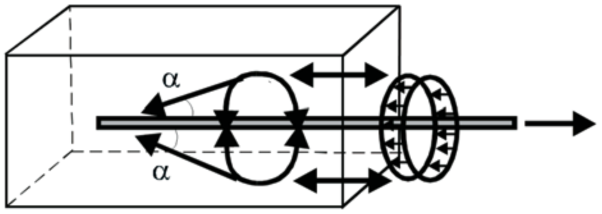


Figure 2 – Representation of the radial component of the bond strength in the anchorage zone (adapted from (3))



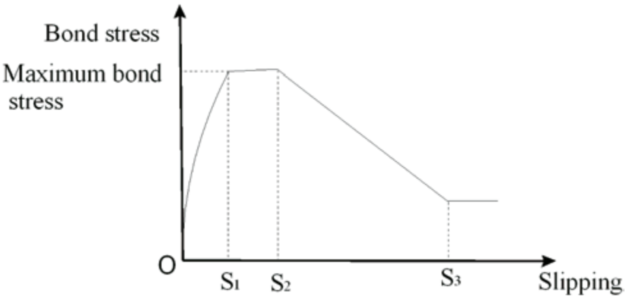
does not affect the bar anchorage, since the stress applied on that specific salience is transferred to others ribs. Therefore, there are two failure situations concerning to the bond: the micro-failure, which is a confined failure of the bond that does not affect the anchorage, and the macro-failure, which is formed after the occurrence of several micro-failures. The second type of failure does not allow a new stress distribution, and, as a consequence, the bar anchorage is no longer effective [2].

Therefore, the bond failure on deformed bars happens due to one the following situations: crush of the concrete in areas around the ribs, shear of the concrete surrounding the bar, or, more frequently, one longitudinal chipping of the concrete cover, being also possible a combination of these three situations. In this context, the bond can be ideally described as being 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.

The researches about the bond stress are usually made by taking in consideration the relationship between the bond stress ($\tau(x)$) and the slipping ($s(x)$) of the steel bar in pull out specimens. The first one is identified by the shearing stress between the bar and the surrounding concrete, and the second one by the relative displacement between the bar and the concrete [2, 7-11].

The concrete strength is one of the main parameters that influence the anchorage length and the transfer of the tensions concentrated on the ribs of the bar. Other factors that have influence in the bond stress are: the surface of the bars, namely its roughness and/or irregularities (increase the bond); the diameter of the bars (an increase in the diameter of the bar reduces the maximum bond stress); the type and arrangement of the ribs in the reinforcement [1, 2, 5].

Figure 3 – Bond stress x slipping (7, 8)



This research studies the bond stress and the slipping of steel bars by using pull out specimens. It makes use of five different concrete strengths, with the estimated strengths of: 20, 40, 60, 80 and 100 MPa, and rib bars with two different diameters, 16.0 and 20.0 mm. The significance of this research has to do with the aim of investigating the applicability of the CEB stipulations and some other formulations in order to achieve prospects concerning to the bond between concrete and steel bars, relating to Brazilian materials and taking in consideration the differences between the building materials. It has also the purpose of analyzing adjustments that may give a precious contribution to the important researches that are being made on this subject.

2. Bond Stress vs. Slipping ((σ (x) x s(x))

The bond stress models have caught and attracted the attention of many researchers since the 19th century. In the following subtopics are summarized some numeric models that are investigated in this paper.

2.1 CEB-FIP Model [7,8]

The bond stress (Figure 3 and Table 1) can be calculated as:

Table 1 – CEB parameter for deformed bars (4)

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}	2.0 . $f_{ck}^{1/2}$	1.0 . $f_{ck}^{1/2}$	2.5 . $f_{ck}^{1/2}$	1.25 . $f_{ck}^{1/2}$
τ_u	0.15 . τ_{max}		0.40 . τ_{max}	

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

$$\tau = \tau_{\max} \quad s_1 < s < s_2 \tag{2}$$

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

$$\tau = \tau_r \quad s_3 < s \tag{4}$$

2.2 Huang et al (1996) [12, 13]

In Table 2, HUANG et al. (1996a) and (1996b) have proposed this change in the CEB model.

2.3 Barbosa [2]

In order to obtain an equation that represents the results related to the medium and maximum bond stress according to the concrete strength and the diameter of the bar, for Brazilian materials, the bond stress can be calculated as:

For compression strength of concrete ≤ 50 MPa:

$$\tau_m = e^{0.082 \,.\, \varnothing} + e^{0.019 \,.\, fc} + 0.86 \quad (\text{erro} = 1.11\ \text{MPa}) \tag{5}$$

$$\tau_{max} = e^{0.05 \,.\, \varnothing} + e^{0.004 \,.\, fc} + 4.35 \quad (\text{erro} = 1.11\ \text{MPa}) \tag{6}$$

For compression strength of concrete > 50 MPa:

$$\tau_m = e^{0.104 \,.\, \varnothing} + e^{0.027 \,.\, fc} + 0.93 \quad (\text{erro} = 1.07\ \text{MPa}) \tag{7}$$

$$\tau_{máx} = e^{0.08 \,.\, \varnothing} + e^{0.003 \,.\, fc} + 6.68 \quad (\text{erro} = 1.08\ \text{MPa}) \tag{8}$$

Aiming the obtaining of an equation that represents the bond stress x slipping for Brazilian materials, the equation 9 to 12 was proposed:

For compression strength of concrete ≤ 50 MPa:

$$\tau = 19.36 \,.\, s^{0.51} \quad (\text{erro} = 1.51\ \text{MPa}) \tag{9}$$

where:

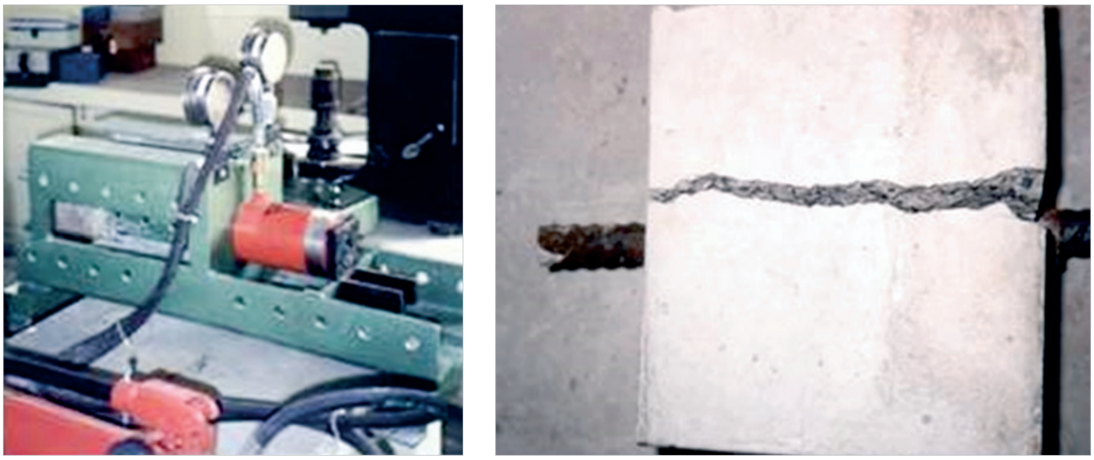
$$s_{max} = 0.25 \,.\, \varnothing^{0.68} \quad (\text{erro} = 1.07\ \text{MPa}) \tag{10}$$

t - bond stress, in MPa;
s – slipping, in mm;
Ø - diameter of bar, in mm.

Table 2 – HUANG et al. (1996a e b) (12, 13)

Parameter	Condition good			
	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}	0.45 f_{cm}	0.225 f_{cm}	0.45 f_{cm}	0.225 f_{cm}
τ_u	0.40 . τ_{max}	0.40 . τ_{max}	0.40 . τ_{max}	0.40 . τ_{max}

Figure 4 – Test apparatus and fractured specimen



For compression strength of concrete > 50 MPa:

$$\tau = 32.58 \,.\, s^{0.48} \ (\text{erro} = 1.32 \text{ MPa}) \tag{11}$$

where:

$$s_{max} = 0.52 \,.\, ø^{\,0.42} \ (\text{erro} = 1.07 \text{ MPa}) \tag{12}$$

3. Experimental procedure

The phenomenon of the bond, concerning the fundamental parameters with regard to the behavior of concrete, was the target of the development of an experimental program, allowing that an analysis with the models previously presented could be made. The concrete had different strengths, in this case an estimated strength of: 20, 40, 60, 80 and 100 MPa as well as reinforced steel with the diameters of: 16.0 and 20.0 mm. The tests were conducted when the concrete mixture had 90 days.

The pull out test was adopted because it is the most traditional of the bond tests and it consists on the extraction of a bar, usually located in the center of a specimen test in a cubic of concrete. This method allowed to calculate, according to RILEM [14], the values of the medium and maximum bond stress for each bar diameter used in concrete with different strengths and to compare them with the values given by some norms, as well as to obtain the characteristic curves of bond stress x slipping. Figure 4 shows the test apparatus and a fractured specimen. All procedures were performed in accordance with the RILEM recommendations.

In relation to the medium bond stress (t_m) (average of the stress) calculations have been made according to Equation (13), being that the values corresponding to the slipping are 0.01 mm; 0.1 mm and 1.0 mm (rupture). If the maximum slipping is smaller than 1.0 mm in the t_m, t_u it should be used in the $t_{1.0}$:

$$\tau_m = \frac{\tau_{0.01} + \tau_{0.1} + \tau_{1.0}}{3} \tag{13}$$

3.1 Materials

Concrete: On Table 3 it can be seen the mix proportions of concrete, while Tables 4 and 5 show the characterization of the Portland cement and the aggregates that were used in the concrete mixture. Table 6 shows the strength obtained by the cylinder compression tests that were carried out in accordance with the Brazilian stan-

Table 3 – Concrete mixture proportions

$f_{cestimated}$ (Mpa)	Mixture proportions (Kg) (cement: sand: aggregate: water/ cement ratio)	Silica fume (kg)	Plasticized (%)	Superplasticized (%)
20	1: 2.93: 3.93: 0.78	0.3	0	0
40	1: 1.68: 2.63: 0.52	0.3	0	0
60	1: 1.22: 1.83: 0.39	0	0.3	0
80	1: 1.22: 1.83: 0.39	0.12	0.3	2.5
100	1: 0.88: 1.54: 0.35	0.12	0.3	2.5

dards. The plasticized was RX 322N and super-plasticized was RX 4000 from REAX.

Reinforced (steel bar): The CEB 151, (1982), stipulations confer to the rib an angle between 55° and 65° being that some authors give it the value of 55°. In the case of the Brazilian steels, with nominal diameters of 16.0 and 20.0 mm, it was verified that this angle is, respectively, 46° and 45° (Figure 5) and Table 7.

3.2 Experimental procedures

Tests were conducted on concrete with all of the diameters of reinforcement and on concrete with all of the different strength according to the pull out test. Subsequently, nine specimen tests were made for each diameter and compression strength of the concrete, being the tests evaluated after 90 days. The average results obtained by the pull out test can be seen on tables 8 and 9. The bond strength is obtained through the pull out test (a 200 mm wide cube), with concretes of different theoretical strengths: 20, 40, 60, 80 and 100 MPa; and steel with the diameters of 16.0 and 20.0 mm.

Figures 6 and 7 show the experimental and analytical results relating to the bond between concrete and steel bar, reported in this paper, allowing to analyze and realize that:

1) If the bar diameter increases, the bond stress increases. This result is, therefore, the opposite of the results presented in some researches [15 – 18]. These researches usually state

Table 4 – Characteristics of Portland cement (type CP V)

Chemical composition (%)		Physical properties		Compressive strength (MPa)	
SiO_2	19.46	Setting time (initial) (min.)	137	days	fc
Al_2O_3	5.09	Setting time (end) (min.)	195	1	28.7
Fe_2O_3	2.97	(%) Fineness modulus #325	1.7	3	42.6
CaO	64.61			7	47.5
MgO	0.70	Volumetric expansion (mm)	0.0	28	56.4
K_2O	0.80				
CO_2	2.05	Density (g/cm³)	4.73		
SO_3	2.99				

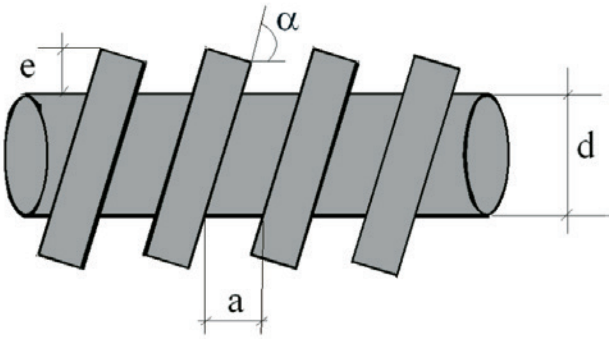
Table 5 – Physical characteristics of the aggregates

Properties	Sand	Coarse aggregate
Maximum diameter	2.40 mm	9.50 mm
Fineness modulus	2.52	–
Specific density	2.58 kg/dm³	2.72 kg/dm³
Powdered material content	1.33 %	1.27 %

Table 6 – Compressive concrete strength (MPa)

$f_{cestimated}$ (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

Figure 5 – Geometric characteristic of bar surface



that the thickness of the transition zone in the bars with bigger diameter along with the higher dimensions of the ribs (longitudinal and transversal) tend to “ hold “ more water in the bottom face of the bar, thus causing exudation and the weakening of the internal connection. This behavior is directly related with the concrete density and not with the thickness of the transition zone;

2) The experimental results have shown that both CEB and Huang et al models for assessing bond stress of both regular strength concrete and high strength concrete are not suitable for Brazilian materials. They have also shown that the research developed by Barbosa is adequate, as seen in Figures 6 and 7.

4. Conclusions

A review of the bond between concrete and steel bars has been conducted. Experimental results reached from pull out test with Brazilian steel concerning to the behavior of the bond were used to be compared with some other results of some theoretical models found in literature.

The study of the bond between the reinforcement and the concrete is not easy. The behavior of the components of reinforced concrete is affected by the slipping of the steel bars inserted in the concrete matrix. A tension stiffening effect and crack evolution occurs since the beginning of slipping; thus, the assessment of those phenomena requires the introduction of a bond–slip interaction model.

This paper introduces some numeric models and an approach to the slip phenomenon affecting the structural behavior of Brazilian materials. The results obtained can be considered reliable in view of the fact that they were obtained from the experimental results as well as other authors.

Table 7 – Geometric and mechanical properties of the steel bars

ϕ (mm)	α (grad)	f_y (MPa)	f_{su} (MPa)	ε_{su} (%)	Rib height (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

Table 8 – Average bond stress (MPa), ultimate bond stress (MPa) and maximum slipping (mm)

Diameter of bar = 16.0 mm													
f_c	Slipping (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	$S_{máx.}$
33.63	3.50	5.10	6.70	7.20	8.00	9.20	11.2	11.6	12.5	–	–	–	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	–	–	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	–	–	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	–	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	–	–	30.6	1.70
f_c	Diameter of bar = 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	–	–	–	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	–	–	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	–	–	48.5	1.70

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Table 9 – Average: bond stress (MPa), failure bond stress (MPa), and maximum slipping (mm)

ϕ (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

Figure 6 – Bond stress vs. slipping for reinforcement ϕ = 16.0mm

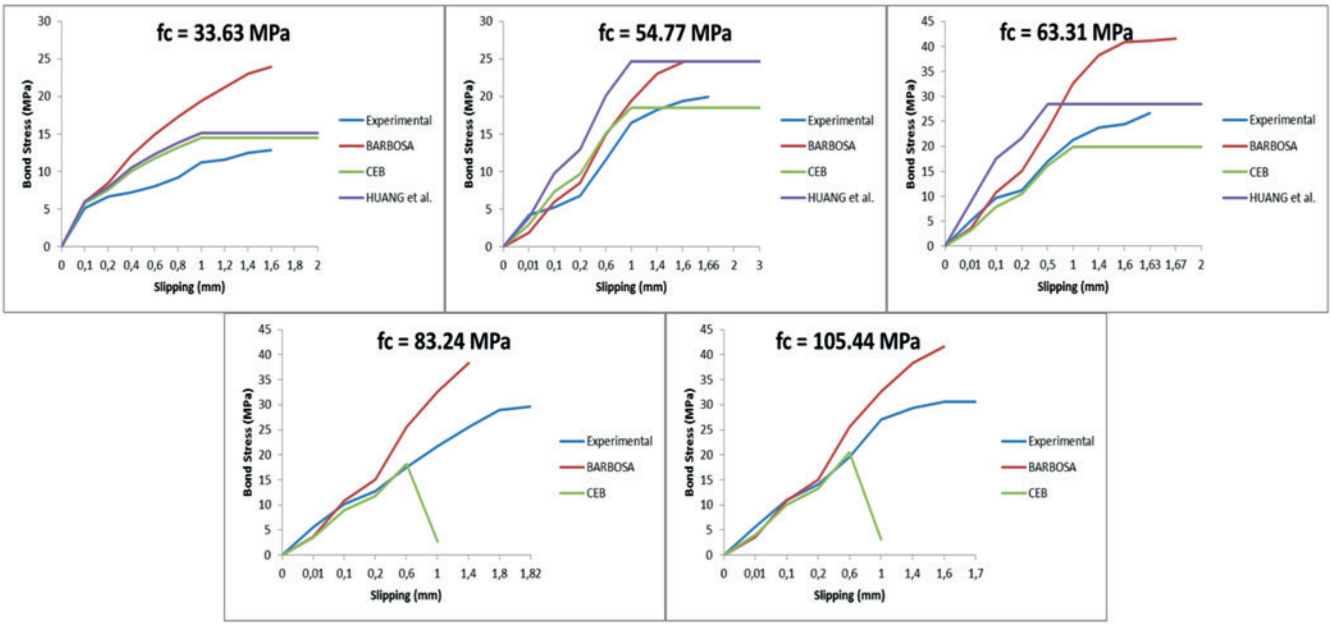
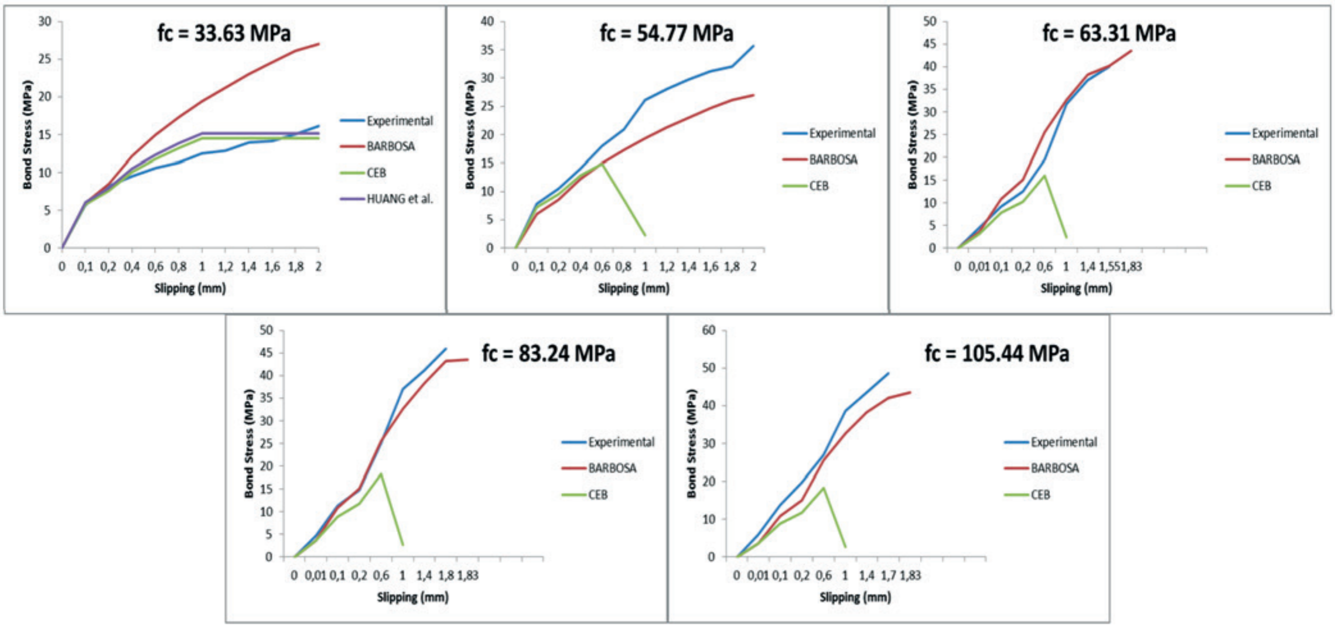


Figure 7 – Bond stress vs. slipping for reinforcement ϕ = 20.0mm



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