GFRP: ASSESSING LOAD TRANSFER FROM BAR SURFACE TO CONCRETE

GFRP: AVALIANDO A TRANSFERÊNCIA DE CARGA DA SUPERFÍCIE DA BARRA PARA O CONCRETO

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This paper presents research on tensile force transfer results from a GFRP (glass-fibre-reinforced-plastic) reinforcing bar to the surrounding concrete. The experimental programme was carried out on 27 tensile strut specimens reinforced with single GFRP bars. Force transfer from the bar to the surrounding concrete is characterized by the number and spacing of the cracks that form in the strut. A comparison of GFRP bars with three different surface characteristics was carried out. The results shows that the force transfer from GFRP to concrete is significantly improved when GFRP bars have a sand-coated surface.

Keywords: Glass-fibre-reinforced-plastic, Concrete, Bond Strength, Friction Coefficient, Strut Test

Este artigo apresenta resultados de pesquisa sobre transferência de esforços de tração de barra de armação em GFRP (plástico reforçado com fibra de vidro) para o concreto que a envolve. O programa experimental foi realizado em 27 corpos-de-prova, tipo tirante, armados com uma única barra GFRP. A carga transferida da barra para o concreto foi caracterizada pelo número e espaçamento entre fissuras formadas no tirante. Foi realizada uma comparação de barras GFRP com três diferentes superfícies características. Os resultados mostram que a carga transferida da barra GFRP para o concreto é significativamente melhorada nas barras com superfície encrustrada com grãos de areia.

Palavras-Chave: Plástico Reforçado com Fibras de Vidro, Concreto, Resistência de Aderência, Coeficiente de Aderência, Ensaio de Tirante

1 INTRODUCTION

The past 20 years have revealed an alarming deterioration of transportation infrastructure due to the corrosion of steel reinforcement[1, 2]. Disintegration of concrete structures, and consequent traffic tie-ups due to repair work, have arroused interest in using noncorrosive glass-fibre-reinforced-plastic (GFRP) reinforcing bars in concrete. GFRP products which are noncorrosive, nonmagnetic and have a high strength to weight ratio, have been investigated for their short and long-term performance.

The use of traditional steel reinforcement in concrete has a long performance history and it is well documented[4; 5]. However, the performance of GFRP bars in concrete is not well established because of their recent introduction in concrete construction. Bond behaviour and the development length of GFRP bars in concrete have to be understood to take advantage of the potential of these bars. To avoid premature slippage between GFRP bars and concrete under bending, manufacturers have devised several techniques to improve bond, including the use of sand coating and spiral ribs. Research on bond strength between reinforcement and concrete has been carried out by measuring resistance to slippage of a GFRP bar embedded in concrete using either pullout tests or beam tests.

Bond strength measurements were carried out using the pullout test described in the ASTM C 234[5]. Boyle and Karbhari[6] used the pullout test where GFRP bars were placed at the centre of concrete cylinders, which had a diameter of 150 mm (6 in.) and a height of 300 mm (12 in.). They[6] concluded that *"roughness in the reinforcement was sheared off during pullout indicating strong frictional interlock that was overcome"*. Moreover they stated that *"damage to concrete and reinforcement surfaces was not uniform, indicating nonconstant friction"*. Nanni et al. [7] have also carried out concentric pullout tests on test specimens similar to that of ASTM C 234[5] using two different concrete strengths. They[7] concluded that bond behaviour of these new reinforcing elements needs to be established. From pullout test results, Brown and Bartholomew[8] concluded that bond strength between GFRP bars and concrete is approximately two-thirds of that which would ordinarily be expected between steel bars and concrete.

The beam test as recommended by RILEM[9] was also used to assess the bond of FRP bars to concrete. Benmokrane et al.[10] carried out tests on beams using GFRP bars with embedment length of 10 *d*, where *d* is the GFRP bar diameter. They[10] concluded that the bond strength observed from beam tests is lower than that obtained from pullout tests.

GangaRao and Faza[11] conducted a series of beam-end tests to assess the bond strength for different GFRP bar surfaces (fine sand coat, coarse sand coat and uncoated ribs) and embedment lengths. In eight of 20 tests, the bars failed in tension at a stress that was about 25% lower than the expected ultimate tensile strength of the bar. Pullout failures occurred in 10% of their tests due to short embedments. GangaRao and Faza[11] concluded that bond strength values from pullout tests (ASTM C 234) were higher than from the beam-end tests (calculation procedure not referred).

In the present study, attention is focused on load transfer from the GFRP bar to the surrounding concrete, through the rebar surface. The experimental technique is described in detail, and a typical set of results for bars with different surfaces conditions are given. The force transfer characteristic of GFRP bars of three different surfaces are compared.

2 TEST APECIMENS

Bond stresses that resist the pullout of a bar embedded in concrete are distributed unevenly along the embedded length of the bar. The average bond stress $ô_{bd}$ (Figure 1(a)) is:

$$\hat{o}_{bd} = F / s\, l_{em}$$

where

F = the force applied to the bar,
s = the perimeter of the bar, and
l_{em} = the embedded length.

The average bond stress decreases with embedded length, l_{em}. An increase in embedded length (l_{em}) above 15 - 20 d (d is the bar diameter) has practically no further effect on the pullout resistance of the bar. Deformed bars with rough surfaces have higher resistance to slipping, owing to adhesion and wedging of the deformations in the concrete (Figure 1 (b)).

In this study, the load transfer characteristics of different bars were evaluated using a tensile strut as shown in Figure 2. Split steel tubes were bonded at both bar ends using epoxy glue. The tensile load was applied using conventional grips. Cracks in the concrete prism were highlighted during the load application and crack spacings were measured after the load was removed.

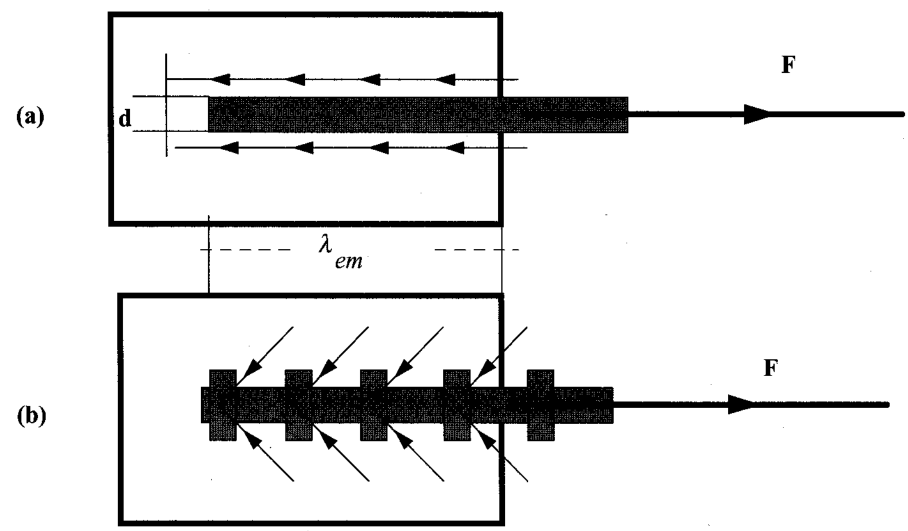

Figure 1 - Smooth and Ribbed Bar: Adhesion and Wedging

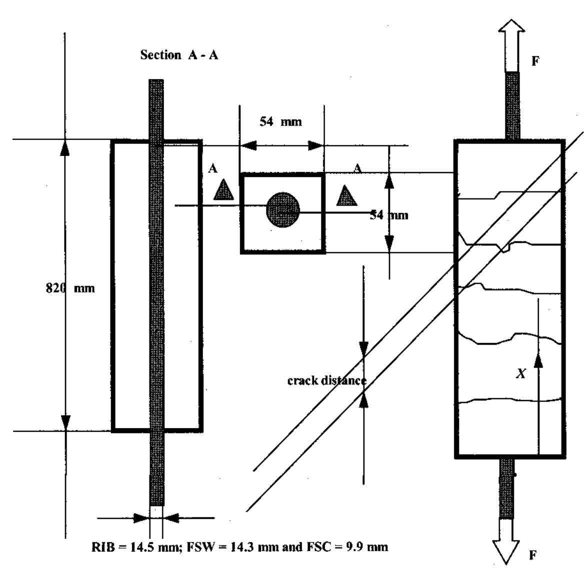

Figure 2 - Reinforced concrete element before and after strut test

$$\acute{o}_r = N / A_r \qquad [1]$$

Note that in the uncracked region, N is resisted by concrete and GFRP reinforcement.

With increasing distance "x", shown in Figure 2, from the first crack, the concrete tensile stress, $\acute{o}_t$, will increase and the bar stress, $\acute{o}_r$, will decrease as long as there is bond between concrete and bar. As the force F is the same along the strut element, the decrease of force in the bar is the same as the increase of tensile force in the concrete. The transfer of tension from the bar to concrete takes place through bond between the bar surface and the concrete.

The tensile force in the concrete is related to the average surface bond stress as follows:

$$ô_{bd}\ s\ x = A_c\ ó_t \qquad [2]$$

$ô_{bd}$ = the average value of bond stress,
s = the total perimeter of bar in contact with concrete,
A_c = the concrete cross section area, and
$ó_t$ = the average tensile stress in the concrete at distance "x".

When $ó_t$ reaches the concrete tensile strength a crack occurs. Thus the relationship between the bond strength, $f_{bd,}$ and the distance, a, between cracks is as follows:

$$f_{bd}\ s\ a = A_c\ f_t \qquad [3]$$
$$f_{bd} = A_c\ f_t / s\ a \qquad [4]$$
$$s = ð\ d \qquad [5]$$
$$f_{bd} = f_t\ (A_c / ð\ d\ a) \qquad [6]$$

Thus for a given concrete strength, a smaller value of crack spacing indicates a higher value of average bond strength.

Assuming that $Ä_c$ is the average distance between concrete cracks in the strut specimen:

$$f_{bd} = f_t\ (A_c / ð\ d\ Ä_c) \qquad [7]$$

Assessing f_{bd} by using $Ä_c$ (the average distance between concrete cracks) is more accurated than by a (single distance between two cracks).

According to the NBR 7477[12] the friction coefficient (ç) is the ratio of the bond strength (f_{bd}) and the concrete tensile strength (f_t).

$$ç = A_c / ð\ d\ Ä_c \qquad [8]$$

2.1 Experimental programme

The experimental programme was carried out on strut elements as shown in Figure 2. The strut test is based on the Brazilian standard NBR 7477 [12] which requires that the reinforcing bar be loaded in tension to 80% of the yield load. However, the tensile stress-strain curves of GFRP bars are charcterized by straight lines, with no yield point and a britle failure. The strut test was carried out by loading the GFRP bar, in an universal testing machine, as in the tensile test. The test specimen was loaded monotonically to a maximum load, equal to 80% of the bar failure load. The load for the strut test was determined by testing two GFRP bars to failure. Cracks distances were measured along the centre of four concrete specimen faces.

In addition to casting strut specimens, cylindrical specimens were cast for compression and splitting tension tests. Three types of GFRP bars with different surface charcteristics were used in the experimental programme. "RIB" bars have a ribbed surface similar to steel bars and a diameter of 14.5 mm. "FSW" bars have a fibre string wrapped in a helical pattern, which provided a deformed bar surface. "FSC" bars were similar to FSW bars but have a sand coated surface. FSW bars were 14. 3 mm in diameter and FSC bars were 9.9 mm in diameter. The nominal diameter was calculated from the measured weight and length of several bars. The average tensile strength of the bars were 417, 655 and 717 MPa and the tensile failure loads varied from 70 to 105 kN. Due to manufacturer requirement tensile strength will not be here related to each FRP bar. The strut test results are shown in Tables 1, 2 and 3 for each of the bar types.

2.1 Analysis of results

The average bond strength varies widely and depends mainly on the following three factors:

- Adhesion of the bar to the cement paste;
- Friction along the bar surface caused by shrinkage of concrete;
- Resistance of concrete to shearing forces that develop because of the surface roughness of the bar.

Previous experimental programmes and analyses of streel reinforcing bars showed that these factors can not be separated, and the numerical value of the bond strength, f_{bd}, is difficult to determine. According to Base [13] the ratio of concrete bond strength (f_{bd}) to tensile strength (f_t) has not been properly determined; however it is generally assumed to be between 1.5 and 2.5 for deformed steel rebars. Reynolds and Beeby[14] stated that: *"bond strength is proportional to the tensile strength of the concrete. This can be considered to be proportional to the square root of the compressive strength".*

In the present analysis, a strut-test result is considered valid when the applied load reaches 80% of the failure load of a bar. The test results show that due to the slippage in the grips 11% of RIB bars, 33% of FSW bars and 33% of FSC bars do not satisfy the load criterion. Therefore a standard tensile test and fitting grip is needed for assessing GFRP bars tensile and bond strength.

In this study the tensile strength of concrete (f_t) was taken as the splitting tensile strength from tests of cylinders 150 mm diameter and 300 mm high. The average distance between cracks formed during the strut tensile test was taken as the "$Ä_c$" value (Eq 6). Most of the cracks occurred before the applied load reached 60% of the bar failure load. From that point on, a significant increase in crack widths ocurred. However, crack widths were not measured.

Bond strength (f_{bd}) was obtained through Eq. 6 and is shown in Tables 1, 2, and 3. In this study the fricition coefficient is used as the strut test result for the purpose of comparison with other results, as shown in Fig. 3. Strut test results reported elswere[13] show friction coefficient values of 1.22 for smooth steel and 1.72 for ribbed steel bars. Also, it was reported that smooth and ribbed epoxy-coated steel bars had values of 1.18 and 1.38 respectively. In this study, the average friction coefficient values (Tables 1, 2 and 3) for FRP bars were: 0.67 for RIB, 0.37 for FSW, and 1.06 for FSC. These results show that the statement by Brown and Bartholomew that the bond between FRP bars and concrete is aproximately 2/3 of that which would be expected between steel and concrete must be carefuly analysed. The bond strength will depend on the type of test carried out (pullout, beam or strut) and on the bar surface. Strut test results confirm Base's statement for the range of friction coefficient of deformed steel bars[15]. Moreover, strut test results show the influence on the friction coefficient due to surface treatment (epoxy coating), bar material (steel and GFRP), and surface type (ribbed, string wrapped with or without sand coating).

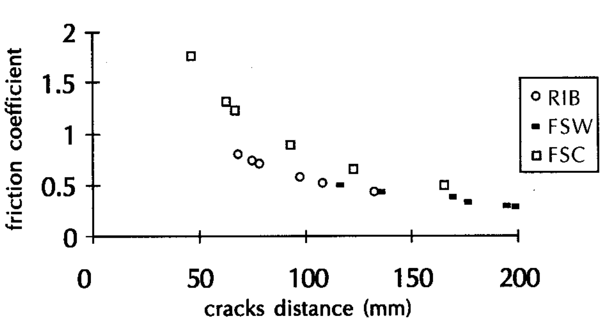

Figure 3 - Strut test results

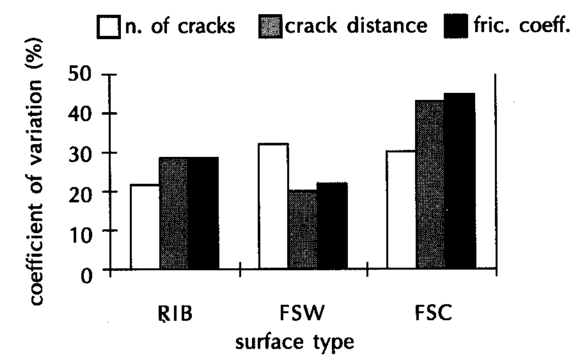

Figure 4 - Within-test variation of strut test results

The within-test variation can be measured by the coefficient of variation (CV) of the test result, which is the friction coefficient (a function of number of cracks and crack distance, Eq. 8). The coefficients of variation for number of cracks and crack distance of the present experimental programme were also studied and are shown in Figure 4. The results show that for FSC bars have a higher CV than the RIB and FSW bars. The high CV values for the FSC bars could be due to non uniform distribuition of sand grains along the bar.

There is no significant difference (at á = 0,05) between the frequency of the number of cracks for RIB and FSC bars, as shown in Fig. 5. However, Fig. 6 shows that the variation of crack distance is less for RIB bar.

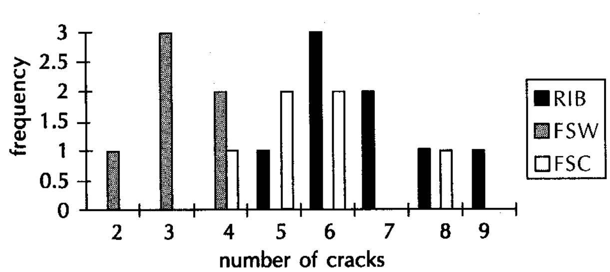

Figure 5 - Frequency analysis of number of cracks

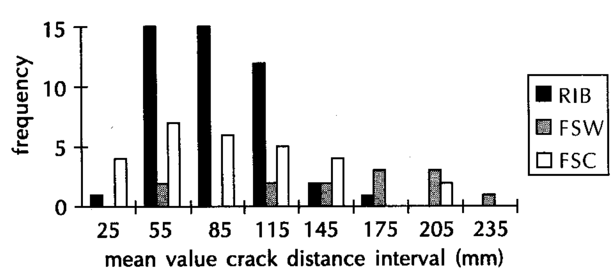

Figure 6 - Frequency analysis of crack distance

3 CONCLUSIONS

The current research investigated the load transfer from GFRP bars to concrete in terms of an average bond stress at the bar surface. The experimental programme was carried out on strut elements reinforced with a single GFRP bar. Preliminary comparisons of experimental data from bars with three different surfaces were made successfully, and details related to bar characteristics and test results were reported. GFRP bar tensile test results, as well as strut test results, are significantly influenced by the grip characteristics. The test results showed that the bar surface transfers the load to concrete and that the frictional interlock is overcome during the test. The distance between cracks along the test specimens seems to bear a correlation to the reinforcement surface.

Load transfer from GFRP bars to concrete is significantly increased when the bars have a sand coated surface, but the variablity of the numbers of cracks and crack spacing was greater. A fibre string wrapped in a helical pattern, which provides a deformed bar surface, does not provide a significant rib height, and results in the lowest bond strength. The GFRP ribbed bars show uniform test results, which means more reliable bond results for strutural design.

TABLE 1

TEST RESULTS FOR RIBBED SURFACE BARS (RIB-BARS)

Percentage Friction of bar failure load	Number of cracks	Crack distance (mm)	Average distance (mm)	f_c (MPa)	f_t (MPa)	(MPa)	f_{bd} coefficient
80%	6	115/ 65/ 60/ 65/ 85	78.0	30.80	3.55	2.58	0.73
80%	9	50/57/56/ 89/ 97/ 83/ 75/ 43	68.75	30.80	3.55	2.91	0.81
80%	6	105/ 100/ 75/90/115	97.0	30.80	3.55	2.07	0.58
80%	5	155/ 75/ 175/ 125	132.5	30.80	3.55	1.52	0.43
80%	7	50/ 95/ 80/ 110/90/ 45	78.3	30.80	3.55	2.57	0.72
68%	5	80/ 140/ 95/ 85	100.0	30.80	3.55	(**)	
80%	6	105/ 120/ 100/135/80	108.0	30.80	3.55	1.86	0.52
80%	8	45/100/ 80/ 35/ 65/ 45/ 110	68.5	30.80	3.55	2.93	0.82
80%	7	115/ 90/80/40/ 55/ 75	75.8	30.80	3.55	2.65	0.75

Note:(**) 80% of the bar tensile failure load was not attained due to slippage in the grip.

TABLE 2

TEST RESULTS FOR FIBRE STRING WRAPPED BARS (FSW-BARS)

Percentage bar failure load	Number of cracks	Crack distance (mm)	Average distance (mm)	f_c (MPa)	f_t (MPa)	f_{bd} (MPa)	Friction coefficient
80%	4	183/ 61/ 159	134.3	27.56	3.52	1.50	0.43
32.84%	1	-	-	27.56	3.52	(**)	
32.21%	1	-	-	27.56	3.52	(**)	
80%	3	205/ 189	197.0	35.88	3.73	1.08	0.29
80%	3	158/ 185	175.0	35.88	3.73	1.22	0.33
80%	2	193	193.3	35.88	3.73	1.11	0.30
40.60%	3	170/ 170	170	32.27	3.75	(**)	
80%	4	215/60/230	168.3	32.27	3.75	1.48	0.39
80%	3	110/ 120	115.0	32.27	3.75	1.87	0,50

Note: (**) 80% of the bar tensile failure load was not attained due to slippage in the grip.

TABLE 3

TEST RESULTS FOR SAND COATED - FIBRE STRING WRAPPED BARS (FSC-BARS)

Percentage bar failure load	Number of cracks	Crack distance (mm)	Average distance (mm)	f_c (MPa)	f_t (MPa)	f_{bd} (MPa)	Friction coefficient
54.4%	4	174/ 96/ 98	122.6	27.56	3.52	(**)	
72%	6	89/ 71/ 50/ 139/ 103	90.4	27.56	3.52	(**)	
80%	4	151/ 139/ 206	165.3	27.56	3.52	1.76	0.50
80%	6	132/199/ 68/105/ 108	122.4	35.88	3.73	2.52	0.66
80%	5	49/ 79/ 47/ 11	46.5	35.88	3.73	6.62	1.77
70.4	7	71/36/ 26/ 99/47/ 110	64.8	35.88	3.73	(**)	
80%	6	100/ 100/ 70/65/ 130	93.0	32.27	3.75	3.33	0.89
80%	5	30/ 40/ 95/ 85	62.5	32.27	3.75	4.95	1.32
80%	8	45/20/ 95/ 120/30/ 95/ 65	67.1	32.27	3.75	4.62	1.23

Note: (**) 80% of the bar tensile failure load was not attained due to slippage in the grip.

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