

Bond Performance of Sand-Coated BFRP Bars to Concrete



V. Pavalan, R. Sivagamasundari

Abstract: This paper presents an experimental study on the bond behaviour of sand-coated basalt fibre reinforced polymer (BFRP) bars and conventional steel bars of 10mm- diameter. The bond strength of these bars were determined according to ASTM D7913/D7913M-14 standards. The pullout specimens consisted of BFRP bars embedded in concrete cubes (200mm on each side) with the compressive strength of 40MPa were constructed. The pullout test results contain the bond failure mode, the average bond strength, the slip at the free and loaded end, and the bond stress-slip relationship curves. The test results showed that the bond strength of sand-coated BFRP bars was about 70% that of the steel bars.

Keywords: ASTM standards, BFRP bars, steel bars, BPE model, pullout test

I. INTRODUCTION

Steel bars have been conventionally used as internal reinforcements for concrete structures all over the world. But, the researchers are not recommending the use of steel bars in marine and coastal areas. Many of structures like dry-docks, tanks, box-culverts, floating piers reinforced with conventional steel bars can be corroded easily due to de-icing salts. In several countries, the highway bridges are not safe due to deterioration caused by corrosion of steel reinforcements. To overcome these corrosion problems, researchers spotted a new non-metallic fibre reinforced polymer (FRP) material and it has been introduced as internal and external reinforcements for concrete structures. The use of fibre reinforced polymer reinforcements in concrete structures have been increased in the construction sector due to their excellent corrosion resistance, high tensile strength and lightweight characteristics (Benmokrane *et al.* 2000, Refai 2014, Wang 2015, Xue *et al.* 2014, Yong *et al.* 2017). However, the modulus of elasticity of FRP bars is relatively low compared to conventional steel bars. In recent years, carbon and glass fibre reinforced polymer materials have been widely used especially in marine fields. Basalt fibre reinforced polymer is a new type of FRP material in which mechanical properties are not yet fully described (Li *et al.* 2017, Meng *et al.* 2015). The toughening mechanism between newly introduced FRP bars and concrete is the most critical aspect which affects the structural behaviour of the concrete structures. So, it is necessary to investigate the bond behaviour of basalt fibre reinforced polymer bars. Numerous experimental investigations on bond behaviour of

sand-coated FRP bars were reported. Adhikari (2009) investigated the mechanical properties of the BFRP bars. The reinforcement bars were 3.0, 5.0 and 7.0 mm diameter with the volume fraction of 44%, 52% and 41%, respectively. Four pullout cylinder tests were conducted for each size of BFRP bars to evaluate the bond-strength. It was concluded that the embedment length of 10 inches was sufficient for the 3 mm basalt bar to develop full tensile strength. Compared with the results for the 5.0 and 7.0 mm basalt bars, it can be observed that the embedment length can be reduced to 7 or 8 inches in the case of 3 mm basalt-FRP bars. In the case of 5 and 7 mm bars, it was evident that the provided embedment of 10 inches was insufficient to develop their full tensile strength and the authors proposed an equation to predict the embedment length of these bars. Baena *et al.* (2009) investigated 88 concrete pull-out test specimens according to ACI 440.3R (2004) and CSA (2002) standards. The influence of the reinforcement bar surface, reinforcement bar diameter and concrete strength on the bond-slip curves were studied for GFRP, CFRP and steel reinforcement. They stated that the strength of the concrete affects the mode of bond failure of the reinforcement bar during the pull-out test. However, for concrete with compressive strength approximately greater than 4.35 ksi (30 MPa) the bond strength of FRP reinforcement bars does not depend greatly on the value of concrete strength, but rather on the reinforcement bar's properties since the bond failure occurs at the surface of the FRP reinforcement bars. Ovitigala (2012) investigated the bond strength of BFRP bars based on the flexure-bond test method. The test was carried out on twenty hinged concrete beams using five different BFRP bar diameters (6, 10, 13, 16 and 25 mm) with different bonded lengths ($5d_b$, $10d_b$, and $15d_b$). It is worth mentioning that many researchers stated that this test procedure simulate the real flexural behavior, since the reinforcement bar is forced to pull out by applying the forces as same as flexural beams. The author concluded that the bond characteristics of BFRP bars are better than the GFRP bars and almost the same as steel reinforcement. Twenty times the bar diameter ($20d_b$) can be considered as the development length for BFRP reinforced flexure specimens, since all the BFRP bars failed by rupture without slippage. As well as the average bond stress increased when the bonded length decreased for the same diameter of BFRP bar specimens, and increased when the diameter of the BFRP bar decreased for the same development length. Refai *et al.* (2014) investigated the effect of five different accelerated environments namely tap water, seawater, elevated temperature on the bond stress-slip response, adhesion to concrete, and bond strength of two types of BFRP bars (sand-coated and helically grooved) and one type of GFRP bar.

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They concluded that all specimens failed in pullout mode by the interlaminar shear between the bar layers for basalt specimens and by shearing of the surface ribs in the glass specimens. Furthermore, the sand-coated BFRP bars showed higher bond strength, higher adhesion to concrete, and less slip at peak stress than the helically grooved BFRP bars. The knowledge gathered from the literature study, it is understood that the bond between reinforcing bars and concrete plays a vital role in transferring the stresses from the rebars to the concrete. Therefore, in this paper by carrying out the pullout test, the bond mechanism of sand-coated basalt fibre reinforced polymer bars and conventional steel bars with the concrete are examined.

II. EXPERIMENTAL PROGRAM

A. BFRP bar Properties

The sand coated BFRP bars of 10mm- diameter supplied by Arrow Technical Textiles Private Limited were used in current study. All the BFRP bars supplied by these industries were manufactured by pultrusion process. Fig. 1 shows photograph and size of BFRP bar. The tensile strength and elastic modulus of BFRP bars were calculated and tested according to ASTM D7205/D7205M-06. The tensile properties of BFRP bars were listed in Table 1.

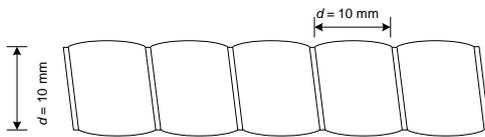


Fig.1 The photograph and size of BFRP bar

B. Concrete mix

The detailed mix ratio of cement-water-fine aggregate-coarse aggregate-superplasticizer was 1:0.38:1.56:2.72:0.005. The maximum size of coarse aggregate was 20mm and the fine aggregate was river sand with particle size of 0-5mm. The specific gravity of fine aggregate and coarse aggregate was 2.63 and 2.72. This concrete mix ratio was used to cast the concrete specimens. The concrete specimens were demoulded after 24 hours and then cured in a water storage tank for 28 days. The average tested compressive strength of concrete at 28 days was 48.5MPa.

C. Specimen Preparation

The pullout specimens consisted of concrete cubes, 200mm on each edge, with a single 1200mm long BFRP bar embedded vertically along the central axis in each specimen. Fig. 2 to 5 show the preparation of specimens. The embedded length of the BFRP bar was five times the diameter of the BFRP bar. The embedded bar was inserted within polyvinyl chloride (PVC) pipe to prevent bonding at top of each specimen, and additionally the PVC pipe was used to avoid splitting of concrete during the pull-out test. Steel tubes were used as anchors at the loaded end of the BFRP bars and were cast with epoxy resin and hardener. The pullout specimens

were casted in accordance with C192/C192M. Then, the moulds were removed from the specimens after 20 hours of casting. Immediately after removing the moulds, the specimens cured until the time of testing. The pullout specimens were tested at an age of 28 days.

Table 1 Tensile Properties of BFRP and Steel bars

Bar	Bar Diameter (mm)	Cross sectional area(mm ²)	Surface characteristics	Tensile strength (MPa)	Elastic modulus (GPa)
BFRP	10	78.5	Sand-coated	1479.7	50.3
STEEL	10	78.5	Deformed	593.3	200



Fig.2 Wooden mould



Fig.3 PVC Tube



Fig.4 Anchor as per ASTM D7205



Fig.5 (a) BFRP bars (Ready for casting)



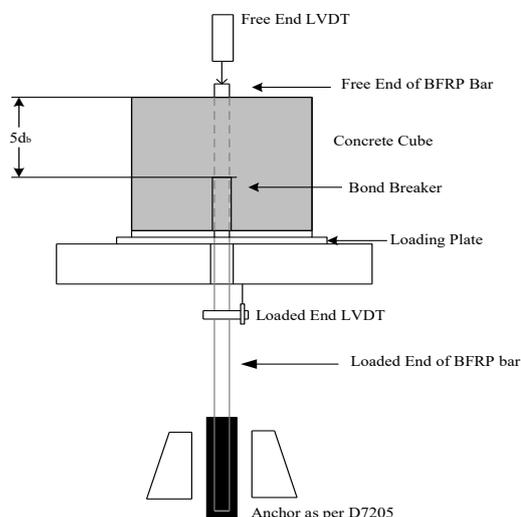
(b) Casting of concrete cubes



(c) Pullout test specimens



Fig. 6 (a) Pullout test setup



(b) Apparatus of Pullout test

D. Test Setup

The bond strength of the BFRP bar was evaluated by testing of five specimens in accordance with ASTM D7913/D7913M-14. This test was conducted at Strength of materials laboratory, Department of Civil & Structural engineering, Annamalai University, Chidambaram. The pullout specimens were placed in a universal testing machine. The steel tube anchorages were used to protect from crushing of the BFRP bar. This steel tube was tightened by conventional wedge frictional grips at machine's lower jaw. The pullout performed by pulling the steel tube at one end. Fig.6 shows the test setup for pullout test. Fig.7 shows one linear variable differential transformer (LVDT) was fitted to the top of extended free end of the BFRP bar at outside of the concrete cube and then load was applied at a constant loading rate of 20kN/min until failure. The pullout load and displacement (slip) values were recorded during the test by a computer-controlled data acquisition system.



Fig.7. LVDT at Free end of BFRP bar

III. TEST RESULTS AND DISCUSSION

The average bond stress was calculated as the maximum force observed during the test divided by the surface area of the bar bonded to the concrete cubes.

$$\tau = \frac{F}{C_b l} \quad (1)$$

Where τ is the average bond stress (MPa), F is the tensile force (N), C_b is the equivalent circumference of FRP bar, calculated as $3.1416 d_b$ and l is the bonded length (mm). The slip of the BFRP bars in concrete can be achieved by,

$$s = s_L - s_F \quad (2)$$

Where s is the slip of the BFRP bars (mm); s_L is the loaded end slip of the BFRP bar (mm); s_F is the free end slip of the BFRP bars (mm).

A. Failure Modes

The observed failure modes for all tested specimens are listed in Table 2. All BFRP specimens failed in typical pullout mode as shown in Fig. 8 (a). No visual cracks were noticed on the BFRP-reinforced concrete cubes. The pullout specimens were split after testing to visually assess the conditions of the bar and concrete surface along the embedded length. Fig. 8 (b) shows the conditions of the bar and concrete for specimen B10-L60-3, respectively. It can be observed that the bar and concrete surface was not damaged at loaded end. Close to the free end, the surface layer of the bar was partly peeled off.



(a)



(b)

Fig.8. (a) Pullout failure (b) Pullout failure pattern of BFRP bar in concrete

B. Bond Stress-Slip responses

Fig.9 shows the bond stress-slip response of BFRP bars in normal strength concrete. In this test, the bond stress and corresponding slip noted at both the loaded and unloaded ends of the BFRP bar. The bar slip was not obtained in all the specimens at free ends (unloaded ends) until the specimen reached to ultimate load whereas the loaded end slip was obtained in all the specimens at all stages of loading. The maximum bond stress and corresponding slip was noted in all the specimens at free ends, these slips are very smaller

(0.09mm). At loaded ends, the slips of 3.65mm were reached at maximum bond stress. The bar slip of free ends were notably smaller than the loaded ends at all stages of loading. However, the high initial stiffness was observed between BFRP bar and concrete at loaded

Table 2 Test results of BFRP and Steel bars

Specimen	Compressive Strength (MPa)	Splitting Strength (MPa)	Pullout Load (kN)	Bond Strength (MPa)	Failure Mode
B10-L60-1	48.5	4.12	33.06	17.53	P
B10-L60-2	48.5	4.12	35.62	18.89	P
B10-L60-3	48.5	4.12	31.68	16.81	P
B10-L60-4	48.5	4.12	29.31	15.54	P
B10-L60-5	48.5	4.12	33.70	17.87	P
S10-L60-1	48.5	4.12	45.46	24.12	P
S10-L60-2	48.5	4.12	48.28	25.61	P
S10-L60-3	48.5	4.12	46.73	24.79	P
S10-L60-4	48.5	4.12	45.52	24.15	P
S10-L60-5	48.5	4.12	47.31	25.10	P

Note: P = Pullout failure

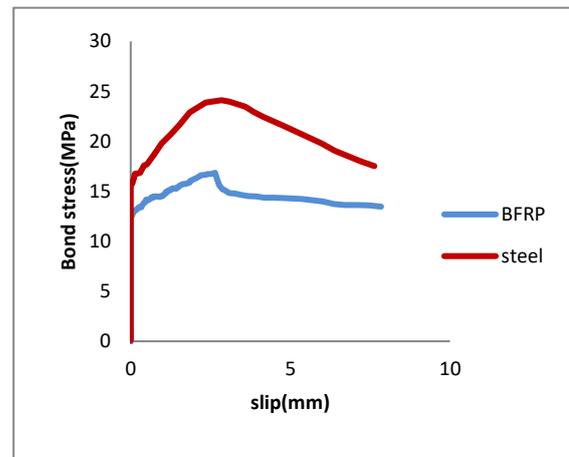
According to the Specifications of the ASTM D7913/D7913M-14, for each series of tests were calculated the average, Standard deviation and coefficient of variation using the following expressions 3 to 5. The coefficient of variation values of BFRP bars of 10mm -diameter were relatively small, less than 2% for these cases.

$$\bar{x} = (\sum_{i=1}^n x_i) / n \quad (3)$$

$$S_{n-1} = \sqrt{(\sum_{i=1}^n x_i^2 - n \bar{x}^2) / (n - 1)} \quad (4)$$

$$CV = 1 - (S_{n-1} / \bar{x}) \quad (5)$$

Where \bar{x} = mean; S_{n-1} = standard deviation; CV = coefficient of variation; n = number of tested specimens; x_i = measured or derived property.



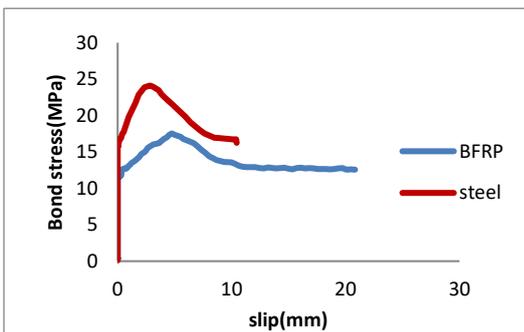
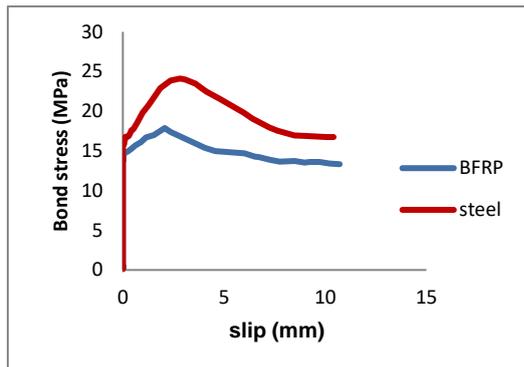
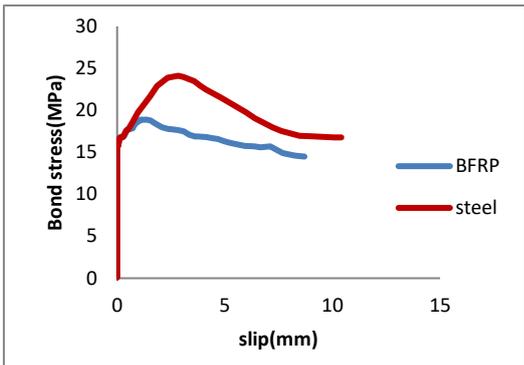
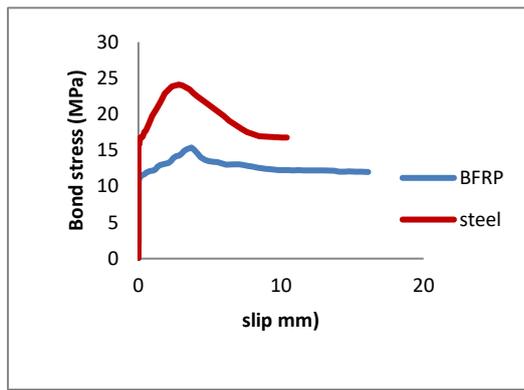


Fig.9. Comparison of bond stress-slip responses of BFRP and steel bars specimens

IV. THEORETICAL ANALYSIS FOR BOND-SLIP RELATIONSHIP

An analytical model of bond-slip law is needed, to describe the bond stress between BFRP bars and concrete, In spite of the numerous formulations proposed in the last two decades. In this research, the well-known Bertero, Eligehausen and

Popov (BPE) model was used to develop bond-slip relationship of steel bars in concrete. This constitutive relationship was very well suited for describing the current test results. In the present study the values of α and p were determined based on the best fitting of the experimental results but considering the measured values of τ_1 & s_1 . The ascending branch of the bond slip ($s \leq s_1$) relationship can be expressed as follows:

$$\frac{\tau}{\tau_1} = \left(\frac{s}{s_1}\right)^\alpha \tag{6}$$

Where τ and s are the bond stress at any stage of loading and its corresponding slip, respectively; τ_1 and s_1 represent the maximum bond stress and corresponding slip, respectively; α is parameter which describes the ascending branch of the curve, that must not be larger than 1. Bereto et.al reported that $\alpha = 0.4$ for deformed steel bars.

The BPE modified model was used to develop the bond-slip relationship of BFRP bars in concrete. The ascending branch of steel and BFRP bars are same. But, the second branch was neglected at BPE modified model. The descending branch of the bond-slip ($s_1 \leq s \leq s_2$) relationship and it is known as the softening branch and given by:

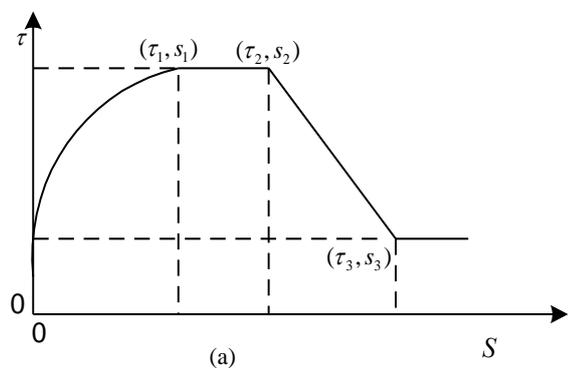
$$\frac{\tau}{\tau_1} = 1 - p \left(\frac{s}{s_1} - 1\right) \tag{7}$$

Where p is parameter based on curve fitting of the current experimental results; s_2 is the ultimate slip (mm). Fig.11. showed that the BPE modified model is more relevant to define the bond-slip response of BFRP bars in concrete.

The developed parameters have been compared with the corresponding values given by Yonmin Yang et al., (Ref),

Table 4 Comparison of developed Model parameters

Model parameters	Current study	Ref
	BFRP	BFRP
α	0.94	1.12
p	0.046	0.042



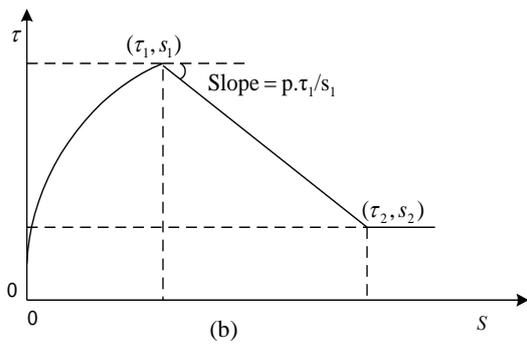


Fig. 10 (a) BPE model for steel bars (b) BPE modified model for FRP bars

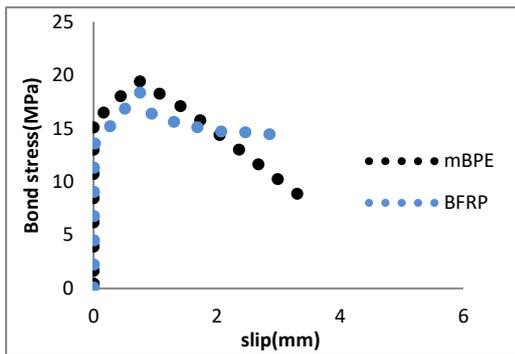


Fig.11. Experimental and Analytical Bond-slip relationships of BFRP bars

V. CONCLUSION

In this research, the bond behaviour between sand-coated BFRP bars and concrete was examined. Based on the experimental data and theoretical analysis of this study the following conclusion can be made:

1. It is confirmed that the bond stress-slip response has been mainly controlled by the surface treatment of the BFRP bars.
2. The average bond strength of sand-coated BFRP bars has been achieved 70% that of the conventional steel bars.
3. The sand-coated BFRP bars exhibited better adhesion to concrete at initial stages of loading than conventional steel bars.
4. The bond slip curve of sand-coated BFRP bars consists of initial hardening, nonlinear behaviour before peak stresses and softening when pullout failure takes place which is similar to that of conventional steel bars.
5. Since no universal models are applicable to describe the bond slip behaviour, BPE model is used in the present study to form simple and reliable results. The fitting parameters α and p have been evaluated as 0.94 and 0.046 respectively which are close to the corresponding values obtained by the previous researchers

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