



Fundamental mechanisms of bonding of glass fiber reinforced polymer reinforcement to concrete

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ABSTRACT

Fundamental mechanisms of bonding between glass fiber reinforced polymer (GFRP) bar and concrete are presented. Contributions from chemical bonding, bearing resistance, and frictional resistance to bond were delineated by measuring the following: the load corresponding to complete debonding of the bar, the load corresponding to onset of sliding and pullout of the bar along the entire embedment length, and the frictional load corresponding to frictional resistance to sliding. Research findings indicate that while chemical bonding was the main contributor to the interfacial bond strength, the other two mechanisms contributed to the pullout strength of the bar. Correlation between the bar's surface geometry and the contributions from the three mechanisms are discussed.

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1. Introduction

Recently, polymer composite materials are used in civil engineering applications in various forms including rebars for concrete structures, sheets for flexural and shear strengthening, and sheets to wrap concrete columns and bridge piers to increase the confinement. Fiber Reinforced Polymer (FRP) bar is an excellent alternative to steel bars due to their relatively higher corrosion resistance and high specific strength and modulus. Several successful applications can be found in North America. While design codes are well established for the use of steel bars in concrete members, they are slowly evolving for FRP bars. Development of these codes requires a good understanding of bond between FRP bars and concrete and the relationship between the bond strength, and various material and test parameters. Past research has substantially advanced the knowledge in this area. Nevertheless, a substantial variation is observed among the published data on interfacial bond strength, which suggests that a comprehensive understanding is yet to evolve.

Several variations of bar pullout and beam test have been used to study the bond characteristics of FRP bars. Various parameters, whose effect on interfacial bond strength have been studied in the past, are bar embedment length, bar diameter, compressive

strength of the concrete, confinement pressure exerted by the concrete on the bar, and surface geometry of the bar.

Al-Zahrani [1] and Benmokrane et al. [2] have observed a decrease in interfacial bond strength with increase in embedment length, as shown in Table 1 for different glass fiber reinforced plastic (GFRP) bars with axi-symmetric lugs [1] and helical lugs [2]. It has been well established that shear stress at the fiber-matrix interface, at any applied load during a single fiber direct pullout test, is not constant. Al-Zahrani et al. [3] and Benmokrane et al. [4] have measured this shear stress distribution experimentally, for concrete reinforced with FRP bar. The interfacial bond strength tabulated in Table 1 has been determined using average shear stress and it varies with embedment length, since the shear stress distribution and the average shear stress would change with embedment length. In addition, reported bond strength values correspond to bar pullout rather than onset or completion of debonding. This is also a reason for the variation observed in Table 1 and will be discussed in subsequent sections.

Test results indicate that increasing bar diameter caused decrease in the bond strength as given in Table 2 for smooth bars [1] and bars with lugs [5]. While variation of shear stress distribution could be one reason, Tighiouart et al. [5] have indicated that bleeding of water could be another reason since an increase in bar diameter could increase the amount of water trapped near the bar leading to higher amount of voids and lesser contact area.

Al-Zahrani et al. [3] have varied the compressive strength of the concrete, reinforced with bars wrapped with lugs, from 31.4 MPa

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Table 1

Published results on effect of embedment length on bond strength.

Reinforcement	Bar diameter (mm)	Embedment length (mm)	Average bond strength (MPa)	Reference
C-BAR™ (P1)	12.7	63.5	18.4	Benmokrane et al. [2]
	12.7	127.0	14.5	
H.B. Rebar	12.5	63.5	15.1	
	12.5	127.0	12.7	
Machined GFRP	12.7	63.5	39.7	Al-Zahrani [1]
	12.7	127.0	29.7	

Table 2

Published results on effect of bar diameter on bond strength.

Reinforcement	Nominal bar diameter (mm)	Embedment length (mm)	Average bond strength (MPa)	Reference
Type A	12.7	127	10.6	Al-Zahrani et al. [3]
	15.9	127	7.3	
	19.1	127	6.6	
	25.4	127	6.4	
Type B	12.7	127	12.3	
	15.9	127	10.8	
	19.1	127	–	
	25.4	127	7.4	
Smooth GFRP	6.35	63.5	1.37	Al-Zahrani [1]
	12.7	63.5	0.97	

to 66.1 MPa and have observed no change in the interfacial bond strength. This is to be expected since the failure was interfacial. Another work of Al-Zahrani [1] has shown that the induced lateral force could be influenced by the mismatch in Coefficient of Thermal Expansion (CTE) between the concrete and the bar as observed in Table 3 for concrete reinforced with a smooth bar. A test temperature lower than the cure temperature resulted in negligible bond strength probably due to lack of lateral pressure caused by the contraction of the bar. However, a test temperature higher than the cure temperature resulted in a bond strength higher than the reference case, for which the test and cure temperatures were same. This is probably due to increase in lateral pressure due to expansion of the bar. These results are similar to the results of Leung and Geng [6], who have shown that the interfacial bond for concrete reinforced with steel bars increases with lateral pressure.

Researchers have also varied the surface geometry of the FRP bars to enhance the resistance to sliding and pullout strength as tabulated in Table 4. Al-Zahrani [1] has observed decrease of the bond strength by increasing the lug width from 3.8 mm to 8.9 mm. The latter also changed the failure mode from interfacial failure to crushing failure of the concrete between the lugs.

Table 3

Published results on effect of lateral pressure on bond strength [1].

Curing temperature, T_c (°C)	Testing temperature, T_t (°C)	Interfacial bond strength (MPa)
60	20	<0.04
20	–20	<0.04
20	60	1.79
20	20	0.831

Table 4

Published results on effect of lugs on bond strength.

Reference	Reinforcement	Description	Lug width (mm)	Lug depth (mm)	Bond strength (MPa)
Al-Zahrani [1]	Smooth GFRP	Smooth	–	–	0.97
	Machined GFRP	Lug	3.8	1.3	39.7
Benmokrane et al. [4]	Machined GFRP	Lug	8.9	1.3	23.2
	C-BAR (P1)	Lug	2.8	1.3	18.4

Note: Embedment length = 63.5 mm; bar diameter = 12.7 mm.

Test results of Benmokrane et al. [2] and Al-Zahrani [1] are compared in Table 5 to illustrate the influence of loading rate and inconsistency in the definition of contact surface area used in the calculation of interfacial bond strength. Since the dimensions and the properties of the reinforcing bar and the concrete were same, the difference in the maximum pullout load is believed to be due to the difference in the loading rates used by the two groups of researchers. In addition, the interfacial bond strength reported by Al-Zahrani [1] is higher than that reported by Benmokrane et al. [2] despite the lower value for the measured pullout load and same bar dimensions. This apparent discrepancy is believed to be due to the difference in the definition and calculation of the contact surface area. While Benmokrane et al. [2] have calculated the contact surface area using the average diameter of the reinforcing bar, Al-Zahrani [1] has calculated the contact area using the actual diameter of the reinforcing bar and the dimensions of the lugs.

The above discussion suggests that the interfacial bond strength could be very much dependent on test parameters and surface geometry of the bar, whereas the interfacial bond strength should be a unique value independent of test parameters and surface geometry of the bar.

2. Fundamental behavior during pullout tests

A brief discussion on the pullout behavior of a FRP bar from concrete is included here to assist in the comprehension of the scatter in published interfacial bond strength and to provide the basis for the research approach used in this study.

This development length for civil engineers (l_c), which is also known as critical length among composite community, can be predicted using Eq. (1) based on assumption of constant shear stress distribution along the embedded fiber length.

$$l_c = \sigma_f d / 4\tau_u \quad (1)$$

where σ_f is the fiber strength, d is the fiber diameter and τ_u is the fiber–matrix interfacial bond strength.

Load applied to the concrete–FRP bar interface, during direct pullout test of a concrete specimen reinforced with a FRP bar of embedment length ($l \leq l_c$), is shown schematically in Fig. 1 as a function of slip between the bar and the concrete. Fig. 1a represents the possible load–slip curves for a concrete specimen reinforced with a smooth FRP bar. Curve A represents the case when debonding of the smooth FRP bar occurs at a maximum load (F'_d). The applied load may drop either to zero or to a finite frictional force value, F'_f . Pullout behavior of the FRP bar may also follow curves B or C since the interfacial stress varies along the embedment length. Curve C represents possible case for a stable debonding of the bar, which starts at F'_f and progresses to completion along the entire embedment length at F'_j . Curve B represents possible partial debonding. In this case, the remaining bonded portion of

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