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A model for the bond-slip of a GFRP bar in concrete

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ABSTRACT

Glass fiber reinforced polymer (GFRP) bars are emerging as desirable alternatives for traditional steel reinforcements in concrete industry. A proper bond between concrete and reinforcement is critical for the performance of reinforced concrete structures. Due to the complexity of modeling the bond action, a perfect bond has been usually considered with the slippage between concrete and reinforcement neglected. The purpose of the present study is to develop a parametric bond-slip model based on pull-out tests performed on sand coated GFRP bars. It included exponential rising, linear descending and residual constant bond stress stages. A sensitivity analysis was performed to determine the bond parameters. Different points along the embedded length of the bar were monitored to illustrate the difference between the average and nodal bond-slip relationships. The proposed bond model was used in a finite element analysis that modeled the cracking in concrete and explicitly simulated the bond action. The model was capable of presenting both concrete splitting and pull-through modes of failure. Simulations were performed on samples with different concrete covers to demonstrate both failure modes.

1. Introduction

Fiber reinforced polymer (FRP) composite bars are getting more attention as an alternative for traditional steel reinforcement in concrete structures. There is an increasing use of glass FRP (GFRP) bars as shear and flexural reinforcement in reinforced concrete (RC) elements especially in applications where corrosion resistance and electromagnetic transparency are required [1]. Various aspects of GFRP structural behavior are still under investigation to provide an understanding of GFRP bars in different loading conditions. Bond development is crucial in GFRP structural behavior since proper bond between concrete and reinforcement is essential to ensure the proper functioning of RC structures [2]. In the process of bond activation, first, the initial contact between the concrete and reinforcement is maintained with the interlock between the reinforcement and the cementitious matrix. After the stress reaches a certain level, the initial bond breaks, and the bond maintains due to the bearing of reinforcement surface against concrete which causes the formation of cone-shaped cracks starting at the reinforcement surface. If the generated cracks propagate through the entire concrete cover, concrete splitting failure which is accompanied by the sudden drop of the bond stress. When the concrete confinement is sufficient enough to prevent the concrete splitting failure, the pull-through of the bar occurs and the load transferring mechanism changes to friction [3,4]. Due to the complexity of modeling the bond, most of the researchers have considered a perfect bond between concrete and reinforcement while ignoring any slippage [5–7]. The main purpose of the present study is to propose a model for developing the bond-slip relation for a GFRP bar in concrete by explicitly accounting for the crack propagation in the surrounding concrete cover. This methodology can be employed to propose proper concrete covers for GFRP bars implemented in different RC structures and to lead to more precise prediction of structural behavior.

A commercially available GFRP bar with a fine sand coated and helically wrapped fiber surface and a nominal diameter of 12.7 mm was investigated in this study. First, the pull-out test was performed on GFRP bars embedded in concrete cylinders. The average bond-slip relationship was extracted using the experimental data. Next, the experimental results were employed to propose a nodal parametric bond-slip formulation which is valid at any point along the embedded length, to be implemented in finite element simulation of the bond behavior of GFRP in concrete. The finite element model was developed in Abaqus which implemented the crack modeling and material properties. Sensitivity analysis was performed to obtain parameters of the proposed bond-slip model from the experimental results. Different points along the embedment length of the GFRP bar were monitored by extracting the force-displacement data in order to investigate the bond behavior along

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the embedment length and to highlight the difference between the nodal bond-slip relationship and the average bond-slip obtained experimentally. Finally, simulations were performed on samples with a different concrete cover and the failure mode was predicted by monitoring the propagation of the cracks in the concrete cover. While one bar type and a specific diameter were selected for this study, the proposed methodology and numerical modeling approach may be extended to any arbitrary GFRP bar.

2. Experimental bond test

The bond-slip behavior of a commercially available GFRP bar with the nominal diameter of 12.7 mm (equivalent to No. 4 steel rebar) was investigated. The bar was characterized by a fine sand coated surface accompanied with helical fiber wrapping to enhance the bond to concrete. Table 1 presents the mechanical properties, nominal and measured area of the bar. The measured area was computed based on a modified method according to standard test methods for density and specific gravity (relative density) of plastics, ASTM D792 [8,9].

The pull-out test was performed to obtain the bond-slip relationship for the free and loaded ends of the bar. Five samples with 203.2 mm bonded length were embedded in 152.4 mm diameter concrete cylinders. The total length of each bar was 1524 mm. A length of 101.6 mm of the bar from the side close to the loaded end was debonded using PVC tape to avoid stress concentrations and to reduce the adverse effects in the area close to the bearing plate. Fig. 1 shows the characteristic dimensions of the bar and confining concrete.

A steel tube filled with expansive grout was mounted at the loaded end of the bar for gripping purposes. Fig. 2 illustrates the prepared samples and the complete setup of the pull-out test.

The tests were performed in displacement control mode with the rate of 0.5 mm/min using a Baldwin universal testing frame with a load capacity of 890 kN. Three linear variable displacement transducers (LVDT) were used to record the slip at the loaded and free ends of the bar.

All the samples exhibited the pull-through mode of bond failure. The concrete cylinder provided adequate confinement that avoided the cracks to propagate through the entire concrete cover. In addition, sand coated and helically fiber wrapped surface of the bar did not transfer a high level of mechanical interlock that could lead to concrete splitting. The average bond stress (τ_{ave}) was calculated using the pull-out load on the bar (F), embedment length (l) and diameter of the bar d, as follows

$$\tau_{ave} = \frac{F}{\pi d l} \tag{1}$$

A brief report of the results is presented in Table 2. Samples were named in the format of AS-X-Y where X refers to the diameter of the bars being equivalent to No. 4 steel rebars and Y stands for repetition of the samples (01 to 05).

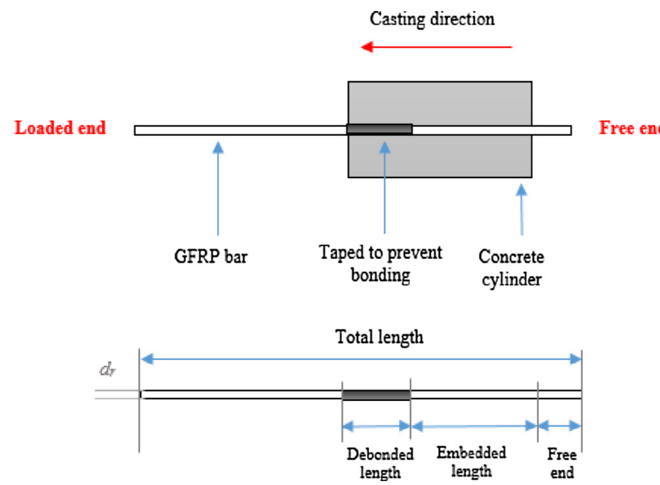

Fig. 1. Schematic of samples, dimensions of GFRP bar and confining concrete.

Fig. 2. A set of prepared samples (left) and complete pull-out test setup (right).

Table 2
Brief summary of the pull-out test results.

Sample ID (AS-04-#)	F_{max} (kN)	τ_{ave}^{max} (MPa)	Bond Failure Mode
01	74.75	9.12	Pull-through
02	62.97	7.71	Pull-through
03	60.96	7.46	Pull-through
04	71.67	8.77	Pull-through
05	78.12	9.56	Pull-through
Ave	69.65	8.53	
SD	6.63	0.81	
COV (%)	9.52	9.52	

Table 1
The characteristic properties of the GFRP bar.

Surface Texture	GFRP	Area (mm^2)		Modulus of Elasticity (GPa)	Ultimate Tensile Strength (MPa)	Ultimate Tensile Strain (%)	Poisson's Ratio
		Nominal	Measured				
Fine sand coated & helically wrapped fiber		126.45	137.8	46.2	757.7	1.64	0.3