Bond-Slip Response of FRP Reinforcing Bars in Fiber Reinforced Concrete under Direct Pullout

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Abstract

A research program was initiated at the University of Missouri aimed at the development of a nonferrous hybrid reinforcement system for concrete bridge decks using continuous FRP rebars and discrete randomly distributed polypropylene fibers with a view to eliminate corrosion while providing requisite strength, stiffness and desired ductility and serviceability. This paper presents the results of a subtask dealing with the bond behavior study of this hybrid reinforcing system under monotonic direct pullout tests.

INTRODUCTION

The last few decades have been marked by degradation of numerous concrete structures due to the corrosion of steel reinforcements that required costly repairs or replacements. To mitigate the corrosion problem, several methods, such as epoxy coated rebars, synthetic membranes, or cathodic protection, have been developed. To date, all of them have showed limited success (Keesler and Powers 1988; Rasheeduzzafar, et al. 1992). In recent years, research has been carried out on fiber reinforced plastic (FRP) bars as an alternative to steel reinforcement. These FRP rebars have already shown a promising future to overcome the corrosion problem in many projects, especially in bridge deck and
parking garage design. However, due to its elastic brittle behavior and lower modulus of elasticity, it also induces unsatisfactory structural ductility and serviceability.

Short polypropylene fibers provide resistance to plastic and drying shrinkage, and improve resistance to crack growth, impact loading, fatigue loading and freeze-thaw durability (ACI 544. 1R-96). It was proven to have notable benefits to structures, especially under service conditions. The combination of FRP reinforcement and short polypropylene fibers may eliminate problems related to corrosion of steel reinforcement while providing requisite strength, stiffness and desired ductility, which are shortcomings of the plain concrete and FRP reinforcement system.

A research project was initiated at the University of Missouri aimed at the development of a nonferrous hybrid reinforcement system for concrete bridge decks using continuous FRP rebars and discrete randomly distributed polypropylene fibers.

The study, sponsored by the Missouri Department of Transportation (MoDOT), is a joint program of the University of Missouri-Columbia (UMC) and the University of Missouri-Rolla (UMR). The specific research objectives of this study includes: (1) development of procedures for FRP/FRC hybrid reinforced bridge deck system, (2) laboratory study of static and fatigue tensile pull-out bond, splitting bond and ductility characteristics, (3) accelerated durability tests on this new hybrid system, and (4) flexural bond study, static and fatigue tests on full-scale hybrid reinforced composite slab. This paper will discuss the pull-out bond slip response of the FRP reinforcing bars embedded in fiber reinforced concrete. A companion paper by UMC team (Gopalaratnam, 2004) is included in this conference to discuss the fatigue response of flexural bond in FRP reinforced concrete.

Considerable research efforts have been conducted on the bond behavior of glass fiber reinforced plastic (GFRP) rebar in plain concrete. Different types of FRP rebars have quite different bond characteristics, which are strongly dependent on mechanical and physical properties of external layer of FRP rods (Katz 1999; Ehsani et al., 1997). On the other hand, because no accepted manufacturing standards for FRP are available yet, bond research is far beyond satisfactory. For
deformed GFRP rebar having similar surface to rebar R1, shown in Fig. 1, the bond strength is equivalent to/or larger than those of ordinary deformed steel (Katz 1999, Cosenza et al. 1997). While research also showed that for some smooth surface rebar, the bond strength can be lower than 1 MPa (Nanni et al., 1995), which is a lot less than steel. Comparing to relatively extensive literature on bond between FRP rebars and plain concrete, research on FRP rebars embedded in fiber reinforced concrete is meager.

The specific objective of this paper is to show the bond-slip performance of commercially available FRP rods embedded in concrete reinforced with discrete randomly distributed polypropylene fibers under monotonic direct pullout loading.

EXPERIMENTAL PROGRAM

MATERIALS

1. FRP RODS
To study the bond characteristics of FRP rebars, three types of commonly used FRP rods were adopted in this study. As shown in Fig. 1, R1 and R2 are GFRP rods. Their nominal diameters are 25.4 mm (# 8) and 12.7 mm (# 4) respectively. The surface of GFRP rods are tightly wrapped with helical fiber strand to create indentations along the rebar and sand particles are added into the surface to enhance its bonding strength. For # 4 GFRP, the pitch of fiber strand is about 25.4 mm and 60 degree to longitudinal direction. For # 8 GFRP, they are 22 mm and 75 degree, respectively. R3 is 12.7 mm (# 4) Carbon Reinforced Plastic rod (CFRP), which has very smooth surface. The resin used for GFRP was Vinylester, and for CFRP was epoxy modified Vinylester.

2 POLYPROPYLENE SHORT FIBERS
To fulfill completely steel-free concept, short fiber was also used in this study. The fibers are fibrillated and commercially available with fiber length of 57 mm.

3. CONCRETE
Concrete mix used in this study is based on an available MoDOT mix design. Polypropylene fibers were added in the plant. For practical application, the volume fracture ($V_f$) of 0.5% was used to ensure good workability of concrete. The compression strength of concrete on the day of testing was 37 MPa and 51 MPa for FRC and plain concrete, respectively.
TEST SPECIMEN
Test specimens were designed according to RILEM recommendations. FRP rods were embedded in concrete through a predetermined length $L_d$ on the pulling side of the concrete block, shown in Fig. 2. PVC pipe was used as bond breaker at the first $5d_b$ length to minimize the bottom plate’s restraint effect on the FRP rebar and eliminate any undesirable confinement that may affect the bond characteristics. Nine groups of 3 specimens each were tested. The notation for specimens is as follows: the first character “P” or “F” indicates the plain concrete or FRC, the second character “C” or “G” indicate CFRP or GFRP; the third character (#4 vs. #8) is the bar size; and the forth character “05” or “10” refer to the embedment length in terms of bar diameter $d_b$; Specimen dimension details are shown in Table 1 and Fig. 2.

TEST PROCEDURES
The pullout tests were conducted in a MTS 880 machine. The test is run through close-loop displacement control using an external LVDT 2 (see Fig. 3). The free end of the FRP rebar is embedded in a steel pipe using an expansive grout as interface. The pullout is then performed by pulling the steel pipe at one end with the concrete block being encased in the steel reaction frame, as shown in Fig. 3. Rebar’s relative slips to concrete were computed from measurements of both LVDTs placed at both ends of the rebars as shown in Fig. 3. To minimize the eccentricity effect, lead sheets were placed between the concrete block and the reaction frame.

The pullout tests were monotonic by increasing slip at 0.0127 mm/sec rate. All measurements, including pullout load and displacements (slips) were recorded by a computer-controlled data acquisition system at the rate of 2 data/sec.

TEST RESULTS AND DISCUSSIONS
The average bond strength was calculated as the pullout force divided by contact area. The slip on the side of loading was calculated as the difference between the measured slip minus the elastic deformation of FRP rebar between the bond zone and the location of LVDT2. Pertaining test results are summarized as shown in Table 2 and Fig. 4.

- EFFECT OF SHORT FIBERS
The ultimate bond strength slightly decreased with the addition of short polypropylene fibers. Reduction ranged from 2% to 17% (see Fig. 4).

The slip corresponding to ultimate bond strength increased significantly with the addition of fibers for GFRP specimens, but not for CFRP specimens.

The addition of short fibers changed the failure mode, most specimens that failed in concrete splitting changed to pullout failure.

- **EFFECT OF REBAR SURFACE CONSIDERATION**

  Due to their significant surface difference, bond behavior of GFRP and CFRP were totally different, as shown in Fig. 8. Bond strength of GFRP was about twice as much as that of CFRP.

  1. **CFRP**  The surface of rebar was severely rubbed and resin was scratched off. Resin powders can be seen left in concrete. Basically, bond between concrete and reinforcement can be divided into three principle elements, chemical adhesion, friction resistance and mechanical bearing. The surface of CFRP in this study (Fig. 1) was very smooth, very low mechanical bearing force can be expected. Thus, for CFRP rebar mechanical bearing can be neglected. Since no mechanical bearing can be expected for the smooth CFRP rebar, maximum bond strength was based on chemical adhesion. Based on bond-slip curve, two peak bond values were observed for each specimen, (1) in the first stage, chemical adhesion dominated bond behavior. The first peak happened when maximum local chemical bond stress moved to free end; (2) in the second stage, friction force dominated the bond behavior. The second peak value happened when friction force reached its peak. As slip increased, chemical bond was broken totally along the whole rebar, afterwards, only friction component was alive. It was observed that as the embedment increased, the average bond strength increased.

  2. **GFRP**  The surface of GFRP rebar was damaged, some resin residue was sheared off from the rebar surface and small pieces of resin scale can be seen left in the concrete. For GFRP specimens, friction force and chemical bond contributed much less significant than for CFRP. It was the mechanical bearing that dominated the bond behavior. Like CFRP, at initial loading, maximum local bond stress happened near the loaded end, as load increased, maximum bond stress extended to free end. Prior to the point of maximum stress, most or all of the mechanical bearing were badly damaged (rebar indentations are sheared off).
The farther away from the maximum point, the smaller bond stress can be secured. For shorter embedment length, the proportion being destroyed was smaller than the larger embedment length. As a consequence, average bond stress decreased as embedment length increased.

**DESIGNING BOND STRENGTH**

The application of the ultimate bond strength data to real design is not considered because of the excessive slip occurring in these specimens at large loads. Too much slip will result in untolerated crack width. Although FRP rebars were relatively inert to environment exposure, it may cause some other problems, e.g. aesthetics. For traditional steel reinforced structures, ACI 318-02 requires maximum crack width of 0.4 mm for interior exposure and 0.33 mm for exterior exposure; ACI 440 recommends crack limitation for FRP structures is 0.5 mm and 0.71 mm for interior and exterior exposure, respectively. From a designer’s point of view, Mathey and Watstein suggested that bond stress corresponding to 0.25 mm slippage of loaded end or 0.050 mm of free end for steel reinforced structures can be defined as critical bond stress. Since the relatively low elastic modulus of FRP materials (GFRP is about 1/5 that of steel, CFRP is about 2/3 that of steel), greater elongation along the embedded rebar will be produced and leads to larger loaded end slip. To keep it comparable to limit imposed on steel rebars, bond strength corresponding to free-end’s 0.050 mm slippage is adopted as designing bond strength. For FRP rebars, the basic development length is defined as the minimum embedment length required to develop fracture tensile strength of the FRP rebar and can be written as

\[ l_d = \frac{A_f f_{ju}}{\pi d_b \mu_f} \]  

(1)

The development length of rebar is generally expressed as follows:

\[ l_d = \frac{f_{ju}}{K \sqrt{f_c}} d_b \]  

(2)

Equating (1) to (2) gives an expression to the coefficient \[ K = \frac{4 \mu_f}{\sqrt{f_c}} \]

Where \( A_f \)=area of the FRP bar in mm²; \( f_{ju} \)=ultimate strength of FRP bar in MPa; \( d_b \)=diameter of FRP rebar in mm; \( \mu_f \)=bond strength in MPa;
Performing a statistical analysis with a confidence of 95% and using the bond strengths of test data of this study, the coefficient K has a value of 3.5. ACI 440 suggests a value of 3.1.

**SUMMARY:**

Bond behavior was studied with 27 pullout specimens. Short fibers, bar surface and embedment length’s effect on bond characteristics were investigated. The following conclusions were made:
1. The addition of polypropylene fibers did not increase the ultimate bond strength, while providing much more ductile bond behavior.
2. Totally different bond mechanisms were observed for CFRP and GFRP due to their different surface treatments. Bond strength decreased with increasing of embedment length for GFRP rebars; while opposite results were observed for CFRP.
3. Bond value corresponding to 0.050 mm of free-end slip was recommended as designing bond strength. The proposed equation agrees with the current equation proposed by ACI 440.

**ACKNOWLEDGEMENT**

The authors thankfully acknowledge the financial support from the Missouri Department of Transportation (MoDOT) and UMR University Transportation Center for this joint research program. The authors are also grateful to Doug Gremmel of Hough Brothers and Don Smith of SI Concrete Systems for their participation on the Research Advisory Panel as well as the in-kind material donation from their companies.

**REFERENCE:**


Table 1: Specimen Details

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<th>Specimen ID</th>
<th>Materials</th>
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<th>a (mm)</th>
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Table 2: Summary of Bond Tests Results

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<th>Slip at First Peak (mm)</th>
<th>Bond Strength Second Peak (MPa) (2)</th>
<th>Slip at Second Peak (mm)</th>
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<td>6.67</td>
<td>P</td>
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Note (1): P=Pullout failure; S=Splitting failure.
(2): Two peak values were observed only in CFRP specimens.
Fig 3: Schematic of Test Setup

Fig 4: Bond Slip Response of Various FRP Rebars in FRC and Plain Concrete

(a) #4 CFRP
(b) #4 GFRP
(c) #8 GFRP
(d) GFRP vs. CFRP

Expansive Grout
Steel Tube
Bonded Region
LVDT 1
LVDT 2
FRP Rebar
Lead Sheet
PVC Conduit
Bolt welded to tube
Upper Stationary Head
Reaction Frame
Lower moving head
Bond strength (MPa)
Slip (mm)

Plain-5db
FRC-5db
FRC-10db
Plain-5db
FRC-5db
FRC-10db
Plain-5db
FRC-5db
FRC-10db
0 5 10 15 20
0 5 10 15 20
0 5 10 15 20