BOND BEHAVIOR AND MODELING OF FIBER REINFORCED POLYMER BARS TO CONCRETE UNDER DIRECT PULLOUT

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ABSTRACT

The bond behaviour of reinforcing bars in concrete is a critical issue in the design of reinforced concrete structures with FRP bars. In the last few years a number of tests on several types of FRP bars have been conducted for investigating the bond behaviour. However some aspects need further studies in order to obtain reliable design indications. The study included pullout tests of eighty-four FRP bars with four diameters from 7 to 14mm and with two types including GFRP and CFRP embedded in concrete specimens. The experimental results of failure mode and average bond stress-slip relationship of FRP bars to concrete under direct pullout are analyzed. The results show in the pullout failure the bond strength is mainly depended on the surface deformation and shape of FRP bars. In addition, a new model is proposed for the entire curve of the bond-slip law. It can be seen that the proposed bond-slip gives results in close agreement with the experimental results.

KEYWORDS

FRP bars, concrete, bond strength, mode of failure, bond-slip relationship.

INTRODUCTION

Due to many advantages such as high strength-to-weight ratio, resistance to corrosion, electromagnetic neutrality and relative ease of applications of Fiber-reinforced polymer bars (FRP bars), they have been recently introduced as reinforcement for concrete structures subjected to corrosive condition or where electromagnetic insulation is required in China. However, there exist essential different aspects both in the mechanical and physical properties of the two materials and in structural behavior between FRP bars and steel reinforcement to concrete. One of the fundamental the latter aspects of structural behavior is bond development, because bond is the key for transmit forces from reinforcing bars to concrete. A better understanding of the bond behavior between FRP bars and concrete is needed in order to use them for practical purposes. Although a large number of bond researches (e.g. Benmokrane 1996; Cosenza 1997; Ehsani 1997; Tighiouart and Benmokrane 1998; Achillides 2004) are published, the studies are not enough in China. Xue (1995) firstly studied the bond behavior between FRP bars and concrete and concluded that the failure of specimens resulted from the ribs with externally spiral stranded wound peeling off the bars simultaneously. The bond process of FRP bars was divided into four stages. The bond failure mode for FRP bars made a difference in that of steel. For this reason, the paper presents the results of an experimental study on bond-slip relationship of FRP bars embedded in concrete under direct pullout. The study included pullout tests of eighty-four FRP bars with four nominal diameters from 7 to 14 mm and with two types including GFRP and CFRP embedded in concrete specimens. The modes of failure are analyzed. Furthermore, a state-of-the-art on some analytical models of bond-slip behavior is presented in detail. A new model for the local bond-slip law is proposed based on the experimental tests as well as examined to assess its accuracy.

EXPERIMENTAL PROGRAM

Material Properties

Concrete and Fiber Reinforced Polymer bars

For each batch of pullout tests, three standard control cubes (150mm on each side) were cast and cured under the same curing condition as the specimens. The control cubes were tested for compressive strength before
conducting the direct pullout tests. The concrete mixes had average compressive strength in the range of 28.6-54.2 MPa.

FRP bars used in this study were supplied by Harbin Fiber Reinforced Plastic Institute. There existed two types of FRP bars, one is GFRP bars (glass fiber reinforced polymers), and the other is CFRP bars (carbon fiber reinforced polymers). These bars had nominal diameter of 7, 10, 12, and 14 mm. The surface deformations, characteristics of FRP bars including externally spiral single-stranded wound with fiber and twisted-stranded wound with fiber were shown in Fig. 1. The mechanical and physical properties of FRP bars were from the manufacturers. These were the tensile strength of 1125 MPa (GFRP); and 1920 MPa (CFRP) and modulus of elasticity of 45 GPa (GFRP) and 128 GPa (CFRP).

![Figure 1. FRP bars utilized in the pullout test](image1)

![Figure 2. Pullout test arrangement](image2)

**Specimens**

For the experimental intention of the bond-slip relationship at the loaded and free end of FRP bars subjected to a pullout load, direct pullout tests with centric bar placement in 150×150-mm concrete cube could be used. The embedment lengths were four, five, six, eight, and ten times the bar diameter. Some of the top and bottom part of each bar was isolated form the concrete using a PVC sheath to eliminate the effect of the support reactions at the loaded end of FRP bars. The part of bar at the anchorage lengths was wrapped by the grass fiber thread with the epoxy resin for the rib local falling off the bars under loading. Before casting, the embedment lengths of FRP bars with PVC sheath were exactly located in the middle of the concrete cube. After casting, the molds were removed for 24h. The specimens were cured by sprayed daily with water so as to maintain moisture for two weeks in a moist room. The specimens were tested after 28 days.

**Experimental Procedure**

The concrete cube with the embedded FRP bars was placed in a specially made steel frame that was positioned in the hydraulic testing machine. The pullout test arrangement was shown in Fig. 2. The pullout loads were measured with the electronic load cell of the machine. The slips of the bar relative to concrete at the loaded and free end were measured with LVDTs. The maximum speed rate of loading was 0.1mm/min. Output were recorded every 120ms using an automatic data acquisition system.

**RESULTS AND DISCUSSIONS**

**Average Bond Stress-slip Relationship**

For all tested specimens the bond stress and the corresponding slip both at the loaded end and free end were evaluated. Under an assumed uniform distribution of bond stress within the bond length, the average bond stress is calculated as

$$\tau = \frac{P}{\pi \cdot d \cdot l_e}$$  \hspace{1cm} (1)

where $\tau$ is the average bond stress (MPa); $P$ is the tensile load (N); $d$ is the effective bars diameter (mm); and $l_e$ is the embedment length (mm). The slip at the free end is the difference between the LVDT readings on the bar and on the concrete. Taking into account the adjustment for the elastic elongation of the bar between the actual loaded end of the embedment length and the attachment point of the LVDTs, the slip at the loaded end is calculated.
In Fig. 3 (a) and (b), the bond stress versus the measured slip is reported for the typical specimens of GFRP bars with single-stranded and twisted-stranded spiral, respectively. It can be seen that the bond strength of GFRP bars with twisted-stranded spiral is larger than that of bars with single-stranded spiral. Analyzing the two figures, the presence of different stages can be seen. There exist five stages from the specimens loaded initially to failure. In the first stage, almost up to 10% of the ultimate value, the slip at the loaded end is very small and appears almost at the beginning of loading, whereas the free end does not slip until the chemical adhesion breaks. The chemical adhesion between concrete and FRP bars is a primary component of bond of FRP bars to concrete and it avoids slip at the free end. In the second stage, almost up to the 30% of the ultimate value, the free end begins slipping. It shows the chemical adhesion has broken. The relative slip of FRP bars and concrete gradually increases by the bond stress increasing. At this stage, the friction contributes mainly to the bond strength. The mechanical interlocking contribution is much smaller. In the third stage, up to the maximum bond stress, the bond between FRP bars and concrete is due to the mechanical interlocking, whereas the friction provides minor effects. When the peak stress is reached, the slip increases but the load decreases. The descending branch called the fourth stage is followed. At this stage the mechanical contribution is progressively reduced. Finally, the friction through wedging of the bars deforms on the surrounding concrete becomes the predominant bond mechanism. The residual bond stress which value is a constant sustains till the bar pulled out from the concrete. However, at the residual branch, in some cases, there exists a further increase of the bond stress. The reason for appearing this phenomenon, also observed by other researchers (Achilleles et al. 1997 and Aiello et al. 2007), is the same. On the one hand, the increase of stress involves a deterioration of bar surface and the damage or complete rupture of the wound fibers and the ribs which observed after tests. On the other hand, the position of the bond length occurs some changes in the pullout test. In fact, when the non-embedded part of the bar is pulled into the bond region, it adds resistance to the pullout load; thus this effect should not be attributed to a real bond characteristic of the bar.

Mode of Failure

There exist the two types of failure observed for the pullout tests, including the specimens failed by pullout of the bars and splitting of the enclosing concrete. In most cases the specimens occur the former failure. Due to the concrete cubes provided adequate confinement of the bars, there are no signs of splitting cracks appeared on the surface of the concrete cubes. However, by the comparing with the failure mode of FRP bars to that of steel bars, an important difference is observed. In a general way, the bond strength of steel bars to concrete for the pullout mode of bond failure is mainly decided by the surrounding concrete strength. But that of the FRP bars is not the case. The ultimate bond strength of the specimens principally depends on the geometrical properties of the bars, mostly the surface deformation and shape, which is validated by Gao (2003).

ANALYTICAL MODELS OF BOND-SLIP RELATIONSHIP

At present, the popular models of bond-slip relationship are Malvar Model, BPE model, BPE Modified model, CMR model and Benmokrane model. The expressions of these models could be referred to the work by Cosenza (1997). Malvar model which was the first modeling of bond-slip between FRP bars and concrete was given by Malvar (1994). The expression included two empirical constants $F$ and $G$ determined for each bar type. BPE model was presented by Faoro (1992), Rossetti et al. (1995) and Cosenza et al. (1995). Actually, it more fitted to
the bond-slip between steel bars and concrete. The curve was divided into three branches, that is, the ascending branch, the branch of constant bond stress, and the linearly descending branch. BPE Modified model was modified by Cosenza et al. (1996). According to the experimental results, the bond-slip relationship for FRP bars had shown that the branch of constant bond stress did not exist. So it was not considered in this model. Cosenza et al. (1997) proposed a new model called CMR model for the ascending branch of the $\tau - s$ curve only considering most structural problems are to be dealt with at the serviceability state level. The exponential expression of the ascending branch was used. There existed two parameters $s_0$ and $\beta$ defined based on curve-fitting of the actual data. Benmokrane (1998) calibrated the two parameters based on the experimental results of a total of 64 concrete beams reinforced with two types of FRP bars. The two parameters $s_0$ and $\beta$ for the ascending branch of $\tau - s$ curve were equal to -0.25 and 0.5, respectively.

**Continuous Curve Model**

Analysing the available models for bond-slip constitutive relationship at the present time, Gao (2003) found that the initial slope (for slip $s = 0$) in BPE model and CMR model equalled to infinity. It well allowed the physical phenomenon of adhesion. But the curves of BPE model and BPE modified model at the peak point were not smooth continuous curve, and there was no the softening (descending) branch in the CMR model. Although the curve was smooth in Malvar model, the initial slope did not equal to infinity, but a finite value, equalled to $F \cdot \tau_u / s_u$. Therefore, these models did not satisfy the requirements which the curve had definite physical concept and the characteristic of smooth continuity. Based on these models, Gao (2003) simplified the $\tau - s$ curve for mathematic model as shown in Fig 4.

The key points O, C, E for the model could satisfy the physical concept, as followings:

1. where $s = 0$, $\tau = 0$ and $\frac{d\tau}{ds} = \infty$
2. where $s = s_0$, $\tau = \tau_0$ and $\frac{d\tau}{ds} = 0$
3. where $s = s_u$, $\tau = \tau_u$ and $\frac{d\tau}{ds} = 0$

![Figure 4. Continuous curve model](image)

Therefore, the bond-slip relationship for continuous curve model was defined by:

\[
\tau = \frac{\tau_0}{s_0 - s} \left( \frac{s}{s_0} \right)^s (0 \leq s \leq s_0) \quad (2a)
\]

\[
\tau = \tau_u \left( \frac{s - s_0}{s_u - s_0} \right)^3 + \tau_r \left( \frac{3s_u - 2s - s_0}{s_u - s_0} \right)^3 (s_0 < s \leq s_u) \quad (2b)
\]

In Eq. (2) there are only four parameters: $\tau_0, s_0$ are the peak bond and slip corresponding to the bond stress; $\tau_u, s_u$ are the residual bond stress and corresponding slip.

**A New Proposed Model**

According to the experimental results, the bond-slip relationship at the loaded end can be determined by the three branches, namely, the ascending branch, the descending branch, and the residual bond branch as shown in Fig 5. The model is given by the following expression:

\[
\frac{\tau}{\tau_u} = B_1 \left( \frac{s}{s_u} \right)^2 \quad (0 < s \leq s_u) \quad (3a)
\]

\[
\tau = \frac{P_1}{P_2} s - P_2 \quad (s_u < s \leq s_1) \quad (3b)
\]

\[
\tau = \tau_r \quad (s > s_1) \quad (3c)
\]

where: $B_1, B_2$ are the coefficients which equal to 2 and -1,
respectively; $P_1, P_2$ are the coefficients which provide by two other expressions:

$$P_1 = \frac{s_\tau s_u - s_\tau s_u}{s_\tau s_\tau (s_u - s_u)}; \quad P_2 = \frac{s_\tau s_\tau s_\tau s_\tau}{s_\tau s_\tau (s_u - s_u)}$$

(4)

In Eq. (4) there are four known values: $\tau_\tau, s_\tau$ are the peak bond stress and slip corresponding to the bond stress; $\tau_s, s_s$ are the residual bond stress that is the friction component of bond resistance and corresponding slip. Due to taking into account the average bond stress (the sum of bond stress at loaded end and that at free end divided by two) and the corresponding slip, thus mathematical expression of the ascending branch is quadratic equation which go through the point $(0,0)$ and $(\tau_\tau, \tau_s)$. The softening branch of curve is generally given by linear expression, e.g. BPE model and BPE modified model. But the pullout tests results showed that the descending branch of curve is in close proximity to hyperbolic form. Thus the expression of hyperbola is adopted by the upper relationship as Eq. (3b). Thanks to the curve is go through the point $(\tau_s, \tau_\tau)$ and $(s_s, s_\tau)$, the coefficients $P_1, P_2$ are deduced as Eq. (4). Because the residual bond stress is the friction component of bond resistance, the third branch is simplified by a straight line which value is a constant equal to $\tau_\tau$.

Based on the available experimental results, the main parameters of the new proposed model $(P_1, P_2)$ have been calibrated in Fig 6 and Table 1. They show the comparison over the entire curve at the loaded end of six typical specimens and two specimens in the literature between the experimental results and predictions of proposed bond-slip model. From Fig 6(a), (b) and (c), it can be seen that the proposed bond-slip gives results in close agreement with the experimental results in this paper. And the ascending branch of the new proposed model gives good fit to the data but that of the descending branch in Fig 6 (d) and Table 1. Therefore, the new proposed model should be calibrated by the more experimental data.

![Figure 6. Experimental results versus predictions of proposed bond-slip model](image-url)
Table 1. Experimental Results of Typical Specimens

<table>
<thead>
<tr>
<th>code</th>
<th>$P_1$ (experiment)</th>
<th>$P_2$ (experiment)</th>
<th>$P_1$ (fitting)</th>
<th>$P_2$ (fitting)</th>
<th>$R^2$ (coefficient of determination)</th>
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</thead>
<tbody>
<tr>
<td>20-2-2</td>
<td>0.107</td>
<td>0.025</td>
<td>0.11</td>
<td>0.027</td>
<td>0.990</td>
</tr>
<tr>
<td>20-2-4</td>
<td>0.201</td>
<td>0.082</td>
<td>0.194</td>
<td>0.082</td>
<td>0.949</td>
</tr>
<tr>
<td>30-2-3</td>
<td>0.110</td>
<td>0.030</td>
<td>0.110</td>
<td>0.030</td>
<td>0.961</td>
</tr>
<tr>
<td>30-3-2</td>
<td>0.110</td>
<td>0.030</td>
<td>0.110</td>
<td>0.030</td>
<td>0.998</td>
</tr>
<tr>
<td>30-5-2</td>
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<td>0.027</td>
<td>0.151</td>
<td>0.028</td>
<td>0.995</td>
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<tr>
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<td>0.037</td>
<td>0.179</td>
<td>0.041</td>
<td>0.982</td>
</tr>
<tr>
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<td>0.128</td>
<td>0.049</td>
<td>0.772</td>
</tr>
<tr>
<td>(Zhang B. R.) Test-AH(Cosenza E)</td>
<td>0.203</td>
<td>0.162</td>
<td>0.162</td>
<td>0.108</td>
<td>0.809</td>
</tr>
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</table>

CONCLUSIONS

In this paper the pullout tests were carried out on FRP bars and the bond behaviour including the average bond stress-slip relationship and mode of failure between different types of FRP bars and concrete was analyzed. Furthermore, a state-of-the-art on some analytical models of the average bond-slip behavior was presented in detail. A new model for the bond-slip relationship was proposed based on the experimental results as well as examined to assess its accuracy. The results of this study can be summarized as follows: (1) in most cases, the specimen occurs the pullout failure, and the ultimate strength of the concrete specimen with FRP bars depends on several factors, mainly the surface deformation and shape of FRP bars in the pullout failure. (2) a new model, as expressed in Eq. (3) is proposed for the entire curve of the bond-slip relationship. A good agreement is obtained between the proposed model results and experimental results in this paper. However, the new proposed model, especially the descending branch, needs to be validated by the more experimental data.

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