BOND CHARACTERIZATION OF HYBRID-BONDED FRP-TO-CONCRETE INTERFACES

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Abstract
Pure adhesive bond of FRP to concrete is not only weak but also unpredictable in a long term. This problem can be effectively overcome by a newly developed bond enhancement system – the hybrid bonded FRP system (HB-FRP) – in which small mechanical fasteners are used to augment the bond. In this paper, experimental testing and theoretical modeling are reported for characterization of the interfacial bond of the HB-FRP system. Local bond-slip model involving adhesive and mechanical mechanisms is proposed. Based on the basic bond-slip model, load-slip response, ultimate bond strength, and effective bond length of the HB-FRP bond interface are obtained by analytical or numerical solution. Good agreement between the analytical and experimental results indicates that the proposed bond-slip model can well predict bond behaviors of HB-FRP joints.

Keywords: FRP, bond, mechanical fastening, bond-slip relationship.

1. Introduction

1.1 Externally-bonded FRP System
Externally-bonded FRP (EB-FRP) has been extensively investigated for rehabilitation (retrofitting/strengthening/repair) of concrete structures in the last two decades. This technology allows the tensile strength of FRP to be transmitted to concrete structures through surface adhesion. However, surface adhesion between FRP and concrete is known to be not only weak but also unpredictable in a long term; hence it often offers inadequate bonding at the FRP-to-concrete interface that may induce premature debonding at the bond interface. This debonding problem has significantly obstructed widespread application of EB-FRP.

To resolve this problem, various special bond enhancement methods have been developed and reported in the literature, such as end anchorage [1, 2], fiber anchor [3, 4], U-jacketing [5-12], near-surface mounting (NSM) [13-17], and Mechanically Fastened FRP (MF-FRP) [18-21]. Although the above methods can improve FRP-to-concrete bond condition more or less, the magnitude of increase is usually limited and often insufficient.

1.2 Hybrid-bonded FRP System
Inspired by mounting paper onto a wall using staples and friction-type steel joint connections, a simple mechanical fastener shown in Fig. 1 was developed by the first author at City University of Hong Kong to enhance the bond [22]. This mechanical fastener is composed of a thin capping plate that applies normal pressure to the FRP sheet to restrain the vertical
separation of the FRP from the concrete substrate and two small concrete screws to fasten the plate onto concrete. Details of the fastener can be found in [22-23]. After the FRP is adhesively mounted, the fasteners are used to “staple” the FRP strip onto the concrete substrate as shown in Fig. 1b. This system is called the hybrid-bonded FRP or HB-FRP due to its utilization of both an adhesive bond and mechanical fastening.

![Image](a) Mechanical fastener  
(b) HB-FRP retrofitted beam

Figure 1. HB-FRP system.

Extensive experimental tests and theoretical studies in the past six years [22-25] have shown that HB-FRP can result in a several-fold increase in bond strength, which is usually sufficient to avoid intermediate crack induced debonding (IC-debonding). This work aims for detailed characterization of the HB-FRP interface that will form the basis for development of design theory and guidelines for the system.

2. Experimental Program

2.1 Details of Test Specimens

Single shear test is adopted to study the interfacial behavior of the HB-FRP system. Three groups of specimens were designed. The difference between Group I and the other two is the degree of roughness of concrete surface for adhesive bonding. The specimens in Group I had a smooth bond face, and specimens in Groups II and III had a rough bond face. Specimens in Group II employed a thicker putty in which the surface smoothened by the putty was at the same level as the original concrete surface before roughening. Specimens in Group III used thinner putty in which the smoothened surface was about 1.5 mm to 2 mm below the original concrete surface before roughening. No putty was used for specimens in Group I as the bond surface was already smooth. Subscript ‘a’ in specimen’s code represents EB-FRP, while subscript ‘b’, ‘c’, ‘d1’, and ‘d2’ represents HB-FRP with 6, 12, 23, and 25 fasteners, respectively. The CFRP strip was bonded onto concrete surface by wet lay-up process. Details of the specimens are provided in Table 1. Spacing between fasteners was typically 100 mm.

<table>
<thead>
<tr>
<th>GROUP</th>
<th>SPEC. ID</th>
<th>BOND SYSTEM</th>
<th>BOND LENGTH (mm)</th>
<th>FRP WIDTH (mm)</th>
<th>FRP PILES</th>
<th>MAX. STRENGTH (kN)</th>
<th>MAX. SLIP (mm)</th>
<th>FAILURE MODES</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>B1a</td>
<td>EB</td>
<td>600</td>
<td>50</td>
<td>7</td>
<td>38.7</td>
<td>1.27</td>
<td>Sika300-FRP interface failure</td>
</tr>
<tr>
<td></td>
<td>B1b</td>
<td>HB</td>
<td>600</td>
<td>50</td>
<td>7</td>
<td>58.6</td>
<td>2.2</td>
<td>Sika300-FRP interface failure</td>
</tr>
<tr>
<td></td>
<td>B2a</td>
<td>EB</td>
<td>600</td>
<td>50</td>
<td>7</td>
<td>42.5</td>
<td>1.6</td>
<td>Sika300-FRP interface failure</td>
</tr>
<tr>
<td></td>
<td>B2b</td>
<td>HB</td>
<td>600</td>
<td>50</td>
<td>7</td>
<td>110.9</td>
<td>3.75</td>
<td>Sika300-FRP interface failure</td>
</tr>
<tr>
<td>II</td>
<td>B3a</td>
<td>EB</td>
<td>600</td>
<td>50</td>
<td>7</td>
<td>47.2</td>
<td>1.79</td>
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<tr>
<td></td>
<td>B3b</td>
<td>HB</td>
<td>600</td>
<td>50</td>
<td>7</td>
<td>119.3</td>
<td>4.04</td>
<td>Concrete failure</td>
</tr>
<tr>
<td></td>
<td>B3c1</td>
<td>HB</td>
<td>1200</td>
<td>50</td>
<td>7</td>
<td>114.0</td>
<td>5.2</td>
<td>FRP tearing</td>
</tr>
<tr>
<td></td>
<td>B3c2</td>
<td>HB</td>
<td>1200</td>
<td>50</td>
<td>7</td>
<td>154.6</td>
<td>9.2</td>
<td>Concrete failure</td>
</tr>
<tr>
<td></td>
<td>B3d1</td>
<td>HB</td>
<td>2500</td>
<td>50</td>
<td>7</td>
<td>176.7</td>
<td>23.06</td>
<td>FRP tearing^{(b)}</td>
</tr>
<tr>
<td></td>
<td>B3d2</td>
<td>HB</td>
<td>2300</td>
<td>45</td>
<td>9</td>
<td>&gt;230.4</td>
<td>&gt;14.6</td>
<td>No failure^{(c)}</td>
</tr>
</tbody>
</table>

^{(a)} Identical design. ^{(b)} Cyclic loading. ^{(c)} MTS actuator reached loading capacity.

The average compressive strength of concrete was 57.6 MPa. The CFRP materials had a nominal thickness of 0.167 mm for each ply. The elastic modulus and the ultimate strain of the CFRP strip were 242 GPa and 1.8%, respectively, obtained from flat coupon tests.
2.2 Test Setup and Instrumentation

The test setup is shown in Fig. 2. The instrumentation included one load cell to measure the applied load, two TML displacement transducers at the beginning and end of bonded zone to measure FRP slips relative to concrete beam, and strain gauges. A fixed spacing of 20 mm was used for strain gauges on EB-FRP. For HB-FRP, three strain gauges were mounted between two adjacent fasteners. All specimens were tested under displacement control.

![Fig. 2. Test setup](image)

3. Test Results and Discussions

3.1 Failure Modes

Four different failure modes were observed: (a) concrete failure - debonding of FRP with a thin layer of concrete being peeled off (Fig. 3a), (b) Sika300-FRP interface failure - debonding without a thin layer of concrete being pulled off (Fig. 3b) which occurred when the bond surface was not roughened, (c) Sika30-FRP interface failure – debonding between the FRP strip and the thick putty (Sikadur-30) (Fig. 3c) which occurred when the putty was too thick, (d) FRP tearing - failure caused by uneven clamping by the collets (Fig. 3d). The failure mode of each specimen is given in Table 1. Failure modes apart from (a) are inadequate and should be avoided in practice [23].

![Fig. 3. Failure modes. (a) Concrete failure, (b) Sika300-FRP interface failure, (c) Sika30-FRP interface failure, (d) FRP tearing.](image)

3.2 Load-displacement Responses

Load-displacement curves are depicted in Fig. 4. A significant decrease in bond stiffness (see Fig. 4a) is observed from the curve for specimen BIIc. In addition, the difference in surface preparation also causes significant difference in load capacity. Such differences can also be clearly seen in HB-FRP specimens in Fig. 4(b). These observations confirm the importance of surface preparation on bond characteristics, and the necessity to roughen the concrete substrate and expose aggregate before adhesive bonding. It should be noted that the pull-off test for specimens BIII_{d2} was stopped because the MTS actuator reached its loading capacity of 230 kN. The peak load of specimens BIII_{c1} and BIII_{d1} was not reached due to tearing of the FRP strip. Furthermore, specimen BIII_{d1} was loaded four times due to fracture of the FRP strip at the loaded end. The fractured end of the FRP strip was then cut off and the specimen was reloaded. The test results of the first cycle for this specimen was lost. The dashed line in
Fig. 4(d) is an estimated curve for the first loading cycle. Due to the above reasons, the load capacities of BIIIc1, BIIId1 and BIIId2 were not obtained.

3.3 Local Bond-slip Responses

From measured FRP strain fields, local bond-slip curves can be produced. Figure 5(a) presents the local bond-slip curves for the EB-FRP specimen BIIIa, and those for the local areas under fasteners for HB-FRP specimens are shown in Figs. 5(b)-(d). It can be seen that the curves are significantly wobbled. For HB-FRP joints, a long yield plateau can generally be observed after the peak in the bond-slip curves, which indicates a ductile bond behavior. Furthermore, no significant softening is seen in Figs. 5(b)-(d). Therefore these curves could be largely incomplete; hence a full bond-slip relationship for HB-FRP has not been directly obtained, although very long specimens were designed to produce a larger slip. As a result, direct characterization of the HB-FRP joint has not been accomplished. In the following section, indirect methods are used to derive the bond-slip model by analyzing the test results.

4. Bond-slip Model for HB-FRP joints

For HB-FRP joints, the bond under a fastener includes three mechanisms: adhesion, dowel action, and friction. The combination of dowel action and friction is termed as mechanical bond. The adhesive and mechanical bonds are discussed separately below.

4.1 Adhesive Bond

The bond-slip model, as shown in Fig. 6(a) and given by Eq. (1), proposed by Zhou et al. (2010) for long adhesive joints, is adopted for the adhesive bond. This model is applicable to EB-FRP joints with a bond length \( L \) significantly larger than effective bond length \( L_e \).

\[
\tau_s(s) = E_f \cdot t_f \cdot \frac{\alpha}{\beta^2} \cdot e^{-\frac{s}{a}} \cdot \left(1 - e^{-\frac{s}{a}}\right),
\]  

(1)
where \( s \) and \( \tau_a \) are interfacial slip and adhesive bond stress, respectively; \( E_f \) is the elastic modulus, and \( t_f \) the nominal thickness, of FRP strip; and \( \alpha \) and \( \beta \) are parameters of the model.

![Adhesive bond-slip model](image1) ![Bond-slip model for mechanical mechanism](image2)

Fig. 6. Bond-slip models

4.2 Mechanical Bond

The bond-slip relationship for local areas under the fasteners is very different from that outside it. The cover plates cover the FRP so that the reinforcement becomes partially “internal”. Therefore, the function of the cover plates is somewhat similar to that of concrete cover for internal reinforcing bars, and the bond-slip characteristics of the HB-FRP could be, to a certain extent, similar to those of internal reinforcing bars as represented by the typical CEB-FIP code model. Thus, a model as shown in Fig. 6(b), that is similar to the CEB-FIP model for reinforcing bars, and expressed by Eq. (2) is adopted for the mechanical bond:

\[
\tau_a(s) = \begin{cases} 
\tau_{\text{max}} \left( \frac{s}{s_1} \right)^{\gamma_1} & (s \leq s_1) \\
\tau_{\text{max}} \left( \frac{s - s_1}{s_2 - s_1} \right)^{\gamma_2} & (s_1 < s \leq s_2) \\
\tau_{\text{max}} \left( \frac{s - s_2}{s_3 - s_2} \right)^{\gamma_3} & (s_2 < s \leq s_3) \\
\tau_0 & (s > s_3)
\end{cases}
\]  

(2)

where \( \tau_{\text{max}}, \gamma_1, \gamma_2, s_1, s_2, \) and \( s_3 \) are parameters of the model as shown in Fig. 6(b).

Therefore, the overall bond-slip model for HB-FRP joints is given by

\[
\tau(x) = \begin{cases} 
\tau_a & \text{for } x \text{ outside fasteners} \\
\tau_a + \tau_m & \text{for } x \text{ under fasteners}
\end{cases}
\]

(3)

5. Analytical Load-slip Response of HB-FRP Joints

The indirect analytical method [26-28] identifies parameters for a bond–slip model from a load–slip response curve measured at the loaded end from pull-off tests. As measurements of load and slip at the loaded end in a pull-off test are much more stable and reliable than strain measurements along bond interface, this method delivers a more consistent and reliable bond–slip relationship for EB–FRP joints [26-28]. This method is also applicable to HB-FRP system. Therefore, load-slip relationship will be derived from the local bond-slip model in this section, which will subsequently be used for identification of bond parameters.

Based on equilibrium, constitutive, and compatibility conditions, the governing differential equation relating local bond stress \( \tau \) and slip \( s \) at the interface can be derived to be [29]

\[
\tau(x) = E_f \cdot t_f \cdot s''(x).
\]

(4)
5.1 Load-slip Response for EB-FRP joints

By substituting Eq. (1) into Eq. (4) and solving for the differential equation, a closed-form solution for the load-slip response can be derived [29]:

\[
\overline{F} = E_f \cdot b_f \cdot t_f \cdot \frac{\alpha}{\beta} \cdot \sqrt{\frac{1 - e^{-\frac{s_i}{\alpha}}}{1 - e^{-\frac{s_l}{\alpha}}}},
\]

where \( \overline{F} \) is the pull force; \( s_f \) and \( s_l \) are the slips at the free end and loaded end, respectively, which are related through the following equation:

\[
\frac{A_i \cdot e^{\frac{s_f}{\alpha}} - 1}{2 \cdot (A_i \cdot A_s - 1)} = \alpha \cdot \ln \left( A_i \cdot e^{\frac{s_f}{\alpha}} - 1 \right),
\]

in which \( A_i = \sqrt{\frac{2 - e^{\frac{s_l}{\alpha}}}{e^{\frac{s_l}{\alpha}}} \cdot \frac{e^{\frac{s_f}{\alpha}}}{e^{\frac{s_l}{\alpha}}} \cdot A_s = 1 - e^{\frac{s_l}{\alpha}}}, A_i = A_i \cdot e^{\frac{s_f}{\alpha}} + 1.
\]

Therefore, for a certain bond length \( L \), and a particular value of \( s_b \), the slip at the loaded end, \( s_l \), and the pull-off force \( F \), can be obtained from Eq. (6) and Eq. (5), respectively.

5.2 Load-slip Response for HB-FRP joints

By substituting Eqs (2) and (3) into Eq. (4), load-slip response can also be resolved for HB-FRP joints. However, the governing equation is discontinuous at the locations of mechanical fasteners. Thus, there is no closed-form solution and numerical solution has to be used.

6. Identification of Parameters

For EB-FRP joints, \( \alpha \) and \( \beta \), can be determined by minimizing the difference between the analytical solution, Eq. (5), and an experimentally measured load-slip curve, or

\[
\text{Min. } \text{Err} (\text{parameters}) = \sum_{i=1}^{n} \left[ F_i - \overline{F}(s_f, s_l) \right],
\]

where parameters here include \( \alpha \) and \( \beta \); \( F_i \) is the pull force corresponding to \( s_l \) on a measured load-slip curve; \( \overline{F} \) is the pull force calculated from Eq. (5); and \( n \) is the number of point used for matching curves. For HB-FRP joints, the parameters in Eq. (7) are \((\tau_{\text{max}}, \tau_{\text{f}}, \gamma_1, \gamma_2, \gamma_3, s_1, s_2, s_3, s_4)\), and numerical solution is used to obtain \( \overline{F} \).

6.1 Value of Parameters and Performance of the Model

The values \( \alpha = 0.1282 \) and \( \beta = 38.665 \) are obtained from the above described regression process for the EB-FRP specimen, BIIIa. Values (4.93, 0.203, 8, 30), (3.85, 0.19, 8, 30), (4.38, 0.21, 8, 30), and (4.6, 0.198, 8, 30) are identified for the parameters of \((\tau_{\text{max}}, \tau_{\text{f}}, \gamma_1, \gamma_2, \gamma_3, s_1, s_2, s_3)\) for the HB-FRP specimens BIIIb, BIIIc1, BIIIc2, and BIIId2, respectively. The other parameters of \((\tau_{\text{f}}, \gamma_1, \gamma_2)\) are determined to be \((0, 1, 1)\) for all HB-FRP specimens. Adopting the identified values, theoretical load-slip responses for the specimens are produced and compared with experimental results in Fig. 7, which shows good agreements.
7. Bond Strength and Effective Bond Length of HB-FRP Joints

For a particular HB-FRP design (certain FRP strip, fastener and spacing, etc.) with a certain bond length $L$, the pull-off force $F$ can be determined for various slip values by numerically solving the second order differential equation, with identified parameters. The maximum value of $F$ gives the bond strength for the HB-FRP joint with a bond length $L$.

Averaging the identified parameters for all specimens, the values of $(0.1282, 38.665, 4.44, 0.2, 8, 30)$ are adopted for the parameters $(\alpha, \beta, \tau_{max}, s_1, s_2, s_3)$ for specimens tested in this work. Theoretical bond strengths for various HB-FRP joints tested in this work are calculated and shown in Fig. 8, together with the experimental results. It should be noted that the test results for specimens BIIIc1, BIIIa1 and BIIIb2, as shown in the figure with hollow circles, do not reflect the real bond strength because the tests were stopped before the ultimate strength was obtained. It can be seen from Fig. 8 that the bond strength increases as the bond length increases. However, after the bond length increases to a value beyond 2000 mm, the increase in bond strength significantly slows down, and the load capacity essentially keeps constant after the bond length exceeds 2500 mm. The effective bond length (defined as distance between the two zero bond stress positions at the loaded end and the free end) is calculated to be 2500 mm, which exactly matches the value shown in Fig. 8. More tests will be conducted in the future to further validate the theoretical curve.

8. Conclusions

In this paper, the bond behavior for EB-FRP and HB-FRP joints were experimentally investigated by employing the single shear pull-off test on three EB-FRP and seven HB-FRP specimens with different bond lengths. Based on test results, an analytical bond-slip model for HB-FRP joints is developed and its parameters identified using load-slip response curves. The effective bond length and bond strength for EB-FRP and HB-FRP joints are then obtained by analytically and numerically solving the governing differential equations that are deduced from the proposed bond-slip model. The analytical and numerical results are then compared with test results. Good agreement between the theoretical and experimental results indicates that the proposed bond-slip model can well predict the bond behavior of HB-FRP joints.

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