INTERFACIAL MODELS FOR FIBER REINFORCED POLYMER (FRP) SHEETS EXTERNALLY BONDED TO CONCRETE

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1. Introduction

With the development of the technology of strengthening existing concrete structures with externally bonded FRP sheets, a number of issues related to the conventional structural behaviors of FRP strengthened RC structures should be studied. Among them, the most important one may be to clarify the mechanisms of the bond between the FRP sheets and concrete. The significance of the bond is due to its critical role on transferring the stress from the existing concrete structures to externally bonded FRP sheets and keeping integrity and durability of the composite performance of FRP-concrete system. A good understanding on the interfacial bond is a prerequisite of achieving a safe and appropriate design of FRP sheet strengthened RC structures.

As the most fundamental and important laws to characterize the bond interaction, the constitutive models for FRP sheet-concrete interfaces under different loading conditions have not yet been well studied up to now. Meanwhile, there is a need in developing suitable test methods to evaluate the bond performance of FRP sheet-concrete interfaces under various stress conditions. Furthermore, plenty of previous studies have shown that the FRP sheet-concrete interface always fails bitterly due to the premature peeling of FRP sheets from the concrete at a stress much lower than the real tensile strength of FRP materials. Therefore, the issues on how to improve the interfacial load transferring performances and ductility, moreover, how to improve the strength efficiency of FRP materials should raise more concerning.

2. Objectives of the dissertation

The main objectives of this dissertation are as follows:

(a) To enhance the fundamental understanding on the stress-transferring mechanisms of the interface between FRP sheet and concrete based on experimental studies in consideration of variety of experimental parameters. Through an overall review on the previous studies and the present parametric studies, the bonding mechanisms of FRP sheet-concrete interfaces can be further clarified.

(b) To develop suitable test methods, through which the bond behaviors of FRP sheet-concrete interfaces under and different loading conditions and different failure modes can be evaluated. These test methods can be used to obtain the most fundamental fracture parameters for engineering design or numerical analysis.

(c) To build up accurate mode-dependent interfacial constitutive models. Similar to that of concrete material, the fracture modes of FRP sheet-concrete interfaces can be also classified into three categories: Mode I failure (failure under tension), Mode II failure (failure under shear) and Mix-Mode failure (failure under tension-shear). To describe those different fracture behaviors quantitatively, it is necessary to propose mode-dependent interfacial constitutive models. Therefore the tension-softening diagram (σ ~ w relationship), the shear bond stress-slip curves (τ ~ s relationship) and the mix-mode interfacial models are to be proposed based on energy criteria and then verified by simulating the different series of experimental results.

(d) To find applicable ways for the optimum design of FRP sheet-concrete interfaces. Based on clarifying the different interfacial fracture mechanisms, some concepts can be formulated for the optimum interfacial design of FRP sheets strengthened concrete structures.

3. Bond behaviors of FRP sheet-concrete interfaces under shear

3.1 Experimental observations

A series of single lap pullout tests of FRP sheet-concrete interfaces were performed (see Fig.1). The test variables cover the stiffness of FRP, the bond length, the types of FRP materials (CFRP, AFRP and GFRP) and the elastic modulus and thickness of adhesive layers. In total 52 specimens were prepared in four batches. The failure types of interfacial bond, the visual observations of the peeled FRP sheets under microscope (see Fig.2), the ultimate interfacial pullout load, the load-slip relationship at the loaded point, the strain distribution in FRP sheets, the stress distribution along the bond interface as well as the effective bond length were discussed parametrically.
The phenomenon observed from the experimental studies can be summarized as follows:

1. Based on appropriate bonding system, decreasing the shear stiffness of adhesives through either increasing the thickness or decreasing the elastic modulus of adhesives may become a selectable way to improve the interfacial performances of FRP sheets bonded to concrete (see Fig.3) and to utilize the high strength of FRP materials in more efficient way. The good toughness and the non-linearity of lower stiffness adhesive contribute more ductile interfacial deformation and higher interfacial fracture energy.

2. FRP stiffness can be regarded as the only parameter to evaluate the properties of FRP materials regardless of their types. Increasing the FRP stiffness can increase the interfacial load carrying capacity. However, the interfacial fracture energy and the strength efficiency of FRP cannot be improved.

3. Either increasing the FRP stiffness or decreasing the shear stiffness of adhesives increases the effective bond length (see Fig.4). And in the case of using low shear stiffness adhesives, the long bond length makes the local peeling between FRP sheets and concrete bring few effects on the overall interfacial stiffness. It should be noticed that in actual structural strengthening, decreasing the shear stiffness of adhesives should have a low limit based on the analysis of overall structural performance to reach optimum interfacial design.

4. The interfacial fracture energy is less affected by the FRP stiffness, however, is affected by the mechanical property of adhesives most and then by the concrete strength. With the decreasing of the shear stiffness of adhesive, the interfacial fracture energy and the interfacial ductility can be improved although the maximum interfacial bond stress decreases. The maximum bond stress increases and the interfacial ductility decreases slightly with the increasing of the FRP stiffness. However, in comparison with the effects of adhesives and concrete, the effects of FRP stiffness on maximum interfacial bond stress are insignificant. In summary, both using lower shear stiffness adhesives and increasing the amount of FRP sheets can improve the load carrying capacity of FRP sheet-concrete interfaces. However, their corresponding bonding mechanisms are different.

5. The local bond behaviors observed in the short bond length tests are similar to those observed in long bond length tests, which indicates the local interfacial bond mechanisms are hardly affected by the boundary condition (with or without slip at the free end).

3.2 Analytical solutions

3.2.1 Bond stress-slip relationship

It is widely known that the tension-softening curve of concrete can be obtained from the load deflection curve of a notched concrete beam under three-point bending through J-integral method. Similarly, a new analytical method has been proposed for defining accurate interfacial nonlinear bond stress-slip ($\tau-s$) curves, which are most fundamental laws being able to quantify those
different bonding mechanisms and describe the bonding characteristics of FRP sheet-concrete interfaces under shear failure (Mode II fracture). By this method, it is not necessary to attach strain gauges on the surfaces of FRP sheets to get the local strain and stress information. Instead, the local bond stress-slip relationship for a FRP sheet-concrete interface can be obtained from the relationships between the pullout loads and the slips at the loaded point \( P = f(s) \) through simple pullout test.

\[
P = f(s)
\]

During a pullout test for FRP sheet-concrete interface as shown in Fig.5, the pullout load information and the slips between FRP sheet and concrete at the loaded point (circled location) can be recorded continuously. With a determined FRP stiffness and bond width the relationship between the strains in FRP sheets and the relative slips can be obtained consequently as follows:

\[
\varepsilon = f(s)
\]  

(1)

For FRP sheet externally bonded to concrete, the interfacial bond stress can be written as:

\[
\tau = \frac{d \varepsilon}{dt} = \frac{d f(s)}{ds} \cdot f(s)
\]  

(2)

because:

\[
\frac{d \varepsilon}{ds} = \frac{d f(s)}{ds} \cdot \frac{ds}{ds} = \frac{d f(s)}{ds} \cdot \frac{f(s)}{f(s)}
\]  

(3)

Present pullout tests, in which different FRP materials, different adhesive layers and different FRP stiffness were used, have shown a constant form of expression as the following Eq.4 can substitute Eq.1 and fit with the experimental perfectly (see an example in Fig.6).

\[
\varepsilon = f(s) = A(1 - \exp(-Bs))
\]  

(4)

Therefore, a two-parameter nonlinear bond stress-slip relationship can be obtained as follows:

\[
\tau = 2BG_f (\exp(-Bs) - \exp(-2Bs))
\]  

(5)

The shape of \( \tau-s \) relationship can be seen in Fig.7, where:

\[
\eta_0 = \ln 2 / B = 0.693 / B
\]  

(6)

\[
\tau_{\text{max}} = 0.5BG_f
\]  

(7)

Only two parameters, the interfacial fracture energy \( G_f \) and a ductility factor \( B \), which can consider the effects of all interfacial components, are necessary in the proposed bond stress-slip relationships. According to regressing the experimental results, the expressions for them have been obtained as follows:

\[
G_f = 0.446(G_{f/L} / \tau_{\text{max}})^{0.352} f^{0.216}(E_f f)^{0.023}
\]  

(8)

\[
B = 6.846(E_f f)^{0.168}(G_{f/L} / \tau_{\text{max}})^{0.433}
\]  

(9)

where \( E_f f \) is the stiffness of FRP(GPa-mm), \( f_c' \) is concrete compressive strength(MPa), \( G_{a/f} \) is the shear modulus of adhesive layer(GPa), \( t_a \) is the thickness of adhesive layer.

### 3.2.2 Anchorage bond length

With the two parameters \( G_f \) and \( B \), a definition for the anchorage bond length (effective bond length) was built up through solving the differential equation of the interfacial bond and interpreting the strain distributions in FRP sheets and stress distribution along the interfacial bond line.

The differential equation governing the bond is:

\[
\frac{d^2 s(x)}{dx^2} = \frac{2BG_f}{E_f f} (\exp(-Bs) - \exp(-2Bs))
\]  

(10)

The solution for Eq.10 can be obtained:

\[
s(x) = \frac{1}{B} \ln[\exp(AB (L - x)) + 1]
\]  

(11)

Corresponding to a load level, the strain distribution in FRP sheet is (see Fig.8):

\[
\varepsilon(x) = \frac{dx}{dx} = \frac{A}{1 + \exp(AB (L - x))(P_{\text{max}} - P)}
\]  

(12)

Subsequently, the interfacial bond stress distribution can be obtained as follows (see Fig.9):

\[
\tau(x) = \frac{E_f f P A^2 B (P_{\text{max}} - P) \exp(AB(L - x))}{[P + (P_{\text{max}} - P) \exp(AB(L - x))]^2}
\]  

(13)

According to the characteristics of the strain distribution in FRP sheets and the interfacial bond stress distribution, the effective bond length \( L_e \) of a FRP sheet-concrete interface is defined as an active bond zone, which undertakes part of the ultimate pullout force most
efficiently as shown in Fig.8. The stress transferred outside the defined effective bonding zone is regarded as less efficient because the slips between FRP sheet and concrete over there are comparatively small or large to produce bond stress. Mathematically, the effective bond length \( L_e \) can be expressed a distance between two locations \( x_1 \) and \( x_2 \) (see in Fig.8), which takes part of the theoretical maximum pullout force \( \alpha P_{\text{max}} \) (\( \alpha \) can be taken as a constant 0.96 as shown in Fig.8 for anchorage design based on experimental observations).

\[
L_e = \frac{\sqrt{2E_{f}f_{f}}}{G_f} \ln\left(1 + \alpha \right) - \frac{1}{1 - \alpha}
\] (14)

A simplified closed-form bond strength model, which can predict the bond strength of FRP sheet-concrete interface with any bond length, was proposed as follows:

\[
\alpha = \frac{\exp\left(\frac{L_b B \sqrt{G_f}}{\sqrt{2 E_{f}f_{f}}} - 1\right)}{\exp\left(\frac{L_b B \sqrt{G_f}}{\sqrt{2 E_{f}f_{f}}} + 1\right)}
\] (15)

\[
P_b = \alpha P_{\text{max}}, \quad P_{\text{max}} = (b_f + \Delta b) \sqrt{E_{f}f_{f} G_f}
\] (16)

where: \( \Delta b_f = 3.7 \text{mm} \), \( b_f \) is the width of FRP sheets (mm), \( P_{\text{max}} \) is the theoretical maximum pullout load achieved in the case of using long bond length, \( L_b \) is the bond length (mm).

Fig.11 Accuracy of the simple unified bond strength model

The simplified model can give approximately same accurate in comparison with the solution based on rigorous numerical analysis using proposed \( \tau - s \) relationship (see the comparison in Fig.11) and can predict the experimental results well.

4. Tension softening behaviors of FRP sheet-concrete interfaces

4.1 Experimental observations

Tension softening behaviors of FRP sheet-concrete interfaces under Mode I fracture were studied through a series of three-point bending test of notched composite beams (see Fig.12). The test variables are bonding substrate types (concrete and mortar), concrete strength and adhesive types. In total 16 specimens were prepared in three series (C1, C2 and M1). C1 and M1 have similar concrete strength. C2 has a comparatively high strength. Four types of adhesive R1–R4 with decreased elastic modulus but increased ductility were used. The interfacial Mode I fracture energy was evaluated by using RILEM recommended method (see Fig.13).
The main conclusions based on Mode-I fracture tests of FRP sheet-concrete interfaces have been reached as follows:

1. The conventional three point bending test can be modified to evaluate the interfacial Mode I fracture of FRP sheet–concrete interfaces bonded with adhesives.

2. The Mode I fracture energy relies greatly on the quality of bonding substrates. Mortar and concrete surface causes significant difference even their tensile strengths are similar.

3. Different from their effects on the Mode II interfacial fracture energy, the adhesives have fewer effects on the interfacial Mode I fracture one. However, when the adhesive shows good toughness under low stress-level, the Mode I fracture can be improved even though the fracture happens always in concrete mostly near the interface and the interfacial peak strength has proved to be determined by concrete strength.

4. Tension softening diagrams of FRP sheet-concrete interfaces

The relationships between interfacial cohesive stress and the interfacial displacement normal to crack surface (σ–w relationship) of all three testing series were obtained based on the improved J integral method as shown in Fig.14 and Fig.15.

\[
\sigma = \sqrt{f_t} + \frac{w}{w_{\text{max}}} = 1
\]  

(17)

where \(\alpha\) is a ductility factor of FRP sheet concrete interface under Mode I fracture. Higher \(\alpha\) means brittle interfacial fracture behaviors. \(\alpha\) is taken as 3.0 for mortar and 2.2–2.5 for concrete. \(w_{\text{max}}\) is the defined maximum crack width, which is defined as 0.3 mm for ordinary adhesive and 0.34 mm for soft adhesives.

The proposed tension-softening model has been verified through FEM simulation based on Hilliberg’s fictitious crack method.

5. Mix-mode fracture of FRP sheet-concrete interfaces

Besides the Mode I and Mode II fractures, Mix-Mode fracture of FRP sheet-concrete interfaces was studied experimentally based on a proposed novel test method, in which the Mode I and Mode II loading conditions (dowel and bending forces) can be imposed into the interfaces through adding dowel and bending force to FRP sheet strengthened concrete beams simultaneously (see Fig.16). Six rectangular RC beams strengthened with FRP sheet were prepared. The only test variable is the dowel force ratio. The observed bending force-mid span deflection relationships of FRP strengthened concrete beams in the cases of different dowel force ratio are shown in Fig.17.

Through experiments, the main phenomenon has been observed as follows:
1. The effective bond length of FRP sheet-concrete interfaces under dowel force action is very short. Whereas for the FRP sheet-concrete interfaces under the dowel action, a longer bond length is needed for a safe design purpose in real retrofitting engineering.

2. In FRP sheet-strengthened RC beams, the dowel force the FRP sheet-concrete interface can undertake is rather low, indicating the contribution of the externally bonded FRP sheet to the shear capacity of the strengthened beam is negligible.

3. In FRP sheet-strengthened RC beams, due to the low bending stiffness of FRP sheets, the FRP sheet interface can accommodate rather big deformation vertically to the interface if there is a short unbonded or debonding length. The effects of imposed dowel force on the shear stress transfer in FRP sheet-concrete interfaces (the maximum tensile strain of FRP sheets at peeling) exist but are not very significant.

\[ \frac{G_{II}^*}{G_{I}^*} + \frac{G_{II}^*}{G_{I}^*} = 1 \] (18)
where \( G_{II}^* \) and \( G_{II}^* \) are the fracture energy obtained under the Mode I and Mode II failure. \( G_{I}^* \) and \( G_{I}^* \) are the Mode I and Mode II energy components of FRP sheet-concrete interface under mix-mode fracture respectively.

6. Concluding remarks

The Mode II, Mode I and Mix-mode fracture tests for FRP sheet-concrete interfaces were studied in the dissertation. The mode-dependent constitutive models developed in this study can be used for accurate simulation of the strength and stiffness behaviors of FRP strengthened RC structures and optimizing the interfacial design. The proposed interfacial bond strength and anchorage length models can be used in engineering design. Besides that, the developed analytical methodology can be used to simplify the present shear bond test methods and evaluate the local bond behaviors of FRP sheet-concrete interfaces in a more reasonable way. In addition, the developed test methods in this study can be used to evaluate the fracture toughness of FRP sheet-concrete interfaces under different failure modes based on proposed analytical models. And finally, the results in the present study are useful for developing optimum performance-based bonding materials.

References

8. Others (In total 97 literatures were quoted)