MODE II FRACTURE ENERGY OF FRP-CONCRETE INTERFACE: ITS EVALUATIONS AND ROLES IN INTERFACE MODELING AND ANCHORAGE DESIGN

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ABSTRACT

Since interface delamination is a most possible factor leading to the overall failure of concrete structures externally strengthened with FRP laminates (plates/sheets), studying the interface behaviors between the FRP laminates and concrete has become a keen interest in the past decade. The interface between FRP laminate and concrete is easy to exceed the peak interface cohesive stress even though there is only a low level of tensile stress in FRP sheets. Therefore, rather than interface bond strength, fracture mechanics-based interface parameters show their more powerful functions on describing the interface softening and the cohesive crack propagation, and also their advantages on evaluating the interface damage due to various negative environmental factors. For interfaces between concrete and externally bonded FRP laminates under shear, Mode II fracture energy, which is related to the work done by the bond stress and affected by all interfacial components, becomes an most important interface characteristic parameter. This paper firstly compares test results of Mode II fracture energy from single and double-lap shear bond tests and parametrically discusses the effects of all test variables. In particular, the large scatter of test results is discussed based on an extensive experimental database (test results of 231 specimens from 11 researchers). The Mode II interface fracture energy is directly used in this paper to model the bond behaviors of FRP sheet-concrete interfaces under shear. A two-parameter fracture energy based bond stress-slip model is introduced. Besides its simplicity, a most significant characteristic of the proposed two-parameter bond model is that other important interface parameters like interface peak cohesive stress and the corresponding slip, which are difficult to be calibrated in shear bond tests, can be related to the Mode II fracture energy mathematically. Finally, the fracture energy-based design models for the bond strength and anchorage length of FRP/concrete interface are proposed. In a summary, an overall picture for the evaluation as well as the uses of Mode II fracture energy of FRP/concrete interface for numerical modeling and engineering design can be seen through the presentations in this paper.

1 INTRODUCTION

The bond failure of FRP laminate-concrete interfaces is a main concern in the concrete structures externally strengthened with FRP laminates (plates/sheets) since the interface is comparatively weaker in the whole composite system but it plays a critical role on transferring the shear stresses between two dissimilar materials FRP and concrete and keeping the integrity of the whole composite system. A significant bond characteristic of the FRP laminate-concrete interface is its high nonlinearity because the interface between FRP and concrete under shear is easy to exceed its peak cohesive stress even though there is only a low level of tensile stress in FRP due to the local shear stress concentration. Therefore, nonlinear fracture mechanics is a more powerful tool to be used to describe the interface softening as well as the propagation of interface cracking at both micro and macro levels. The Mode II interfacial fracture energy, as a most important fracture parameter which governs the overall shear bond properties of FRP-concrete interfaces, should be studied appropriately. The objective of this paper is to show the calibration of Mode II fracture energy, its influencing factors, and its role in interface modeling and anchorage design as well.

2 CALIBRATION OF THE INTERFACIAL MODE II FRACTURE ENERGY

Mode II interfacial fracture energy G_f of an FRP laminate-concrete interfaces is a parameter to evaluate the interfacial bond properties from the viewpoint of fracture mechanics. The G_f is the amount of energy per unit bond area that is required for interfacial fracture to occur and can be linked to the interfacial bond stress-slip relationship as follows:

$$G_f = \int_0^\infty \tau(s)\,ds \tag{1}$$

where G_f is the Mode II fracture energy of FRP laminate-concrete interfaces (N/mm), $\tau(s)$ is the interfacial bond stress-slip relationship.

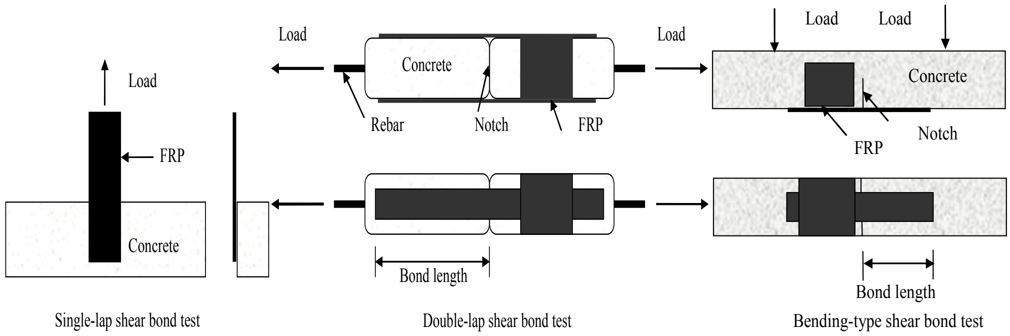


Figure 1 conventional shear bond test for FRP laminate-concrete interfaces

There are three conventional methods for evaluating the bond behaviors of FRP laminate-concrete interfaces. They are single-lap type (Chajes et al [1]), double-lap type (JSCE [2]) and bending-type shear bond tests (Lorenzis et al. [3]) respectively (see Figure 1). It has been verified through assuming different shapes of τ~s models that the following relationship between the Mode II fracture energy and the bond strength can be obtained if a long enough bond length is used in a single-lap shear bond test (Täljsten [4], Yuan et al. [5]):

$$G_f = \frac{(P_{max} / b_f)^2}{2 E_f t_f} \tag{2}$$

where: P_{max} is the maximum pullout force achieved in FRP during (N); E_f is the elastic modulus of FRP laminates (N/mm^2); b_f and t_f are the width and thickness of FRP laminates respectively (mm), $E_f t_f$ is the stiffness of FRP laminates (kN/mm).

3 INFLUENCING FACTORS ON THE INTERFACIAL FRACTURE ENERGY

Figures 2 to 5 show the effects of concrete strength, adhesive layer, bond width of FRP used for bond test, and the stiffness of FRP on the obtained G_f respectively. Experimental data of 231 specimens previously published by 11 researchers (Chajes et al. [1], Ueda et al. [6], Garbriel et al. [7], Lorenzis et al. [3]. Brosens et al. [8], Täljsten [9], Sato et al. [10], Yoshizawa et al. [11], Nakaba et al. [12], Dai et al. [13], Bizindavyi and Neale [14]) are included in Figure 5. From Figures 2 to 5 the following conclusions can be drawn up:

1. As indicated in Figure 2, the G_f increases with the concrete compressive strength f_c'. This is understandable because the interface always fractures in a thin layer concrete just beneath the adhesive layer.
2. The G_f increases with the decrease of the shear stiffness of adhesive layer G_a/t_a, which is defined as the shear modulus divided by the thickness of adhesive layer (see Figure 3).

Experimental evidences show that both increasing the thickness of adhesive and decreasing the elastic modulus can increase the bond strength of an FRP laminate-concrete interfaces if a long enough bond length is given. The interfacial fracture energy is the work done by the shear stress through producing the interfacial slip. Soft and thick adhesives permit larger interfacial slips. And also, the soft adhesives usually have significant nonlinearity, which also can improve the interface fracture energy (Dai et al. [13]).

3. As shown in Figure 4, the obtained Mode II fracture energy is usually higher when the bond width of FRP is narrower. When the width of concrete is larger than that of FRP, the shear stress flows can spread to the vicinity areas of both sides of FRP laminates and the adhesives always penetrate to those areas somehow, which makes the effective contact areas between FRP laminates and concrete wider than the real ones. But as shown in Figure 4, the effect will not be significant after the width of FRP exceeds 50 mm.

4. It can be seen that FRP sheet-concrete interfaces usually have higher fracture energy than the FRP plate-concrete interfaces (see Figure 5). In the former system, FRP usually has smaller stiffness due to its smaller thickness whereas the stiffness of FRP in later case is generally higher. The possible reason is that FRP sheets can produce more rough fracture surface than FRP plates.

5. According to the present databases, the Mode II fracture energy of FRP sheet laminate-concrete interface observed in the single-lap shear bond tests are usually higher than that observed in double-lap and bending-type shear bond tests. That may be due to the fact that always the bond failure on a weaker side is observed in the double-lap shear bond tests. There is almost no difference between the double-lap and bending type shear bond test results on the Mode II interfacial fracture energy (see Figure 5).

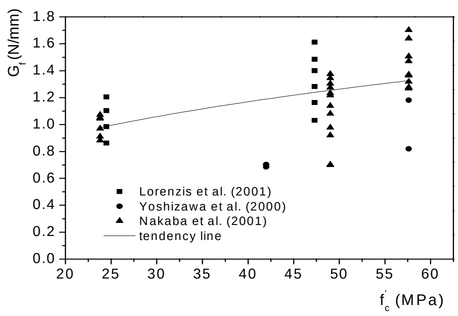


Figure 2 effects of concrete strength on G_f

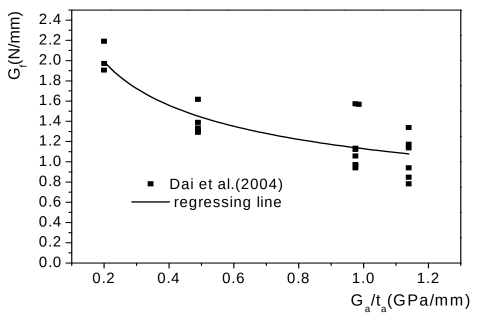


Figure 3 effects of adhesive layer on G_f

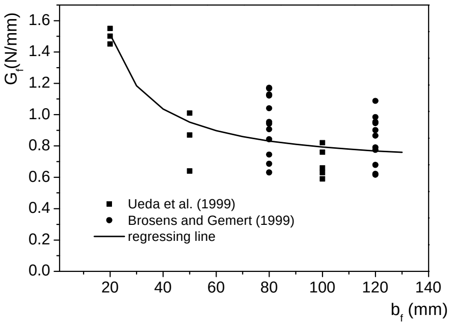


Figure 4 effects of bond width on G_f

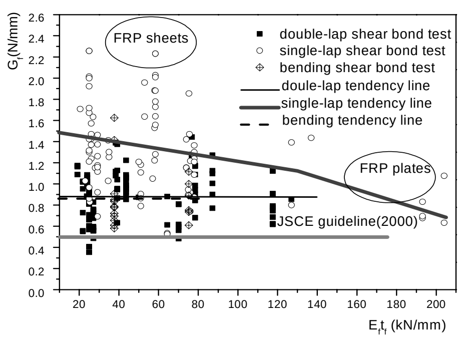


Figure 5 effects of FRP stiffness on G_f

6. As seen in Figure 5, the observed interfacial fracture energy shows rather big scatter. The scatter of observed G_f is comparatively higher in the case of using single-lap shear bond test in comparison with using double-lap and bending-type shear bond test method. A reference value 0.5N/mm of the Mode II interface fracture energy proposed by JSCE [2] regardless of the interfacial materials used brings a rather conservative estimation as shown in Figure 5.

4 MODE II FRACTURE ENERGY FOR CONFIGURING A τ~s RELATIONSHIP

Conventionally, to configure the τ~s relationship for a bi-material interface, some important bonding characteristic parameters like the peak shear stress and the slip corresponding to it should be known. However, it is rather difficult to calibrate those parameters for FRP laminate-concrete interfaces during bond tests. Comparatively, it is easy to get the Mode II fracture energy G_f for an FRP laminate-concrete interface because it can be back-calculated from the maximum pullout force as shown in eqn (2), which is applicable not only for the often used bilinear and cutoff type τ~s relationships but also for any other one with unknown configuration (Dai et al [13]). Therefore, it is a nice choice to use G_f as a controlling interface parameter to configure the τ~s relationship for an FRP laminate-concrete interface instead of using other bonding parameters with the difficulty of being calibrated. The authors have developed a simple method to propose the τ~s relationship for an FRP laminate-concrete interface by using G_f directly (Dai et al. [15]).

A lot of experimental studies show the relationship between the pullout load and the interfacial slip at the loaded point can be well expressed by the following equation.

$$P(s) = P_{\max}(1 - \exp(-Bs)) \tag{3}$$

where P(s) is a function expressing the relationship between the pullout loads and the interfacial slips at the loaded point, P_{max} is the maximum pullout load, and B is an experimental parameter, which mainly stands for the properties of adhesive layer.

The local bond stress of an FRP laminate-concrete interface can be expressed as:

$$\tau = E_f t_f \cdot \frac{d\varepsilon}{dx} = \frac{dP(s)}{ds} \cdot \frac{ds}{dx} = \frac{dP(s)}{ds} \cdot \varepsilon = \frac{P(s)}{E_f t_f} \cdot \frac{dP(s)}{ds} \tag{4}$$

By combing eqns (2), (3) and (4), it is not difficult to get the following relationship:

$$\tau = 2BG_f(\exp(-Bs) - \exp(-2Bs)) \tag{5}$$

In eqn (5) the interfacial fracture energy G_f is directly used in the τ~s model. And also it is not necessary to observe the local interfacial bond behaviors as usual ways. Instead, the local τ~s relationship can be derived from the relationship between the pullout loads and the interfacial slips at the loaded point as shown above. In addition, the relationship among the G_f, the maximum bond stress and the corresponding slip can be determined mathematically as follows:

$$s_{\max} = 0.693 / B \tag{6}$$

$$\tau_{\max} = 0.5BG_f \tag{7}$$

It can be seen the peak shear stress is linearly proportional to the Mode II fracture energy. However the slip occurring at the interface peak stress is independent of the interfacial Mode II fracture energy. Instead, it is determined by an interfacial parameter B, which indicates the effect of adhesive bond layer. It has been found that a value of 10.4 can be taken as a reference for B in the cases of using most conventional adhesives in the present retrofitting engineering through averaging a lot of experimental results (Dai et al. [15]).

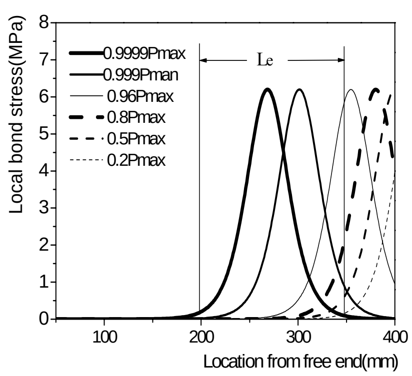
5 MODEL II FRACTURE ENERGY FOR INTERFACE ANCHORAGE DESIGN

The bond strength and the anchorage length models can be developed in a general rather than empirical way if the interfacial τ~s relationship can be known. Consequently, the interfacial fracture energy G_f, which has been used for developing the interfacial τ~s model, can be used in anchorage design for FRP laminate-concrete interfaces as well. By using the proposed τ~s relationship as shown in eqn (5), Figure 6 shows an example of the predicted shear stress distributions of an FRP laminate-concrete interface under different pullout loading levels. It can be seen that there only exists a limited distance with visible bond stresses even though a very long length is available. That is the reasons why FRP laminate-concrete interfaces cannot increase their bond strength any more after the bond length reaches a value so called as the effective bond length. Therefore the effective bond length can be defined as that active bond distance L_e indicated in Figure 6. Mathematically the bond strength can be expressed as follows:

$$L_e = \frac{\sqrt{2E_f t_f}}{B\sqrt{G_f}} \ln\left(\frac{1+\alpha}{1-\alpha}\right) \tag{8}$$

where L_e is the effective bond length, α is the ratio of the bond force that the effective bond area can bear to the theoretical maximum bond strength shown in eqn (2). Once the proposed method (eqn.(3)) is applied, theoretically there always exists even a tiny shear stress between the FRP and concrete no matter how big the interfacial slip becomes, meaning that the interface can never achieve the maximum theoretical bond strength (α always smaller than 1.0). Based on experimental observations α can be taken as 0.96 for the purpose of anchorage design.

The L_e increases with the stiffness of FRP, but decreases with the increase of interfacial fracture energy and the B. B is higher in the cases of using stiffer adhesive and vice versa.



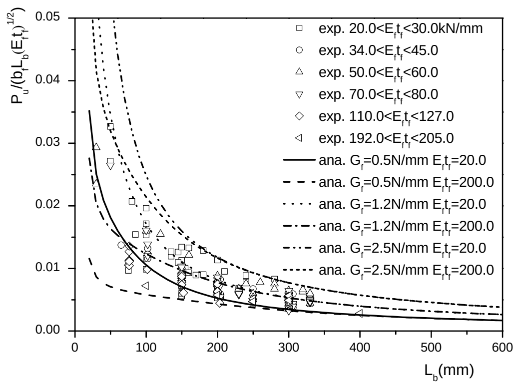


Figure 6 definition of the effective bond length L_e Figure 7 average bond strength ~L_b relationship

For an FRP laminate-concrete interface with a bond length L_b, its bond strength can also be obtained based on the definition of α as follows:

$$P_u = \alpha P_{max} \tag{9}$$

$$\alpha = \frac{\exp\left(\frac{L_b B\sqrt{G_f}}{\sqrt{2E_f t_f}}\right) - 1}{\exp\left(\frac{L_b B\sqrt{G_f}}{\sqrt{2E_f t_f}}\right) + 1} \tag{10}$$

As shown Figure 4, the G_f is higher when a narrower bond width is used in the test. To remove this effect of test sizes on calibrating the G_f, an additional width $2\Delta b_f$=7.4 mm can be added to the width of FRP laminates b_f (Sato et al. [10]). Then eqn (2) becomes the following eqn (11):

$$P_{max} = (b_f + 2\Delta b_f)\sqrt{2E_f t_f G_f} \tag{11}$$

Figure 7 shows the comparison of experimental and analytical relationships between the average interface bond strength and the bond length L_b. The sources of experimental data are same as those used for Figure 5. It is well predicted that the average bond strength decreases with increase of bond length, and also decreases more sharply in the cases of using low stiffness FRP in which case the effective bond length is smaller. Moreover, when the G_f is changed from 0.5 N/mm to 2.5N/mm as indicated in Figure 5, all experimental data are well enveloped regardless of the bond length the FRP laminates and the stiffness of FRP. The value of 1.2 N/mm for G_f shows a good agreement with experimental data at an average level (see Figure 7) and the value 2.5N/mm seems a likely maximum value that the interface can achieve in the real retrofitting. .

6 CONCLUDING REMARKS

This paper has an overall view on the Mode II fracture energy G_f of FRP laminate-concrete interfaces and its roles in interface modeling and anchorage design. The influencing factors of interfacial materials and test methods on the G_f are discussed. The relationships among the G_f, the interface peak shear stress and the corresponding slip are built up through configuring the fracture energy-based τ~s relationship. Models for anchorage design by using the G_f are also proposed.

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