Roughness Effects on the Fracture Energy between FRP and Concrete

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Abstract: The single test is carried out on totally 54 concrete samples with 6 different interface-roughness conditions, as to delve into the influence of concrete surface roughness on the concrete-FRP interface. Accordingly the closed-form solution based on the compressive strength and interface roughness parameters of concrete is acquired. As the research result indicates, the extremum and extreme point exist in terms of influence of concrete surface roughness on fracture energy, the model acquired in line with the test data is appropriately applicable under the condition 0.34≤\(f_i\)≤0.56, and such model is overall applicable under the concrete strength of 30MPa≤\(f_c\)≤50MPa. The model proposed hereof in this paper is superior to the existing models, as not only the significant contribution made by concrete strength to fracture energy is considered, but the influence of concrete surface roughness on interface is highlighted.

1 Introduction
The research on the interface between FRP and concrete (after referred to as interface) is always the emphases and hotspot at home and abroad. Because the action of shear stress, the interface failure pattern mainly divides into four modes: (1)Debonding from the interface between FRP and epoxide resin (2) Failure from the epoxide resin inside (3) Debonding from the interface between concrete and epoxide resin (4) Cracking and debonding form the concrete surface layer; No matter whatever the failure mode is, it is a complicated mechanics process, considering the failure process contains energy transfer, Hillerborg[1]proposed fracture energy in the first place on the ground of the virtual crack model,due to the fracture can not rely on failure pattern, so using \(G\) to interpret interface degradation rule is more appropriate and convenient.

There are many interface fracture energy models .According to the experiment phenomenon, in the 1990 s Holzenkampfer [2] found many damage occurred in the concrete surface, so he thought tensile strength of concrete took great impact on interface, interface fracture energy calculation model is put forward for the first time, only one variable named a tensile strength of concrete in the model;In 1997 Neubauer and Rostasy [3] found important role for the first time that the relationship between FRP sheet and concrete bonding surface width ratio \(\frac{b_f}{b_y}\) on the interface, thus proposedthemodel using twovariable parameters named concrete tensile strength \(f_t\), width ratio \(\frac{b_f}{b_y}\);In 2000, Niedermeier[4] revised Neubauer and Rostasy model, the new stripping bearing capacity model was put forward, but
the model of the fracture energy was not timely update; Dai and Ueda [5] in 2003 noticed epoxide resin failure mode, therefore presented new model based on the concrete compressive strength \( f_c \) and shear stiffness \( \frac{G_s}{I_a} \) of epoxide resin; Dai [6] proposed fracture energy model twice in 2005, first of all, he emphasized the axial compressive strength of concrete contribution to the interfacial energy, in addition in the new model, he considered the stiffness \( E_f/t_f \) of the FRP plate, epoxide resin shear stiffness \( \frac{G_s}{I_a} \), and the compressive strength of concrete \( f_c \) that above three parameters supported the new fracture energy model; In 2005, a new interfacial fracture model based on a new fine unit was proposed by Lu et al. [7], the model weakened the stiffness of CFRP sheet, emphasized the great impact such as the concrete tensile strength \( f_t \), shear stiffness \( \frac{G_s}{I_a} \) the width ratio \( \frac{b_f}{b_c} \) on the fracture energy. In 2013 YuFei Wu and Chen Jiang [8], put forward interface fracture model based on concrete compressive strength \( f_c \), width ratio \( \frac{b_f}{b_c} \), and took the comparison with other existing models.

There are many fracture models nowadays, and more and more scholars reached a unified viewpoint that the concrete tensile (pressure) strength, width ratio contributed a lot to interface, but how much contribute to fracture energy based on the morphology between FRP and concrete and roughness of concrete surface had not report. From experimental research domestic and abroad in recent 20 years found [9-12], concrete surface roughness, have important influence on bearing capacity of interface. So far, the countries about the reinforcement project guide has a clear pretreatment of interface, it can take a positive influence on reinforce the performance [13, 14], thus if we ignore the research on the effects of surface roughness of the RC beam concrete, so this paper through the single test with totally 54 concrete samples and 6 different interface-roughness conditions to examine the effects of concrete roughness on fracture energy.

2 Experimental Program

2.1 Test Specimens

Test sets concrete specimen size is 80x80x200mm³, as shown in figure 1. Considering surface roughness and concrete strength would affect the interfacial bonding in local area, there are fifty-four specimens all of which are C30, C40, C50, each strength degree assumes six kinds of interface roughness, and three specimens are in a group unit. HICOMA - HITEX series carbon fiber cloth made in Nanjing Hitech Composites Co. Ltd was used in this experiment, epoxy resin AB glue, by 2:1 compound the same corporation made, all details are shown in table 1.

| Specimen  | \( f_c \) (MPa) | \( f_t \) (MPa) | \( E_f \) (MPa) | \( t_f \) (mm) | \( m_f \) (g/m²) |
|-----------|----------------|----------------|----------------|--------------|--------------|
| C30       | 35.0           | 5.3            |                |              |              |
| C40       | 46.0           | 6.4            |                |              |              |
| C50       | 57.5           | 7.4            |                |              |              |
| CFRP      | 3400           |                | \( 2.3 \times 10^6 \) | 0.167        | 300          |
| Epoxide resin | 38         |                | \( 2.4 \times 10^7 \) |              |              |

Note: \( f_c = \frac{(f_c)^{0.3}}{2} \)
2.2 Test preparation
Make fifty-four FRP-concrete pieces of single shear specimens, paste a group strain gages on each of the pieces’ scope of specimen surface (60×140mm²), and detect the change in strain in the direction of bonded length in the process of the test. The way to paste way is shown in figure 2. For the purpose of homogenizing influence on the interface due to the interfacial random roughness, two columns strain gauges were made along the interface bonding length, where spacing is 20 mm and the one gauge bonding area is 5mm×3mm. Strain calculation used in this work is average of the two columns strain gauges of each section.

2.3 Roughness quantitative definition
At present Chinese commonly used sand filling method [15] to detect the roughness, its measurement method is as follows: the concrete specimen is surrounded with plastic plank, the highest point of the plastic plank and the highest point of concrete surface convex is level, the standard sand is poured into plastic plank, removed all the sand and weigh its volume, the average depth \( h \) of the sand filling can be represented by sand volume \( V \) divided by the bond area \( ab \). Detailed expressed as:

\[
h = \frac{V}{ab} \tag{1}
\]

Where: \( a \), \( b \) is the length and width of the concrete specimen respectively.
Roughness can be calculated as follows[16] (2):

\[
f_i = \frac{h}{\delta} \tag{2}
\]

Where: \( f_i \) is the interfacial roughness, it is dimensionless value from zero to one, \( h \) is the average depth, mm, \( \delta \) is biggest value of the concrete surface, mm. The calculation result is as follows from table 2.
### 2.4 Test procedure

All trials are loading with 20 t electro-hydraulic materials testing machine, as shown in figure 3. Loading rate is 5mm/min. During the experiment process, IMC dynamic acquisition system is connected to the strain gauge, the status of strain is observed with the change of the loading force in real time. At the same time, collect ultimate load, the limit displacement and ultimate displacement in the process of CFRP debonding, and observe the specimen failure pattern.

![Figure 3 Single shear experimental setup](image)

### 3. Experiment results and analysis

#### 3.1 Important parameters in the bonding experiment

For single shear test of concrete specimens whose roughness is f0-f5, the important parameters related to interfacial load slip curves are as shown in table 3.

| Specimens | Roughness | $F_u$ (kN) | $\varepsilon_m$ (MPa) | $s_f$ (mm) | $s_f$ (mm) |
|-----------|-----------|------------|-----------------------|-------------|-------------|
| C30       | f0        | 12.500     | 3.280                 | 0.003       | 0.348       |
|           | f1        | 15.030     | 5.790                 | 0.010       | 0.288       |
|           | f2        | 17.770     | 7.350                 | 0.018       | 0.312       |
|           | f3        | 12.230     | 3.170                 | 0.013       | 0.345       |
|           | f4        | 6.770      | 1.650                 | 0.010       | 0.202       |
|           | f5        | 2.560      | 0.970                 | 0.008       | 0.049       |
|           | f0        | 13.200     | 3.530                 | 0.003       | 0.358       |
|           | f1        | 15.780     | 5.920                 | 0.010       | 0.305       |
|           | f2        | 19.240     | 8.550                 | 0.021       | 0.315       |
| C40       | f3        | 13.550     | 4.080                 | 0.017       | 0.328       |
|           | f4        | 5.760      | 1.680                 | 0.010       | 0.143       |
|           | f5        | 2.440      | 1.020                 | 0.009       | 0.044       |
|           | f0        | 14.000     | 3.760                 | 0.003       | 0.379       |
|           | f1        | 19.770     | 9.410                 | 0.016       | 0.301       |
|           | f2        | 21.230     | 11.900                | 0.030       | 0.275       |
| C50       | f3        | 17.560     | 8.130                 | 0.034       | 0.276       |
|           | f4        | 5.770      | 2.490                 | 0.015       | 0.099       |
|           | f5        | 2.560      | 1.070                 | 0.009       | 0.046       |

Table 2 Quantitative interfacial roughness values

| Interfacial specimens | $f_0$ | $f_1$ | $f_2$ | $f_3$ | $f_4$ | $f_5$ |
|-----------------------|-------|-------|-------|-------|-------|-------|
| Roughness             | 0.25  | 0.34  | 0.44  | 0.56  | 0.68  | 0.88  |
3.2 The influence of roughness on interface behavior

$G_f$ is the fracture energy of the interface, is the area contained in the bond stress-slip curve of the interface. Such energy determines the bearing capacity of the interface. Additionally this data can be perceived as the important parameter of the bond stress-slip curve. The research indicates that the bearing capacity of the CFRP-concrete interface in direct proportion to the interface energy square [11][17]. Here are the following expressions:

$$G_f = \frac{P_f^2}{2b_f E_f t_f}$$

Where $b_f$ refers to the width of CFRP, $P_f$ refers to the failure load, $E_f$ and $t_f$ respectively refer to the CFRP elasticity module and the calculated thickness. The interface fracture energies under various types of roughness are calculated as in Table 4.

### Table 4. Fracture energy of interfacial roughness (MPa·mm)

| Material | f0  | f1  | f2  | f3  | f4  | f5  |
|----------|-----|-----|-----|-----|-----|-----|
| C30      | 0.565 | 0.817 | 1.142 | 0.541 | 0.166 | 0.024 |
| C40      | 0.630 | 0.900 | 1.339 | 0.664 | 0.120 | 0.022 |
| C50      | 0.709 | 1.413 | 1.630 | 1.115 | 0.120 | 0.024 |

It is acquired through the table 4 that before the f2 interface, the overall interface fracture energy is elevated as the concrete strength grade increases, and as the roughness increases. The maximum interface energy is reached at the f2 interface, and accordingly the influences of the concrete strength grade are respectively 14.7% and 42.7%. As the roughness exceeds the f2, and reaches between f3 to f5, the interface fracture energy shall be decreased with the increase of roughness. It shall be decreased by 98.5% to the largest extent. The concrete strength grade at the roughness section of this interface shall not exert the influence, bespeaking that while the roughness is relatively large, the huge failure of the colloid at the contact point between the fiber reinforced polymer and the concrete shall result in the loss of bonding property. The analysis result mentioned is consistent with the result that the average shearing strength tends to be in direct proportion of the failure time in the single shearing test.

Given the convergence of data, the $G_f$ and $\tau_w$ are fitted. The $G_f$ is fitted through adopting the method combining the Marquardt method and global optimization, and the $\tau_w$ is fitted through adopting the Guass2D. The fitting results are indicated as follow:

$$G_f = \frac{0.196 + 0.002 f_{ws} - 0.325 f_i}{1 - 0.001 f_{ws} - 3.684 f_i + 3.893 f_i^2} \quad (30 \leq f_{ws} \leq 50; 0 \leq f_i \leq 1), \quad R^2 = 0.97$$

![Figure 4. Variation of the Gf with fi and fc0.](image)
It is acquired through viewing the Fig 4 that the $G_f$ curve for different concrete strength grades can be approximately elevated in the preliminary stage and decreased in the follow-up stage. Three sections can be divided, viz. the A-B, B-C, C-D sections. In AB section, as the $f_i$ increases, the $G_f$ increases. Moving into the BC section, from C1 to C2, $G_f$ is significantly increased as the $f_i$ increases. In C2, the maximum $G_f$ value is acquired, and the corresponding $f_i$ equals to 0.44. Moving into C2 to C3, the $G_f$ turns out to be decreased. Reaching to D, the minimum value of $G_f$ is acquired, and the corresponding $f_i$ equals to 0.88. The process mentioned above bespeaks that the bonding effect shall not be absolutely better with the increase of roughness on the interface, but there are an extreme value and a corresponding extreme value point. For this reason, in the engineering structure, the appropriate roughness shall reinforce the interface energy and be conducive to reinforcing the engineering structure.

Additionally, it is acquired from the Fig 4 that the concrete strength grade is higher than $f_i$ in the contribution to the $G_f$, which is consistent with the recognition made by other scholars in the research towards the contribution made by the concrete strength grade.

It is acquired from Fig 4 that as $0.34 \leq f_i \leq 0.56$, the fitting is favorably realized. As $f_i=0.88$, the error is relatively bigger. The maximum error shall reach 212%, which also indicates the application range of the formula (4).

![Figure 5. Models of fracture energy](image)

From Fig 5 we can draw the opinion that the existing model, except for the Holzenkampfer and Dai et al models without considering the influence of $b_i/b_h$, the width ratio, on the interface energy, the other models all consider the influence of width ratio on the interface energy. As the width ratio $b_i/b_h \approx 0.5$, the interface energies under Yunfei-Wu et al and Niedermeier shall be higher than that of other models to 28.5%, or even higher than Lu et al model to 70%. As $b_i/b_h = 1$, the interface energies under Yun-Fei Wu et al and Niedermeier shall be lower than that of other models to 20%, or even lower than Lu et al model to 40%. Hence it is bespoken that width ratio parameter exerts the larger influence to those two models with larger discrete distribution. If FRP width ratio is 0.5, as shown in Fig 5, the interface energy shall be overestimated, posing the potential safety hazard to the engineering structure. The model proposed in this paper can be well geared into the mean sections. Both the influence of concrete strength grade on the interface energy and the roughness of concrete surface are considered. The interface energy calculated under $b_i/b_h = 0.75$, the width ratio adopted in this research, can better geared into three models, viz. Holzenkampfer, Lu et al and Dai et al. This is because the influence of width is not considered, and because the influence of concrete strength grade on the interface is approved.
4. Conclusion

(1) Surface roughness of concrete which impacts on fracture energy cannot be ignored, there exists one extremum points and extremum about fracture energy, when fi=0.44, Gf reaches its maximum which is 1.142 MPa. mm, 1.339 MPa. mm and 1.630 MPa. mm respectively.

(2) The new proposed models suggests that concrete compressive strength fcm takes higher contribution to interface the interface roughness fi.

(3) For 0.34≤ fi≤0.56, 30MPa≤ fcm≤50MPais applicable for the closed-form solution of Gf based on the experimental data, whereas for more interfacial study about lower strength and higher strength of concrete, it remains further research.

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