

# Research on Interfacial Bond-Slip Constitutive Relation Between FRP and Concrete Based on Two Parameters

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**Abstract.** The paper is to quantify and assess the roughness of 108 concrete samples with 6 kinds of interface roughness to investigate the influence of surface roughness on the bond property of FRP-concrete interface. And in order to solve the problem of so many parameters in interfacial stress-slip constitutive relation between FRP and concrete that hard to practise for engineers, so adopting shear test to establish two parameters ( $f_{c0}$ ,  $f_i$ ) constitutive relation which are more suitable for engineers' construction design. Results shows that the compressive strength ( $f_{c0}$ ) and interfacial roughness ( $f_i$ ) are the two keys who influence the interfacial bond strength; The closed-form solution of  $\tau_m$  and  $s_f$  can be solved by the two factors  $f_{c0}$ ,  $f_i$ , this method supplies a new algorithm for the interface calculation, due to the theoretical value is less than the measured values, so there is a certain safety stock to construction.

## 1. Introduction

Fiber-reinforced polymer (FRP) have been used to strengthen deficient RC structures damaged by durability issues, earthquake, fires, and unexpected loads since he 1980s. FRP based on its superior properties, such as light weight, high tensile strength, high fatigue strength, magnetic neutrality, easy of application in a confined space, and practically unlimited availability in size, geometry and dimension.

Fiber-reinforced polymer (FRP) has been widely applied to the reinforcement engineering of reinforced concrete structure (hereinafter referred to as the RC structure) since 1980. The key points of the advantage and disadvantage of RC structure reinforcement effect are based on the bonding performance of the concrete and fiber sheet interface. The interface constitutive relation is the key research content in RC interface behavior. On the interface bond stress-slip curve, local stress-slip constitutive relation is a theoretical basis to carry out other researches about interface behavior.

At present, the research methods of RC interface constitutive relation include numerical analysis and experimental data fitting [1]. The former sets a constitutive unit of a similar interface form by using numerical analysis software, and get the stress-slip relation by setting similar parameters; The latter gets FRP surface strain development process based on a large number of experimental studies [2-9], and gets local shear stress and slip distribution by using differential and integral arithmetic, in order to obtain the interface bond-slip constitutive relation. However, both numerical analysis and



experimental data fitting have the similarity with the discrete data found everywhere. Especially, the parameters building constitutive equation based on the experimental study are complex. Up to now, there has been nineteen kinds of parameters accumulated by scholars at home and abroad to describe the constitutive relation [10-19]. In the expression of the constitutive relation from domestic and foreign scholars, some using as less as a parameter (the concrete compressive strength), some using as more as twelve parameters to describe the constitutive relation, such as Brosens and Xin-Zheng Lu. Speak to constitutive model, the Savoia model is corrected from Nakaba model, and it is also based on the measured FRP strain. Therefore, from the curve shape, the constitutive relation is close to the actual situation, but there are still many discrete strain values measured due to the patch location restrictions and the randomness of aggregate below the patch. With simple interface constitutive relation expression, Savoia model is corrected based on Nakaba model, but its accuracy is not high. The constitutive relation expressed by Brosens and Xin-Zheng Lu is much more accurate than Nakaba and any other models, but with as many as twelve parameters, and some parameters are difficult to quantify and measure, making calculation complex and having no engineering application value. So, it is necessary to build a clear and simple RC interface constitutive relation expression with easily measured parameters and the accuracy which can meet the needs of engineering design.

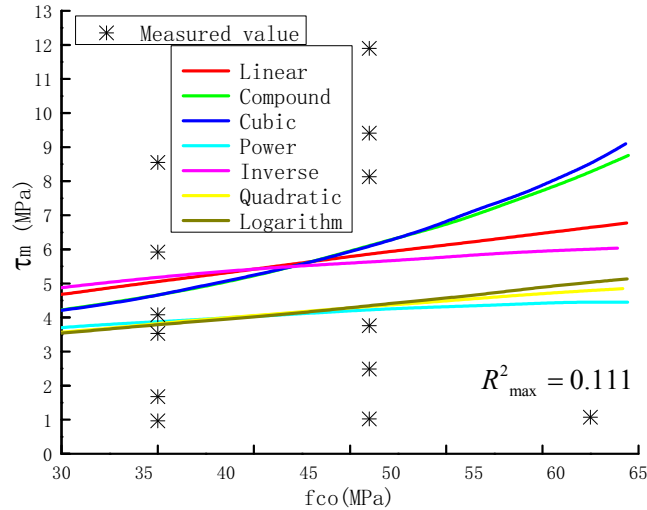
## 2. Experiment and Database

To date, an ample amount of experimental works is already available on the bonding of FRP materials to concrete. Experiments have been carried out using several different types of specimen, including single shear and double shear tests. Based on the literature survey, a database containing 118 shear tests on FRP-to-concrete interface was assembled in the current study. The database includes experiments reported by Ueda T, Dai JG, Sato Y [20], Nakaba K, Kanakubo T, Furuta T, et al [21], Wang H T, Wu G, Wu Z S, and Liu H Y [22], and Canada ISIS [23]. It is clear that the database covers a wide range of each parameter and can be expected to provide a reliable benchmark for qualifying different models to predict debonding behavior and related parameters.

## 3. The Proposed Bond Strength Model Based on the Roughness Parameter

### 3.1. The Establishment of The Single Parameter Model

Some scholars regard  $\tau_m$  as the function of only one parameter named compressive strength or tensile strength among existing models, this is due to the failure mode for the ordinary concrete surface layer peeled, also is the strength of the concrete decrease that caused debonding damage. In this paper, the research for most aggregate appeared, the situation has changed. In order to verify the single parameter that influences the interfacial constitutive curve, based on the above 118 test data, to establish  $\tau_m = f(f_{co})$ , and according to the eight kinds of functions with SPSS software data fitting, found that the maximum correlation coefficient is the quadratic function, three functions model, the  $R_{\max}^2 = 0.111$ , it indicates fitting effect is not good, as shown in figure 1.



**Figure 1.** Various functions fitted

Expand the samples, so based on the literature, adopt 118 groups of experimental data, adopt concrete compressive strength directly  $f_c$  to express  $\tau_m, s_\tau, s_f$  the, You can get:

$$\tau_m = 0.1679f_c - 0.112 \quad (1)$$

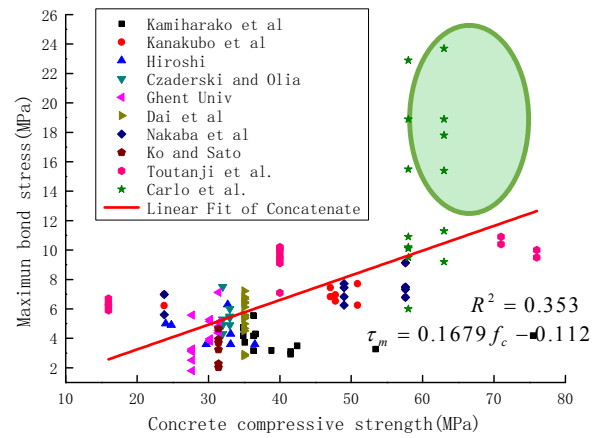
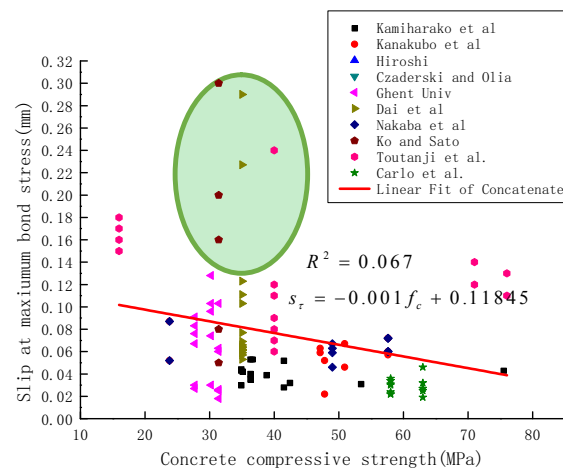
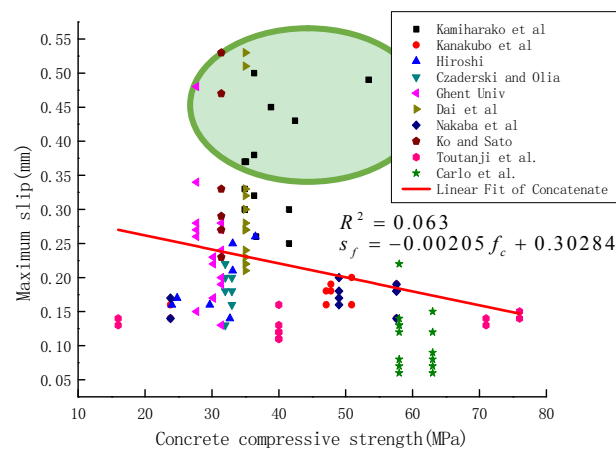
$$s_\tau = -0.001f_c + 0.11845 \quad (2)$$

$$s_f = -0.00205f_c + 0.30284 \quad (3)$$

Because when  $f_c = 0$ ,  $\tau_m$  would not negative, so  $\tau_m = 0.1679f_c$ .

As can be seen from figure 2 to 4, fitting relationship using single parameter is still not very good. Can therefore be pointed out that only with the concrete physical index to depict the interface bonding performance, it is not enough, also is not accurate.

Fitting  $R^2$  is small, on the one hand, when the sample is 41,  $R^2 = 0.05749$ ; When the sample is 80,  $R^2 = 0.11745$ ; When the sample is 118,  $R^2 = 0.25277$ ; It is clear that with the increase of the samples, the  $R^2$  increased continuously. so we can imagine: if there is enough samples, the relationship between the fitting of the curve and the test data will be significantly improved, but from the magnitude of increasing  $R^2$ , is not very ideal. On the other hand, it can be seen from the scatterplot: the number of discrete data is very large (as shown in the circle), and they are not dealt with in the fitting analysis processing, who affect  $R^2$  seriously.

Figure 2. Relationship between  $\tau_m$  and  $f_c$ Figure 3. Relationship between  $s_r$  and  $f_c$ Figure 4. Relationship between  $s_f$  and  $f_c$

### 3.2. The Establishment of the Two Parameter Model Based on the Roughness

From the 118 groups of experimental data in literature, taking out discrete data, and selecting 66 groups of experimental data effectively, using 1StOpt mathematical software to do regression analysis, given the fitting formula is convenient for application, get the following equation:

$$\begin{cases} \tau_m = \frac{f_{c0}}{10} + \frac{9.5}{1 + \left(\frac{0.4 - f_i}{0.1}\right)^2} - 5 \\ s_r = \frac{2.03 + 4.02f_{c0} - 1.52f_i + 2.76f_i^2 - 1.53f_i^3}{1 - 6.4f_{c0} + 1.49f_{c0}^2 - 1.01f_{c0}^3 + 1.98f_i - 1.63f_i^2} \\ s_f = 0.556 - 0.001f_{c0} - 0.483f_i \end{cases} \quad (4)$$

Where  $f_{c0}$  refers to the compress strength of concrete;  $f_i$  refers to the roughness value.

### 4. Validation of the proposed equation

Due to the limited available literature, at present only Ivano, et al can be referred, and because of different evaluation mechanism of the roughness, so  $f_i$  is dealt with mean value to take  $f_i$  falls from 0 to 1, the adjusted data are shown in the following table 1.

**Table 1.** Comparison between Ivano's data and proposed equation

$f_i$	$\tau_m$		$s_f$	
	Ivano	Proposed equation	Ivano	Proposed equation
0.04	1.94	2.18	0.053	0.52
0.07	2.00	2.29	0.07	0.51
0.12	2.17	2.56	0.09	0.48
0.36	2.35	9.42	0.10	0.37
0.42	3.20	10.70	0.12	0.34

Table 1 shows that when  $f_i \leq 0.12$ , fitting relationship is better, the max and min error is 18% and 12% respectively. When  $f_i \geq 0.12$ , the result is bad. The fitting relationship of  $s_r$  does not apply to Ivano data. Based on above the analysis is as follows: first of all, the evaluation mechanism of  $f_i$  is different, that resulted small  $f_i$  value from Ivano data; Secondly the important Interfacial parameters  $\tau_m, s_r$  are derived from experiment analysis whose the compressive strength of the concrete is form C30 to C50, while Ivano data is C15, so different concrete grade, especially for low strength concrete, whether practical or not is questionable; Thirdly,  $f_i$  contribute great influence to interfacial bonding property in the expression of  $s_f$  while  $f_i, f_{c0}$  are both small value in Ivano data, so the fitting formula of  $s_r$  is invalid.

In order to test the validation of the fitting formula, to do the other set supplementary experiment, the experimental data is shown in table 2.

**Table 2.** Experimental results of single shear test

Specimen s	Roughnes s	$\tau_m$ (MPa)			$s_r$ (mm)		$s_f$ (mm)		
		Experimen t	<i>Equatio n</i>	Error	Experimen t	<i>Equation</i>	Experimen t	<i>Equatio n</i>	Error
C30	0.12	5.03	4.57	10.00 %	0.003	-5.67632e- 05	0.50	0.46	8.00%
	0.23	6.48	5.94	9.00%	0.010	-6.55231e- 05	0.44	0.41	7.00%
	0.47	10.47	9.88	6.00%	0.018	-8.76679e- 05	0.31	0.29	6.00%
	0.57	6.42	5.94	8.00%	0.013	-9.75609e- 05	0.27	0.25	9.00%
	0.68	4.99	4.57	9.00%	0.010	0.00010851 4	0.21	0.19	7.00%
C40	0.88	4.05	3.90	4.00%	0.008	- 0.00012768 7	0.11	0.10	10.00 %
	0.08	5.77	5.45	6.00%	0.003	-2.35399e- 05	0.51	0.47	8.00%
	0.21	7.13	6.66	7.00%	0.010	-2.78948e- 05	0.45	0.41	9.00%
	0.37	14.51	13.32	9.00%	0.021	-3.41054e- 05	0.35	0.33	7.00%
	0.50	9.91	9.35	6.00%	0.017	-3.95891e- 05	0.30	0.27	10.00 %
	0.69	5.72	5.61	2.00%	0.010	-4.78413e- 05	0.19	0.18	8.00%
C50	0.80	5.31	5.16	3.00%	0.009	-5.25204e- 05	0.13	0.12	9.00%
	0.09	6.91	6.65	4.00%	0.003	-1.21431e- 05	0.49	0.46	7.00%
	0.18	7.75	7.38	5.00%	0.016	-1.36596e- 05	0.45	0.41	10.00 %
	0.33	12.85	12.13	6.00%	0.030	-1.65408e- 05	0.37	0.34	8.00%
	0.57	9.01	8.19	10.00 %	0.034	-2.17037e- 05	0.24	0.22	8.00%
	0.66	7.60	6.97	9.00%	0.015	-2.3699e-05	0.20	0.18	9.00%
	0.80	6.88	6.31	9.00%	0.009	-2.67433e- 05	0.12	0.11	7.00%

From table 2 can be seen that apart from  $s_r$ , the relationship between equation and experiment is very well, the error is between 4% and 10%, and the recommended equation is to be safer, convenient directly used by engineers, the important reason is the parameters in the constitutive equations greatly simplified.

For double-linear constitutive model, the improved model and parameters are as follows:

$$\left\{ \begin{array}{l} \tau = \tau_m \left( \frac{s}{s_r} \right) 0 \leq s \leq s_r \\ \tau = \tau_m \left( 1 - \frac{s - s_r}{s_f - s_r} \right) s_r \leq s \leq s_f \end{array} \right. \quad (5)$$

Where:

$$\begin{cases} \tau_m = \frac{f_{c0}}{10} + \frac{9.5}{1 + \left(\frac{0.4 - f_i}{0.1}\right)^2} - 5 \\ s_f = 0.556 - 0.001f_{c0} - 0.483f_i \end{cases} \quad (0 \leq f_i \leq 1, 35 \text{MPa} \leq f_{c0} \leq 57.5 \text{MPa}) \quad (6)$$

## 5. Conclusion

One hundred and eight single shear tests are carried out in concrete-CFRP interfaces, and different stress-slip relations of interface under different types of roughness are acquired. Additionally, the influence of roughness carried by the concrete interface on the bonding property of FRP-concrete interface is analysed. Sixty-six groups of experimental results in literatures are adopted, two parameters of interface constitutive relation is established. The following conclusions are drawn.

(1) Single parameter model is not suit for express the concrete-CFRP interface bonding performance. Its discreteness and error is larger, and not in good agreement with the test result;

(2) Two parameters ( $f_{c0}, f_i$ ) of the constitutive relation is suitable for the concrete strength from 35 MPa to 57.5 MPa, the maximum deviation is 10%, due to the parameters are greatly simplified than existing models, so the proposed equation this work is more convenient for engineering's application.

(3) Through the concrete compressive strength and interface roughness, the closed-form solution of  $\tau_m$  and  $s_f$  can be solved, this supply a new algorithm for the interface calculation, due to the theoretical value is less than the measured values, so it has a certain safety stock to construction.

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