

# Research Progress of Bond Slip at The Interface of FRP Bars and Concrete

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**Abstract:** The bond between FRP bars and concrete is the key to the strength and durability of FRP reinforced concrete members, and it is the decisive factor to make full use of the light, high strength and corrosion resistance of FRP bars. In this paper, according to the research results of bond properties of FRP bars and concrete at home and abroad, the paper analyzes four aspects, including test method of bond properties of FRP bars, bond mechanism, factors affecting bond properties of FRP bars and bond slip constitutive relationship model. The shortcomings of the existing research results and the problems to be solved are analyzed and compared comprehensively. At last, some references and suggestions are provided for the further research and application of FRP reinforced concrete structures.

**Keywords:** FRP rebar; Concrete structure; Bond behavior; Constitutive relation.

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## 1. Introduction

Practical engineering applications show that many reinforced concrete components fail to reach the specified service life due to various factors. The reason may be the lack of resistance caused by the structural design, but more is the damage caused by the durability of the structure, among which the corrosion of the steel bar is one of the important reasons for the durability of the structure. Fiber Reinforced Polymer (FRP) is gradually made into reinforcing material to replace steel reinforcement in order to enhance the durability of concrete members due to its advantages of light weight, high strength and corrosion resistance.

Since the 1980s, Europe, the United States, Japan, Canada and other countries have begun to use FRP bars instead of steel reinforcement in concrete structures, and have achieved good results in theoretical research and practical applications. The European Fib Bulletin 40 specification [1], the American ACI440.1R-15 specification [2], the Japanese JSCE-E539-1995 [3], and the Canadian ISIS Canada specification [4] provide systematic recommendations for the design of FRP-reinforced concrete structures in terms of material use, characteristic strength and bond anchorage.

Based on the current research achievements on the bond slip of FRP bars and concrete interfaces, this paper analyzes and summarizes the existing research from four aspects, including the bond slip mechanism, bond performance test methods, influencing factors and bond slip constitutive relationship model. It provides reference for the subsequent research on the bond slip between FRP bars and concrete.

## 2. Bond Mechanism

The key to the application of FRP bars to concrete structures instead of traditional steel bars lies in the adhesion between FRP bars and concrete, which is also the premise to ensure good collaborative work. Similar to the bonding mechanism between ordinary steel bars and concrete, the bonding force between FRP bars and concrete is also composed of three parts: the chemical adhesion of cement gel

and the surface of reinforcement, the friction on the contact surface of concrete and FRP bars, and the mechanical meshing force between the uneven surface of FRP bars and concrete [5]. The difference is that because FRP is made of resin as the matrix and fiber as the reinforcement extrusion, its longitudinal and transverse characteristics are controlled by fiber and resin respectively, resulting in the failure of its bond with concrete may result in the surface thread of the reinforcement being shear damage rather than concrete cracking damage, so it shows different longitudinal and transverse physical characteristics and mechanical properties from the reinforcement.

## 3. Test Method for Bonding Properties

At present, domestic and foreign scholars commonly used FRP bar and concrete bonding performance test methods are mainly center pull-out test and beam test two, of which the pull-out test is divided into the Losberg pull-out test and the standard pull-out test specified in GB50152-92 [6]. The schematic diagram is as follows:

Compared with the standard pullout test, the difference between Losberg pullout test and standard pullout test is that the unbonded section is set at the free end and the loaded end respectively, which can avoid stress concentration during loading and thus affecting the bond test results. The advantage of the beam test is that it can better simulate the bonded anchorage state of FRP bars at the beam end. As can be seen from the figure, the specimen of the beam test is made in two halves, and the two specimens are connected with steel hinges in the middle of the specimen with a clear force arm, which is helpful for the accurate calculation of the bonding force, and the same as the Losberg pullout test, the loaded and supported ends of the beam test are also set up with unbonded segments respectively. Considering that the beam test is more complicated to fabricate, while the center pull-out test device is simple and easy to operate and analyze, most scholars at home and abroad generally adopt the center pull-out test to measure the bonding performance of FRP bars with concrete.

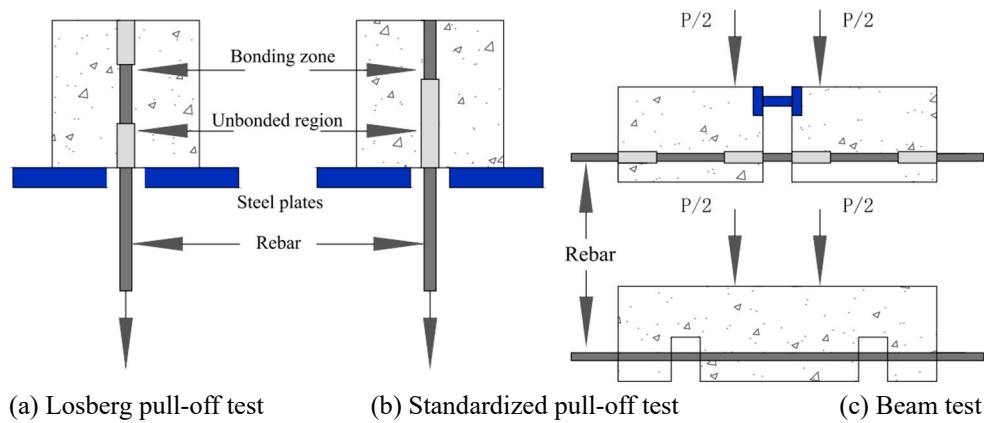


Figure 1. Bonding performance test method

## 4. Factors Affecting Bonding Properties

### 4.1. Concrete strength

The bond between the steel bar and concrete is proportional to the square root of the compressive strength of concrete within a certain range. However, due to the physicochemical properties and mechanical properties of FRP bars different from those of steel bars, their bond strength with concrete is also different compared to that of steel bars.

Achillides et al [7] analyzed 130 FRP-reinforced concrete specimens by pullout tests, and the test results showed that when the concrete strength is greater than 30 MPa, the bond damage of FRP-reinforced concrete occurs on the surface of the reinforcement, and at this time, increasing the concrete strength does not significantly improve the bond performance. When the concrete strength is less than 15MPa, the bond damage is the same as that of ordinary reinforced concrete, which is greatly affected by the concrete strength. Davalos et al [8] also obtained similar conclusions as above: when the concrete strength is lower, the bond damage between FRP reinforcement and concrete manifests itself in the surface of the concrete being destroyed, and when the concrete strength is higher, the interfacial bond damage manifests itself in the surface of the FRP reinforcement being damaged, and the concrete strength has less influence on the bond at this time.

Prof. Gao Danying of Zhengzhou University and Prof. B. Brahim of Shebrooke University, Canada [9] found through the comparative test of bonding performance of FRP bars with ordinary and high-strength concrete that the relationship between bond strength of reinforced concrete and compressive strength of concrete is still difficult to draw a definite conclusion whether the relationship between bond strength of reinforced concrete and compressive strength of concrete is fully applicable to FRP bar concrete, mainly due to the fact that FRP bars are different from the steel bars in terms of differences in the surface. The main reason is that FRP reinforcement is different from steel reinforcement in terms of surface and pullout mechanism. Xiao Jianzhuang et al. [10] studied the bonding performance of GFRP bars with seawater and sea sand recycled concrete, and the test results showed that the bonding performance of GFRP bars with seawater and sea sand recycled concrete was enhanced with the increase of concrete compressive strength.

### 4.2. Bonding Length

The bond length has a large effect on the bonding performance of FRP reinforcement to concrete, Tighiouart et al [11] concluded from 64 beam tests and 18 pullout tests that with the same diameter of reinforcement, the average bond strength decreases as the bond length increases and the applied load approaches the tensile strength of the reinforcement, and the smaller the bond length, the higher the bond strength of the specimen.

Okelo et al [12] also have similar and basically consistent conclusions: that is, in the bond length is small, the average bond strength of FRP reinforcement and concrete and the actual maximum bond stress is close to; when with the increasing bond length, FRP reinforcement and concrete in the force after the bond stress will become uneven, at this time, the ratio of the average bond strength and the actual maximum bond stress becomes smaller, presenting an inverse relationship between the increase in bond length of FRP reinforcement and the bond stress.

Yang Chao et al [13] pointed out through the study of the bond properties of BFRP tendons and coral concrete that: the specimens with a bond length of 7.5d (except for the diameter of 12mm) showed splitting damage to their bond with coral concrete, and the rest of the specimens with different bond lengths showed pullout damage, and the maximum average bond stress decreased significantly with the increase of the diameter and the length of the bond.

### 4.3. Diameter of FRP bars

The increase in diameter of FRP reinforcement due to Poisson effect, shear hysteresis, etc. is not conducive to the enhancement of bond with concrete. Ehsani et al [14] showed that the ultimate tensile strength of GFRP reinforcement is closely related to the diameter of the reinforcement, and as the diameter of the GFRP reinforcement increases, the ultimate tensile strength decreases rapidly. This decrease is attributed to the "shear hysteresis" phenomenon, which is related to the tensile force of the reinforcement fibers and the bond between the reinforcement and the contact surface. Baena et al [15] showed experimentally that an increase in the diameter of the FRP reinforcement leads to a decrease in the bond strength. During the drawing process, the peak value of bond stress moved gradually from the loading end to the unloading end, while the value of bond stress at the loading end decreased significantly, and the stress was reduced in a nonlinear distribution along the bar direction, and the bond strength of FRP concrete specimens decreased with the increase in the

diameter of the reinforcement.

Hao Qingduo [16] et al. studied 90 concrete specimens with GFRP bars through experiments, and concluded that the bond strength between GFRP bars and concrete decreases with the increase of bar diameter, and analyzed the reason for this is that the increase of bar diameter makes the relative bond area with concrete smaller, resulting in the emergence of shear hysteresis, which is detrimental to the improvement of bond strength. Song Zepeng [17] and others chose different diameters of threaded GFRP bar to study the bond performance between it and concrete, the test results show that: the bond strength increases with the increase in the diameter of the GFRP bar, the diameter of 8, 12mm threaded GFRP bar pullout specimen damage mode is mainly when the pullout damage, while the diameter of 16mm GFRP bar is mainly splitting damage.

#### 4.4. Surface form of FRP bars

Similar to steel reinforcement, the surface form of FRP reinforcement has a large impact on it. However, it is different from the surface treatment as well as the modulus of elasticity and strength of steel reinforcement, so it is affected in a different way. Xue Weichen [18] et al. concluded through multiple sets of pullout and beam tests that almost all the damages of FRP-reinforced concrete specimens were due to the damage of the outer wrapped ribs of the FRP reinforcement or the peeling off from the core. Therefore, the bond strength between FRP reinforcement and different environmental media mainly depends on the bond strength between FRP and surface ribs at the core.

Saleh et al [19] pointed out through the bond test of GFRP reinforcement with high strength concrete that: bond failure of GFRP reinforcement is usually caused by damage to the surface of the reinforcement, and spiral-wound GFRP reinforcement showed better bond performance than that of sand-adhered GFRP reinforcement. Solyom et al [20] investigated the effect of different FRP reinforcement surface forms, including sand-adhered, spiral-wound, spiral-wound with sand-adhered, ribbed, and shallow-threaded on the bond performance of the GFRP reinforcement. The effect of different FRP reinforcement surface forms on the bond performance was investigated, and the test results indicated that the bond strength between FRP reinforcement with sand-bonded surface and concrete was relatively high, and the bond strength of FRP reinforcement with shallow threads was relatively small.

#### 4.5. Concrete protection layer

The thickness of the protective layer of concrete affects its damage mode, when the thickness of the protective layer is small, the FRP reinforcement and concrete are susceptible to splitting damage, and when the thickness of the protective layer of concrete becomes large, the damage mode will change from splitting damage to pullout damage.

Aly et al [21] tested six full-size beams reinforced with GFRP bars and found that the bond strength of the specimens increased by about 27% when the protective layer of concrete was increased from one to four times the diameter of the bars, indicating that the proper protective layer thickness can lead to higher load carrying capacity of the specimens.

Wang Lei et al [22] investigated the bond properties of GFRP reinforcement and coral concrete through experiments and pointed out that the average bond stress of GFRP reinforcement-coral concrete decreased significantly with

phase. When the relative protective layer thickness is small, the specimen undergoes splitting damage; when the relative protective layer thickness is large, with the increase of bond length, the form of damage gradually changes from the tendon being pulled out to the tendon fracture.

Zhao Jun [23] et al. pointed out through 60 pullout tests of BFRP reinforcement low-polymer concrete that, within a certain range, increasing the thickness of the concrete protective layer is favorable to improve the bond strength between BFRP reinforcement and geopolymer concrete, and the effect becomes smaller when it exceeds this range, and the damage mode changes from cleavage damage to pullout-split or pullout damage with the increase of the protective layer.

In addition to the above influences, changes in ambient temperature, location of FRP reinforcement in concrete, and damage patterns may all have an effect on bond performance.

### 5. Bond Slip Constitutive Model

In the numerical analysis of FRP-reinforced concrete members, it is necessary to consider the strength criterion of bond damage and the bond-slip intrinsic relationship model. At present, the models studied by domestic and foreign scholars are shown in Table 1-1.

Bertero-Popov-Eligehausen (BPE) model is a constitutive relationship model of bond slip between deformed steel bars and concrete proposed by Eligehausen et al[24], which was later successfully applied to concrete members with FRP bars. However, the horizontal section of BPE model can not accurately describe the interface mechanical behavior of FRP reinforced concrete. The results obtained by this model are relatively discrete, which causes some limitations in the subsequent calculation. The improved BPE (MBPE for short) model is an amendment to the BPE model proposed by Cosenza [25] through the comparative analysis of a large number of bond test curves between FRP bars and concrete, and the content of the horizontal segment inconsistent with the reality in the BPE model is removed. The optimized BPE model has a general adaptability to bonding most FRP reinforced concrete members, and the structure is simple and easy to apply. However, the MBPE model has a rough description of the microslip and descent stages. In addition, the model does not consider the effect of different reinforcement types and diameter changes.

In 1994, Malvar[26] proposed for the first time a constitutive relationship model of bond slip between GFRP bars and concrete through a large number of bond tests between FRP bars and concrete. When  $s=0$ , the slope of this model is limited, which is far from the actual bond phenomenon, and the formula is complex, which is rarely applied. Cosenza-manfredi-realfonzo (CMR for short) model is a relationship model of the rising section of the bond slip curve between FRP bars and concrete given by Cosenza et al[27]. considering the actual use stage. The structure of CMR is relatively simple, and the initial slope is infinite. However, there are decreasing segments and residual segments that lack S-curves, so in practice CMR will have some limitations. After summarizing the relevant  $\tau$ - $u$ -S constitutive model, Gao Danying [28] et al proposed a  $\tau$ - $u$ -S continuous curve model, which has a smooth and continuous curve at the maximum bonding stress, which accords with the practical engineering application phenomenon and has strong applicability.

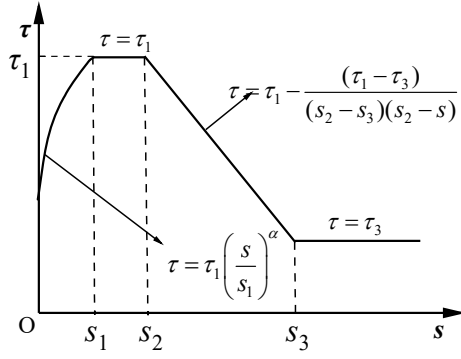


Figure 2. BPE model

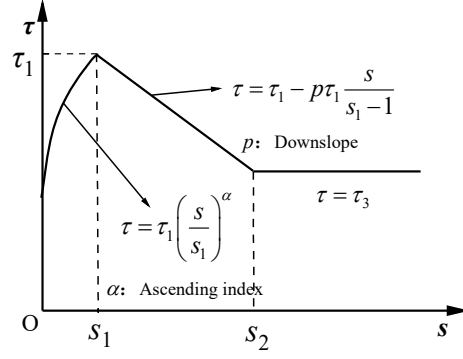


Figure 3. MBPE model

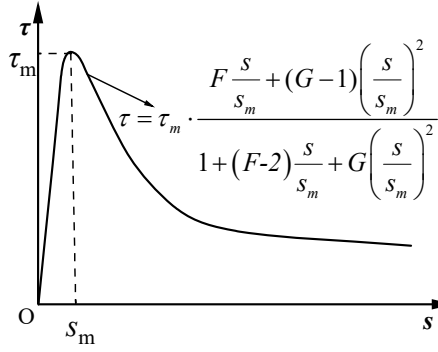


Figure 4. Malvar model

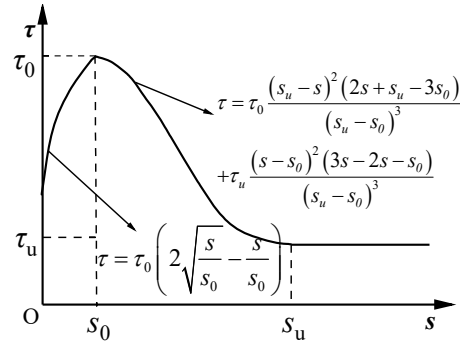


Figure 5. Continuous curve model

Table 1. Bond slip constitutive relationship model

	Mathematical model	Key parameters and notes
BPE model	$\tau / \tau_1 = (s / s_1)^\alpha, s \leq s_1$ $\tau = \tau_1, s_1 \leq s \leq s_2$ $\tau = \tau_1 - \frac{(\tau_1 - \tau_3)}{(s_2 - s_3)(s_2 - s)}, s_2 \leq s \leq s_3$ $\tau = \tau_3, s_3 < s$	$\tau_1$ denotes the peak bond stress; $s_1$ is the bond slip corresponding to the peak stress; $s_2$ 、 $s_3$ 、 $\tau_3$ need to be determined by test; $\alpha$ denotes a constant not greater than 1.
MBPE model	$\tau / \tau_1 = (s / s_1)^\alpha, s \leq s_1$ $\tau = \tau_1 - p\tau_1 \frac{s}{s_1 - 1}, s_1 \leq s \leq s_2$ $\tau = \tau_3, s_2 < s$	$\tau_3$ is the friction component, P is the parameter associated with the descent section, $\alpha$ is the area A under the rising section of the theoretical curve of $\tau$ -s is equal to the area under the actual curve, $\alpha = (\tau_m \cdot s_m / A\tau_1) - 1$ .
CMR model	$\tau = \tau_m \left[ 1 - e^{(-s/s_r)} \right]^\beta, s \leq s_1$	$\tau_m$ is the peak bond strength, $s_r$ 、 $\beta$ are determined experimentally.
Malvar model	$\tau = \tau_m \frac{F(s/s_m) + (G-1)(s/s_m)^2}{1 + (F-2)(s/s_m) + G(s/s_m)^2}$	$\tau = f_t \left[ A + B \left( 1 - e^{-C\sigma/f_t} \right) \right]$ $s_m = D + E\sigma$
Continuous curve model	$\tau = 2 \left( \tau_0 \sqrt{s/s_0} - s/s_0 \right), 0 \leq s \leq s_0$ $\tau = \tau_0 \frac{(s_u - s)^2 (2s + s_u - 3s_0)}{(s_u - s_0)^3} + \tau_u \frac{(s - s_0)^2 (3s - 2s - s_0)}{(s_u - s_0)^3}, s_0 \leq s \leq s_u$	$\tau_0$ - Bond strength at peak point; $s_0$ - The amount of slip corresponding to the bond strength at the peak point; $\tau_u$ - Residual bond strength; $s_u$ - The amount of slip corresponding to the residual bond strength.

## 6. Conclusions

In recent years, scholars at home and abroad have carried out extensive experimental and theoretical research on the

bond performance of FRP bars and concrete. Based on the analysis of relevant studies, this paper draws the following conclusions and suggestions:

(1) Currently commonly used bonding performance test

methods include center pull out test and beam test. The center pull-out test specimen is simple to make and easy to measure, so it is the test method adopted by most researchers at present. The beam test takes into account the stress state of FRP bars in actual components when they are in service, but the production of specimens is complicated, the measurement and collection of data is difficult, and the cost is high.

(2) The factors affecting the bond slip performance of FRP and concrete mainly include: the diameter of FRP bars; Bond length; Concrete strength grade; Surface form of FRP bars; Concrete protective layer and lateral restraint.

(3) The bond slip constitutive models of FRP bars and concrete mainly include: BPE model; mBPE model; malver model; CMR model and continuous curve model.

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