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A Review of the Bond Behavior between Concrete and Deformed Rebar

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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Review Article

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ABSTRACT

As a composite structure, the most important performance of the reinforced concrete structure is the bond behavior between them. Good bond behavior is the key to ensuring the service performance of reinforced concrete structures, which affects the performance of the structure at various stages in its life cycle. However, in the actual structural analysis, it is generally believed that the two do not produce relative slips, resulting in some differences between the analyzed structure and the actual engineering situation. At present, many scholars all over the world have used different test methods, comprehensively considered various factors affecting the bond behavior between deformed rebar and concrete, and obtained many conclusions. In this paper, based on the relevant research results of many scholars, starting from the bond mechanism, the experimental research method of the bond behavior, and the influencing factors of the bond behavior, a detailed review of the research status of the bonding performance of reinforced concrete is carried out. It is hoped that it can provide a reference to scholars that will study the bond behavior of reinforced concrete in the future.

Keywords: Reinforced concrete structures; bond strength; bond-slip; repeated loading.

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1. INTRODUCTION

The basic condition for deformed rebar and concrete to form a composite structural material is that there is a reliable bond behavior between them. Bond behavior is a complex interaction between deformed rebar and concrete. In reinforced concrete structures, external loads rarely act directly on the deformed rebar, and the force transfer and deformation coordination performance between the deformed rebar and the concrete can only be achieved by bond. The macro effect of bond is a shear force. The plane-section assumption of the bending theory of reinforced concrete is valid if only the bond is effective between the two materials. On the one hand, the bond behavior has an important influence on the cracking, deflection, ultimate bearing capacity, and internal force distribution of components. On the other hand, under the action of Previous studies have achieved a preliminary understanding of the deterioration of bond performance under repeated loading, but the bond-slip constitutive model and bond fatigue life prediction model of reinforced concrete is still lacking. When most scholars study the bonding performance under repeated load, the external load often acts directly on the steel bar, which is inconsistent with the actual situation of the project. Follow-up studies can use lap beam specimens to study the deterioration of bond performance under repeated load, the bond behavior is gradually degraded, which leads to the increase of deformed rebar slip. Therefore, only good bond behavior can make the reinforced concrete structure give full play to its mechanical properties.

Many scholars have carried out a series of experimental studies on the bond behavior between deformed rebar and concrete. Due to the complex force transfer mechanism between the deformed rebar and the concrete interface and the different test methods of many influencing factors, the test data are discrete. To sum up, this paper discusses the bond mechanism, the experimental research method of bond behavior, and the influencing factors of bond behavior, and provides a reference to the research on bond behavior between deformed rebar and concrete.

2. BOND MECHANISM

2.1 Definition of Bond Stress

The bond stress between deformed rebar and concrete consists of three parts: chemical adhesion, friction, and mechanical interlock [1]. The chemical adhesion is produced by the hydrogel in the concrete on the surface of the deformed rebar, which is mainly related to the properties of the cement and the roughness indicated by the deformed rebar. Frictional resistance occurs when the concrete shrinks or the load and external force exert radial pressure on the deformed rebar, and there is a tendency for sliding or relative sliding between the two. The magnitude of the frictional resistance depends on the radial pressure of the concrete on the deformed rebar and the friction coefficient between them. Mechanical interlocking refers to the mechanical interlocking effect of the ribs of the deformed rebar and the concrete, i.e. the longitudinal component of the oblique pressure exerted by the concrete on the rebar surface. Influence of splitting strength of concrete on the extreme value of mechanical bite force [2]. At the initial stage of loading, the bond stress of deformed rebar is mainly composed of chemical adhesive and frictional. When the deformed rebar is deformed or the local steel bar is slipped, the chemical adhesion force is destroyed, and the friction resistance and mechanical bite force begin to play a role. When the external force is less than a certain value, the minimum change of friction resistance can be considered a fixed value. When the external force reaches a certain value, the friction resistance begins to decrease. The change of mechanical bite force can be divided into two stages, increasing gradually to a certain value and then decreasing [3].

The composition of bond stress is very complex. To simplify the calculation of bond stress, some scholars [4-8] use the concept of average bond stress to describe the bond strength between deformed rebar and concrete. When the bond length is short, it can be assumed that the bond stress is evenly distributed in the bond section. The expression is as follows:

$$\tau = \frac{P}{\pi d L} \quad (1)$$

where τ is the average bond stress between deformed rebar and concrete, P is the external load, d is rebar diameter, L is the length of the bond length. The average bond stress for bond failure is called average bond strength.

2.2 Definition of Bond-Slip Relationship

In 1987, Shima et al. [9] proposed to use bond stress-slip-steel strain to describe the bond-slip relationship. Concrete specimens with an anchorage length of 50d were studied by pull-out tests. It was found that the bond-slip relationship was significantly affected by steel strain. Considering the effects of steel strain, diameter, and concrete strength, a bond slip constitutive model is proposed. The model is given by Eqs. (2)~Eqs. (4). Xu et al. [10] conducted pull-out tests on 334 reinforced concrete specimens. The influencing factors include concrete strength, cover thickness, and stirrup ratio. They divided the bond-slip process into five stages according to different stress mechanisms: micro-slip stage, slip stage, split stage, drop stage, and residual slip stage. Finally, based on the regression analysis of the test results, formulas of characteristic strength and bond-slip constitutive relation are obtained (Eqs. (5)~Eqs. (9)). Xu et al. also obtained the position function by measuring the distribution law of the bond stress of deformed steel bars along the length of grade section (Eqs. (10)), and further established the bond-slip constitutive relation considering the influence of position (Eqs. (11)).

$$\tau(f_c,\ s,\ \varepsilon_s,\ d_b) = \tau_0(f_c,\ s,\ d_b) \cdot g(\varepsilon_s) \quad (2)$$

$$\tau(f_c,\ s,\ d_b) = 0.73 \cdot f_c \cdot [\ln(1 + 5000 \cdot \frac{s}{d_b})]^3 \quad (3)$$

$$g(\varepsilon_s) = \frac{1}{1+\varepsilon_s \cdot 10^5} \quad (4)$$

where f_c is the compressive strength of concrete, ε_s is the strain for steel, τ_0 is the reference value for bond stress, $g(\varepsilon_s)$ is the reduction factor.

$$\tau_s = 0.99 f_t \quad (5)$$

$$\tau_{cr} = (1.6 + 0.7\frac{c}{d}) f_t \quad (6)$$

$$\tau_u = \left(1.6 + 0.7\frac{c}{d} + 20\rho_{sv}\right) f_t \quad (7)$$

$$\tau_r = 0.98 f_t \quad (8)$$

$$\tau = \begin{cases} \tau_s\sqrt{\frac{s}{s_s}} & (0 \le s \le s_s) \\ k_1 + k_2\sqrt{s} & (s_s \le s \le s_{cr}) \\ k_3 + k_4 s + k_5 s^2 & (s_{cr} \le s \le s_u) \\ \tau_u - \frac{\tau_u - \tau_{cr}}{s_{cr} - s_u}(s - s_u) & (s_u \le s \le s_{cr}) \\ \tau_r & (s \ge s_r) \end{cases} \quad (9)$$

$$\psi(x) = \begin{cases} 1.35[1 - (1.25\frac{x}{l_a})^2] & (x \le 0.8 l_a) \\ 1.35\sqrt{1 - (5\frac{x}{l_a} - 4)^2} & (x > 0.8 l_a) \end{cases} \quad (10)$$

$$\tau(x) = \tau \cdot \psi(x) \quad (11)$$

where f_t is the tensile strength of concrete； $\tau_s, \tau_{cr}, \tau_u, \tau_r$ are internal crack strength, splitting strength, ultimate strength, and residual strength, their corresponding slips are s_s , s_{cr} , s_u , s_r . k_1,k_2,k_3,k_4,k_5 are undetermined coefficients; ρ_{sv} is the transverse stirrup ratio.

2.3 Failure Modes of the Bond

The bond failure between deformed rebar and concrete can be divided into splitting failure, pull-out failure, and yield failure. Longitudinal splitting cracks occur when transverse ribs cannot resist the circumferential tensile stress produced by squeezing the surrounding concrete due to the small thickness of the cover or other forms of transverse restraint. Cracks develop on the surface of the member, causing the concrete bond to split before the deformed rebar is pulled out. When the concrete cover is large enough or other forms of lateral restraint enough to resist the transverse ribs by squeezing the concrete around the ring tensile stress, the deformed rebar is subjected to a greater constraint, and the concrete between the transverse ribs is destroyed by the shear force, resulting in the deformed rebar is directly pulled out from the concrete. When the bond length reaches a certain requirement, the failure mode is that the deformed rebar is broken and no obvious slip occurs. The ultimate bond strength is determined by the ultimate tensile strength of the steel bar.

3. EXPERIMENTAL RESEARCH METHOD OF THE BOND BEHAVIOR

Research on bond behavior between deformed rebar and concrete has always been a hot research direction. Due to the complexity of the bond problem, relevant scholars have done a lot of research on this issue, but have also put forward a variety of test methods to study the bond problem. At present, the commonly used test methods to study the bond behavior are the center pull-out test, beam end test, and beam test.

The Center pull-out test (Fig. 1) is the most widely used bond test method in the world. Many scholars [11-16] use this method to study bond behavior. The advantage of the central pull-out test is that the test piece is easier to make than the test piece used in other test methods, the production cost is lower, the loading is convenient and the test data is easier to measure.

So the test can set a large number of parameters to qualitatively analyze the factors affecting the bonding performance. In this method, the steel plate is generally set at the concrete at the loading end as a constraint. The steel plate will limit the cracking of the concrete, so the bond strength measured by the central pull-out test is higher. In addition, the external load of this test directly acts on the deformed rebar, the deformed rebar is tensioned and the concrete is compressed, which is inconsistent with the structural stress state in practical engineering (most of the external loads act on the concrete and both the deformed rebar and the concrete are tensioned or compressed).

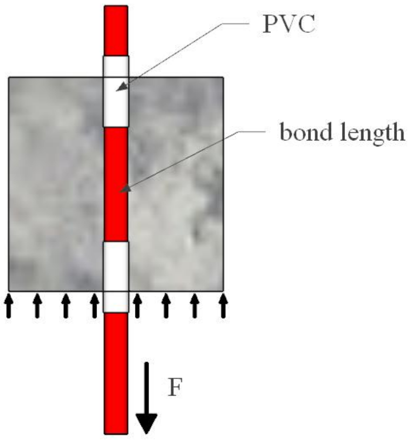

Fig. 1. Schematic illustration of a concentric-pullout specimen

The beam-end test is mainly used to simulate the beam-end anchorage test, as shown in Fig. 2. The beam-end test is often used to simulate the influence of pressure, bending moment, and shear force on the bonding performance of the bearing, and is suitable for studying the anchorage bonding problem of the steel bar in the shear span area. It is an ideal test method, which is in good agreement with the structural stress state in practical engineering. Chana [17] first proposed a beam-end test. After that, some scholars [18-20] improved the beam-end specimens based on this test and proposed other forms of beam-end specimens. Lin et al. [21] studied the bond behavior between concrete and corroded steel bars under repeated loading based on a beam end test. Based on the test results, it is found that if the geometric size, constraint position, and bond length of the specimen are not properly designed, shear failure or insufficient bond failure will occur [22].

The beam test is an ideal bonding test method. The specimens commonly used in the beam test are divided into three types : (a) full-beam specimens with two half-beams connected by steel hinges [23,24] (Fig. 3). (b) beam-end anchorage specimens with slotted shear spans [25] (Fig. 4). (c) beam-type specimens with anchored deformed rebar in pure bending sections [26-29] (Fig. 5). The beam test can simulate the real stress state of flexural members and reflect the real bonding state. Compared with the other two types of specimens, the beam specimen is more complex, more expensive, and prone to shear failure, so it is necessary to configure appropriate stirrups.

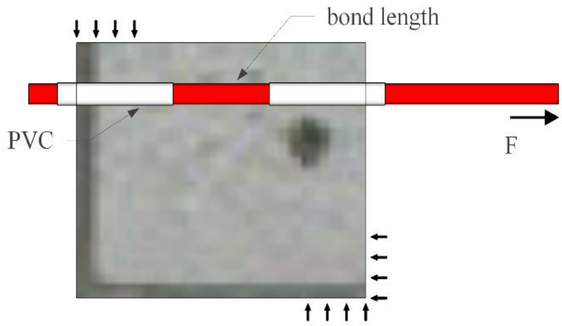

Fig. 2. Schematic illustration of a beam-end specimen

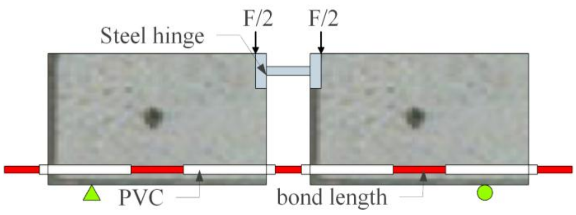

Fig. 3. Schematic illustration of beam specimen for bond tests

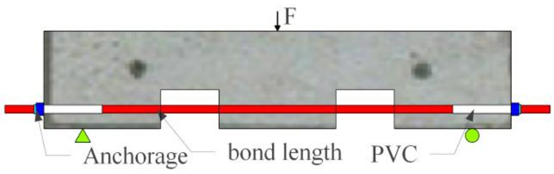

Fig. 4. Schematic illustration of beam anchorage specimen for bond tests

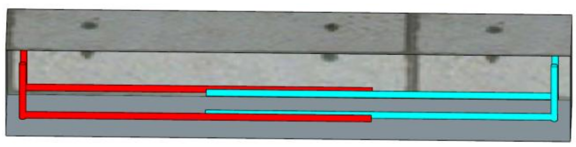

Fig. 5. 3D Schematic illustration of splice beam specimen for bond tests

4. INFLUENCING FACTORS OF THE BOND BEHAVIOR

According to previous studies, the main factors affecting the bond behavior can be roughly divided into the following :

1) Strength grade of concrete. Studies have shown that [30,31] bond strength and concrete strength were positively correlated bond strength depends mainly on the tensile strength of concrete. With the increase of concrete strength grade, the water-cement ratio decreases so that the concrete is dense, and the chemical adhesive force and mechanical bite force between concrete and deformed rebar increase, thus increasing the ultimate bond strength.

2) Concrete cover thickness and deformed rebar spacing. The spacing between the concrete protective layer and the deformed rebar gradually increases, and the failure mode gradually changes from the concrete splitting failure to the deformed rebar pull-out failure. The reason [32] is that when the concrete protective layer is small, the concrete around the deformed rebar is prone to horizontal cracks, resulting in a decrease in the splitting tensile capacity of the concrete and a decrease in the bond strength.

3) Diameter of deformed rebar, rib spacing, and bond length. Studies have shown that [33] the bond strength decreases with the increase of deformed rebar diameter and the slip between deformed rebar and concrete increases. The rib height and rib spacing also affect the bond strength. To comprehensively consider the influence of the diameter and geometric form of the deformed rebar on the bond behavior, the American Concrete Institute defines the relative rib spacing :

$$R_r \approx \frac{h_r}{s_r}\left(1 - \frac{\sum gaps}{\pi d_b}\right) \tag{12}$$

where h_r is the rib height of deformed rebar, s_r is the rib spacing of deformed rebar. The bond strength decreases with the increase of relative rib area. When the bond length is short, the bond stress is approximately evenly distributed. As the bond length increases, the bond stress is averaged over a larger length, so that the average bond strength is reduced [8].

4) The stirrup ratios. The role of stirrups is to provide lateral constraints for concrete after the splitting of the concrete protective layer. Increasing the stirrup ratio can improve the bond strength to a certain extent. However, when the stirrup ratio is too large, the bond strength no longer increases with the increase of the stirrup ratio [34].

5) Load form. Lin et al. [35] designed 43 eccentric pull-out specimens and studied the bond behavior of corroded reinforced concrete under monotonic and repeated loading. The results show that the residual slip between deformed rebar and concrete accumulates under repeated loading, and the increase in stress level and loading times will lead to the increase of residual slip. The bond strength of the repeated loading specimens did not decrease significantly compared with the monotonic loading specimens, and the effect of repeated loading on the bond strength was negligible. Oh et al. [36] also based on experimental results found that compared with monotonic loading, if fatigue failure does not occur in constant amplitude cyclic loading, the previous repeated loading has no negative effect on bond strength. In addition, they found that the residual slip increases approximately linearly with the logarithm of the number of repeated loadings Therefore, based on the above findings, they derived the bond fatigue life prediction formula and the local bond stress-slip constitutive model after repeated loading. Edwards et al. [37] studied the bond-slip behavior between deformed rebar and concrete after nine times of lateral loading in the 1970s. The test shows that under the action of fatigue load, the unrecoverable residual slip will occur between the deformed rebar and concrete. Due to the different loading and unloading paths, the bond-slip curve forms a hysteresis curve. With the increase in fatigue times, the hysteresis curve continues to move to the right and the movement rate continues to slow down. They further pointed out that the bond performance between steel and concrete is mainly affected by the loading amplitude and loading times. Rehm et al. [38] studied the bond fatigue performance of reinforced concrete and found that when the lower limit of fatigue load is constant, the number of cycles of fatigue load will increase with the decrease of the upper limit of load. They proposed that mean stress and stress range can be used as parameters to describe fatigue life under fatigue loading. The test also found that the concrete strength and the diameter of the steel bar did not affect the bond fatigue life. The peak bond stress and the corresponding slip value of the specimen after repeated loading did not change significantly compared with the monotonic loading specimen. Finally, when the

residual slip exceeds the slip value corresponding to the peak bond force under monotonic loading, the residual slip increases sharply until the pull-out bond failure occurs. Therefore, Balazs [39] suggested that the slip value corresponding to the peak bond force under monotonic load can be used as a criterion for judging the failure of bond fatigue failure. With the load level and the number of load cycles as parameters, the slip growth law, bond-slip constitutive model, and the number of loading cycles corresponding to bond fatigue failure between concrete and deformed steel bars under repeated load can be studied.

6) Other factors. Such as stress state around concrete, loading rate, steel yield, and other factors [40].

5. CONCLUSIONS

In this paper, the research results of the bond-slip behavior of reinforced concrete are analyzed from three aspects: bond mechanism, the experimental research method of bond performance, and influencing factors of bond performance. The methods of relevant experimental research and the factors affecting bond behavior are introduced, which provides a reference for subsequent researchers.

1) Many scholars have carried out a large number of experimental studies on various factors that affect bond behavior. However, due to the complexity of the bond interface between deformed rebar and concrete, the discreteness of the test data, and the difference in the test conditions, the bond-slip constitutive relationship proposed by scholars is often only applicable to specific situations. The subsequent research can start from the theoretical aspect and comprehensively consider various factors to establish a more accurate and extensive bond-slip constitutive model.

2) Previous studies have achieved a preliminary understanding of the deterioration of bond performance under repeated loading, but the bond-slip constitutive model and bond fatigue life prediction model of reinforced concrete is still lacking. When most scholars study the bonding performance under repeated load, the external load often acts directly on the steel bar, which is inconsistent with the actual situation of the project. Follow-up studies can use lap beam specimens to study the deterioration of bond performance under repeated load.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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