JURNAL INFOMANPRO
p-ISSN 2460-9609
e-ISSN 2774-7956

https://ejournal.itn.ac.id/index.php/infomanpro
vol.14 No.1 Tahun 2025 , pp. 9-16

An Examination of the Bond Characteristics between Concrete and Deformed Reinforcing Bars

Danang Hadi Nugroho[1], Danang Wijanarko[2] dan Lutfan Anas Zahir[3]
[1,2,3]*Program Studi S1 Teknik Sipil, Fakultas Teknik, Universitas Tulungagung*
Alamat korespondensi :
[1]*email: danangmarkko@gmail.com*
[2]*email: danangwjnrk11@gmail.com*
[3]*email: lutfananas@gmail.com*

ABSTRACT

The most critical performance of a reinforced concrete composite structure is the binding behavior between its components. Optimal bond behavior is essential for guaranteeing the service performance of reinforced concrete structures, influencing the structure's performance throughout its life cycle. In practical structural analysis, it is commonly accepted that the two do not generate relative slippage, leading to discrepancies between the studied structure and the real engineering conditions. Currently, numerous scholars worldwide have employed diverse testing methodologies, thoroughly examining various aspects influencing the binding behavior between bent rebar and concrete, resulting in numerous results. This paper provides a comprehensive review of the research status regarding the bonding performance of reinforced concrete, grounded in the pertinent findings of various scholars. It examines the bond mechanism, the experimental methodologies for assessing bond behavior, and the factors influencing this behavior. It is anticipated that it will serve as a reference for scholars examining the bond behavior of reinforced concrete in the future.

Keywords: Reinforced concrete buildings; bond strength; bond-slip; cyclic loading

INTRODUCTION

The fundamental requirement for deformed rebar and concrete to constitute a composite structural material is the establishment of a dependable link between the two. The bond behavior represents a complicated interaction between deformed reinforcement bars and concrete. In reinforced concrete constructions, external loads seldom directly impact the deformed rebar; the transmission of forces and coordination of deformations between the deformed rebar and the concrete is solely facilitated by bond. The macro impact of a bond is a shear force. The plane-section assumption in the bending theory of reinforced concrete holds true only when the link between the two materials is effective. The bond behavior significantly affects cracking, deflection, ultimate bearing capacity, and internal force distribution of components. Conversely, prior research has provided an initial comprehension of the degradation of bond performance under cyclic loading; nonetheless, a bond-slip constitutive model and a bond fatigue life prediction model for reinforced concrete remain deficient. In the majority of scholarly investigations regarding bonding performance under cyclic loading, the external load typically exerts direct pressure on the steel bar, which does not align with the actual conditions of the project. Subsequent investigations may utilize lap beam specimens to investigate the degradation of bond performance under cyclic loading, as the bond behavior progressively deteriorates, resulting in an increase in the slip of deformed rebar. Consequently, optimal bond performance is essential for the reinforced concrete structure to fully exhibit its mechanical capabilities.

A multitude of researchers have conducted a number of experimental investigations on the binding behavior between bent rebar and concrete. The intricate force transfer process between the deformed rebar and the concrete interface, along with the varied testing methodologies of numerous contributing elements, results in discrete test data. This work elucidates the bond mechanism, the experimental methodology for investigating bond behavior, and the factors influencing bond behavior, so offering a reference for research on the bond behavior between deformed rebar and concrete.

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BOND MECHANISM

Definition of bond stress

The binding stress between deformed rebar and concrete comprises three components: chemical adhesion, friction, and mechanical interlock (Xu et al., 1994). Chemical adhesion occurs between the hydrogel in the concrete and the surface of the deformed rebar, primarily influenced by the cement's characteristics and the roughness of the rebar. Frictional resistance arises when concrete contracts or when the load and external forces apply radial pressure on the deformed rebar, leading to a propensity for sliding or relative movement between the two. The extent of frictional resistance is contingent upon the radial pressure exerted by the concrete on the deformed rebar and the friction coefficient that exists between the two materials. Mechanical interlocking pertains to the interlocking effect between the ribs of deformed rebar and concrete, specifically the longitudinal component of the oblique pressure applied by the concrete on the rebar surface. The impact of concrete splitting strength on the maximum mechanical bite force (Guo et al., 2013). During the initial loading phase, the bond stress of deformed rebar mostly consists of chemical adhesion and friction. When the deformed rebar is distorted or the local steel bar slips, the chemical adhesion force is compromised, and the frictional resistance and mechanical interlocking force become significant. When the external force is below a specific threshold, the minimal alteration in frictional resistance can be regarded as a constant value. Upon reaching a specific magnitude, the frictional resistance commences to diminish. The alteration of mechanical biting force can be categorized into two phases: a progressive increase to a specific value followed by a decrease (Wang et al, 2012).

The nature of bond stress is highly intricate. To facilitate the computation of bond stress, several researchers (Zhao et al., 2016; Cao et al., 2017; Zhao et al., 2022; Ma et al., 2021; Fang et al., 2019) employ the notion of average bond stress to characterize the binding strength between deformed rebar and concrete. When the bond length is minimal, it can be presumed that the bond stress is uniformly distributed over the bond section. The expression is stated as follows:

$$\tau = \frac{P}{\pi d L} \tag{1}$$

When τ represents the average bond stress between deformed rebar and concrete, P denotes the external load, d indicates the rebar diameter, and L signifies the length of the bond. The mean bond stress associated with bond failure is referred to as average bond strength.

Definition of bond-slip relationship

In 1987, Shima et al. proposed use bond stress, slip, and steel strain to characterize the bond-slip connection. Concrete specimens featuring an anchoring length of 50d were examined by pull-out tests. The bond-slip relationship was notably influenced by steel strain. A bond slip constitutive model is given, taking into account the impacts of steel strain, diameter, and concrete strength. The model is represented by the equations. (2) Equations (4). Xu et al. (1997) performed pull-out experiments on 334 reinforced concrete specimens. The determinants comprise concrete strength, cover thickness, and stirrup ratio. The bond-slip process is categorized into five stages based on distinct stress mechanisms: micro-slip stage, slip stage, split stage, drop stage, and residual slip stage. Ultimately, the regression analysis of the test findings yields formulas for characteristic strength and the bond-slip constitutive relation (Eqs. (5)~Eqs. (9). Xu et al. derived the position function by analyzing the distribution of bond stress in deformed steel bars over the length of the graded section (Eqs. (10)), and subsequently formulated the bond-slip constitutive relation while accounting for positional effects (Eqs. (11)).

$$\tau = (f_c, s, \varepsilon_s, d_b) = \tau_0(f_c, s, d_b).\, g(\varepsilon_s) \tag{2}$$

$$\tau = (f_c, s, \varepsilon_s, d_b) = 0{,}73.\, f_C.\left[ln\left(1 + 5000.\frac{s}{d_b}\right)\right]^3 \tag{3}$$

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

What is the compressive strength of concrete, the strain for steel, the reference value for bond stress, and the reduction factor?

$$\tau_s = 0.99 f_t \tag{5}$$

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

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

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

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

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

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

where is f_t the tensile strength of concrete ； τ_s, τ_{cr}, τ_u, τ_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.

Bond failure modes

The bond failure between deformed rebar and concrete can be categorized into splitting failure, pull-out failure, and yield failure. Longitudinal splitting cracks arise when transverse ribs fail to withstand the circumferential tensile stress generated by the compression of the surrounding concrete, attributable to insufficient cover thickness or alternative kinds of transverse restraint. Cracks appear on the surface of the member, resulting in the separation of the concrete bond prior to the extraction of the deformed rebar. When the concrete cover or other forms of lateral restraint are sufficient to counteract the transverse ribs by compressing the concrete around the ring tensile stress, the deformed rebar experiences increased confinement, leading to the failure of the concrete between the transverse ribs due to shear forces, ultimately resulting in the deformed rebar being directly extracted from the concrete. When the bond length meets a specific criterion, the failure mechanism is characterized by the rupture of the distorted rebar without any significant slippage. The ultimate bond strength is dictated by the ultimate tensile strength of the steel bar.

EXPERIMENTAL RESEARCH METHOD OF BOND BEHAVIOR

Definition of bond stress

Investigations on the binding behavior between bent rebar and concrete have consistently been a prominent area of research. Owing to the intricacy of the bond problem, pertinent scholars have conducted extensive research on the subject and proposed many testing methodologies to examine the bond issue. The prevalent testing methodologies employed to examine bond behavior include the center pull-out test, beam end test, and beam test.

The Center pull-out test (Fig. 1) is the most prevalent bond testing method globally. Numerous scholars (Xuan et al., 2022; Seara et al., 2014; Xiao et al., 2007; Prince, 2007; Zhao et al., 2013; Okelo et al., 2005) employ this methodology to investigate bond behavior. The central pull-out test offers the advantage of simpler test piece fabrication compared to other methods, resulting in reduced production costs, convenient loading, and more straightforward measurement of test data.

The test can establish numerous metrics to qualitatively assess the elements influencing bonding success. In this method, the steel plate is often positioned against the concrete at the loading end as a restraint. The steel plate will restrict the breaking of the concrete, resulting in an elevated bond strength as determined by the central pull-out test. Furthermore, the external load in this test directly influences the deformed rebar, resulting in tension on the rebar and compression in the concrete, which does not align with the structural stress conditions observed in practical

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p-ISSN 2460-9609
e-ISSN 2774-7956

https://ejournal.itn.ac.id/index.php/infomanpro
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engineering (where most external loads are applied to the concrete, causing both the deformed rebar and concrete to experience tension or compression).

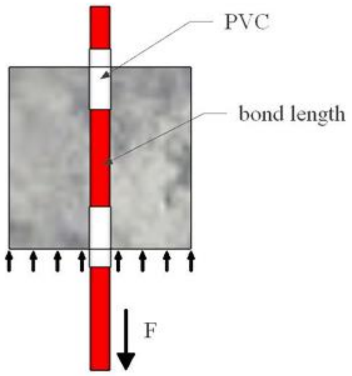

Fig 1. Schematic representation of a concentric pullout specimen

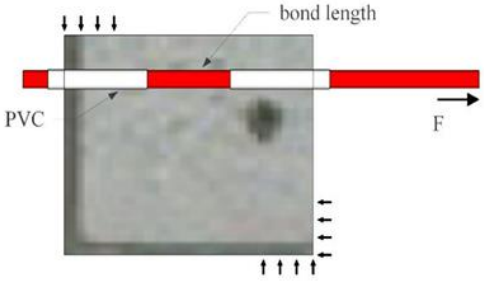

Fig 2. Schematic representation of a beam-end specimen

The beam-end test primarily serves to replicate the beam-end anchorage test, as illustrated in the figure. Two. The beam-end test is frequently employed to replicate the effects of pressure, bending moment, and shear force on the bonding efficacy of the bearing, making it appropriate for investigating the anchoring bonding issues of the steel bar within the shear span region. This test method is optimal and aligns well with the structural stress conditions observed in practical engineering. Chana (1990) initially introduced a beam-end test. Subsequently, other researchers (Law et al., 2011; Hanjari et al., 2011; Sharma et al., 2016) enhanced the beam-end specimens derived from this test and introduced alternative configurations of beam-end specimens. Lin et al. (2017) investigated the binding behavior between concrete and corroded steel bars subjected to repeated loads by a beam end test. The test results indicate that improper design of the geometric dimensions, constraint positioning, and bond length of the specimen may lead to shear failure or inadequate bond failure (Lin et al, 2018).

The beam test is an exemplary method for assessing bonding quality. The specimens utilized in the beam test are categorized into three types: (a) full-beam specimens including two half-beams joined by steel hinges (Zhag et al. 2022; Cao et al. 2020) (Fig. 3). Beam-end anchorage specimens including slotted shear spans (Lin et al., 2016) (Fig. 4). Beam-type specimens including anchored deformed rebar in pure bending sections (Gaurav et al., 2017; Arezoumandi et al., 2018) (Fig. 5). The beam test can replicate the actual stress conditions of flexural members and accurately represent the true bonding status. In comparison to the other two specimen types, the beam specimen is more intricate, costlier, and susceptible to shear failure, necessitating the incorporation of suitable stirrups.

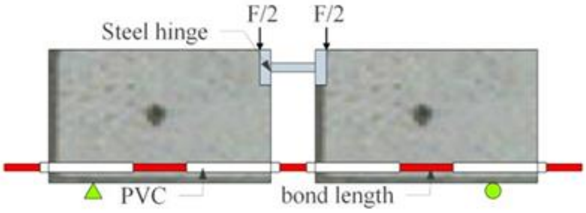

Fig 3. Schematic representation of beam specimen for bonding testing

JURNAL INFOMANPRO
p-ISSN 2460-9609
e-ISSN 2774-7956

https://ejournal.itn.ac.id/index.php/infomanpro
vol.14 No.1 Tahun 2025 , pp. 9-16

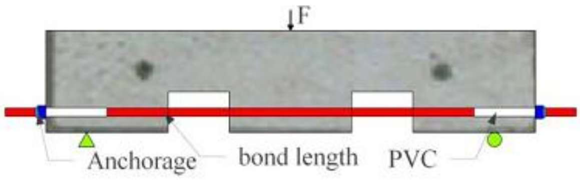

Fig 4. Schematic representation of beam anchorage specimen for bond testing

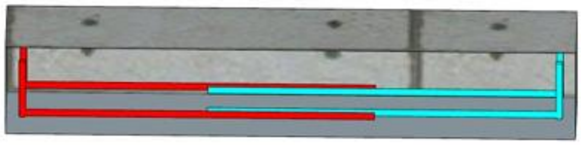

Fig 5. Three-dimensional schematic representation of splice beam specimen for bond testing

FACTORS INFLUENCING BOND BEHAVIOR

Previous studies indicate that the primary factors influencing bond behavior can be categorized as follows:

1) Concrete strength classification. Research indicates that bond strength and concrete strength are positively connected, with bond strength mostly dependent on the tensile strength of concrete (Zuo et al., 2000; Zuo et al., 1998). As the concrete strength grade rises, the water-cement ratio diminishes, resulting in denser concrete. This enhances both the chemical adhesion and mechanical interlock between the concrete and deformed rebar, hence augmenting the ultimate bond strength.

2) Concrete cover thickness and spacing of distorted rebar. The gap between the concrete protective layer and the deformed rebar progressively widens, resulting in a transition of the failure mode from concrete splitting failure to deformed rebar pull-out failure. Morris (2015) asserts that a diminished concrete protective layer renders the concrete surrounding the deformed rebar susceptible to horizontal cracking, which subsequently reduces both the splitting tensile capacity of the concrete and the bond strength.

3) Diameter of deformed reinforcement bar, rib spacing, and bond length. Research indicates that (Xu, 1990) bond strength diminishes as the diameter of deformed rebar rises, resulting in greater slip between the deformed rebar and concrete. The rib height and rib spacing influence the bond strength as well. To thoroughly evaluate the impact of the diameter and geometric configuration of the deformed rebar on bond performance, the American Concrete Institute delineates the relative rib spacing:

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

What is the rib height of deformed rebar, and what is the rib spacing of deformed rebar? The binding strength diminishes as the relative rib area increases. When the bond length is reduced, the bond tension is nearly uniformly distributed. As the bond length rises, the bond stress is distributed across a greater length, resulting in a diminished average bond strength (Fang et al, 2019).

4) The ratios of the stirrups. Stirrups serve to offer lateral support for concrete following the rupture of the concrete protective layer. Augmenting the stirrup ratio can enhance the binding strength to a certain degree. Nonetheless, when the stirrup ratio is very high, the bond strength ceases to augment with further increases in the stirrup ratio (Plizzari et al, 1998).

5) Load the form. Lin et al. (1990) fabricated 43 eccentric pull-out specimens and examined the bond behavior of corroded reinforced concrete under both monotonic and cyclic stress conditions. The findings indicate that the residual slip between deformed rebar and concrete accumulates with repeated loading, and that elevated stress levels and increased loading cycles contribute to the augmentation of residual slip. The bond strength of the specimens subjected to repeated loading did not significantly diminish in comparison to those under monotonic loading, indicating that the impact of repeated loading on bond strength was minimal. Oh et al. (2007) determined through experimental results that, in the absence of fatigue failure during constant amplitude cyclic loading, prior repeated loading does not adversely affect bond strength when compared to monotonic loading. Moreover, they discovered that the residual slip

JURNAL INFOMANPRO
p-ISSN 2460-9609
e-ISSN 2774-7956

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escalates roughly in proportion to the logarithm of the frequency of repeated loadings. Consequently, based on these findings, they formulated the bond fatigue life prediction equation and the local bond stress-slip constitutive model following repeated loading. Edwards et al. (1978) investigated the bond-slip behavior of deformed rebar and concrete following nine instances of lateral stress in the 1970s. The test indicates that under the influence of fatigue stress, irreversible residual slip will occur between the deformed rebar and the concrete. The varying loading and unloading trajectories result in the formation of a hysteresis curve in the bond-slip relationship. As fatigue times grow, the hysteresis curve progressively shifts to the right, and the rate of movement continues to decelerate. The bond performance between steel and concrete is primarily influenced by the loading amplitude and frequency of loading cycles. Rehm et al. (1979) investigated the bond fatigue performance of reinforced concrete and determined that, with a constant lower limit of fatigue load, the number of fatigue load cycles increases as the upper load limit decreases. They suggested that mean stress and stress range may serve as metrics to characterize fatigue life under cyclic loading. The examination revealed that neither the concrete strength nor the diameter of the steel bar influenced the bond fatigue life. The maximum bond stress and the associated slip value of the specimen after cyclic loading exhibited minimal variation when compared to the specimen subjected to monotonic loading. Ultimately, when the residual slip surpasses the slip value associated with the peak bond force under monotonic loading, the residual slip escalates significantly until pull-out bond failure transpires. Consequently, Balazs (1992) proposed that the slip value associated with the maximum bond force under monotonic loading may serve as a criterion for assessing bond fatigue failure. The slip growth law, bond-slip constitutive model, and the number of loading cycles leading to bond fatigue failure between concrete and deformed steel bars under repeated loading can be analyzed using the load level and the number of load cycles as factors.

6) Additional considerations. Including the stress condition surrounding concrete, loading rate, steel yield, and additional parameters (Li et al., 2016).

CONCLUSIONS

This work analyzes the research findings on the bond-slip behavior of reinforced concrete from three perspectives: bond mechanism, experimental research methods for bond performance, and factors influencing bond performance. This text introduces the methodologies of pertinent experimental research and the variables influencing bond behavior, serving as a reference for future researchers.

1) A multitude of experts have conducted several experimental investigations on diverse aspects influencing bond behavior. Nonetheless, owing to the intricate nature of the bond interface between deformed rebar and concrete, the variability of the test results, and the discrepancies in testing settings, the bond-slip constitutive relationships posited by researchers are frequently limited to particular scenarios. The ensuing research may commence from the theoretical perspective and thoroughly evaluate several elements to develop a more precise and complete bond-slip constitutive model..

2) Previous investigations have attained a foundational comprehension of bond performance degradation under cyclic loading; nonetheless, a bond-slip constitutive model and a bond fatigue life prediction model for reinforced concrete remain absent. In most scholarly examinations of bonding performance under repeated loads, the external load typically exerts direct pressure on the steel bar, which does not accurately reflect the project's actual conditions. Subsequent studies may utilize lap beam specimens to examine the degradation of bond performance under cyclic loading.

REFERENCES

Arezoumandi M, Steele AR, Volz JS. Evaluation of the bond strengths between concrete and reinforcement as a function of recycled concrete aggregate replacement level. Structures. Elsevier. 2018;16:73-81.
Balazs GL. Fatigue of bond. Materials Journal. 1992;88(6):620-630.
Cao FB, Liu L, Lu ZM, et al. Beam test study on bond performance of recycled concrete and steel bar under coupling effect of steel corrosion and freeze-thaw cycles. Journal of Building Structures. 2020;41(12):103-112.
Cao WL, Lin DZ, Dong HY, et al. Beam-type experimental study on bond-slip properties between rebars and medium/high strength recycled concrete. Journal of Building Structures. 2017;38(04):129-140.
Chana PS. A test method to establish realistic bond stresses. Magazine of Concrete Research. 1990;42(151):83-90.
Edwards AD, Yannopoulos PJ. Local bond-stress–slip relationships under repeated loading. Magazine of Concrete Research. 1978;30(103):62-72.

Fang Z, Chen X, Zhang MZ, et al. Experimental study on the performance of lap-spliced ribbed steel bars interactive powder concrete. China Civil Engineering Journal. 2019;52(03):20-28+49.

Gaurav G, Singh B. Analytical investigation in bond of deformed steel bars in recycled aggregate concrete. Journal of Sustainable Cement-Based Materials. 2020;9(4):191-217.

Gaurav G, Singh B. Bond strength prediction of tension lap splice for deformed steel bars in recycled aggregate concrete. Materials and Structures. 2017;50(5):1-20.

Guo ZH. Principle of reinforced concrete (3rd Edition). Beijing: Tsinghua University Press. 2013;(03):134-135.

Hanjari KZ, Coronelli D, Lundgren K. Bond capacity of severely corroded bars with corroded stirrups. Magazine of Concrete Research. 2011;63(12):953-968.

Law DW, Tang D, Molyneaux TKC, et al. Impact of crack width on bond: Confined and unconfined rebar. Materials and Structures. 2011;44(7):1287-1296.

Li X, Wu Z, Zheng J, et al. Effect of loading rate on bond behavior of deformed reinforcing bars in concrete under biaxial lateral pressures. Journal of Structural Engineering. 2016;142(6):04016027

Lin H, Zhao Y, Ožbolt J, et al. The bond behavior between concrete and corroded steel bar under repeated loading. Engineering Structures. 2017;140:390-405.

Lin H, Zhao Y. Bond behavior between concrete and deformed steel bar: A review. Journal of Building Structures. 2018;40(1):11-27.

Lin H, Zhao Y. Effects of confinements on the bond strength between concrete and corroded steel bars. Construction and Building Materials. 2016;118:127-138.

Ma FD, Deng MK, Sun HZ, et al. Bond behavior of deformed steel bars lap-splice in ultra-high performance concrete. Acta Materiae Compositae Sinica. 2021;38(11):3912-3924.

Morohashi N, Sakurada T, Yanagibashi K. Bond splitting strength of high–quality recycled coarse aggregate concrete beams. Journal of Asian Architecture and Building Engineering. 2007;6(2):331-337.

Morris GJ. Experimental evaluation of local bond behavior of deformed reinforcing bars in concrete structures. 2015.

Oh BH, Kim SH. Realistic models for local bond stress-slip of reinforced concrete under repeated loading. Journal of Structural Engineering. 2007;133(2):216-224.

Okelo R, Yuan RL. Bond strength of fiber reinforced polymer rebars in normal strength concrete. Journal of Composites for Construction. 2005;9(3):203-213.

Plizzari GA, Deldossi MA, Massimo S. Transverse reinforcement effects on anchored deformed bars. Magazine of Concrete Research. 1998;50(2):161-177.

Prince MJR, Singh B. Bond behavior of deformed steel bars embedded in recycled aggregate concrete. Construction and Building Materials. 2013;49:852-862.

Rehm G, Eligehausen R. Bond of ribbed bars under high cycle repeated loads. ACI Journal Proceedings.1979;76(2):297-309.

Seara-Paz S, González-Fonteboa B, Eiras-López J, et al. Bond behavior between steel reinforcement and recycled concrete. Materials and Structures. 2014;47(1):323-334.

Sharma A, Bošnjak J, Ožbolt J, et al. Numerical modeling of reinforcement pull-out and cover splitting in fire-exposed beam-end specimens. Engineering Structures. 2016;111:217-232.

Shima H, Chou LL, Okamura H. Micro and macro models for bond in reinforced concrete. Journal of the Faculty of Engineering. 1987;39(2):133-94.

Wang B, Bai GL, Li J, Wu SH, et al. Experimental and theoretical analysis of bond stress distribution between the rebar and recycled concrete. Industrial Construction. 2012;42(04):10-14.

Xiao J, Falkner H. Bond behavior between recycled aggregate concrete and steel rebars. Construction and Building Materials. 2007;21(2):395-401.

Xu YL, Shen WD, Wang H. Experimental study on bond anchorage performance of reinforced concrete. Journal of Building Structures. 1994;(03):26-37.

Xu YL. A simplified model of bond-slip relationship for reinforced concrete. Engineering Mechanics. 1997;(a02):34 (in Chinese).

XU YL. Experimental study of anchorage properties for deformed bars in concrete. Beijing Tsinghua University.1990:22-76.

Xuan VT, Manh HN, Trung HN, et al. Experimental study on the bond strength between reinforcement bars and concrete as a function of concrete strength and confinement effect. CIGOS 2021, Emerging Technologies and Applications for Green Infrastructure. Springer, Singapore. 2022:257-263.

Zhang J, Tao X, Li X, et al. Analytical and experimental investigation of the bond behavior of confined high-strength recycled aggregate concrete. Construction and Building Materials. 2022;315:125636.

Zhao J, Wang SB, Wang ZK, et al. Experimental investigation on bond behavior of basalt fiber reinforced polymer bars to geopolymer concrete. Journal of Building Structures. 2022;43(06):245-256.

Zhao Y, Lin H, Wu K, et al. Bond behavior of normal/recycled concrete and corroded steel bars. Construction and Building Materials. 2013;48:348-359.

Zhao YX, Sun M, Lin HW, et al. Bond strength between concrete and deformed bars under combined effects of stirrups and concrete cover. Industrial Construction. 2016;46(06):128-132.

Zuo J, Darwin D. Bond strength of high relative rib area reinforcing bars, SM Report, 46, University of Kansas Center for Research. 1998;25:2017.

Zuo J, Darwin D. Splice strength of conventional and high relative rib area bars in normal and high-strength concrete. American Concrete Institute; 2000.