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# EFFICIENCY OF BOND-SLIP RESPONSE FOR FE NUMERICAL MODELING OF REINFORCED CONCRETE- A REVIEW

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**Abstract:** The realistic response of reinforced concrete (RC) structures can be reflected through numerical modeling in finite element (FE) analysis when the true bond-slip response is assigned. The bond on rebar with the surrounding concrete prevents excessive slipping to maintain compatibility. The bond controls the stiffness and capacity of RC members, including cracking, deformations, and hysteretic response under seismic loading. This paper reports on bond-slip responses adopted between deformed rebar and concrete. The complexity of the bond-slip behavior presents a significant challenge in developing accurate bond-slip models; since the factors like rebar surface deformation and rib area, concrete strength and stiffness, rebar diameter and spacing, casting position, and confinement of the surrounding concrete influence the bond. This paper highlights different types of bond-slip models adopted by researchers, including complex cyclic bond-slip deterioration model under reverse cyclic loading. It emphasizes the application of bond-slip models to simulate the interaction between the deformed rebar and the surrounding concrete in the analysis of RC structures, as the bond stress depends on the corresponding slip. Several studies have been reported on the bond-slip characteristics of deformed rebar, on its application in finite element analysis. In this study, two modeling techniques have been adopted using bond-slip characteristics of rebar in FEA of RC structures to predict crack spacing, stiffness, and deformation.

## 1 INTRODUCTION

Reinforced concrete (RC) structures are considered in various infrastructure projects like bridges, buildings, hydraulic structures, and other projects due to their functionality and durability. The reinforced concrete structure is a composite structure of concrete and reinforcement; its performance depends on the bonding between concrete and reinforcement. Bond stress is shearing stress between the interface of reinforcement and concrete; stress in reinforcement changes by transferring bond stress from surrounding concrete. To analyze the structural properties of reinforced concrete structures and improve its performance, it is necessary to accurately determine the bond-slip mechanism between reinforcement and concrete. The bond-slip mechanism is particularly relevant for evaluating deformation in beam-column joints and rotation due to rebar slip in beams, columns, shear walls, and foundations; it provides valuable insights and theoretical implications for engineering practice. Transfer of force between deformed reinforcement and the surrounding concrete occurs by chemical adhesion, mechanical anchorage, and friction. Bond between reinforcement and concrete are very complex, influenced by reinforcement and concrete properties, cover and spacing of reinforcement, size, surface condition, and geometry of rebar. Bond is structural properties, depends not only on material properties but also on the geometry of structural member. Pullout, beam end, beam anchorage, and beam splice are the test configuration used to evaluate the bond between reinforcement and concrete.

## 2 FRACTURE MECHANICS ON BOND

In relative deformation between reinforcement and surrounding concrete, two failure modes of bond failure can occur. The first mode is in which ribs on the bar can push the concrete away from the bar through a wedging action, causing concrete splitting, and the Second in which the bar moves relative to the concrete, the concrete in front of the ribs can get crushed, resulting in a pullout failure. Structural elements may lose bond caused by primary concrete longitudinal splitting or secondary concrete radial splitting. Nonlinear fracture mechanics can be employed to analyze the splitting phenomenon and understand how it leads to a loss of bond in reinforced concrete elements [1]. Mix mode fracture principles with a fictitious crack model have been applied to analyze the bond behavior at the microscopic level [2]. Fracture mechanics concepts, such as stress intensity factors and energy release rates, are used to analyze the initiation and propagation of cracks in the concrete surrounding the rebar. Studying the crack growth and propagation can determine the critical crack length or critical bond length, which represents the limit of the bond's capacity to transmit forces between the rebar and concrete. Fracture mechanics concepts are used to understand the influence of size effect on bond behavior.

## 3 FACTORS AFFECTING BOND

A review of the literature demonstrates that several factors influence the bond-slip behavior in reinforced concrete (RC) structures to varying degrees. These factors encompass reinforcement characteristics (such as geometry, strength, type of reinforcement, and presence of corrosion), properties of concrete (concrete type, mechanical characteristics), state of stresses in surrounding concrete, loading type, and environmental conditions.

### 3.1 Concrete characteristics

The mechanical characteristics of concrete, including its modulus of elasticity, Poisson's ratio, tensile strength, and compressive strength, are influenced by the type of concrete. High-strength concrete poses high bearing capacity, preventing the concrete's crushing in front of bar ribs and reducing local slip. It increases tensile stress locally and starts a concrete splitting without uniform bond stress distribution. Fiber concrete exhibits improved tensile strength and fracture energy. Hence it exhibits high bond strength. The strength of concrete is directly influenced by the constituent materials, such as mineral admixtures and aggregate type, which affect the bond strength. Researchers reported that the average bond strength is proportional to tensile strength of concrete and can be represented in power terms of concrete compressive strength $(f'_c)^n$. Power term (n) is defined by many researchers as 0.5 [3,4], 0.33 [5], 0.25 [6,7], 0.75 [8], 0.667 [9].

### 3.2 Reinforcement characteristics

Reinforcement is mainly characterized by bar size, geometry, yield, and stress level in bar and bar surface conditions. Bar surface condition can be affected by cleanliness, coating, and corrosion on the bar. The friction between reinforcing steel and concrete is influenced by the surface condition and deformation geometry of the bars. The geometry of the reinforcement is quantified by relative rib area ($R_r$); it encompasses factors such as deformation height of ribs, spacing of ribs, width, and face angle. When a deformed bar with a rib face angle greater than 40° is used, the bond between the bar and concrete is established through a progressive crushing of the concrete in front of the ribs [10]. This crushing action, combined with the friction between the rib face and the concrete, prevents relative movement at the interface. In cases where the relative rib area and bar diameter are high and confined by transverse reinforcement, the bond strength is also high [11]. However, when rebar with a high relative rib area is coated with epoxy, the detrimental effect on splice strength is reduced [12]. Bond strength of high-strength reinforcing rebar is significantly reduced at high-stress levels beyond the proportional limit [13]. Overall, the surface roughness, deformation geometry, rib area, epoxy coating, and stress levels all play a role in the bond strength between reinforcing steel and concrete.

### 3.3 Structural detailing

The determination of cover to reinforcement is based on considerations of environmental severity and fire exposure. An increase in the cover and bar spacing enhances the bond strength by preventing splitting failure [4]. However, for larger cover and spacing, there is a possibility of experiencing a pullout failure. On the other hand, utilizing smaller cover and bar spacing may lead to splitting tensile failure, resulting in lower bond strength. The bond strength of bars, when confined by transverse reinforcement, tends to increase with an increase in the relative rib area. Nevertheless, there is a point beyond which the transverse reinforcement no longer exhibits its effectiveness. Transverse reinforcement serves as passive confinement to the bar by restricting the propagation of splitting cracks and change failure from splitting to pullout, thereby enhancing the bond strength [14].

To estimate development and splice length, average bond stresses are considered such that it develops full strength of reinforcement. Average bond stress decreases as rebar diameter and bonded length increase. Size effect was observed in the bond failure of bars.

### 3.4 Construction practices

Requirement of concrete slump and workability depends on construction methodology and practices. High slump concrete is used to pump concrete and shows high bleeding and settlement properties, thus reducing bond stress. Bond stress is also affected by the casting position of the bar. Top-cast bars have lower bond stress than bottom-cast bars due to bleeding and entrapped air void below top bars. Precast members are mostly cast on the horizontal bed; member having more than 300 mm depth top bar effect needs to be considered due to the reduction of bond strength for designing anchorage and splice length. Vibration and consolidation play a significant role in improving the bond strength. Construction-related vibrations while concrete is setting have a negative effect on bond strength. Re-vibration reduces bond strength in high-slump concrete.

### 3.5 State of stress and moment gradient

Bond develops under different stress in tension, compression, shear, and varying moment along the rebar. *Untrauer et al.* [15] observed through pullout experiments that the ultimate bond strength of reinforced concrete (RC) is directly proportional to the square root of the active confinement by applied lateral compressive pressure. Furthermore, with an increase in the lateral pressure, the primary mode of damage transitions from splitting to pullout failure. In contrast, bond stress exponentially decreases under lateral tensile stress [16]. Under earthquake loading, columns and beams resist shear force, developing a moment gradient, which affects bond strength [17]. Failure in the moment gradient region initiates from the extremity with a higher moment. The moment gradient along the lap splice influences deformability, and a larger moment gradient is required to increase the ductility capacity [18].

### 3.6 Loading rate and type

During an earthquake, structures experience repeated and reversed cyclic loading, demanding good bond strength. Under such conditions, the performance of the bond compromises under reversed cyclic loading. Reverse cyclic loading exhibits lower bond stress relative to monotonic loading. The energy dissipation under reverse cyclic loading predominantly occurs during the descending and residual phases of the loading cycle. In pullout specimens under reverse cyclic loading, slippage occurs at both free and forced ends, leading to a degradation in both the maximum bond stress and stiffness [19]. RC structures are sensitive to the rate of loading, *Eligehausen et al.* [20] reported a linear relationship between the bond strength and loading rate in the pullout test.

## 4 BOND MECHANISM AND FAILURE

The performance of RC structures relies on the effective transfer of forces between the reinforcement and the surrounding concrete. The transfer of forces between the deformed rebar and the concrete takes place through chemical adhesion, mechanical anchorage by bearing, and frictional forces due to the roughness of the interface.

Initially, during Stage I, the bond is primarily due to the weak chemical adhesion in the uncracked concrete. Once the chemical adhesion fails, Stage II initiates, leading to the formation of internal micro-cracks in concrete. At this stage, the bearing and friction forces acting on the ribs and barrel of the bar are mobilized. The bearing at the rib occurs due to the slip of rebar relative to the surrounding concrete caused by the strain and axial deformation in the rebar [10]. During Stage III, slip begins through the crushing of the surrounding concrete. Subsequently, the main resistance is provided by the bearing and friction forces acting on the ribs. The resistance depends on the mechanical interlocking that occurs in deformed rebar, which contributes to a superior bond. The influence of rebar bearing on deformation results in shear stress within the concrete. It induces internal cracking at an angle of 45 to 80 degrees to the rebar axis.

In cyclic loading, the adhesion gradually loses within a few cycles, leading to the bond due to mechanical resistance of bar deformation and friction. The presence of an inclined internal crack-like tooth increases the frictional resistance by tightening, causing hoop tension in the concrete around the bar and leading to the formation of longitudinal cracks [21].

During Stage IV, failure of deformed rebar due to splitting or pullout failure depends upon the cover and transverse confinement. At this stage, slip is highly pronounced, and as slip increases, the bond stress reaches its peak and then starts to decrease [22].

### 4.1 Splitting failure

Concrete splitting occurs in low-cover and unconfined concrete. The bond stress is provided by the crushing and shearing of the concrete keys between the ribs, along with dry friction at the tip of the ribs (Figure 1). Splitting failure is due primarily to tensile radial stresses caused by deformation bearing force. In unconfined concrete, a longitudinal splitting crack propagates throughout the cover and bar spacing, resulting in sudden bond failure.

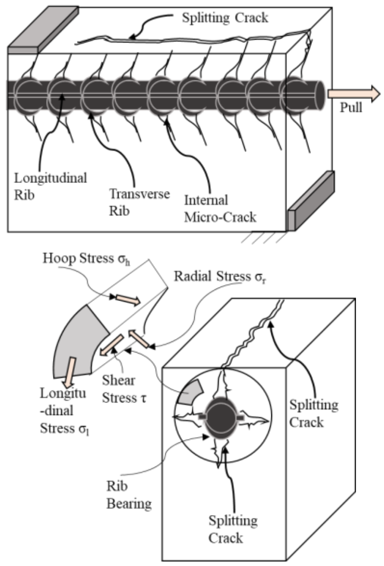


**Figure 1:** Splitting failure mechanism and stress component in beam-end specimen

### 4.2 Pullout failure

In highly confined concrete, pullout failure occurs when the longitudinal splitting crack is prevented. Pullout failure occurs with poor shear strength of concrete between the ribs (Figure 2). Pullout resistance depends on concrete shear strength, geometry of rebar, cover, and confinement. Light to medium confinement by transverse reinforcement improves bond efficiency despite the longitudinal splitting of concrete.

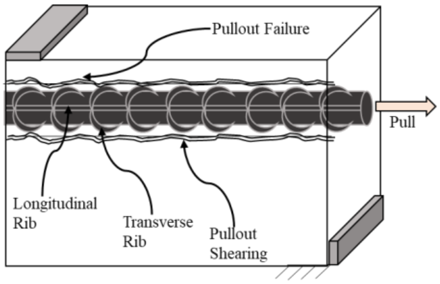


**Figure 2:** Pullout failure mechanism in beam-end specimen

## 5 BOND TEST SET-UP

Pullout, beam-end, beam anchorage, and lap spliced are common testing methods to assess the bond strength between rebars and concrete. The test method affects not only measured bond strength but also the nature of the failure to assess the performance and integrity of RC structures. Due to its simplicity, the pullout test is a widely used method to evaluate bond strength, which involves transfer load to pull a single rebar out of the concrete to measure the maximum force and slip at failure (Figure 3). Pullout tests rarely configure the actual structural element stress field condition. Thus, it does not give realistic bond strength. In the pullout test, rebar is in tension, concrete in compression, and a strut forms between supporting plate and rebar surfaces is balanced by concrete tension hoop and shear stress (Figure 4). In RC structural members, the rebar and surrounding concrete stress state are in tension, which is not in the pullout test. Estimation of anchorage and splice length, pullout test is not recommended by ACI 408 [23].

Beam-end tests simulate a more realistic stress field state as in structural RC element; rebar and surrounding concrete are in tension. The size of the beam-end specimen and supporting location are estimated as per ASTM A944-22 such that the compressive concrete region is away at least by bonded length to testing rebar. Pullout and beam-end tests have short specimen sizes and simple tests and loads are applied directly on the rebar to evaluate bond strength. These two-test methods are preferred to test a large number of specimens by varying the various parameters.

The main objective of finding bond strength is to estimate optimal anchorage and lap splice length to the desired level of deformation of the RC element. Pullout and beam end tests are generally conducted on short bond lengths to evaluate local bond strength, which gives higher bond strength and is unsuitable for average bond strength for long anchorage and lap splice length. So, beam anchorage and lap splice tests are conducted to simulate large-scale specimens to directly evaluate anchorage and lap splice strength. The beam-end and spliced tests are conducted to evaluate the bond strength in the actual stress field of the RC structural element under the action of shear and bending moments.

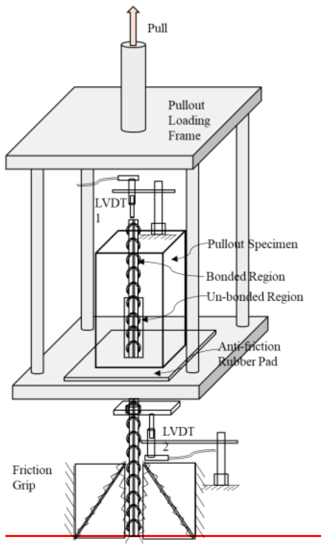


**Figure 3:** Pullout testing set-up.

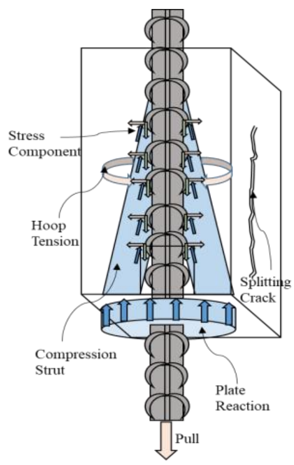


**Figure 4:** Pullout bond mechanism

To study the effect of axial load on rebar anchorage strength, *Ueda et al.* [24] studied the bond on rebar anchorage in exterior beam-column joints with axial load. Full-scale models of members are recommended to be performed with combined loading of axial, shear, and bending moment to simulate the actual stress state on the performance of anchorage and lap splice length of rebar [17].

The bond stress-slip response is measured between rebar and concrete at different slip values to facilitate a complete analysis of the bond response under varying loading conditions.

## 6 BOND-SLIP CHARACTERIZATION

Bond stress-slip response to structural performance depends on structural detailing. Researchers commonly rely on average and local bond stress to represent the bond strength between rebar and concrete. Early studies demonstrated the "τ-s" relationship; *Tassios et al.* [25] described experimental analysis to include descending and residual portions, assuming a uniform distribution of bond stress along the anchorage length.

The mathematical bond-slip model illustrates the bond stress-slip relationship. It captures the variations in bond stress vs. rebar slip relative to the surrounding concrete, which typically exhibits four distinct phases: ascending, asserting, descending, and residual phases (Figure 5).

In the ascending phase, as the slip between the rebar and concrete increases, the bond stress typically rises due to the interlocking action of the rebar deformations with the surrounding concrete. This phase represents the development of bonds and the transfer of forces between the rebar and concrete. In the asserting phase, as the slip between the rebar and concrete increases, the bond stress typically maintains due to the sustained crushing of cement paste in front of the ribs. This phase develops a pullout failure in confined concrete. The descending phase occurs when the slip continues to increase, and the bond stress starts to decrease. This decrease in bond stress is often associated with the onset of localized damage or failure mechanisms, such as concrete splitting or rebar slippage. Finally, in the residual phase, the bond stress reaches a minimum, where the bond stress stabilizes at a lower level due to friction from concrete.

Various bond-slip models have been proposed in the literature, ranging from simplified analytical models to more complex numerical models. *Eligehause* [20] proposed a bond-slip equation for pullout failure under monotonic and cyclic loading, whereas *Harajli* [26] proposed a model for splitting damage. The bond strength proposed by *Xu* [27] considers concrete tensile strength and the slip. CEB-Fib Model Code 2010 (MC2010) [28] gives a bond-slip model that considers rebar properties, concrete properties, cover, confinement, and bond length to capture the bond behavior accurately. A new bond-slip model based on the elasticity solutions of thick-walled cylinders and the tensile stress-strain model of concrete is formulated by *Li et al.* [19] for small rebar diameters subjected to monotonic and reversed cyclic loading. A recent bond-slip model is proposed by *Hu et al.* [29] for early-age concrete under unidirectional cyclic loading.

The bond-slip model is crucial for predicting the structural response of RC elements subjected to various loading scenarios, such as tension, bending, or shear. It allows researchers to assess the bond performance and structural integrity and optimize the design of RC structures for safe and efficient construction.

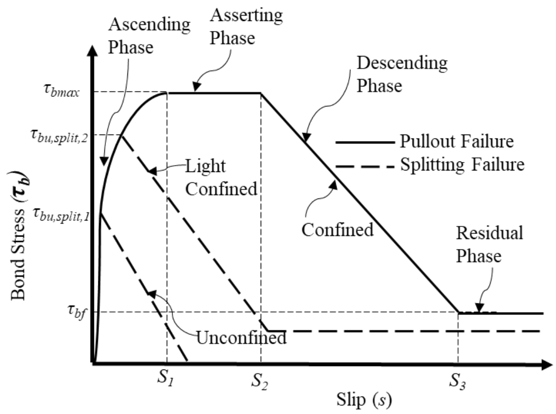


**Figure 5:** Bond-slip character

## 7 BOND-SLIP MODELS IN FEA

Finite element analysis calculations performed on RC structures often overlook the influence of slip between concrete and reinforcement. This oversight significantly underestimates lateral deformations that lead to erroneous values. Macroscopic and microscopic are two broad modeling methods for bond-slip used in FEM. The microscopic approach involves contact analyses for the bond interface, where bonding action between the reinforcement rib geometry and concrete is considered through interface properties. The microscopic simulation method utilizes the direct contact relationship as cohesion, friction, and bearing force against rebar rib geometry. In microscopic-scale models, the friction and cohesion at the interface have less influence on the bond behavior compared to the bearing force provided by the interlocking of ribs against concrete through relative displacement [30]. It gives high computational accuracy in different stress states and corresponding failure modes to any changes in affecting parameters. The microscopic-scale finite element model does not require known bond stress–slip relationship to define the interface property between reinforcement and concrete. FE software uses general contact or Coulomb friction law to calculate unknown bond stress vs. slip response. However, it is not ideal for systematic or large-scale structures due to the modeling process and high computational effort.

*Lundgren et al.* [31] developed a 3D interface element for simulating the bond-slip effect between concrete and rebar, estimating splitting failure and bond stress loss after rebar yielding. *Mendes et al.* [32] developed a bond element considering factors affecting the bond mechanism, accurately modeling bond slip under monotonic and cyclic loading in pullout tests. *Casanova et al.* [33] use truss elements to simulate crack development, avoiding stress-concentration issues. *Santos et al.* [34] created a four-node planar element with orthotropic properties suitable for analyzing crack spacing and minimum reinforcement ratio in RC structures. *Murcia-Delso et al.* [35] introduced a bonding interface element to predict concrete bond performance under constrained conditions accurately. Later, *Murcia-Delso* developed an elastic-plastic expansion interface element, extending its applicability to constraints in RC structures [36]. 3D microscopic modeling of the interface behavior between ribbed steel bars and concrete has been studied to evaluate bond stress and failure pattern [30], [37–39].

In the macroscopic method, FE software adopts many ways to add bond slip properties like nonlinear spring, surface-to-surface contact cohesive element, node-to-node translator element, or embedded element with reduced stiffness. It accounts for bond-slip effects by modifying the constitutive relationship of steel or incorporating spring elements at the ends of the members. This method is suitable for modeling complex and large-scale structures to evaluate the deformations, but it may not predict the failure and effect of the stress state.

*Ngo et al.* [40] introduced linear and nonlinear springs to simulate the bond between steel bars and concrete, utilizing a double-spring coupling element. This method has uncertainties in defining the normal stiffness, leading to discrepancies between the actual structure geometry and the analytical model. *Zhao et al.* [41] proposed a novel approach using a single spring coupling element based on a hybrid coordinate system, incorporating tangent concrete solid and reinforcement elements to model the tangential interaction. Bond-slip relationships determined the tangential stiffness, while normal deformation coordination was achieved through constraint equations, avoiding the challenge of manually selecting the normal stiffness coefficient. *Mohemmi et al.* [42] applied nonlinear springs to connect adjacent nodes of concrete and reinforcements, conducting macroscopic modeling analyses of drawn specimens using ABAQUS finite-element software.

## 8 MODELLING OF BOND-SLIP IN FEA

The pullout test was numerically validated on pullout experiment by *Rao et al.* [43] using the ABAQUS software. To simulate the test, Concrete Damaged Plasticity (CDP) model of concrete and elastoplastic for reinforcing steel has been defined to reflect the actual behavior in the experiments. CDP model considers plasticity parameters: dilation angle ($\psi$), eccentricity (∈), ratio of biaxial compressive strength to uniaxial compressive strength ($f_{b0}/f_{c0}$), and ratio of the second stress invariant on the tensile meridian to that on the compressive meridian at initial yield ($K_c$), are defined as 35°, 0.1, 1.16, and 0.667, respectively to describe the complex stress state. To avoid the numerical convergence viscosity parameter (ν) is considered as 0.000001. The stress-strain relationship for compression and stress-crack width for tension were used to describe the behavior of concrete from MC2010 in the uniaxial state. Fracture energy ($G_F = 73.f_{cm}^{0.18}$) was considered to define the crack opening. The concrete and the reinforcing bar were modeled using 4-node bilinear axisymmetric quadrilateral (CAX4) elements. Smaller element sizes (1 mm) were used near the contact area (Figure 6). The ABAQUS Standard solver was used to perform the analysis.

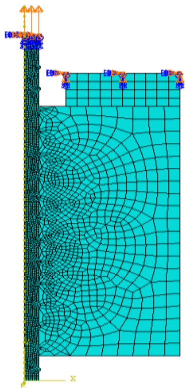

**Figure 6:** Mesh and boundary condition of Microscopic Bond-slip Modelling

The microscopic method uses the actual shape of a ribbed reinforcement and the bond properties as Coulomb friction and hard contact since the mechanical interlocking phenomenon is due to the geometry of the bar. The friction coefficient (μ) between reinforcement and concrete is considered 0.3. To model actual geometry of the deformed rebar, axis symmetry part is modeled with 1 mm rib height and width. Face angle for rib geometry is given $45^0$, and the spacing between ribs is 10 mm.

Macroscopic bond pullout numerical simulations were modeled by the local bond stress–slip relationship as per Model Code 2010 to consider the interaction between reinforcement and concrete. For macroscopic bond pullout modeling cohesive element available in ABAQUS was employed to model the concrete–bar interface. Cohesive property was generated by considering MC2010 bond stress–slip model. Stiffness of cohesive element is determined by the ratio of limiting bond stress till linear relationship and corresponding slip. Contact cohesive damage was considered for simulations controlled by displacement.

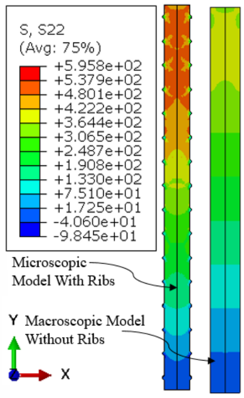


**Figure 7:** Axial Stress in Rebar at Peak Bond Stress

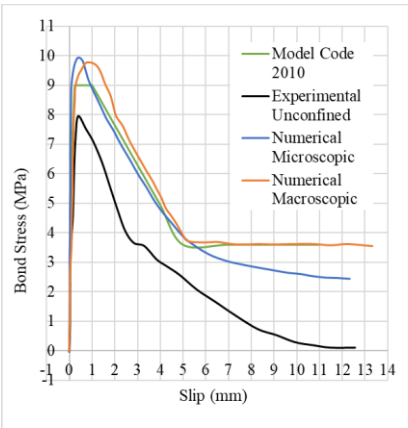


**Figure 8:** Bond-slip Comparison of numerical results with experimental observations

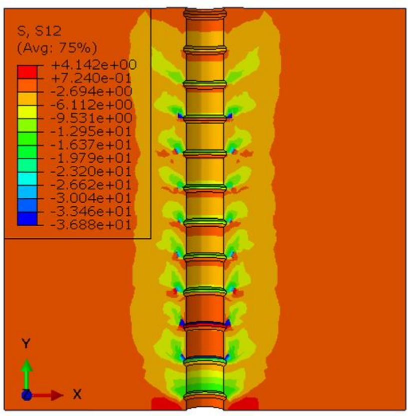


**Figure 9:** Shear Stress Variation in Microscopic

Numerical Model and Micro Cracking

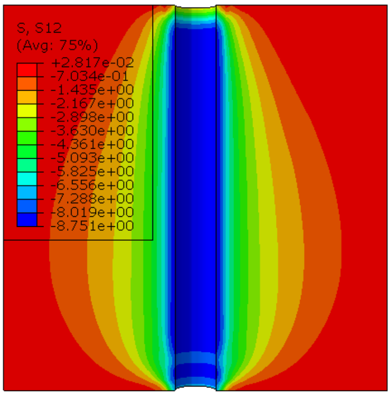


**Figure 10:** Shear Stress Variation in Macroscopic Numerical Model

A comparison of bond-slip response between macroscopic and microscopic modeling with experimental observation and Model Code 2010 is shown in Figure 8. Peak bond stress in the numerical model is 20% higher than experimental value and 10% than Model Code. Microscopic model with ribs shows higher axial stress in rebar due to reduced cross-section due to rib modeling (Figure 7). Shear stress variation in the microscopic model shows compressive stress and micro cracking formation in front of ribs (Figure 9). Microscopic modeling shows bond transfer happens through bearing on concrete in front of ribs. Whereas the macroscopic model shows uniform shearing of concrete (Figure 10).

## 9 CONCLUSIONS

In this research work, the mechanism of bond–slip failure, test methods, and various factors affecting the bond–slip properties of RC structures were comprehensively reviewed. Theoretical bond-slip model and finite element numerical analysis were summarized for the bond–slip in RC structures. Microscopic and macroscopic bond-slip FEA modeling are presented. The nonlinear analysis needs bond-slip response to accurately predict failure, deflection, and overall stiffness of RC members. Microscopic models can generate bond slip response under different stress conditions, which can be used in macroscopic modelling for complex structure with less computational cost.

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