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High-resolution finite element modeling for bond in high-strength concrete beam

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ABSTRACT

This study presents a physics-based rib-scale finite element (FE) model to study bond-zone behavior for spliced longitudinal bars in reinforced concrete beams subjected to monotonically increasing loading. In this model, a high-resolution mesh is used in the vicinity of the bar-concrete interface to capture the geometry of the ribs on the reinforcing steel. At the concrete-bar interface, a contact formulation that properly represents normal and frictional force transfer is used; adhesion between concrete and steel is ignored. The FE model is calibrated using data from beam splice tests performed by Ramirez and Russell [1]. It is observed that concrete tensile strength and tangential friction at the concrete-steel interface determine simulated response; these quantities are calibrated to provide accurate simulation of experimental results. The calibrated model provides results in good agreement with test data. Load-displacement response as well as concrete crack patterns are accurately simulated, and the proposed model can distinguish between the behavior of uncoated and epoxy-coated deformed bars as well as simulate the impact on bond strength of confinement provided by transverse steel.

1. Introduction

1.1. Motivation for numerical study on bond in reinforced concrete structures

Acceptable performance of a reinforced concrete (RC) structure requires transfer of forces between concrete and reinforcing steel via bond. Adequate bond in regions where bars are anchored or spliced is particularly critical to structural performance. The characterization and prediction of bond-zone behavior are challenging due to the complexity of stress and strain fields in the bond-zone, the development of localized inelasticity, and the dependence of these on a variety of parameters including concrete strength and reinforcement configuration and coating.

Numerous experimental tests have addressed bond-zone behavior and the factors that affect it [1–7]. Data from these tests supported the development of present-day specifications for design and detailing of bond-zone including tension splices and bars anchorage. Because bond-zone behavior is complex, many individual tests are required to develop and validate design specifications. With the recent advent of ultra-high strength concrete and high-strength steel [8–10], it is necessary to revisit current specifications for bond-zone, and many new laboratory tests are required to develop and/or validate current design requirements for bond-zone that include these new high-strength materials.

Additionally, in comparison with experimental testing, numerical simulation provides much richer data sets characterizing bond-zone behavior. Using numerical simulation, high-fidelity bond-zone stress, strain, and damage fields are immediately available; experimental data typically include only global load-displacement response and steel, and possibly concrete, strains at relatively a few locations.

The research presented here seeks to develop and validate a numerical modeling approach for RC bond-zone, with the expectation that this modeling approach can be used to supplement experimental testing and provide data required to develop advanced design requirements for RC bond-zone, including those comprising high strength concrete and/or steel.

1.2. Experimental efforts to understand bond

A bond comprises chemical adhesion, friction, and mechanical interaction [2,11]. Many material properties and geometric design characteristics affect these bond mechanisms, including bar size (i.e. diameter), rib configuration (e.g., height, angle, spacing, etc.), presence of coating on the bar, concrete strength, bar strength, confining pressure provided by transverse reinforcement, and the length of the anchorage

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or splice zone. Previous experimental research studies by many research groups provide an understanding of bond-zone behavior and the impact of various design parameters on this behavior; those studies that have had the greatest impact on the current understanding of bond-zone behavior are discussed here.

- Abrams [2] tested numerous pullout and beam specimens with a wide range of material properties and design configurations. Findings from this study provided a basic understanding of bond-zone response.
- Goto [12] investigated internal crack initiation and propagation in tension bond-zone by injecting ink into the bond region of pullout specimens. The author observed differences in crack formation and propagation between specimens with smooth and deformed bars as well as between specimens with different bar deformation patterns (lateral ribs, diagonal ribs, and wavy ribs).
- Eligehausen et al. [13] examined local bond behavior using test specimens that represent beams with bar embedded in RC beam-column joint. Multiple parameters including external confining pressure and concrete compressive strength were considered in this investigation. The main conclusions of this study include the followings: a splitting-type bond failure is characterized by rapid loss of bond resistance; bond strength increases with higher confining pressure but remains constant once confining pressure exceeds the certain level, and bond strength is proportional to the square root of concrete compressive strength.
- Tholen and Darwin [14] investigated the impact on bond of the deformation properties of deformed bars, using pull-out type specimens with and without confinement. The main investigation parameters were bar size, relative rib area (discussed later and quantified by Eq. (1)), and the ratio of rib width to rib spacing. Based on dozens of experimental tests, the authors concluded that bond strength for confined specimens increases with higher bar size and with higher relative rib area. However, the variation in relative rib area did not affect bond strength for bars anchored in unconfined concrete.
- Zuo and Darwin [15] tested beam-splice specimens to investigate the bond strengths of uncoated and epoxy-coated bars having high relative rib area. The researchers confirmed the same observations on the relationship between relative rib area and bond strength in beam-splice specimens as those observed in pull-out specimens in the work of Tholen and Darwin [14].
- Murcia-Delso et al. [16] conducted pull-out tests of large-diameter (#11 (36 mm), #14 (43 mm), and #18 (57 mm)) bars embedded in well-confined concrete. This study concluded that bond strength tends to increase slightly with bar size and remarkably with concrete compressive strength.

1.3. Numerical approach to simulate bond-zone behavior

Despite all those experimental efforts above, there is still an increasing need for studying on bond behavior due to the continuing improvement of either concrete and reinforcement materials or design configuration [7]. Finite element (FE) simulation can supply the need as a supportive tool with relatively inexpensive investigation effort. To do so, a validated numerical model is necessary. Developing the model validated for bond-zone response requires careful consideration because of various bond mechanisms observed in experimental investigations, all of which do not need to be reflected in the model. In other words, FE model for bond has been developed in a way to be able to represent bond response approximated in accordance with its own investigation purpose (details are given in the following) and it is closely related with modeling scales. The followings are brief explanation and characteristics of the FE models developed at several scales: (1) element-scale, (2) bar-scale, (3) rib-scale, and (4) intermediate-scale.

- In an element-scale model, structural components such as beams and columns are modeled using line elements, and a rotational spring is introduced at the column-foundation or beam-column interface to simulate deformation, and potentially strength loss, associated with slip of reinforcement resulting from loss of bond strength. This modeling approach has been favored because it enables an analysis of the structural component or even entire structure with great efficiency [17,18].
- In a bar-scale model, the reinforcing bar is modeled using a truss element and is embedded in a concrete volume modeled using solid elements. For many applications, perfect bond between bar and concrete elements is assumed, due to simplicity and efficiency of this modeling approach [19]. Alternatively, a bond constitutive model, representing the local bond stress versus slip response, is introduced. This bond model is typically defined using experimental data [13,20–22].
- A rib-scale model treats both the bond-zone concrete and reinforcing bar as continuums, represented with solid elements. This highly refined model enables explicit modeling of the ribs of the bar and concrete at the concrete-bar interface. A contact model is used to account for shear and normal stress transfer at the interface. Rib-scale model is computationally intensive due to a large number of elements. Nevertheless, it has an advantage in that bond-zone response such as shear and radial stress developed in the course of debonding and interlocking of ribs can be directly reproduced as the analysis result [23–25].
- In some cases, both concrete and bar are modeled with solid elements and a cohesive element is introduced at the concrete-steel interface. The influence of the deformation of a bar such as ribs is implicitly considered through the interface law (or interface model) defined at the cohesive element. Thereby, radial stress by mechanical interlocking can be simulated. This model is called intermediate-scale model. As like the bar-scale model, it is required to use a phenomenological interface model based on test data to account for bond effect [26,27].

To sum up, element-scale and bar-scale models are considered appropriate for simulating global behavior of RC structures, where local bond response is not significant to the global response. By contrast, rib-scale and intermediate-scale models have a potential to reproduce local bond response. Of them, rib-scale model has a characteristic that it does not require an "empirically-derived" bond model to represent bond response such as radial bond stress and slip, which plays a critical role in producing local crack or crushing of concrete material. It must be noted that a bond model is limited to wide application, as developed considering the limited material and geometrical properties (e.g., concrete strength, reinforcement configuration and coating, and confinement level). Thus, with the purpose of reproducing local bond response by means of FE simulation, rib-scale modeling seems more appropriate approach [25]. Similarly, this study utilizes a rib-scale modeling approach to benefit from its feature that can mitigate the reliance on a phenomenological bond model.

1.4. Rib-scale FE model for bond

Interesting examples of a rib-scale FE analysis to simulate bond response in pullout test of a single bar embedded in normal-strength concrete can be found in the work of Salem and Maekawa [23] and Li [24]. Salem and Maekawa [23] simulated bond response using a 2D axisymmetric rib-scale finite element model. In defining contact properties, a linear elastic bond behavior, in both the normal and shear directions, was assumed; a range of bond-zone stiffnesses was considered as part of a sensitivity analysis. Results developed using this modeling approach were compared with those generated assuming a *hard* contact model in the direction normal to the concrete-steel surface; with this *hard* contact model, contact pressure resulting from ribs