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Probabilistic prediction model for average bond strength at steel–concrete interface considering corrosion effect

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ABSTRACT

Considerable numbers of reinforced concrete (RC) bridges in the US are structurally deficient mainly due to corrosion. Corrosion affects the structural integrity by deteriorating the material properties and the bond at the steel–concrete interface. Currently, the available bond strength models considering corrosion deterioration are either complex or developed based on the limited database. This paper proposes a simple probabilistic model of bond strength considering corrosion using multivariable regression based on a comprehensive database collected from the literature. The predictions are found to be accurate and unbiased when compared with the experimental results. Then, the proposed bond model is employed in the nonlinear finite element models of intact and corroded RC beams to investigate the importance of steel–concrete bond modeling on evaluating flexural behavior of the beams. Lastly, the minimum required development length for a given corrosion level is calculated and its sufficiency is investigated through a numerical analysis.

1. Introduction

Chloride induced corrosion is one of the prevalent causes of deterioration in reinforced concrete (RC) structures particularly in marine environments. According to the FHWA report [1], 13.7% of the total rural and urban bridges in United States are structurally deficient mainly due to corrosion. It is also estimated by NACE [2] that the annual direct cost of corrosion (e.g., repair and maintenance of RC bridge decks, maintenance painting of steel bridges) is $8.3 billion in the US. Furthermore, indirect costs, such as traffic delays and lost productivity, are estimated to be as high as 10 times that of direct costs, while 25–30% of these costs could be saved if optimum corrosion management practices were used [2]. To develop cost-effective corrosion management strategies, information on how corrosion affects the structural integrity and service life becomes essential [3].

In RC structures, corrosion initiates at the interface of rebar and concrete. Once corrosion initiates, the diameter of the rebar reduces and there is a volumetric expansion around the rebar due to the corrosion products. The magnitude of this expansion depends on the type of corrosion product that can be up to six times the original volume of the rebar [4]. These expansive corrosion products create tensile stresses in the surrounding concrete, leading to cracking and spalling of concrete cover, and reduction of the steel–concrete bond [5]. It has also been recognized that corrosion affects the mechanical properties of the rebars such as decreasing the yield strength, ultimate strength, and ultimate elongation of steel [6].

With such corrosion effects on the mechanical properties and the bond behavior between concrete and rebar, corrosion could change the stiffness [7], structural load carrying capacity [7–14] and even change the ductile failure mode that the design intends to achieve, to the brittle failure that usually increase the risk of catastrophic failure without warning [12]. Note that this particular failure mode is more likely to take place in structural members without sufficient development length in rebars. Meanwhile, the minimum development length strongly depends on the steel–concrete bond behavior; thus the deterioration in the bond behavior caused by corrosion could make the development length insufficient, which can cause brittle bond failure. Therefore, to evaluate structural performance of corroded structures, the modeling of corrosion effect on both the mechanical properties and the bond behavior between concrete and rebar is crucial.

Considerable research on modeling corrosion effects has been focused on the changes of diameter, yielding strength, and ultimate strain (ductility) of rebar. Zhang et al. [15] developed a linear relationship between the corrosion level and the ratio of yield strength of corroded rebar to the nominal yield strength of intact rebar.

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Cairns et al. [6] proposed linear equations to estimate the yield strength, ultimate strength, and ultimate strain of corroded rebars for different exposure conditions. Yang and Zhu [16] used the nonlinear function to consider the effect of corrosion on yield strength in finite element model (FEM) analysis. Castel et al. [17] evaluated the effect of steel cross-section and bond strength reduction on mechanical behavior of corroded rebars. They found that the ductility (ultimate strain) of rebars decreases exponentially with steel cross section reduction and stabilizes quickly around 25% of its initial ductility. To consider the corrosion effect on the diameter reduction of rebar, it is usually assumed that corrosion forms around the rebar uniformly and the ratio of corroded rebar cross sectional area to the intact rebar cross sectional area is proportional to the corrosion level [16].

Few studies have investigated the deterioration effect on the bond behavior in RC structures [18], while some studies have modeled the corrosion effect on bond strength. Those studies can be categorized into two groups: one uses theoretical procedures and the other one uses regression analysis on the experimental data. The theoretical approaches are usually complicated and computationally intensive. For example, the corrosion effect modeling developed by Choi and Lee [19] involves confining pressure around the rebar due to corrosion; however, to calculate this confining pressure, a finite element analysis is needed.

Compared with theoretical approaches, regression models, on the other hand, are straightforward and easily to be used by engineers. Some regression models developed previously are based on very limited experimental data (e.g. Lee et al. [20], Stanish et al. [21]); thus, they cannot be directly applied to other structure members. Many researchers predict corroded bond strength by multiplying an empirical reduction factor by the bond strength of intact rebar, and the reduction factor is usually evaluated based on a regression analysis using the experimental results of corroded specimens [14,22–24]. The main shortcoming of such models is that the intact bond strength needs to be estimated first, where the model error in estimating the intact bond strength should also be considered.

In this study, a probabilistic model is developed to predict bond strength as a function of corrosion level using nonlinear regression analysis. Instead of modeling the reduction factor, this model predicts intact and corroded bond strength directly. A comprehensive database is collected from literature and is used for the model development so that the proposed model is valid for a wide range of structural properties. In the proposed model, the predictors selected from literature consist of parameters that influence bond strength (such as concrete compressive strength, stirrups, development length, etc.). Then the model selection procedure is applied to select the predictors that statistically contribute to the model prediction. The proposed probabilistic model considers statistical uncertainties and model error. Then, we adopt the proposed bond strength model to a FE beam model to investigate the importance of steel–concrete bond behavior on evaluating flexural behavior of corroded beams. Furthermore, to ensure ductile failure, we suggest minimum development length for intact and corroded rebars. Lastly, the calculated minimum development length is compared with the one based on ACI 318-11 design code [25] through studying flexural behavior of intact and corroded FE beams.

2. Research significance

Modeling corrosion effect on the bond behavior between rebar and concrete is important as the deterioration on the bond could potentially change the failure mode of the structure. This paper proposes a probabilistic model using multivariable regression to predict the average bond strength at the steel–concrete interface considering corrosion. The model formulation is straightforward and can be easily used by engineers. The model is developed based on a comprehensive database collected from literature, and thus is sufficiently valid for a wide range of structural properties. It considers prevailing uncertainties including statistical uncertainties and model error. The proposed bond strength model can be used for a probabilistic performance evaluation of the existing corroded RC structures and also for calculating the minimum required development length considering corrosion.

3. Probabilistic bond strength model

3.1. Bond behavior

To describe bond between rebar and concrete, the relationship between bond stress and slip at the steel–concrete interface is usually modeled. One of the most widely accepted models is the MC90 bond-slip model suggested by CEB-FIP [26] and it is defined by the following equation:

$$\tau = \begin{cases} \tau_{\max}\left(\frac{s}{s_1}\right)^{\alpha} & \text{for } 0 \leqslant s \leqslant s_1 \\ \tau_{\max} & \text{for } s_1 \leqslant s \leqslant s_2 \\ \tau_{\max} - (\tau_{\max} - \tau_f)\left(\frac{s-s_2}{s_3-s_2}\right) & \text{for } s_2 \leqslant s \leqslant s_3 \\ \tau_f & \text{for } s_3 \leqslant s \end{cases} \tag{1}$$

where τ is the bond stress, $\tau_{\max}$ is the maximum bond stress, s is the relative slip between rebar and concrete, τ_f is the frictional bond stress, and model parameters (s_1, s_2, s_3, α) are defined based on the confinement of concrete with good or other bond conditions, as shown in Table A.1 in Appendix A. This model is to predict the bond stress as a function of relative displacement under monotonic loading. However, this relationship cannot be applied to describe bond behavior deteriorated by corrosion. In this study, we focus on the corrosion effect on $\tau_{\max}$ by developing a probabilistic bond strength model using experimental data.

The experimental bond strength data reported in the literature is usually calculated based on the applied force on the rebar divided by the nominal area around the rebar, given an embedment length. Therefore, this bond strength is different from $\tau_{\max}$ in Eq. (1), and refers to the average bond strength (τ_{avg}) by assuming the uniform stress distribution along the rebar. To relate τ_{avg} to $\tau_{\max}$, the distribution of the bond stress needs to be estimated. It has been agreed upon that the distribution of bond stress can be considered as uniform only for the cases with short embedment lengths; while in cases with long embedment lengths, the distribution is nonlinear and rather complex [27–31]. Despite the complexity, some researchers have proposed some simple functions to describe the distribution of bond stress along rebar. For example, Jiang et al. [30] suggested using a parabolic function for bond stress distribution based on their experimental results which also agrees with the experimental results obtained from Perry and Thompson [28] (as shown in Fig. 1). Using a parabolic function, the following relationship can be obtained between $\tau_{\max}$ and τ_{avg}:

$$\tau_{\max} = 1.5\tau_{\text{avg}} \tag{2}$$

3.2. Formulation of average bond strength

As the experimental bond strength refers to average bond strength, we develop a probabilistic model to predict τ_{avg}, and then $\tau_{\max}$ can be estimated using Eq. (2). The formulation of the probabilistic average bond strength model uses a multivariable regression model as follows:

$$y(\mathbf{x}, \mathbf{\Theta}) = \sum_{i=0}^{p} \theta_i h_i(\tilde{\boldsymbol{\theta}}, \mathbf{x}) + \sigma\varepsilon \tag{3}$$