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Bond strength of reinforcing bars considering failure mechanism

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ABSTRACT

Because the bond strength between a reinforcement and concrete is affected by various factors, including the compressive strength of the concrete, concrete cover thickness and reinforcement geometry, the bond mechanism is very complicated. This study proposed an analytical model that estimates the bond strength of the steel reinforcement considering both the splitting and pullout failure modes based on mathematical modeling of the stress field in reinforcement and the surrounding concrete. The results of the comparison between the analytical results obtained by the proposed model and test results reported in the literature showed that the proposed model can adequately estimate the bond failure mode and bond strength of the collected test specimens.

1. Introduction

The bond stress between reinforcement and surrounding concrete is developed by chemical bonds, friction and bearing forces acting on the ribs [1]. Initially, the chemical bond is fully active in the presence of small stresses on the reinforcing bar. However, when the initial slip occurs between the reinforcing bar and the concrete, most of the chemical bond is lost, and the bond mechanism is dominated by friction and the bearing forces of the bar ribs [1]. Due to this bond mechanism, a very complicated stress field is formed in the surrounding concrete, and a bond failure occurs if the concrete fails before the reinforcing bar reaches its yield strength. Therefore, it is very important to investigate the bond mechanism of reinforcing bars because the bond performance between the reinforcing bar and concrete is directly related to serviceability, shear, and flexural strengths of reinforced concrete (RC) structures [2–5].

Tepfers [6] classified the bond behaviors between reinforcement and concrete into elastic, partly cracked elastic, and plastic stages, and presented these behaviors as functions of the tensile strength of concrete (f_t), the concrete cover thickness (C), and the diameter of steel reinforcement (d_b). Xu [7] represented the stress generated in the surrounding concrete due to the friction and bearing forces of the reinforcing bar subjected to the tensile force as a function of rib geometry. Many other studies have also been carried out [8–13], and various empirical equations have been proposed based on the test results, as shown in Table 1. Nevertheless, there is still a lack of theoretical research on the bond failure mechanism, and it is difficult to find an analytical model able to accurately reflect the bond failure mode (i.e., the pull-out failure or splitting failure). In this regard, the stress distribution that occurs in the surrounding concrete due to bearing and friction forces exerted by the bar ribs was mathematically modeled, and the splitting failure and pull-out failure modes were separately.

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Table 1
– Bond strength equations proposed by previous researchers.

Authors	Equation*	Note
Orangun et al. [8,9]	$\tau = \left(0.1 + 0.25\frac{c_{\min}}{d_b} + 4.15\frac{d_b}{l_d}\right)\sqrt{f_c'}$	Bond strength
Zuo and Darwin [10,11]	$T_c = [1.43 l_d (c_{\min} + 0.5 d_b) + 56.2 A_s]\left(0.1\frac{c_{\max}}{c_{\min}} + 0.9\right) f_c'^{1/4}$	Bond force
Esfahani and Rangan [12,13]	$T_c = 2.7\pi l_d \frac{(c_{\min} + 0.5d_b)\left(1 + \frac{1}{M}\right)}{\left(\frac{c_{\min}}{d_b} + 3.6\right)(1.85 + 0.024\sqrt{M})}\left(0.12\frac{c_{med}}{c_{\min}} + 0.88\right)\sqrt{f_c'}$	Bond force, $f_c' < 50\text{MPa}$
	$T_c = 4.73\pi l_d \frac{(c_{\min} + 0.5d_b)\left(1 + \frac{1}{M}\right)}{\left(\frac{c_{\min}}{d_b} + 5.5\right)(1.85 + 0.024\sqrt{M})}\left(0.12\frac{c_{med}}{c_{\min}} + 0.88\right)\sqrt{f_c'}$	Bond force, $f_c' \geq 50\text{MPa}$

* Note: τ= bond strength, T_c= concrete contribution to bond force, A_s= sectional area of steel bar being developed or spliced, c_{med}= median of c_{so},c_b and $c_{si} + d_b/2$, $c_{\min}$= minimum concrete cover or 1/2 of clear spacing between bars = min (c_{so},c_b,$c_{si} + d_b/2$), c_b= bottom concrete cover, c_{si}= 1/2 of bar clear spacing, c_{so}= side concrete cover, $M=\cosh(0.0022 l_d\sqrt{3f_c'}/d_b)$ for conventional reinforcement.

defined in this study. The lower value of the bond strengths estimated by assuming splitting failure and pull-out failure modes was then defined as the bond strength between reinforcement and concrete. Consequently, the analytical model can determine not only the bond strength between the reinforcement and concrete but also the failure mode. The proposed model was also verified by comparing with the experimental results collected from previous studies.

Most of the proposed equations were derived based on the experimental results, in which the compressive strength of concrete (f_c'), and the ratio between the concrete cover thickness to the diameter of reinforcing bar (C/d_b) were considered as the main variables. Based on the equation proposed by Zuo and Darwin [10,11], the ACI Committee 408 [1] specifies that the concrete contribution to the bond force (T_c) should be calculated using the following equation:

$$T_c = [1.43 l_d (c_{\min} + 0.5 d_b) + 57.4 A_s]\left(0.1\frac{c_{\max}}{c_{\min}} + 0.9\right) f_c'^{1/4} \quad (1)$$

where l_d is the embedded length of the steel reinforcement, while $c_{\min}$ and $c_{\max}$ are the minimum and maximum values of the concrete cover thickness or half of the clear spacing of the steel bars, respectively. However, the following condition should be satisfied in order to apply Eq. (1):

$$\frac{1}{d_b}(c_{\min} + 0.5 d_b)\left(0.1\frac{c_{\max}}{c_{\min}} + 0.9\right) \leq 4.0 \quad (2)$$

Eq. (1) presented by ACI Committee 408 [1] provides unconservative analysis results for cases where C/d_b is low (See Fig. 11). According to Tepfers [6], the bearing force (P_b) induced by the bar ribs can be decomposed into radial stress (p) and friction stress (τ) as shown in Fig. 1 and represented by the following relationship:

$$p = \tau \tan\alpha \quad (3)$$

where α is the angle between bond forces and the longitudinal steel reinforcement. In addition, the concrete surrounding the reinforcing bar was divided into elastic, partially cracked, and plastic stages and the bond strength equations for each stage were proposed, as follows:

$$\tau = \frac{(C + 0.5d_b)^2 - (0.5d_b)^2}{(C + 0.5d_b)^2 + (0.5d_b)^2}\cdot\frac{1}{\tan\alpha}\cdot f_t \ (\textit{for elastic stage}) \quad (4a)$$

$$\tau = \frac{(C + 0.5d_b)}{1.664 d_b}\cdot\frac{1}{\tan\alpha}\cdot f_t \ (\textit{for partially cracked stage}) \quad (4b)$$

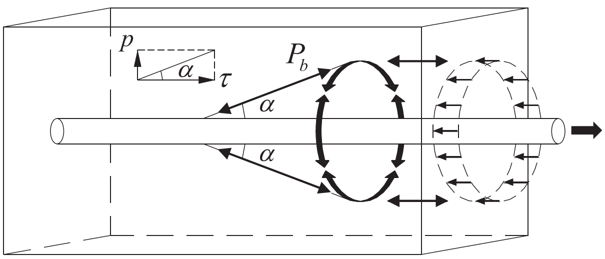

Fig. 1. Bond mechanism of reinforcing bar.