Towards an Improved Understanding of Bond Behaviors

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ABSTRACT

A reducing bearing angle theory for bond of ribbed reinforcing bars to concrete is proposed to simulate experimental observation. Analytical expressions to determine bond strength for splitting and pullout failure are derived, where the bearing angle is a key variable. As bearing angle is reduced, splitting strength decreases and shearing strength increases. The proposed reducing bearing angle theory is effective to simulate damage of the deformed bar-concrete interface and understand bond mechanism of ribbed reinforcing steel in concrete structures.

Keywords: bearing, bond (concrete to reinforcement); concrete cover; deformation of bars.

1. Introduction

Since the beginning of the past century, reinforced concrete researchers have endeavored to increase the bond characteristics of deformed reinforcing steel. The ribs act as wedges and the concrete in front of the ribs gradually crushes, resulting in a 'plow-through' or pullout-type failure. Rehm (1957) and Lutz (1970) found that the concrete in front of the ribs undergoes gradual crushing, followed by a pullout mode. The high rib face angle is flattened by the crushed concrete wedge, which reduces the effective rib face angle to a smaller angle (Fig. 1).

Rib geometry of bar deformation pattern governs bond behavior and is instrumental in guaranteeing in an adequate bond resistance. The geometry of ribs, as well as the interfacial properties, have been addressed and explicitly modeled to examine the underlying mechanism that produces the observed bond behavior. Analytical studies on interfacial bond with key variables, such as bearing angle, friction coefficient, cohesion and confinement force were performed to predict bond strength of reinforcing bars with rib deformation for the case of splitting bond failure.

With this information as background, this study is intended to analyze further the basic bar-concrete interaction. Analytical expressions to determine bond strength for splitting and pullout failure are derived, where the key variable is the bearing angle

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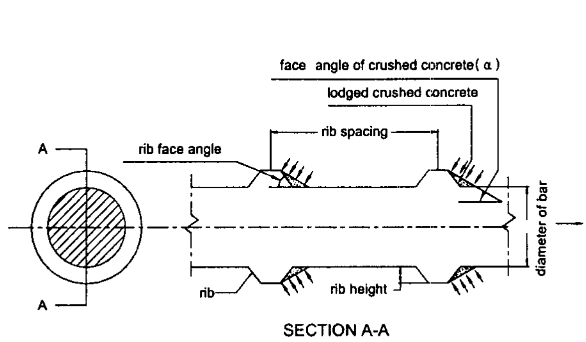

Fig 1. Flattened rib face angle by concrete crushing

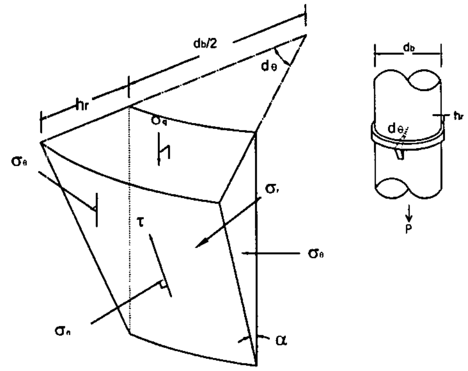

Fig 2. Stress acting on rib of bar

2. Analysis of Bond Mechanism

2.1 Splitting Failure

Wedging action by the rib of deformed bars makes it possible to resolve bond forces into normal stress σ_n and tangential shear stress τ as shown in Fig.2. The resultant of normal component along the bar is what places the surround concrete in tension. When reinforcing bars in tension P, concrete under the bearing side of a rib is known to be in a state of tri−axial compression with a major principal stress, the bearing stress, σ_q, on the rib acting parallel to the bar axis. As the radial force, the wedging force is applied to the concrete cover and confining bars.

Bond force equal to the sum of the bearing stress on a single rib area, T, is given by

$$T = A_r \sigma_q \tag{1}$$

in which A_r = projected area of rib parallel to the bar axis, approximated by $A_r = \pi d_b h_r$
where h_r is the rib height, σ_q = bearing stress on the bar rib acting parallel to the bar axis
The frictional force between the concrete and the steel (Fig. 3) on the inclined surface of the rib may be represented using the Mohr−Coulomb relation,

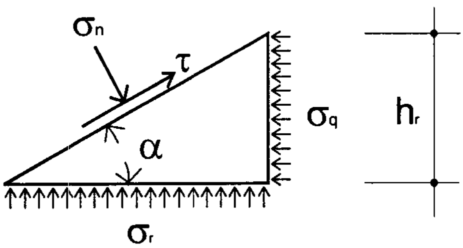

Fig 3. Stress along interfacewith angle α

$$\tau = c + \mu\,\sigma_n \tag{2}$$

where c = cohesion, μ = coefficient of friction, σ_n = normal stress.

Suppose the stresses along the interface with an angle of α are in equilibrium with the sliding force by σ_q and the normal force by σ_n. The variable σ_q in Fig. 3 is given by

$$\sigma_q = \left(\sigma_r \frac{(1+\mu\cot\alpha)}{(1-\mu\tan\alpha)} + \frac{c}{\sin\alpha(\cos\alpha - \mu\sin\alpha)} \right) \tag{3}$$

Equation (3) is substituted into equation (1) to obtain

$$T = A_r \left(\sigma_r \frac{(1+\mu\cot\alpha)}{(1-\mu\tan\alpha)} + \frac{c}{\sin\alpha(\cos\alpha - \mu\sin\alpha)} \right) \tag{4}$$

where σ_r acting radially around the bar axis applies to concrete cover as radial stress. The radial stress σ_r acts over a distance of $h_r \cot\alpha$ below the rib, and exerts a bursting force on the concrete around the bar. The component of force in the x-direction is

$$dF_x = \sigma_r h_r \cot\alpha \frac{d_b}{2} d\theta \cos\theta \tag{5}$$

The summation of the component force on the perimeter is given by

$$F_x = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} dF_x = \sigma_r \cot\alpha h_r d_b \tag{6}$$

Eq. (6) is substituted in to Eq. (4) resulting in the final equation to predict bond strength, which is expressed as follows.

$$T = F_x \pi \tan\alpha \frac{(1+\mu\cot\alpha)}{(1-\mu\tan\alpha)} + A_r \frac{c}{\sin\alpha(\cos\alpha - \mu\sin\alpha)} \tag{7}$$

This simple expression to predict bond strength agrees well with the test results and empirical equations. Based on the comparison between the analytical results and the test results, realistic ranges of the friction coefficient, cohesion, the effective rib face angle can be determined.

2.2 Pullout Failure

As in the vicinity of composite connections, direct shear may cause the failure and potential failure plane can be established for such cases along which direct shear stresses are high. Based on the early study, for cracks in monolithic concrete shear strength should not be assumed greater than $0.2f_{ck}A_c$ as in Eq. (8).

$$V_n = 0.2f_{ck}A_c \tag{8}$$

where A_c is the area of cracked surface.

The area of cracked surface which is sheared off forming a cone with an angle of α ;

$$A_c = \frac{2\pi d_b h_r}{\sin\alpha} \tag{9}$$

From Eq. (8) and (9), shearing bond strength is

$$T_{shear} = \frac{0.2f_{ck}\pi d_b h_r}{\sin\alpha} \tag{10}$$

3. Reducing Bearing Angle Theory

While the ribs undergo gradual crushing from the rigid body motion of the steel bars, the high rib face angle is flattened by the crushed concrete wedge, which reduces the effective rib face angle to a smaller angle. The bearing angle may be continually reduced in any circumstance such as bars are confined by heavy transverse reinforcement. Reducing of bearing angle definitely changes the bond resistance in splitting. Let us also examine Eq. (10) and the key variables of bond resistance in pullout failure. Bearing resistance is obtained by the concrete key between the ribs resisting from crushing or shearing off.

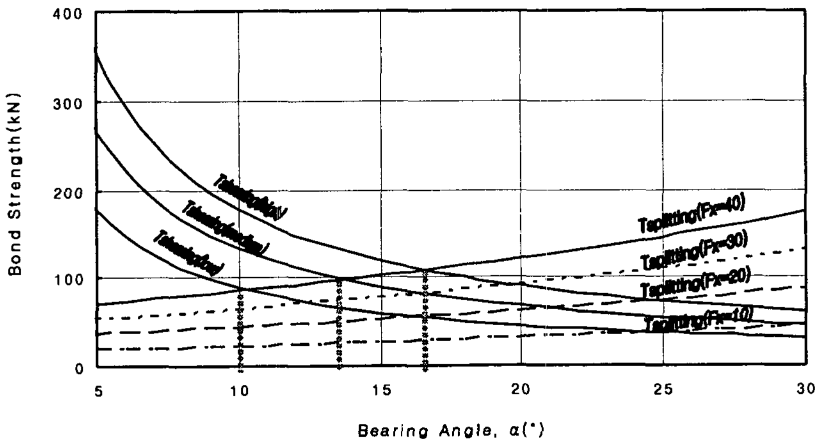

Fig 4. Bond strength with reducing bearing angle

Reducing of shearing angle definitely increase the area of the cone increasing the bond resistance. The weaker of the two mechanisms is considered to control bond strength. The concrete key should be sheared off the concrete key resulting in reducing bearing angle and bond strength, until a limiting resistance of the concrete is reached. Splitting strength is maintained to be less than the shearing strength. Thus,

$$T_{split} \leq T_{shear} \quad (11)$$

As the concrete key is crushed or sheared off, the bearing angle is reduced decreasing splitting bond strength and increasing possible shearing bond strength. The bearing angle at the interface is continually reduced so that splitting strength is maintained to be less than the shearing strength as bars slip. The bond force resistance considering two failure types is schematically illustrated in Fig. 4.

4. Conclusions

Analytical expressions to determine bond strength for splitting and pullout failure are derived. As the concrete key is crushed or sheared off, the bearing angle is reduced decreasing splitting bond strength and increasing possible shearing bond strength. As the splitting strength is higher than the shearing strength, the concrete key is crushed or sheared off and the splitting strength decreases with reducing bearing angle. The bearing angle at the interface is continually reduced so that splitting strength is maintained to be less than the shearing strength as bars slip.

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