BOND IN FLEXURE: A REVIEW OF ACI CODE 408R

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ABSTRACT

Bond between steel reinforcement and concrete is responsible for transfer of stresses of concrete to steel in flexural elements. Bond strength was earlier assumed to be a material property alone however many researchers concluded that the geometrical parameter and interface properties plays an important role. This paper presents an overview of the compilation of the contribution of many researchers in the ACI code 408 R. The paper briefly describes the basis of the code formulation and suggests some of the future scope of work to be done for up gradation of code.

Keywords: Flexure Bond, Bond equations, Splice specimen, splitting failure, Pullout failure

I. INTRODUCTION

Bond of embedded in steel reinforcement often refers to transfer of force between reinforcement and concrete. Bond affects the structures in two ways broadly: at serviceability the deflection and crack width and at limit state rotation capacity of plastic hinge regions. Many researchers from the past have been investigating the factors influencing it and the mode of failure and concluded their results in equation based on regression. The bond failed in two modes: splitting and pull out. Out of both splitting possesses the least value and designers are choosing this value however the structure to be ductile, pull out mode is preferred over the earlier one. The code ACI 408 R compiled the work of the researchers in the field of bond in flexure and recommends the equation which is relatively more robust and versatile.

II. MECHANISM OF BOND

The bond between steel and concrete consists of three mechanisms: adhesion, friction and mechanical interlock. The effect of chemical adhesion is small and friction forces do not develop until adhesion has failed and relative displacement between reinforcement bar and concrete occurs. Both mechanisms are important in the case of plain bars. For deformed bars, the mechanical interlock of the ribs of the bars embedded in concrete governs the bond stress deformation behaviour. The various forces that acts at steel and concrete interface during transfer of concrete to steel is shown in the fig 1 (a).When bond failure is approached, transfer of force between a ribbed bar and concrete is achieved by the bearing of the ribs on the concrete. The resultant compressive forces are exerted by the ribs, which spread into the surrounding concrete at a certain angle. These inclined forces create circumferential tension forces in the concrete around the bar fig. 1 (b). If these tensile forces exceed the tensile capacity of concrete, splitting failures occur. However if the tensile capacity is not reached by the circumferential tension forces the concrete in the ribs start crushing and leads to another type of failure known as pull out type of failure.

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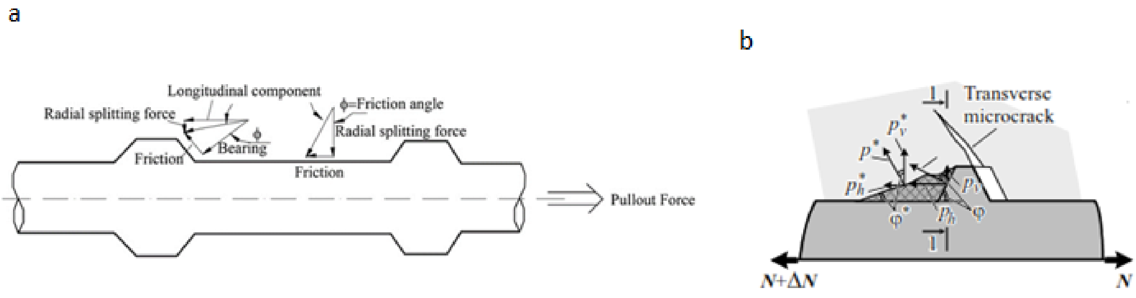

Figure 1 (a) Forces acting on interface (b) wedging action of ribs

III. EVOLUTION OF BOND EQUATION

The researchers idealised the bond problem with the thick cylinder with water pressure in the centre. However it needs the angle subtended by the crushed concrete. Goto [1] worked and found the angle to be between 40 to 80 degrees. However the research on the angle is limited and uncertainty exists in regard of angle so researchers fall on the most convenient method that is regression.

Using statistical techniques, Orangun, Jirsa, and Breen [2-3] developed expressions (3.1) and (3.2) to describe the bond strength of bars without and with confining transverse reinforcement. For bars not confined by transverse reinforcement, a regression analysis based on 62 beams, including four with side-cast bars, one with top-cast bars, and 57 with bottom cast bars, produced an expression for the average bond stress at failure. The sample specimen during the research is shown in Figure 2.

$$\frac{u_c}{\sqrt{f_c}} = 1.22 + 3.23\frac{C_{min}}{d_b} + 53\frac{d_b}{l_d} \quad .... \quad (3.1)$$

Where the notations c_{min} = smaller of minimum concrete cover or 1/2 of the clear spacing between bars; l_d = development or splice length; and d_b = bar diameter; u_c is the bond strength; f_c cylindrical concrete compressive strength; s is the spacing between the stirrups; n is the number of pairs of bars spliced; A_{tr} is the area of transverse reinforcement; f_{yt} is the yield strength of stirrup steel. In their analysis the bond strength of a bar confined by transverse reinforcement was represented by

$$\frac{u_c}{\sqrt{f_c}} = 1.2 + 3\frac{C_{min}}{d_b} + \frac{50d_b}{l_d} + \frac{A_{tr}f_{yt}}{500snd_b} \quad .... \quad (3.2)$$

The above equations are restricted to the condition as follows.

$$\frac{1}{d_b}\left(C_{min} + 0.4\,d_b + \frac{f_{yt}A_{tr}}{1500\,sn}\right) \leq 2.5$$

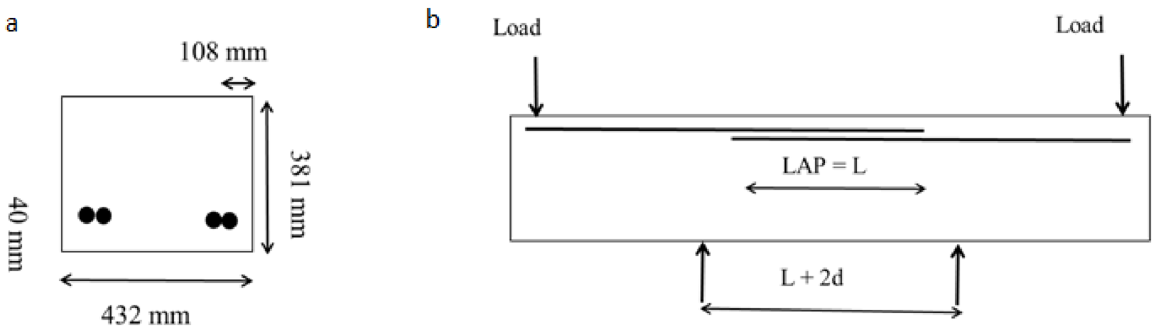

Fig 2. (a) Cross sectional details of specimen (b) spliced region in splice specimen

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Darwin et al. [4-5] used a larger database, consisting of 133 splice and development specimens in which the bars were not confined by transverse reinforcement and 166 specimens in which the bars were confined by transverse reinforcement. All specimens contained bottom-cast bars. They observed that $fck^{1/4}$ provided a better representation of concrete strength on development and splice strength than the more traditional $fck^{1/2}$. They also incorporated the effect of relative rib area Rr as shown in figure 3, which they observed to have a significant effect on the bond strength of bars confined by transverse reinforcement. Based on their studies, the best-fit equations for the bond strength of bars not confined by transverse reinforcement and for confined concrete are (3.4) and (3.5).

$$\frac{A_b f_s}{f_c^{1/4}} = [63 l_d (c_{min} + 0.5 d_b) + 2130 A_b]\,(0.1\frac{c_{max}}{c_{min}} + 0.9) \quad \text{..................... ....} \quad (3.4)$$

where $(0.1\frac{c_{max}}{c_{min}} + 0.9) \leq 1.25$

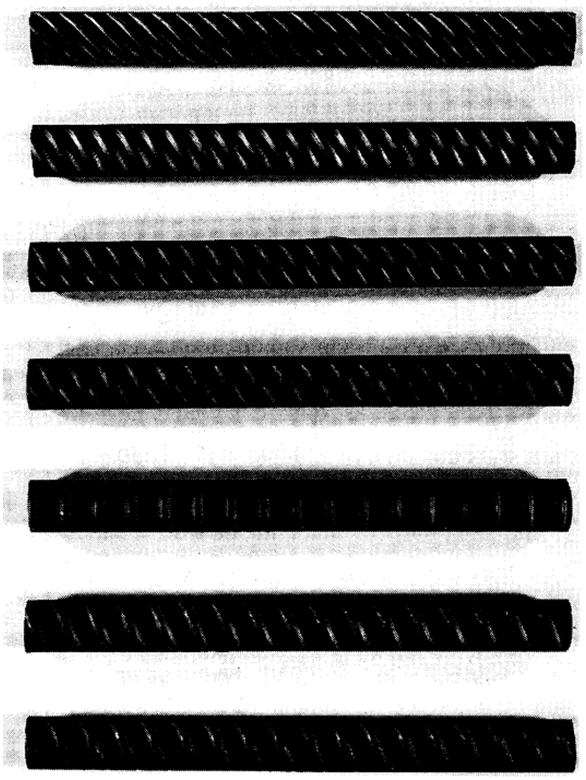
$$\frac{A_b f_s}{f_c^{1/4}} = [63 l_d (c_{min} + 0.5 d_b) + 2130 A_b]\,(0.1\frac{c_{max}}{c_{min}} + 0.9) + 2226 t_r t_d \frac{N A_{tr}}{n} + 66 \quad \text{..............} \quad (3.5)$$

where N = no of transverse bars in development length

$t_r = 9.6 R_r + 0.28$ and $t_d = 0.72 d_b + 0.28$

The above equations hold good only when the following equation is satisfied.

$$\frac{1}{d_b}[(c_{min} + 0.5 d_b)\,(0.1\frac{c_{max}}{c_{min}} + 0.9) + (\frac{35.3 t_r t_d A_{tr}}{sn})] \leq 4.0$$



Rib spacing (inches)	Rib Spacing (inches)	Relative Rib ratio (inches)
0.350	0.035	0.082
0.275	0.041	0.109
0.589	0.063	0.085
0.504	0.060	0.101
0.471	0.074	0.140
0.650	0.054	0.069
0.487	0.068	0.119

Fig 3. Reinforcing steel rib bar details

Zuo and Darwin [6] expanded the work of Darwin et al. [4-5] by increasing the database and adding substantially to the percentage of test specimens containing high-strength concrete (fck > 8000 psi [55 MPa]). The database included 171 specimens containing bars not confined by transverse reinforcement and 196 specimens containing bars confined by transverse reinforcement. All bars were bottom cast. Their analysis supported the earlier observations that $fck^{1/4}$ realistically represents the contribution of concrete strength to bond strength for bars not confined by transverse reinforcement. As shown in figure 4 however, they observed that fck^{p}, with p between 3/4 and 1.0, best represents the effect of concrete strength on stress in bar, the contribution of confining transverse reinforcement to bond strength. However from the fig 4 it can be concluded that the value of p = 1 gives a negative slope moreover the value of p = 3/4 gives more independent equation than other powers of p. They selected p = 3/4 for their descriptive equations. For bars not confined by transverse reinforcement, the best-fit equation describing development and splice strength is

$$\frac{A_b f_s}{f_c^{1/4}} = [59.8 l_d (c_{min} + 0.5 d_b) + 2350 A_b] \left(0.1 \frac{c_{max}}{c_{min}} + 0.9\right). \quad \text{......} \quad (3.6)$$

For Confined concrete

$$\frac{A_b f_s}{f_c^{1/4}} = [59.8 l_d (c_{min} + 0.5 d_b) + 2350 A_b] \left(0.1 \frac{c_{max}}{c_{min}} + 0.9\right) + \left(31.14\, t_r t_d \frac{N A_{tr}}{n} + 4\right) f_c^{1/2} \text{......} (3.7)$$

where N = no of transverse bars in development length

$t_r = 9.6 R_r + 0.28$ and $t_d = 0.78 d_b + 0.22$

To ensure splitting type of failure the below equation must satisfy

$$\frac{1}{d_b}\left[(c_{min} + 0.5 d_b)\left(0.1 \frac{c_{max}}{c_{min}} + 0.9\right) + \left(\frac{0.52\, t_r t_d A_{tr}}{sn}\right) f_c^{1/2}\right] \leq 4.0$$

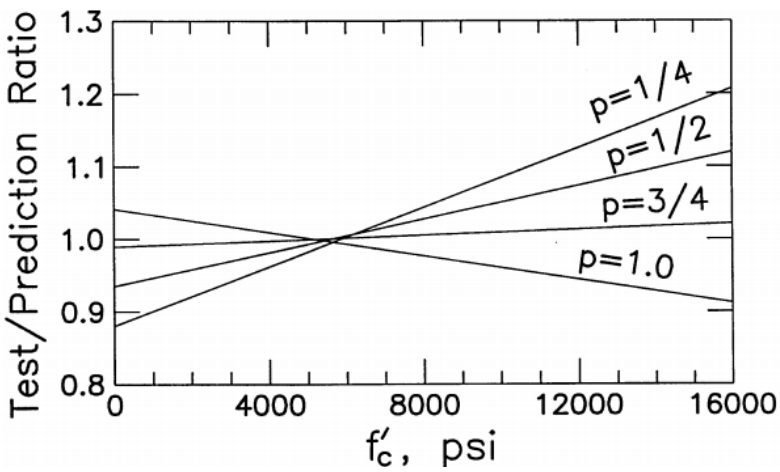


Fig 4. Test to prediction ratio verses strength of concrete

Using ACI 408 [7] Database 10-2001, the committee has updated the above equations with only minor changes.

$$\frac{A_b f_s}{f_c^{1/4}} = [59.9 l_d (c_{min} + 0.5 d_b) + 2400 A_b] \left(0.1 \frac{c_{max}}{c_{min}} + 0.9\right) \text{......} (3.8)$$

Confined concrete

$$\frac{A_b f_s}{f_c^{1/4}} = [59.9 l_d (c_{min} + 0.5 d_b) + 2400 A_b] \left(0.1 \frac{c_{max}}{c_{min}} + 0.9\right) + \left(30.88\, t_r t_d \frac{N A_{tr}}{n} + 3\right) f_c^{1/2} \text{......} (3.9)$$

where N = no of transverse bars in development length

$t_r = 9.6R_r + 0.28$ and $t_d = 0.78d_b + 0.22$

$$\frac{1}{d_b}[(c_{min}+0.5d_b)\,(0.1\frac{c_{max}}{c_{min}}+0.9)+(\frac{0.52t_rt_dA_{tr}}{sn})f_c^{\ 1/2}] \leq 4.0$$

IV. COMPARISON OF EQUATIONS

The test to prediction ratios with respect to concrete compressive strength of different proposed equations for confined beam specimens are shown in figure 5(a). For the beam specimens which are not confined by transverse reinforcement the figure shows that the test to prediction ratio for equation proposed by Orangun, Jirsa and Breen[2-3] shows that for strength up to 8000 psi [55 MPa] the equation over estimates the bond strength however the as the strength increases from 800 psi [55 MPa] the equation starts over estimating the bond strength. Moreover the equations proposed by Darwin et al [4-5] shows unbiased results but becomes unconservative as the strength increases. Also Zuo and Darwin [6] shows the same pattern with increase in compressive strength however shows close results when compared to earlier equation. The ACI 408 R [7] equation among all the equations proved to be the most unbiased to compressive strength in comparison to other equations.

The effect of confined beam specimen on the test to prediction ratio verses compressive strength is represented in the figure 5(b). The Orangun Jirsa and Breen[2-3] equation shows the similar behaviour with increase in strength as shown with unconfined beam specimen however the equation proposed by Darwin et al [4-5]shows significant departure as was shown in unconfined ones. The test to prediction ratio in compressive strength up to 4000 psi [27.5 MPa] shows unconservative results however as the strength it becomes more and more conservative. Also the equations recommended by Zuo and Darwin[6]and ACI 408 R [7] kept close to the earlier values as in unconfined concrete.

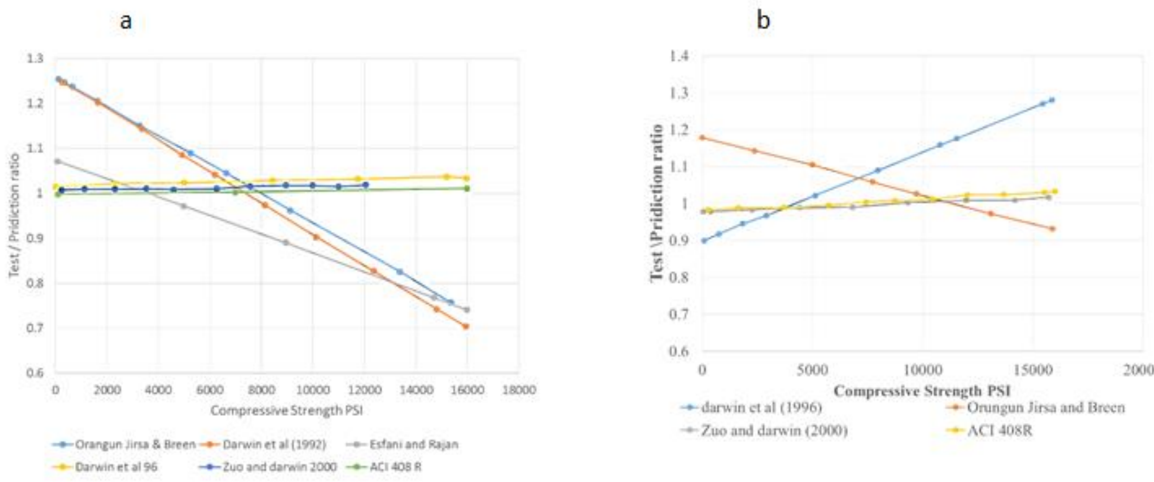


Fig 5 (a) Comparison of equations (a) unconfined (b) confined beam specimen

V. CONCLUSION AND SCOPE OF FUTURE WORK

- The ACI 408 R equation gives the lower bound of the bond strength (splitting type of failure) however it give no equation for the upper bound of the bond strength (pull out type of failure).
- The equation is unbiased with respect to concrete strength for a range of up to 110 MPa. As we are moving to higher strength of concrete the equation need to be revised.
- The ACI 408R recommended equation is based on regression. As regression analysis is dependent upon the number of samples so with larger data base, coefficients of equations can always be modified.
- With the advancement in regression techniques the equations need to be updated.
- The bond strength is more affected by the fracture energy but unfortunately the fracture energy is implicitly incorporated in the equation.
- Also the code does not signify about the load slip models and does not prescribe any specimen for the bond characteristics determination.
- The code is silent about the modifications that should be made if the bar is corroded.
- Lastly the code does not account in the expression for elevated temperature.

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