

Bond Strength of Bare and Coated Bars – Splice Length and Confinement Requirements

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ABSTRACT: The performance of reinforced concrete structures depends on adequate bond strength between the concrete and reinforcing steel. The main parameters that influences the bond strength of concrete includes concrete cover, splice length, confinement to concrete and protective coating to reinforcement. Concrete cover is effective only up to cracking of concrete and after cracking the strength of the splice depends on the confinement provided to concrete. In beams and columns passive confinement is provided by the stirrups. Theoretical prediction of the effect of passive confinement provided by stirrups is not addressed in the past. Therefore this paper aims at theoretically predicting the bond strength of coated and uncoated bars confined with stirrups. The lap length required to offset bond failure is reported for medium and high strength concrete and the amount of confinement required to achieve flexural failure is also reported. Moreover, the increase in splice length required for bars with coating is also reported for bond reduction of 10 to 30%. The increase in splice length for coated bars embedded in concrete varied from 50% to 70% for medium strength concrete and 18 % to 51% for high strength concrete..

KEYWORDS: concrete cover, confinement, bond (concrete to reinforcement), splice length, bond strength, epoxy coating, stirrups, bond ratio.

I. INTRODUCTION

Bond in reinforced concrete is made up of three components: 1) chemical adhesion; 2) friction; and 3) mechanical interaction between ribs of the bar and the surrounding concrete. Most of the force transfer from the reinforcement to the surrounding concrete is by bearing and friction. When a deformed bar slips relative to the surrounding concrete, surface adhesion is lost, while bearing and frictional forces are mobilized. The force transfer mechanism is shown in Fig. 1.

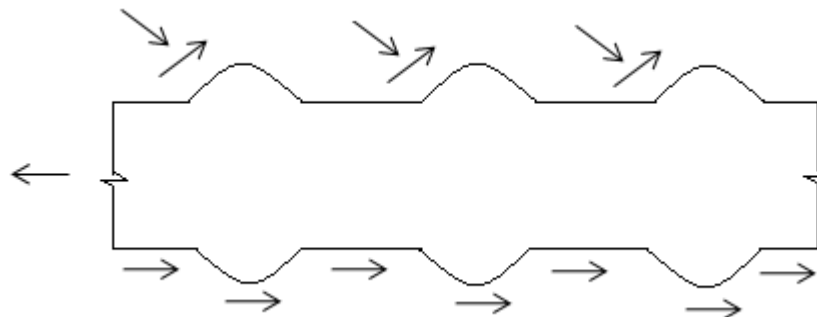


Fig.1 Bond transfer mechanisms – Friction , Adhesion and Bearing

The frictional resistance in coated bars is less when compared to that of an uncoated bar. The change in the frictional resistance accounts for major reduction in the bond strength of coated bars. The deficiency introduced by coating can be overcome by the following ways: 1) increasing the splice length of the coated bars 2) increasing the cover provided

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to the reinforcement 3) increasing the confinement provided to the reinforcement. Increasing the cover seems to be effective in the initial stages of load transfer, until concrete cracks. Hence, the best way to increase the bond performance of coated reinforcement is to provide increased lap lengths. Most of the slips of the reinforcement will take place after cracking of concrete. After cracking, effective confinement to concrete is provided by transverse reinforcement. Much of theoretical support is not available for the experimental results reported to study the effect of confinement. For this reason, a theoretical study using the available confinement models is used in this study, to find the effect of confinement and lap length in improving the bond stress. Various confinement models available in the literature are compared and the best model is identified and coded in C language to find the splice strength of beams with lap splices. The developed program is used to compute the strength of splices with different lap lengths and confinements. The minimum splice length required to achieve flexural failure is calculated and reported for uncoated bars. Knowing this splice strength, the increase in splice length required for coated bars is calculated.

II. REVIEW OF EARLIER RESEARCH ON CONFINEMENT

The bond between the reinforcing bar and the concrete is mainly influenced by the confinement. The cover provides confinement to the bar embedded in concrete before cracking. The pressure exerted by the reinforcing steel bar on the concrete induces radial and circumference stresses on the cover concrete. The cracking of concrete cover takes place at the point where the circumferential stress exceeds the tensile strength of concrete. The cover concrete is effective only up to a cover to diameter ratio of 4.

Tepfers(1973) proposed a theory which predicts the bond stress of spliced bars and different modes of failure at the splice region.

Malvar (1992) tested 12 reinforced concrete specimens of 3 inches in diameter. He studied the effect of external confining pressure on the bond stress improvement by conducting experiments on pull out specimens confined by external pressure applied to the concrete. Fig. 2 shows a cylindrical reinforced concrete specimen subjected to external confinement. Prior to cracking some amount of confinement is provided by the concrete core itself via tensile hoop stresses. Once the specimen starts cracking, the concrete cylinder fails to provide the confinement and the externally applied confinement comes into action.

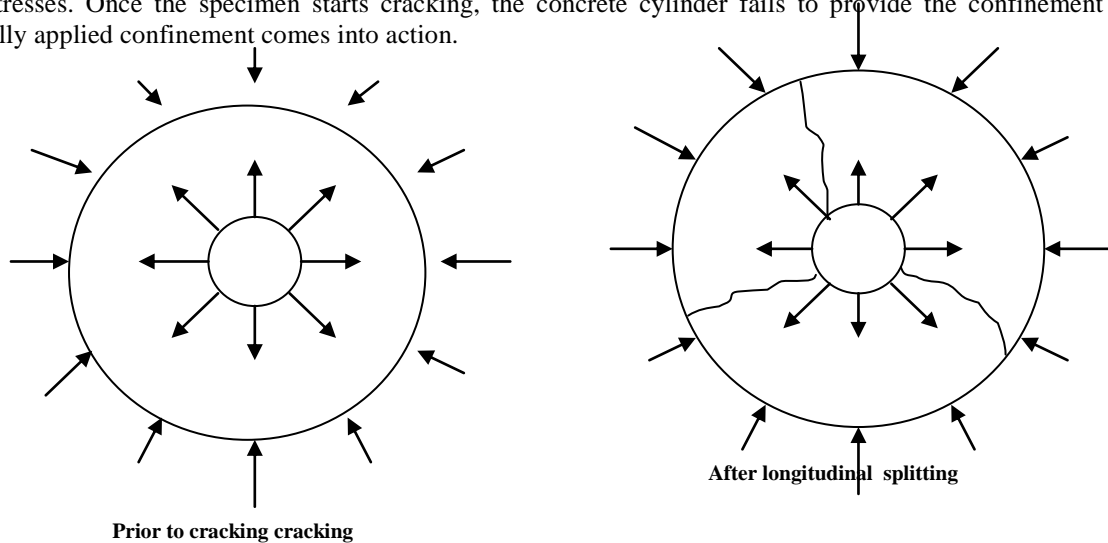


Fig. 2 Cylindrical specimen subjected to external confinement

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Thus prior to cracking of the concrete cover the confinement provided is a combination of concrete cylinder confinement and the externally applied one and it is variable but after cracking confinement is provided by the externally applied pressure and this remains constant. Fig 3 shows the effect of external confining pressure in increasing the bond stress of concrete. Previous work on the effect of confinement of concrete as reported by Malvar is reproduced below.

Untrauer and Henry tested 20 mm and 28 mm bars pulled from 150 mm cubes subjected to lateral pressure on two opposite faces. the normal pressure was increased from zero to 16.34 MPa (2370 psi). Bond strength was observed to increase proportional to square root of the normal pressure.

Doerr subjected 16 mm deformed bars embedded in 75 mm diameter cylindrical concrete specimens to tension. Specimens were subjected to confining pressures up to 15 MPa. It was found that bond stress could be incremented up to 50 %. Doerr also attributed the large scatter in bond stress results reported in the literature to the various dimensions of test specimens.

Robins and Standish pulled 8 and 10 mm bars from 100 mm cubes and found that increasing confinement up to 10 MPa increased the bond strength by 100 % and when the confining pressure was increased up to 28 MPa , did not increase the failure loads.

Elighausen et.al tested 125 pull-out specimens and increased confinement in one direction from 0 to 13 MPa and found that there was a 25% increase in the maximum bond resistance. Confinement provided by lateral confinement was not evaluated.

Gambarova, Rosati and Zasso pulled 18 mm bars embedded in a cracked concrete specimen and studied the effect of confinement perpendicular to the longitudinal cracking plane, keeping the crack opening constant during the test. Bond was found to increase with increasing confinement i.e., with decreasing crack opening by up to 40%.

Hungspreug also carried out pullout tests on cylindrical specimens with constant radial pressure. he found that a linear increase in maximum bond force and corresponding slip with confining pressure upto a confinement of 2.8 MPa at the bar surface. For higher confinements increase in maximum bond force appeared to have been inhibited by radial cracking.

Modena, Coltro and Rossaro studied the effects of a constant confining pressure perpendicular to the longitudinal cracking plane in a specimen similar to Gambarova. The longitudinal cracking plane was preformed and a 16 mm bar with lugs at 45 degrees was used. During the testing, the slip was increased upto 5 mm. they reported an increase in bond strength from about 3 to 8.5 MPa for a confining pressure varying from 1.8 to 8.6MPa. They also reported an increase in the crack opening up to a limit value that decrease with the confining pressure.

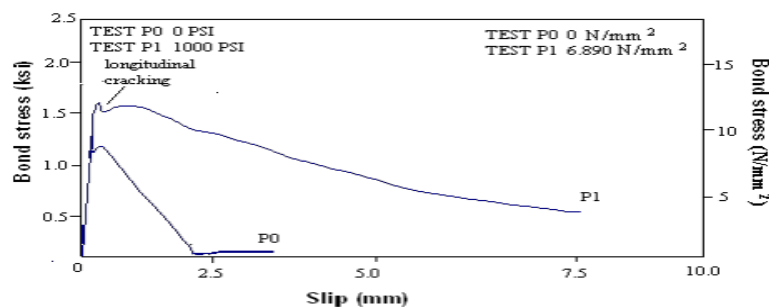


Fig.3 Effect of confining pressure on the bond stress slip relationship of concrete

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III. PROPOSED MODEL

The available confinement models are analyzed and the one which suits this study is chosen and appropriately modified to suit confinement in beams and a C program is coded. Using this program, the load at which flexure failure takes place and the splice strength of beams which fail in bond is also computed. It is observed that Legeron and Paultre's model is the best available model reported in literature so far. Therefore Legeron and Paultre's model is chosen to study the effect of confinement on splice strength of lap splices. To make this model suitable for beams, certain modifications should be applied to the model. The proposed modifications are as follow:

1. In the case of columns the whole cross section of the column is under compression. However in the case of beams, the Depth of the compression zone extends only up to x_u from the top of the beam. Hence, the depth of the section under compression that should be considered in beams is x_u . But to simplify the analysis this depth is considered to be half the depth of the beam.
2. Further the strain distribution in the case of columns is constant but in the case of beams the strain distribution varies linearly from zero at neutral axis to maximum at the extreme compression fiber. Hence, the average strain on the concrete is only half that prevails at the extreme fiber. Hence the strain in concrete is assumed to be half.
3. The area of the stirrups in the x direction is ineffective in confining the concrete and hence ignored in the calculations.
4. In calculating the longitudinal reinforcement ratio, the area of the steel in the compression face of the beam is considered and the reinforcement in the tension face is not considered.

The modified model is coded and is used in carrying out the parametric study.

IV. PREDICTION OF THE ULTIMATE STRENGTH OF THE SPLICE

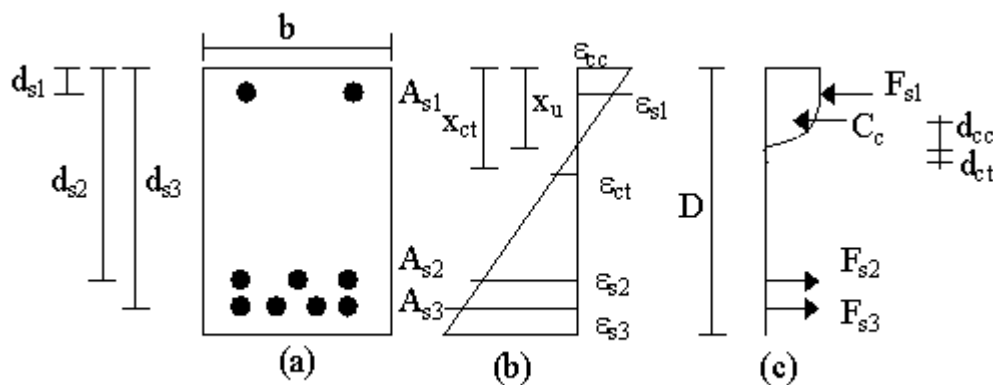


Fig. 4 Strain, Stress and forces acting in the cross-section of a beam

The main aim of this study is to find the ultimate strength of the splice. Fig.4 shows the cross section of the beam with details of force in the bars and the strains in the concrete and steel. The procedure to be followed to find the strength of the splice is given below. A C program is coded based on the procedure and the ultimate strength is determined.

The force on the bottom bar is calculated based on the model recommended by ACI 408 committee,

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$$F_b = [1.43l_d(c_{min} + 0.5d_b) + 57.4A_b] \left(0.1 \frac{c_{max}}{c_{min}} + 0.90\right) \quad (1)$$

For coated bars, the above force is reduced by assuming 10%, 20% and 30% reduction in the bond strength.

The strain of the bottom steel bars is calculated assuming the E value of steel. In contradiction to the customary analysis followed to find the ultimate flexural strength of the beam, in this analysis the strain in the bar is fixed first and the neutral axis depth is calculated based on an iterative procedure.

$$\varepsilon_{b.slip} = \frac{F_b}{E_s(\pi \phi_b^2/4)} \quad (2)$$

The strain of the top steel bar and top most fibre of concrete are calculated assuming a linear variation of strain,

Initially, a starting value of x_u is assumed and the strains in concrete and steel are calculated

$$\varepsilon_{ci} = \frac{\varepsilon_{b.slip}}{d_{eff} - x_u} (x_u - x_i) \quad (3)$$

The strain on the concrete,

$$\varepsilon_{cc} = \frac{\varepsilon_{b.slip}}{d_{eff} - x_u} x_u \quad (4)$$

Force on the top bar,

$$F_T = \varepsilon_{ci} E_s A_T \quad (5)$$

The compressive force on the concrete,

$$c_c = 0.67 * b * f_{ck} * x_u * \text{area of stress block} \quad (6)$$

The total force acting on the beam,

$$\text{Total force} = -c_c - F_T + F_b \quad (7)$$

For equilibrium, the total force acting on the cross section should be zero. If the calculated force is not equal to zero, the value of x_u is incremented in steps of 5 mm and continued till equilibrium is achieved.

Once x_u is determined, Moment acting at the section can be calculated as shown in Equ. 8

$$\text{Moment, } M_u = c_c(1 - 0.42x_u) + F_T(x_u - x_i) + F_b(d_{eff} - x_u) \quad (8)$$

As the beam is subjected to four point bending, Ultimate load on the beam is calculated as

$$\text{Ultimate load, } P = 2(M_u/a) \quad (9)$$

Where a is the shear span of the beam

The program developed should be validated before it could be used to do a parametric study.

Hence to validate the program, the theoretical splice strength obtained from the developed program is validated with the experimental results. (Pandurangan and Appa Rao (2009)). The predicted and experimental value of the loads for uncoated bars with 100 mm spacing of stirrups is 116.45 kN and 120.32 kN respectively. The percentage error involved in the prediction is 3.7%. Hence it can be considered that the above theoretical results are valid. The developed program is used to do a parametric study by varying the parameters mentioned in Table 1 and the results of the parametric study are discussed.

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Table 1 Parameters and their range

Sl.No	Parameters	Minimum Value	Maximum value
1	Lap length ,mm	500	1750
2	Spacing of stirrups	8 mm @ 50 c/c	8 mm @ 300 c/c
3	Reduction in bond strength due to coating	0	30%
4	Compressive strength of concrete ,MPa	40	80

The effectiveness of increasing the lap length, confinement and compressive strength of concrete is studied and reported. The diameter of bar used in this study is 25 mm. The lap length is varied from 20 times diameter to 70 times diameter. The main intention of any design is to ensure ductile mode of failure. The brittle bond failure that may occur in a beam may be due to insufficient lap length and confinement. The failure for varied lap lengths and confinement is computed and compared with that of the load required for flexural mode of failure. The minimum required lap length is found and the confinement required for this lap length is also reported in Table 2.

TABLE 2 REQUIRED CONFINEMENT LEVELS AND LAP LENGTHS

Compressive Strength, MPa	Lap Length , mm	Required Confinement, mm	Flexural Load, kN
40	20D	Insufficient lap length	162.06
	30D	Insufficient lap length	
	40D	Lap length is sufficient and needs high confinement of 8 mm @ 50mm c/c	
	48D	Lap length is sufficient and needs at least confinement of 8 mm @ 100 mm c/c	
	60D	Lap length is sufficient and needs minimum confinement of 8 mm @ 300 mm c/c	
	20D	Insufficient lap length	

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60	30D	Insufficient lap length	165.80
	38D	Lap length is sufficient and needs at least confinement of 8 mm @ 100 mm c/c	
	40D	Lap length is sufficient and needs minimum confinement of 8 mm @ 300 mm c/c	
	60D	Lap length is more than sufficient and needs minimum confinement of 8 mm @ 300 mm c/c	
80	20D	Insufficient lap length	167.99
	30D	Insufficient lap length	
	34D	Lap length is sufficient and needs at least confinement of 8 mm @ 100 mm c/c	
	38D	Lap length is sufficient and needs minimum confinement of 8 mm @ 300 mm c/c	

The additional lap length required for splices with coated bars to achieve the splice strength of the uncoated bars is also reported. The most unfavorable bond ratio (BR), which is the ratio of least bond strength in coated bars to maximum bond strength in uncoated bars, for bamboo rib pattern, inclined rib pattern and diamond rib pattern is found to be 10 %, 20 % and 30 % respectively. Therefore the additional lap lengths needed for 10%, 20% and 30% reduction in bond strength is calculated and reported in Table 3. The length required is more in the case of normal strength concrete and comparatively less in the case of high strength concrete. The confinement required for confining the splice decreases with increase in lap length. More lap length is needed in the case of coated bars with diamond pattern and less in the case of bamboo pattern.

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TABLE 3 LAP LENGTH REQUIRED FOR COATED BARS

Sl.No	Compressive strength of concrete, MPa	Splice strength of uncoated bars for Flexural failure	Splice length for uncoated bars, mm	Splice length for coated bars, BR = 0.90	Splice length for coated bars, BR = 0.80	Splice length for coated bars, BR = 0.70
1	40	150.62	40D	60D	66D	68D
2	60	159.48	38D	44D	52D	64D
3	80	162.46	34D	40D	50D	58D

V. CONCLUSIONS

Based on the work, the following conclusions are arrived

1. In order to achieve the same splice strength, the lap length required for medium strength concrete is more compared to high strength concrete. A lap length of 60 times diameter is required for medium strength concrete without confinement and a lap length of 48 times diameter is required with heavy confinement. However in the case of high strength concrete a lap length of 38 times diameter itself is sufficient without any confinement and 34 times diameter with confinement.
2. The increase in lap length required in the case of coated bars embedded in normal strength concrete is 50% to 70% additional to than required for uncoated bars respectively. Similarly the increase required is 18% to 51% in the case of high strength concrete.
3. The confinement model proposed in this study predicts the splice strength accurately in well confined concrete and further studies are needed to modify the present confinement models to suit low levels of confinement in flexure.

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