Development length of reinforcing bars — Need to revise Indian code provisions

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The bond between concrete and reinforcement bars is very important to develop the composite behaviour of reinforced concrete. Bond strength is influenced by several factors such as bar diameter, cover of concrete over the bar, spacing of bars, transverse reinforcement, grade and confinement of concrete around the bars, aggregates used in concrete, type of bars and coating applied on bars, if any, for corrosion prevention. In the Indian code on concrete structures which was revised in the year 2000, the provisions regarding development length remained unchanged. Many of the above parameters are not considered in the revised code. Hence in this paper, the Indian code provisions are compared with those of American code provisions (which consider all these parameters). The effect of high strength concrete, self consolidating concrete and fibre reinforced concrete on the development length is also discussed. A formula for inclusion in the Indian code is also suggested based on recent research.

Keywords: *Development length, reinforcement, code provisions, bond strength, lap splices*

Bond in reinforced concrete refers to the adhesion between the reinforcing steel and the surrounding concrete. The bond between steel and concrete ensures strain compatibility (the strain at any point in the steel is equal to that in the adjoining concrete) and thus composite action of concrete and steel. Bond in reinforced concrete is achieved through the following mechanisms[1]:

- chemical adhesion due to the products of hydration
- frictional resistance due to the surface roughness of the reinforcement and the grip exerted by the concrete shrinkage.
- mechanical interlock due to the ribs provided in deformed bars.

Since plain bars do not provide mechanical interlock many codes from other advanced countries prohibit their use in reinforced concrete and allow their use only for lateral spirals, stirrups and ties smaller than 10 mm in diameter. However, there is no such restriction in the Indian code.

Traditionally, design for bond required the consideration of both flexural (local) bond stress, u_f, and development (anchorage) bond stress, u_{av}. It was later realised that the exact value of flexural bond stress could not be accurately computed owing to the unpredictable and non-uniform distribution of actual bond stress. It was also found that localised bond failures can and do occur and they do not impair the ultimate load carrying capacity of beams, provided the bars are adequately anchored at their ends. Thus, in the limit state design, the focus shifted from checking the flexural bond to the development of required bars stresses through provision of adequate anchorage at simple supports and at bar cut-off points. Special checking of anchorage length is required in the following cases:

- in flexural members that have relatively short length
- at simple supports and points of inflection
- at points of bar cut-off
- at cantilever supports
- at beam-column joints in lateral load (wind and earthquake) resisting frames
- for stirrups and transverse ties and
- at lap splices.

Several failures have occurred due to the non-provision of adequate anchorage lengths, especially at cantilever

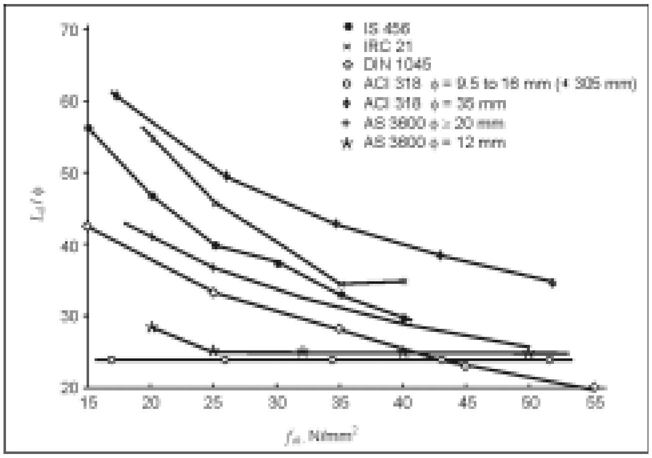

Fig 1 Comparison of L_d/ϕ values for tension bars[3]

supports, lap splices and beam-column joints. Hence, the provision for anchorage length assumes greater importance. This paper discusses the Indian code provisions on anchorage length as compared with the ACI code provisions. The various drawbacks of the Indian code provisions are discussed and a suitable expression based on recent research is suggested.

Indian code provisions

According to clause 26.2 of the Indian code, the calculated tension or compression in any bar at any section shall be developed as each side of the section by an appropriate development length, L_d, given by[2]

$$L_d = \frac{d_b \sigma_s}{4\tau_{bd}} \qquad \ldots(1)$$

where

d_b = nominal diameter of bar

σ_s = stress in the bar at the section considered at design load (for fully stressed bars, $\sigma_s = 0.87 f_y$), and

τ_{bd} = design bond stress as per *Table* 1

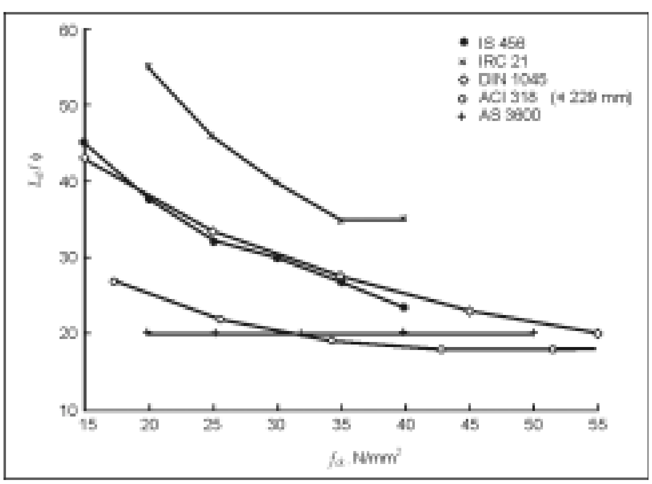

Fig 2 Comparison of L_d/ϕ values for compression bars[3]

Table 1: Design bond stress in limit state method for plain bars in tension

Grade of concrete	*M 20*	*M25*	*M30*	*M35*	*M 40 and above*
Design bond stress, τ_{bd}, MPa	1.2	1.4	1.5	1.7	1.9
As per Equation (2), MPa	1.17	1.37	1.54	1.71	1.87

The code states that for deformed bars in tension these values can be increased by 60 percent and for the bars in compression, the values of bond stress for bars in tension can be increased by 25 percent.

Prakash Rao has shown that anchorage and lap lengths differ significantly as per various codes of practice[3], *Figs* 1 and 2. It is seen that generally the IRC 21 code yields the most conservative values followed by IS 456, AS 3600 and DIN 1045.

Though it is not clear how the values given in *Table* 1 have been derived, they may be approximated by the following equation

$$\tau_{bd} = 0.16 \times (f_{ck})^{\frac{2}{3}} \qquad \ldots(2)$$

Jain identified the following flaws in the IS Code provisions on development length[4].

- The bond strength (for limit state design) and permissible bond stress (for working stress method) have not been adjusted to give uniform development length, see *Table* 2)
- Specifying bond stress values with significant digit only up to one place of decimal in the code, alone leads to variations in development length up to 8 percent
- Equation as function of characteristic strength, instead of the tabulated values, *Table* 1, is more suitable for computer applications.

Jain also observed that IS code inadequately deals with compression lap[4]. Development length in compression is taken as 80 percent of the length in tension, due to 25 percent higher bond stress. However, for compression, lap length in foreign codes is finally taken almost same as for tension[4].

Table 2: Development length (in terms of L_d/d_b) for HYSD bars (f_y = 415 MPa)[4]

Grade of concrete	*M15*	*M20*	*M25*	*M30*	*M35*	*M40*
IS limit state	-	47	40	38	33	29.7
IS working stress	60	45	40	36	33	30
BS 8110*						
Type I deformed	67	58	52	47	44	41
Type 2 deformed	54	46	42	38	35	33
DIN 1045						
Bond class I	42	-	33	-	27	-
Bond class II	85	-	66	-	54	-
AS 3600+						
Good bond	53	46	41	38	35	32
Poor bond	94	81	73	66	61	57

*Lap length to be increased by 40 percent to 100 percent depending on the position of the bar; +Assuming that clear cover = bar size

While most of the codes recommend a reduction in development length for steel area in excess of the required value at the section, the Indian Code does not include any such provision[3]. In addition, the Indian code provisions are not generally applicable to high strength concretes (though the same bond stress of 1.9 MPa is suggested to be taken for M40 and above) and do not consider other developments such as epoxy coated bars as reinforcement.

Factors affecting the bond strength

Bond strength is influenced by the following parameters.[1,5]

(i) *Bar diameter:* A beam reinforced with a larger number of small bars requires a smaller development length than a beam reinforced with smaller number of larger bars of the same total area

(ii) *Cover concrete over the bar:* If the concrete cover is increased, more concrete tensile strength can be developed, which will delay vertical splitting

(iii) *Spacing of bars:* If the bar spacing is increased, more concrete per bar would be available to resist the horizontal splitting

(iv) *Transverse reinforcement such as stirrups:* Stirrups with increased area, reduced spacing and / or higher grade of steel resist both vertical and horizontal splitting

(v) *Grade of concrete:* Higher grade of concrete has improved tensile strength and increased bond strength

(vi) *Confinement of the concrete around the bars*

(vii) *Aggregates used in concrete:* Light weight aggregate concrete will require more development length than normal weight concrete

(viii) *Coating applied on reinforcement to reduce corrosion:* Epoxy coating and galvanisation prevent adhesion between the concrete and the bar and for typical cases a factor of 1.5 is imposed on development length. If the cover and spacing is large, the effect of epoxy coating is not so pronounced and the factor is reduced to 1.2[5,6].

(ix) *Type of reinforcement:* Deformed (ribbed) bars have enhanced bond strength than plain bars.

Another factor which influences bond strength is the depth of fresh concrete below the bar during casting. Excess water (often used in the mix for workability) and entrapped air invariably rise towards the top of the concrete mass during vibration and tend to get trapped beneath the horizontal reinforcement, thereby weakening the bond at the underside of these bars. This effect is called the top bar effect. The code provisions should include all these factors, so that the development length is correctly computed.

American code provisions

By comparing the provisions for development length given by various codes, it is found that the American code considers most of the parameters affecting the bond strength[6]. The American code provisions are based on the work of Orangun, Jirsa and Breen[7]. They derived the following best-fit equation to estimate the average bond stress (bond strength, U) that develops along the bar development/splice length at bond failure.

$$\frac{U}{\sqrt{f_c'}} = 1.22 + 3.23\frac{c_m}{d_b} + 53\frac{d_b}{L_d} \qquad ...(3)$$

Rounding of the constants and considering the incremental increase in bond strength due to transverse reinforcement, ACI 318-99 considered the following equation.

$$\frac{U}{\sqrt{f_c'}} = 1.2 + 3\frac{c_m}{d_b} + 50\frac{d_b}{L_d} + \frac{U_{tr}}{\sqrt{f_c'}} \qquad ...(4)$$

where,

$$\frac{U}{\sqrt{f_c'}} = K_{tr} = \frac{A_{tr} f_y}{500 s d_b} \le 3.0 \qquad ...(5)$$

where,

U and f_c' are in psi

c_m = smaller of side cover, bottom cover or half the clear distance between the bars

L_d = development/splice length

d_b = diameter of the reinforcing bar

A_{tr} = area per one spliced bar

s = development bar spacing

f_y = yield stress of transverse reinforcement, psi

Equation (4) is applicable for $\frac{c}{d_b} \le 2.5$.

This equation has been modified in the subsequent edition of the code and according to the current version of the American code, the development length of straight deformed bars and wires in tension, expressed in terms of bar or wire diameter is given by [6,8]

$$L_d = \left(\frac{9 f_y}{10\sqrt{f_c'}} \times \frac{\alpha\beta\gamma\lambda}{\frac{c + k_{tr}}{d_b}} \right) d_b \ge 300\,\text{mm} \qquad ...(6)$$

where,

L_d = development length, mm

d_b = nominal diameter of bar or wire, mm

f_y = specified yield strength of bar or wire, MPa

f_c' = specified compressive strength of concrete, MPa

α = reinforcement location factor

= 1.3 for horizontal reinforcement so placed that more than 300 mm of fresh concrete is

Table 3: Comparison of L_d/d_b for bars in tension (for F_e 415 grade steel)

	Bar diameter, mm	Grade of concrete				
		M20	M25	M30	M35	M40
IS 456: 2000	All bars	47	40	38	33	29.7
ACI 318	< 19	48	43.2	39.4	36.5	34.2
$c_c = 1.5\ d_b$	> 22	60	54	49.3	45.6	42.7
ACI 318	<19	72	64.8	59.2	54.7	51.2
$c_c = 1.0\ d_b$	> 22	90	81	74	68.4	64
Equation (10) $c_c = 1.5\ d_b$	All bars	60	55	52	49	47

cast below the bar being developed or spliced
= 1.0 for other reinforcement

β = Coating factor
= 1.5 for epoxy coated bars or wires with cover less than 3d or clear spacing less than 6d.
= 1.2 for all other epoxy coated bars or wires
= 1.0 for uncoated reinforcement

The product of α and β should not be greater than 1.7.

γ = reinforcement size factor
= 0.8 for 19 mm and smaller bars and deformed wires
= 1.0 for 22 mm and larger bars

λ = lightweight aggregate concrete factor
= 1.3 when lightweight aggregate concrete is used, or

= $\frac{f_c'}{1.8 f_{ct}}$ but not less than 1.0 when f_{ct} (split cylinder tensile strength) is specified
= 1.0 for normal weight concrete

χ = Spacing or cover dimension (mm)
= the smaller of *(i)* distance from centre of bar or wire being developed to the nearest concrete surface, and *(ii)* one – half the centre-to-centre spacing of bars or wires being developed.

K_{tr} = transverse reinforcement index = $\frac{A_{tr} f_{yt}}{10sn}$

where,

A_{tr} = total cross-sectional area of all transverse reinforcement which is within the spacing s and which crosses the potential plane of splitting through the reinforcement being developed, mm^2

f_{yt} = specified yield strength of transverse reinforcement

s = maximum spacing

n = number of bars being developed along the plane of splitting.

Note that the term $\frac{c+K_{tr}}{d_b}$ cannot be greater than 2.5 to safeguard against pullout type failures.

As a design simplification, it is conservative to assume K_{tr} = 0, even if transverse reinforcement is present. The term $\frac{c+K_{tr}}{d_b}$ in the denominator of Equation (6) accounts for the effects of small cover, close bar spacing and confinement provided by transverse reinforcement. The ACI code also gives some simplified versions of Equation (6) for pre-selected values of $\frac{c+K_{tr}}{d_b}$. However, the development lengths, L_d, computed by Equation (6) could be substantially shorter than development lengths computed from the simplified equations. It has also to be noted that development length of straight deformed bars or wires, including all modification factors must not be less than 300 mm.

It is difficult to compare the IS code provisions with those of the ACI code, since the ACI code equation considers several parameters affecting development length in tension bars. *Table* 3 shows the comparison for grade 415 reinforcement (f_y= 415 MPa) and different concrete compressive strengths, for normal weight concrete (λ = 1.0) and uncoated (β = 1.0) bottom bars (α = 1.0).

It is seen from *Table* 3 that the IS code requires less development length than the ACI code. ACI code accounts for increase in bond length for smaller diameter bars. As the cover increases, the ACI code gives less development length, which is not considered in the Indian code. The Indian code provisions are applicable to concrete strength up to 40 MPa only, whereas the ACI code limits the value of f_c' to 25/3 MPa (that is, for a concrete cube strength up to 86.8 MPa).

Excess reinforcement

The ACI code allows for reduction in development length by the ratio [(A_{st} required)/(A_{st} provided)] when excess reinforcement is provided in a flexural member. However, this reduction does not apply when the full f_y development is required as for tension lap splices, development of positive moment reinforcement at support and for development of shrinkage and temperature reinforcement. This reduction is also not permitted for reinforcement in structures located in regions of high seismic risk. Similar recommendation is available in the Indian code[9].

Bars in compression

Shorter development lengths are required for bars in compression than in tension since the weakening effect of flexural tension cracks in the concrete are not present. Hence, for deformed bars in compression, the following equation is given in the ACI code.

$$l_{dc} = \frac{0.02 d_b f_y}{d_b} \geq 0.0003\, d_b f_y \text{ or } 200 \text{ mm} \qquad \text{...(7)}$$

This development length may be reduced where excess reinforcement is provided and where confining ties or spirals are provided around the reinforcement (25 percent reduction). Comparison of Equation (7) with Indian code provisions shows that the development length as per IS code is 1.5 to 1.8 times longer than that required by ACI code[10].

Bundled bars

Increased development length for individual bars within a bundle, whether in tension or compression, is required when 3 or 4 bars are bundled together. The additional length is required because the grouping makes it more difficult to mobilise resistance to slippage from the "core" between the bars[8]. The ACI code given a modification factor of 1.2 for a three-bar bundle and 1.33 for a four-bar bundle. For the factors of Equation (6) which are based on bar diameter, d_b, a unit of bundled bar must be treated as a single bar of a diameter derived from the total equivalent area[6]. In the Indian code, the development length is increased by 10 percent for two bars in contact, 20 percent for three bars in contact and 33 percent for four bars in contact — which are similar to ACI code.

Standard hooks in tension

Development length, L_{dh}, measured from the critical section to the outside end of the standard hook (that is, the straight embedment length between the critical section and the start of the hook, plus the radius of bend of the hook, plus one bar diameter) and it is given in the ACI code by[6]

$$L_{dh} = \frac{0.24\beta\lambda f_y d_b}{f_c'} \qquad ...(8)$$

where,

β = 1.2 for epoxy coated reinforcement

λ = 1.3 for lightweight aggregate concrete.

For other cases, β and λ are equal to 1.0.

Modification factors are also specified for L_{dh} to account for:

(i) favourable confinement conditions provided by increased cover (for side cover not less than 60 mm, it is equal to 0.7)

(ii) favourable confinement provided by transverse ties or stirrups to resist splitting of concrete (0.8)

(iii) more reinforcement provided than required by analysis. After multiplying the development length, L_{dh}, by the applicable modification factors, the resulting development length must not be less than the larger of 8 d_b or 150 mm. *Fig* 2 shows L_{dh} and the standard hook details for all standard bar sizes.

Thus, the ACI code gives directly the anchorage length of different bends and hooks as a function of the bar size and strength of bars and concrete. Whereas the IS code specifies the anchorage value of bends and hooks as a multiple of the bar diameter. The anchorage value of bends and hooks allowed by IS 456 is as high as 2.5 times the anchorage value given by ACI code for smaller diameter bars and about 0.85 times the ACI code value for larger diameter bars[10]. Besides, straight extension of bars beyond the standard hook is allowed by IS 456 to be included as additional anchorage length provided, whereas ACI code does not. Tests have shown that this straight extension beyond a hook is not effective and should not be included[7].

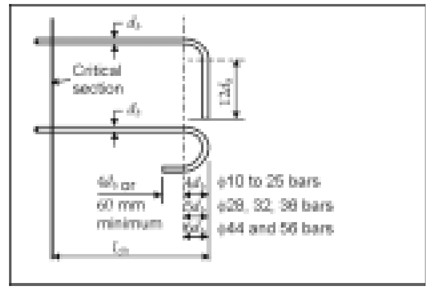

Fig 3 Development length of standard hook as per ACI code

Lap splices

IS 456 suggests the value for lap length (as a multiple of development lengths) only for bars stressed less than 50 percent of their capacity and only if less than 50 percent of bars are spliced at a section. On the other hand, ACI code classifies lap splices into two categories depending on the magnitude of tensile stress in the reinforcement and the percentage of bars spliced at the section and gives the lap length for each category as a multiple of development length (1.0 L_d or 1.3 L_d). Both the codes require splice length equal to development length when more than 50 percent of bars are spliced at a section and stressed to less than 50 percent of the capacity due to flexure at a section. IS 456 stipulates that the splice length of tension bar should be increased up to a factor of 2.0 (splices in tension member shall be enclosed by spirals of 6 mm diameter bars or more and with a pitch of 100 mm or less). On the other hand, as per ACI code, splices in tension tie members are required to be made with full mechanical or welded splice with 750 mm stagger between adjacent splices. The American code also stipulates that in the calculation of development length for splices, the factor for excess A_{st} must not be used and the minimum lap length must be 300 mm.

Review of recent research

Globally, there is an increased usage of high strength concrete (HSC) and high-performance concrete (HPC) with compressive strength of 70 to 120 MPa. Yet the bulk of knowledge on bond and anchorage behaviour between steel and concrete that is used in practice is from the experience on reinforced concrete elements having much lower concrete strength[11]. For higher strength concrete, a higher degree of elastic and more stiffer bond behaviour is expected due to the improved strength and the higher modulus of elasticity[12]. The average bond strength is increased in HSC as the porosity is reduced due to the addition of much finer material such as fly ash and silica fume. However, a more brittle bond behaviour has been reported in HSC[13]. Though the bond characteristics of the normal concrete are reasonably well established, the bond characteristics of HPC using supplementary cementition materials like GGBS, fly ash and silica fume have not been studied in detail[14-16]. In a recent paper, Balasubramanian *et al* have shown that the addition of slag (up to 50 percent as cement replacement material) did not result in any reduction in the bond strength characteristics[17].

Azizinamini *et al* studied the effect of HSC on bond and found that the average bond stress at failure, normalised with respect to the square root of concrete compressive strength, $f_c^{'}$, decreases with an increase in compressive strength. The rate of decrease becomes more pronounced as the splice length increases[18]. Darwin and coworkers compared a large data of experimental investigations and found that the best fit for experimental results is provided by $f_c^{'1/4}$ and not $f_c^{'1/2}$ as given in ACI and other codes[19,20]. They also suggested that the effect of transverse reinforcement on the increase in splice strength is better characterised using $f_c^{'3/4}$. They proposed the following equation for the development length.[20,21]

$$\frac{L_d}{d_b} = \frac{\dfrac{f_y}{f_c^{'1/4}} - 50.26\,\dfrac{0.1\,c_{max}}{c_{min}+0.9}}{1.63\,\dfrac{c+K_{tr}}{d_b}} \qquad \text{...(9)}$$

For design purposes, the above equation may be simplified to

$$\frac{L_d}{d_b} = \frac{\dfrac{f_y}{f_c^{'1/4}} - 50.26}{1.63\,\dfrac{c+K_{tr}}{d_b}} \qquad \text{...(10)}$$

where ,

$$K_{tr} = \frac{6.26\,t_r t_d A_{tr}}{sn} f_c^{'1/2} \qquad \text{...10(a)}$$

$$t_r = 9.6\,R_r + 0.28 \le 1.72 \qquad \text{...10(b)}$$

$$t_d = 0.03\,d_b + 0.22 \qquad \text{...10(c)}$$

For conventional bars, the average value of R_r is 0.0727.

For conventional reinforcement,

$$K_{tr} = \frac{6 t_d A_{tr}}{sn} f_c^{'1/2} \qquad \text{...10(d)}$$

Though the format of Equation (10) is similar to that of Equation (6) of ACI – 02 code, the application of Equation (10) differs from Equation (6) in three ways:

(i) Equation (6) distinguishes 19 mm diameter and smaller bars from larger bars using the g term, leading to 20 percent drop in development/splice length for the smaller bars,

(ii) The K_{tr} term in Equation (6) includes the yield strength of the transverse reinforcement, f_{yt}, even though test results show that, f_{yt} has no effect on bond strength

(iii) The development length, L_d, calculated using Equation (6) must be increased by 30 percent for class B splices (splices in which the area of steel provided is less than two times the area of steel required or where more than 50 percent of the steel is spliced). A comparison of this equation is made in *Table* 3 for $c_c = 1.5\,d_b$.

Another equation taking into account high performance concretes has been proposed by Yerlici and Oezturan[11]. They showed that the bond strength is related to $f_c^{'2/3}$ and proposed the following equation (without any factor of safety)

$$\frac{L_d}{d_b} = \frac{4\,f_y\sqrt{d_b}}{3\,f_c^{'2/3}c^{0.8}(1+0.08K_{tr}^{\;0.6})} \qquad \text{....(11)}$$

Another study by Miller *et al* showed that epoxy coatings with a thickness in the range of 160 to 510 mm reduce the bond strength of deformed bars of 19 mm diameter and larger bars and hence the maximum allowable coating thickness should be increased from 300 mm to 420 mm for 19 mm diameter and larger bars[22]. Tests conducted by Hamad and Mike indicated that hot-dip galvanised reinforcement causes a 16 to 25 percent decrease in bond strength in high strength concrete, though they have a negligible effect (reduction of 4 to 6 percent only) on bond strength of normal strength concrete[23].

Development of bond strength of reinforcement steel in self-consolidating concrete (which are cast without applying any vibration) was studied by Chan *et al*[24]. They observed that as compared to NSC, SCC exhibits significantly higher bond strength and less significant top-bar effect.

Harajli and his associates conducted analytical and experimental investigations to evaluate the bond strength of steel reinforcements in plain and fibre-reinforced concrete[25,26]. They also found that for plain unconfined NSC or HSC, normalising the bond strength to $f_c^{'1/4}$ leads to a more accurate representation of the effect of concrete strength on development/splice strength in comparison with $f_c^{'1/2}$. Fibre reinforcement in the region of the splice/development length played a role similar to ordinary transverse reinforcement in that it restricted the growth of the splitting cracks and increased the splitting bond strength. They also proposed the same design equation as that proposed by Zuo and Darwin, Equation (10) with an additional term in K_{tr} to account for the effect of fibres[20].

Suggested formula

Based on the recent research on high performance concrete and the above discussions, the Equation (10), proposed by Darwin *et al* is recommended for the Indian code[20,21]. The present Indian code formula considers only the diameter, yield stress and grade of concrete as variables. Whereas the proposed formula considers the diameter, cover, spacing of bar, grade of concrete and transverse reinforcement as variables. Hence, it is supposed to truly represent the bond behaviour of reinforcement. To account for coating, type of aggregate and reinforcement location, the β, λ and α factors as suggested by the ACI code could be incorporated in Equation (10).

Though the development lengths predicted by Equation (10) are higher than the Indian code formula, *Table* 3 and *Appendix* A, it gives a realistic estimate of bond behaviour, since it incorporates all the factors affecting the bond strength. It is to be noted that the ACI committee 408 has also accepted this equation[27].

Summary and conclusions

The composite action of concrete and steel in reinforced concrete structures is provided by bond strength. The required bond strength is achieved by providing sufficient development length. Non-provision of adequate development lengths often results in failures, especially in cantilever supports, lap splices and beam - column joints. The bond strength is influenced by several factors which include: bar diameter, cover concrete, spacing of reinforcement, transverse reinforcement (such as stirrups), grade of concrete, confinement of concrete around the bars, aggregates used in concrete, coating applied on bars to reduce corrosion, and type of reinforcement bars used.

Though the Indian code was revised recently, mainly to take care of durability considerations, the development length provisions remain unchanged and do not cover the effect of several parameters. However, the American code considers all these parameters. Hence the provisions of the Indian code are compared with the American code.

Recent research has shown that the best fit for experimental results is provided by $f_c'^{1/4}$ and not $f_c'^{1/2}$ as given in ACI code. Hence the Equation (10), proposed by Darwin *et al* which is supposed to truly represent the bond behaviour of reinforcement bars is proposed for the Indian code. The ACI committee 408 has also accepted this equation.

Effect of high strength, high performance concrete, self-consolidating concrete and fibre reinforced concrete on the bond strength of reinforcements are also discussed. With few modifications, the suggested formula could be applied to take into account the confinement offered by fibre reinforcement also.

References

1. Pillai, S.U., And Menon, D. *Reinforced Concrete Design*, Tata McGraw Hill Company Ltd., New Delhi, 2nd edition, 2003.
2. ______*Indian standard code of practice for plain and reinforced concrete*, IS 456:2000, Fourth Revision, Bureau of Indian Standards, New Delhi.
3. Prakash Rao, D.S. Detailing of reinforced concrete structures, *Proceedings of the IABSE Conference on Structural Concrete*, Stuttgart, Germany, 1991, pp. 819-824.
4. Jain, R. Detailing for bond, shear and torsion - comparison of codes, *Civil Engineering and Construction Review*, 2001, Vol.14, No.8, pp. 38-46.
5. Nilson, A.H and Winter, G. *Design of concrete structures*, Eleventh Edition, McGraw Hill, 1991.
6. ______*Building code requirements for structural concrete and commentary*, ACI 318 : 2002, American Concrete Institute, Farmington Hills, Michigan, 2002.
7. Orangun, C.O., Jirsa, J.O. and Breen, J.E. A re-evaluation of test data on development length and splices, *ACI Journal*, Proceedings, 1977, Vol.74, No. 3, pp.114-122.
8. Fanella, D.A. and Rabbat, B.G., ed., *Notes on ACI – 318-02, Building code requirements for structural concrete with design applications*, Portland Cement Association, Illinois, Eighth Edition, 2002.
9. ______*Handbook on concrete reinforcement and detailing*, Special Publication SP: 34, Bureau of Indian Standards, New Delhi, 1987.
10. Kalyanaraman, V. Special design requirements: A Comparison of IS: 456-1978 with ACI 318-77, *Journal of the Institution of Engineers*, Civil Engineering Division, 1984, Vol.65, pp. 76-81.
11. Yerlici, V.A. and Oezturan, T. Factors affecting anchorage bond strength in high performance concrete, *ACI Structural Journal*, 2000, Vol. 97, No.3, pp. 499-507.
12. Rashid, M.A. Consideration in using HSC in RC flexural members: A review, *The Indian Concrete Journal*, May 2004, Vol. 78, No. 5, pp. 20-28.
13. Ezeldin, A.S., and Balaguru, P.N. Bond behaviour of normal and high-strength fibre reinforced concrete, *ACI Materials Journal*, 1989, Vol. 86, No. 5, pp. 515 -524.
14. Azizinmini, A. Bond performance of reinforced bars embedded in high strength concrete, *ACI Structural Journal*, 1993,Vol. 90, No. 5, pp. 554-561.
15. Gjrov Effect of condensed silica fume on the steel concrete bond, *ACI Materials Journal*, 1990, Vol. 87, No. 6, pp. 573-580.
16. Hamad, B.S. Bond strength of reinforcement in high performance concrete: Role of Silica fume, casting position and superplasticiser dosage, *ACI Materials Journal*, 1998, Vol. 95, No. 5, pp. 499-511.
17. Balasubramanian, K., Krishnamurthy, T. S., Gopalakrishnan, S., Bharathkumar, B.M., and Kumar, Girish Bond characteristics of slag-based HPC, *The Indian Concrete Journal*, August 2004, Vol. 78, No. 8, pp. 39-44.
18. Azizinamini, A., Chisala, M., Roller, J.H., And Ghosh, S.K. Tension development length of reinforcing bars embedded in high-strength concrete, *Engineering Structures*, 1995, Vol.17, No.7, pp.512-522.
19. Darwin, D., Zuo, J., Tholen, M.L., and Idun, E.K. Development length criteria for conventional and high relative rib area reinforcing bars, *ACI Structural Journal*, July-August 1996, Vol.95, No.4, pp.347-359.
20. Zuo, J., and Darwin, D. Splice strength of conventional and high relative rib area bars in normal and high-strength concrete, *ACI structural Journal*, July-August 2000, Vol.97, No.4, pp. 630-641.
21. Darwin, D. Private communications, May 2003
22. Miller, G.G., Kepler, J.L., and Darwin, D. Effect of epoxy coating thickness on bond strength of reinforcing bars, *ACI Structural Journal,* 2003, Vol.100, No.3, pp. 314-320.
23. Hamad, B.S., and Mike, J.A. Experimental investigation of bond strength of hot – dip galvanised reinforcement in normal and high-strength concrete, *ACI Structural Journal*, 2003, Vol.100, No.4, pp. 465-470.
24. Chan, Y.W., Chen, Y.S., and Liu, Y.S. Development of bond strength of reinforcement steel in self-consolidating concrete, *ACI Structural Journal*, 2003, Vol.100, No.4, , pp. 490-498.
25. Harajli, M.H., And Mabsout, M.E. Evaluation of bond strength of steel reinforcing bars in plain and fibre-reinforced concrete, *ACI Structural Journal*, 2002, Vol. 99, No.4, pp.509-517.
26. Hamad, B.S., Harajli, M.H., And Jumaa, G. Effect of fibre reinforcement on bond strength of tension lap splices in high-strength concrete, *ACI Structural Journal,* 2001,Vol.98, No.5, pp. 638-647.
27. ______*Bond and development of straight reinforcing bars in tension*, ACI 408R-03, American Concrete Institute, Farmington Hills, MI, 2004, pp. 49.

Appendix A: Numerical example

The calculation of development length as per the existing IS code formula and the proposed formula is given below and is based on the following data.

Concrete grade = M 20

Diameter of bar = 20 mm

Characteristic strength of main reinforcement = 415 MPa

Cover to reinforcement = 30 mm

Spacing of reinforcement = 85 mm

Area of transverse reinforcement, A_{tr} = 50.26 mm^2

Characteristic strength of transverse reinforcement, f_{yt} = 415 MPa

No. of bars being developed along the plane of splitting, $n = 3$

As per Equation (1) and *Table* 1,

$$L_d = \frac{d_b \sigma_s}{4\tau_{bd}}$$

$$= \frac{20 \times 90.87 \times 415}{4 \times 1.21 \times 1.6}$$

$= 940$ mm

As per the suggested formula

$$t_d = 0.03\ d_b + 0.22 = 0.03 \times 20 + 0.22 = 0.82$$

$$K_{tr} = \frac{6 t_d A_{tr}}{sn} f_c'^{0.25} = \frac{6 \times 0.82 \times 50.26}{85 \times 3} (20 \times 0.8)^{0.5} = 2.18$$

$$\frac{c + K_{tr}}{d_b} = \frac{30 + 2.18}{20} = 1.61 < 2.5. \text{ Hence adopt } 1.61.$$

$$L_d = \frac{d_b \left(\frac{f_y}{f_c'^{0.25}} - 50.26 \right)}{1.63 \frac{c + K_{tr}}{d_b}}$$

$$= 20 \left(\frac{415}{20 \times 0.8^{0.25}} - \frac{50.26}{1.63 \times 1.61} \right)$$

$= 1198$ mm

Though in the above example M20 grade concrete has been considered for comparison, the suggested formula is applicable to concretes of grade up to about 100 MPa whereas the Indian Code formula was based mainly on concrete having strength less than 40 MPa.

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