

# Review of design codes for tension development length for reinforced concrete members

M. M. Hoque<sup>1</sup>, N. Islam<sup>2</sup>, Mohammed<sup>2</sup> and O. Faruk<sup>2</sup>

<sup>1</sup>*Department of Civil Engineering  
Dhaka University of Engineering and Technology, Gazipur 1700, Bangladesh*  
<sup>2</sup>*Development, Design and Management  
46, Kazi Nazrul Islam Avenue, Dhaka 1205, Bangladesh*

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## Abstract

A review of provisions of different design codes for development lengths of reinforcing bars used in reinforced concrete structures has been presented. The reviewed codes are ACI (2002), BNBC (1993), IS (2005), AASHTO (2007), CEB-FIP Model (1990) and EURO Code 2(2003). Development length is calculated for particular strength of concrete and reinforcing bars. A parametric study has been conducted for selected parameters. It has been found from the study that the BNBC code recommends the largest value of the development length for 22mm diameter and larger diameter meter bars as compared with the requirements of the other codes, while the EURO code recommends the smallest value. The EURO code and CEB-FIP Model code recommends almost the similar development lengths.

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*Keywords:* Development length, Reinforcing bar, Bond, Design codes

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## 1. Introduction

Reinforced concrete (RC) has been gaining popularity era by era. In RC construction, the development length of reinforcing bars is very important for developing the tensile strength of the bar. Inadequate development length will induce less stress in the bars as compared to its strength. Therefore a minimum length of bar is required for developing the stress from zero to its yield stress. It means that if the minimum length is not provided, premature bond failure may occur which lead to member failure. The premature bond failure often happens in the structures erected in seismic prone region requiring a proper development length, and due to the shortage of sufficient development length leads the structures to collapse. Different design codes have proposed different formulas for determining development length. In the present study the authors attempted to calculate the development lengths using the code ACI (2002), BNBC (1993), IS (2005), AASHTO (2007), CEB-FIP Model (1990) and EURO Code 2(2003) by conducting a parametric study. In the parametric study, yield strength of reinforcing bars, compressive strength of concrete and bar diameter meter

have been used as basic parameters. A specific beam-column joint of a building frame has been taken into consideration for the study. In selecting the compressive strength of concrete, a wide range of strength has been taken into consideration. The compressive strength of concrete was used 10 MPa, 15 MPa, 20.5 MPa, 23.9 MPa, 26.67 MPa, 30 MPa and 35 MPa, while the yield strength of the reinforcing bars were used 274 MPa, 410 MPa and 500 MPa.

In this study the authors found that each code recommends different length of development length. The BNBC (1993) code recommends the largest development length for 22 mm diameter and larger diameter meter bar than other codes as well as EURO Code2 and CEB-FIP (1990) recommend the smallest development length and almost the same development length.

## 2. Basic aspects of development length

Development length is the shortest length needed for reinforcing bar so that the stresses induced in the bar can increase from zero to the yield strength of the bar. The development length is a function of the bar size, yield strength, concrete strength and other factors such as coating of the bar. Also, the development length of a bar is dependent to whether the bar is in tension or compression. Tension development lengths are larger than compression development lengths because in compression, the reinforcing bar gets some help from the concrete, while in tension it does not. The development length depends on the following factors.

### 2.1 Bond force

Development length depends on bond strength or bond force between the reinforcing bar and the surrounding concrete. Bond forces between reinforcing bars and the surrounding concrete may vary due to variations in the force carried along the length of a bar. This is illustrated in Fig. 1, where the bond force per unit length is shown to be highest where the rates of change in the bar force is highest; bond forces are not uniform along the length of reinforcement but, rather, can vary in a nonlinear manner. The key point of bond design is, therefore, not to limit the peak bond force, but to ensure that bars are adequately anchored when developed or spliced.

Some design codes (CEB-FIP Model Code 1990 and Euro code 2(2003)) invoke the concept of bond stress, the stress at the interface between steel and concrete, suggesting that bond strength is a material property. Bond force, rather than stress, however, provides a more general representation of the response of members and correctly represents bond strength as a structural property, based on both the constituent material properties and member geometry. Expressing bond strength in terms of force also makes it easier to visualize the effects of the key parameters.

### 2.2 Failure mode

Bond failure usually occurs in two different forms. In the first kind bond failure is governed by splitting of the concrete, as illustrated in Fig. 2, when the cover  $c_b$  is greater than one-half of the clear spacing between bars  $c_{s,i}$  splitting failures of the type shown in Fig. 2(a) predominate, with the key cracks running from the bars, perpendicular to the concrete surface. For closer bar spacing and higher covers, the cracks tend to form in the plane of the bars, as shown in Fig. 3b. Transverse reinforcement that crosses splitting cracks will increase bond strength. If the cover or transverse reinforcement is increased sufficiently, a pullout failure will occur in which the concrete between the transverse ribs on the bars fails by shear or crushing. Increasing the cover or transverse reinforcement beyond that required to cause a pullout failure will provide little, if any, additional bond capacity.

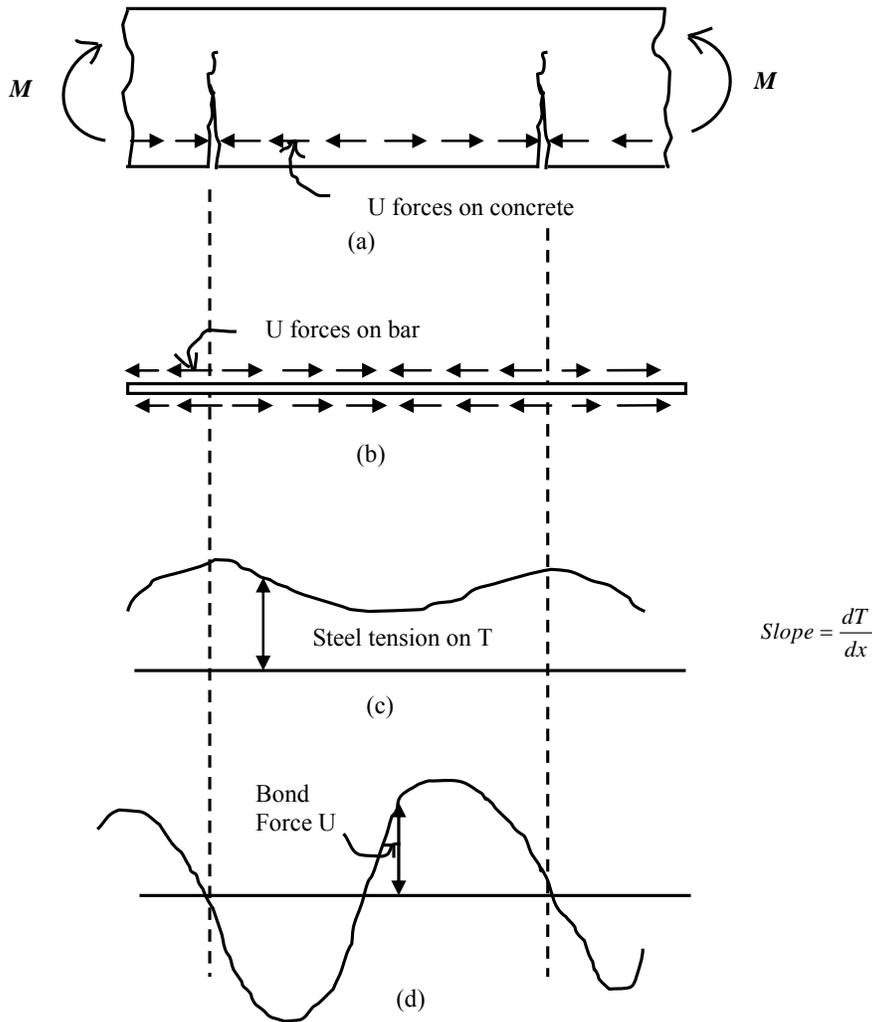


Fig. 1. (a) Cracked concrete segment, (b) bond stress acting on reinforcing bar, (c) variation of tensile force in reinforcing bar; and (d) variation of bond force along the bar (adapted from Nilson et al., 2005)

### 2.3 Cover distance

Cover conventionally the distance measured from the centre of the bar to the nearest concrete face and measured either in the plane of the bars or perpendicular to that plane-also influences splitting. Clearly, if the vertical or horizontal cover is increased, more concrete is available to resist the tension resulting from the wedging effect of the deformed bars, resistance to splitting is improved, and development length requirement decreases.

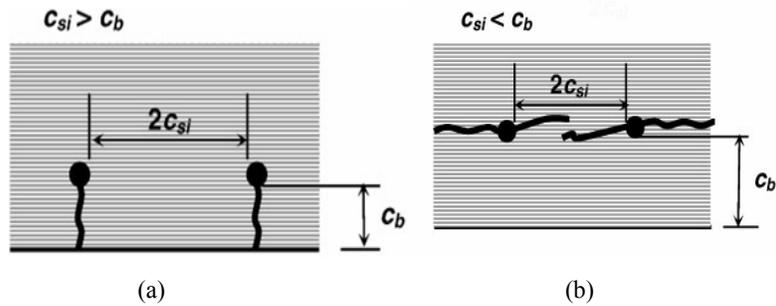
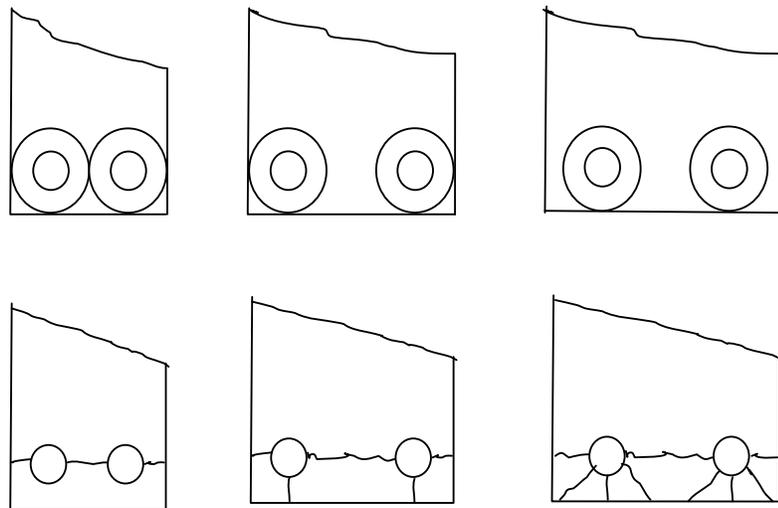


Fig.2 Bond cracks: (a)  $c_{si} > c_b$ , (b)  $c_{si} < c_b$

2.4 Bar spacing

With the increase of bar spacing, more concrete surrounding per bar would be available to resist horizontal splitting. In beams, bars are typically spaced about one or two bar diameter meters apart. On the other hand, for slabs, footings and certain other types of member, bar spacing are typically much greater, and the required development length is reduced.



(a) Side cover and half the bar spacing both less than bottom cover.

(b) Side cover = bottom cover, both less than half the bar

(c) Bottom cover less than side cover and half the bar spacing.

Fig. 3. Bar spacing and splitting failure

2.5 Transverse reinforcement

Such as that provided by stirrups, improves the resistance of tensile bars to both vertical or horizontal splitting failure because the tensile force in the transverse steel tends to prevent opening of actual or potential crack. The effectiveness of such transverse reinforcement depends on its cross sectional area and spacing along the development length.

## 2.6 Vertical bar location

Vertical bar location relative to beam depth has been found to have an effect that a substantial depth of concrete is placed bellow those bars, there is a tendency for excess water, often used in the mix for workability, and for entrapped air to rise to the top of the concrete during vibration.

## 2.7 Concrete strength

Development length is usually fails by splitting, and splitting failure depends on the tensile strength of concrete. The tensile strength of concrete is a function of  $f'_c$ . The choice of  $f'_c{}^{-0.14}$  in place of the more traditional  $f'_c{}^{1/2}$  or  $f'_c{}^{2/3}$  (where  $f'_c$  is the specified compressive strength and  $f_{tk}$  is the characteristic strength to represent the contribution of concrete strength to bond strength is based on the analysis summarized in Fig. 4. the relative scatter (relative intercept) was minimized using a power of 0.24. For practical purposes, a value of 0.25 was adopted.

An explanation as to why the  $1/4$  power of compressive strength provides superior results to those produced by higher powers is presented by Darwin et al. Their research indicates that, while the tensile strength of concrete increases at a rate that is  $\geq \sqrt{f'_c}$  the fracture energy of concrete,  $G_f$ , the energy per unit area required to propagate a crack once it has formed, is nearly independent of  $f'_c$ . The overall result is that the influence of compressive strength on bond strength is less than normally considered in design.

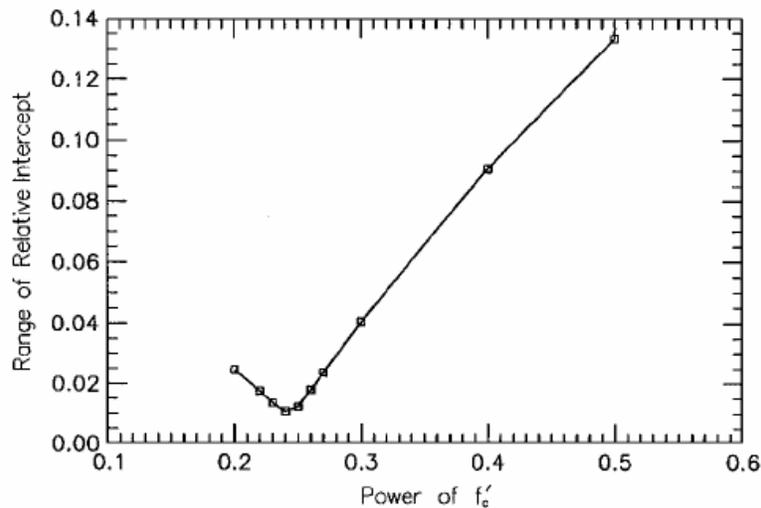


Fig. 4. Range of relative intercept obtained for dummy variables analysis for experimental bond force, normalized with respect to  $f'_c$  for optimized bond strength expressions versus the power  $p$  of  $f'_c$  for bars without confining transverse reinforcement. (Ref. David Darwin, 2005).

## 3. Bar surface condition

In addition to the factors mentioned earlier, development length also depends on the types of reinforcement, whether the bars are coated or uncoated. Coatings on the surface of a bar reduce the friction between the steel and concrete and it can have a negative impact on bond strength. This is why, design codes require minimal levels of cleanliness for the bar, restricting the presence of dirt or

oil. Reasonable quantity of rust has been shown to have little effect on bond strength, while thick rust reduces the bond by separating the base metal from the surrounding concrete. Epoxy coatings, used to improve the corrosion resistance of reinforcement, have a negative impact on bond because they reduce the coefficient of friction between the steel and the concrete. In most cases, test results demonstrate the need to increase development and lap splice lengths by approximately 50% for epoxy-coated bars compared to the lengths required for uncoated bars. Tests of bars with relative rib areas  $R_r$  in excess of 0.10, however, show that an increase on the order of 20% is satisfactory for high relative rib area reinforcement.

#### 4. Design provisions

The design codes reviewed in this study for tension development length of members in reinforced concrete structures are ACI (2002), BNBC (1993), IS (2005), AASHTO (2007), CEB-FIP Model (1990), And EURO Code 2. To allow direct comparison of design equations, the expressions are written using notation similar to that used in ACI 318-02.

##### 4.1 ACI Code (2002)

Basic equation for development of tension bars:

$$l_d = \frac{3}{40} \frac{f_y}{\sqrt{f_c'}} \left( \frac{\alpha \beta \gamma \lambda}{C + K_{tr}} \right) \frac{1}{d_b} \quad (1)$$

In which the term  $\frac{C + K_{tr}}{d_b}$  shall not be taken greater than 2.5. where  $\alpha$  is reinforcement location factor

,1.3: for Horizontal reinforcement so placed that more than 12 in. of fresh concrete is cast in the member below the development length or splice and 1.0: for other reinforcement ;  $\beta$  is coating factor ,1.5: for Epoxy –coated bars or wires with cover less than  $3d_b$  or clear spacing less than  $6d_b$ ,1.2: for All other epoxy coated bars or wires,1.0: for Uncoated reinforcement;

$\gamma$  = reinforcement size factor 0.8: for No. 6 (no.19) and smaller bars and deformed wire, and 1.0: for No. 7 (no.22) and larger bars;  $\lambda$  is lightweight aggregate concrete factor 1.3: when lightweight aggregate concrete is used,1.0: when normal weight concrete is used, However, when  $f_{ct}$  is specified,  $\lambda$  shall be permitted to be taken as  $6.7\sqrt{f_{ct}} / f_c'$  but not less than 1.0 ; C is spacing or cover dimension, in. inch, use the smaller of either the distance from the center of bar to the nearest concrete surface or one-half the center to center spacing of the bars being developed.

$K_{tr}$  is transverse reinforcement index:  $K_{tr} = \frac{A_{tr} f_{yt}}{1500sn}$  where  $A_{tr}$  is the area of each stirrup or tie crossing the potential plane of splitting adjacent to the reinforcement being developed, s the spacing of transverse reinforcement in inch,  $f_{yt}$  theyield strength of transverse reinforcement in psi, and n the number of bars being developed along the plane of splitting. It shall be permitted to use  $K_{tr} = 0$  as a design simplification even if transverse reinforcement is present. The limit of 2.5 on  $\frac{C + K_{tr}}{d_b}$  is imposed to avoid pullout failure. With that term taken equal to its limit of 2.5,

evaluation of Eq. (1) results in  $l_d = 0.03d_b f_y / \sqrt{f_c'}$ , the experimentally derived limit found in earlier ACI codes equations relating to the development length.

4.2 CEB-FIP Model code (1990)

##### 4.2 CEB-FIP Model code (1990)

The CEB-FIP model code (1990) uses the format compatible with those used in ACI 318-02.

$$l_d = \frac{1}{1.228} \left( 1.115 - 0.15 * \frac{c_{min}}{d_b} \right) \left( 1 - k \frac{\sum A_{str} - \sum A_{str,min}}{A_b} \right) \eta \frac{f_{yd}}{f_{ck}^{2/3}} d_b \tag{2}$$

where,  $d_b$  is diameter of bar;  $\eta = 1.0$  for  $d_b \leq 32$  mm,  $\eta = \frac{100}{132 - d_b}$  for  $d_b > 32$  mm; each term in parentheses of Eq. (2) is limited to the range of 0.7–1.0;  $f_{yd}$  is design yield strength of the bar in MPa.  $f_{yk} = \frac{f_y}{1.15}$ , where  $f_y$  is the characteristics yield strength of reinforcement, it is the value that is exceeded by 95% of all possible test results, often described as the 5% fractures value. In the United States  $f_{yk} \approx 1.06 f_y$ , where  $f_y$  is the minimum specified yield Strength;  $f_{ck}$  is the Characteristic compressive strength of concrete.  $f_{ck} = f_c' - 2.75$  MPa;  $c_{min} = \min(a/2, c_1, c_2)$  from Fig.5;  $\sum A_{str}$  is the cross-sectional area of the transverse reinforcement along  $l_d$ ;  $\sum A_{str,min}$  is the cross sectional area of the minimum transverse reinforcement =  $0.25 A_s$  for beams and 0 for slabs;  $A_b$  is the area of a single bar being developed or spliced, with maximum bar diameter; k = values are, k = 0.10 for a bar confined at a corner bend of a stirrup or tie, k = 0.05 for a bar confined by a single leg of a stirrup or tie, and k = 0 for a bar that is not confined by transverse reinforcement; The value of  $l_d$  in Eq. (2) may be multiplied by  $0.7 \leq (1 - 0.04p) \leq 1.0$  where p is transverse pressure in MPa at the ultimate limit state along the development length perpendicular to the splitting plane. The effect of bar placement for top-cast reinforcement is included by dividing  $l_d$  by 0.7 for bars with an inclination of less than 45° with the horizontal that are both (1) more than 250mm from the bottom and (2) less than 300mm from the top of a concrete layer during placement. The development length  $l_d$  may be multiplied by the ratio of (As required)/ (As provided). The development length is limited as expressed in following equation,

$$l_{d,min} = \max \left[ \frac{0.3 \eta f_{yd}}{1.228 f_{ck}^{2/3}} d_b; 10d_b; 100mm \right] \tag{3}$$

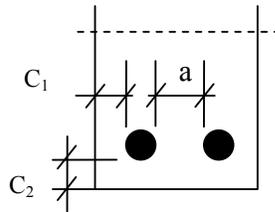


Fig.5.  $c_{min} = \min(a/2, c_1, c_2)$

### 4.3 EURO code 2

The development length provisions of Euro code 2 is expressed as

$$l_d = \frac{1}{1.26} \left( 1.15 - 0.15 * \frac{c_{min}}{d_b} \right) \left( 1 - k \frac{\sum A_{tr} - \sum A_{tr,min}}{A_b} \right) \frac{\eta f_{sd}}{f_{ck}^{2/3}} d_b \tag{4}$$

where,  $f_{sd}$  is the design stress of the bar at the position from where anchorage is measured at the ultimate limit state =  $f_{sd}$  (As required)/ (As provided). The other terms are as defined for CEB-FIP Model Code 1990, except that the value of  $f_{ck}$  used here is limited to a maximum of 60MPa unless it

can be demonstrated that the average bond strength increases above this limit. Development length in tension is limited as shown in equation

$$l_{d,\min} = \max \left[ \frac{0.3}{1.26} \frac{\eta f_{sd}}{f_c^{2/3}} d_b; 10 d_b; 100 \text{ mm} \right] \quad (5)$$

#### 4.4 BNBC code (1993)

Development length  $l_d$  for deformed bar in tension shall be computed as the product of the basic development length  $l_{db}$  and the applicable modification factors given below, but  $l_d$  shall not be less than 300 mm,

Basic development length:

$$l_{db} = \frac{0.02 * A_b f_y}{\sqrt{f_c}} \quad (\text{for 36 mm diameter bar or smaller}) \quad (6)$$

$$l_{db} = \frac{25 f_y}{\sqrt{f_c}} \quad (\text{for 45 mm diameter bar}) \quad (7)$$

$$l_{db} = \frac{35 f_y}{\sqrt{f_c}} \quad (\text{for 55 mm diameter bar}) \quad (8)$$

where,  $f_y$  is the yield strength of reinforcement in MPa;  $f_c$  is the compressive strength of concrete in MPa; and  $A_b$  is the area of an individual bar in  $\text{mm}^2$ .

- (a) The basic development length is further multiplied by: 1.0

For all bars satisfying any one of the following conditions:

- i) Bars in beams or columns with minimum cover not less than 40 mm, transverse reinforcement satisfying tie requirements, minimum stirrup requirements of sec 6.2.7.4(d) and 6.2.7.4e(ii) along the development length, and with clear spacing of not less than  $3d_b$ ,
  - ii) Bars in beams or columns with minimum cover not less than 40 mm (for primary reinforcement) and enclosed within transverse reinforcement  $A_{tr}$  along the development length satisfying,  $A_{tr} \geq \frac{d_b s n}{40}$ ,
  - iii) Bars in the inner layer of slab or wall reinforcement and with clear spacing of not less than  $3d_b$ ,
  - iv) Bars in the inner layer of slab or wall reinforcement and with clear spacing of not less than  $3d_b$ .
- b) For bars with a cover of  $d_b$  or less or with a clear spacing of  $2d_b$  or less: 2.0
  - c) For other bars not satisfying (a) or (b) above: 1.4
  - d) 0.8 for 35 mm diameter bar and smaller, with clear spacing not less than  $5d_b$ , and with at least  $2.5d_b$  clear from face of member to edge of bar.
  - e) 0.75 for reinforcement enclosed within spiral reinforcement not less than 6 mm diameter and not more than 100 mm pitch.

But the basic development length multiplied by the previous factors shall not be taken less than  $\frac{0.375 d_b f_y}{\sqrt{f_c}}$ .

The basic development length also is multiplied by the following factors:

1.3 for Top horizontal reinforcement so placed that more than 300 mm of concrete is cast in the member below the bar; 1.5 for Epoxy coated reinforcement with cover less than  $3d_b$  or clear spacing less than  $6d_b$ ; 1.2 epoxy coated bars for all other conditions. The product of factor for top reinforcement and the factor for epoxy coated reinforcement not need to be taken greater than 1.7.

The development length may be reduced by the factor  $\frac{((A)_s \text{ provided})}{((A)_s \text{ required})}$  = where reinforcement in a flexural member is in excess of that required by analysis except where anchorage or development for  $f_y$  is specially required.

4.5 Indian Standard code (2005)

According to clause 26.2 of the Indian Standard 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 the following equations,

$$l_d = \frac{d_b \sigma_s}{4 \tau_{bd}} \tag{9}$$

$$\tau_{bd} = 0.16 (f_{ck})^{2/3} \tag{10}$$

where,  $d_b$  nominal diameter of bar,  $\sigma_s$  = stress in the bar at the section considered at design load (for fully stressed bars,  $\sigma_s = 0.87 f_y$ ) and  $\tau_{bd}$  = design bond stress as per Table 1.

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

Grade of concrete	M 20	M25	M30	M35	M40 and above
Design bond stress $\tau_{bd}$ in (MPa)	1.2	1.4	1.5	1.7	1.9
As per eq. 10 (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.

4.6 AASHTO (2007)

The tension development length  $l_d$  in mm can be calculated by the following equations. But the tension development length shall not be less than 300 mm, except for lap splices,

$$l_{db} = \frac{0.02 * A_b f_y}{\sqrt{f_c}} \text{ (For 36mm diameter bar or smaller)} \tag{11(a)}$$

But not less than  $0.06 d_b f_y$

$$l_{db} = \frac{25 f_y}{\sqrt{f_c}} \text{ (For 43 mm diameter bars)} \tag{11(b)}$$

$$l_{db} = \frac{34 f_y}{\sqrt{f_c}} \text{ (For 57 mm diameter bars)} \tag{11(c)}$$

where,  $A_b$  is the area of bar ( $\text{mm}^2$ ),  $f_y$  yield strength of reinforcing bars in MPa,  $f_c$  Compressive strength of concrete at 28 days, unless another age is specified (MPa), and  $d_b$  diameter of the bar (mm). The

development lengths given in Eq. (11) are multiplied by one or more factors: 1.4 for horizontal or nearly horizontal reinforcement placed with more than 300mm of fresh concrete cast below the reinforcement (top-bar factor);  $\frac{0.58\sqrt{f_c}}{f_{ct}} \geq 1.0$  for low-density concrete, where  $f_{ct}$  is the splitting tensile strength of the concrete; 1.3 for concrete in which all aggregate is lightweight or 1.2 for sand-lightweight concrete, where  $f_{ct}$  is not specified; 1.5 for epoxy-coated bars with cover less than  $3d_b$  or clear spacing less than  $6d_b$ , or 1.2 for epoxy-coated bars not covered by the previous criterion. The product obtained when combining the factor for top reinforcement with the factor for epoxy coated bars need not be taken greater than 1.7 under the assumption that the reduced contact area, because of concrete settlement, and the lower coefficient of friction for epoxy-coated bars are not fully additive. In addition, development or splice lengths may be multiplied by 0.8 for reinforcement being developed in the length under consideration when it is spaced not less than 150mm center-to-center, with not less than 75mm clear cover measured in the direction of spacing, (As required)/(As provided) when anchorage of the full yield strength of the reinforcement is not required or when reinforcement in flexural members is in excess of that required by analysis, and 0.75 when reinforcement is enclosed within a spiral composed of bars of not less than 6mm in diameter and spaced at not more than a 100mm pitch. The AASHTO provisions recognize no other cases in which confining reinforcement contributes to bond strength. The minimum value of  $l_d$  is 300mm.

### 5.0 Parametric study for development lengths

Figure.6. Shows a beam-column joint in a continuous building frame .Beam dimensions are 250mm x 525mm Stirrup spaced four at 75mm, followed by constant125mm spacing in the region of the support, with 37.5mm clear cover .Normal density concrete is to be used.

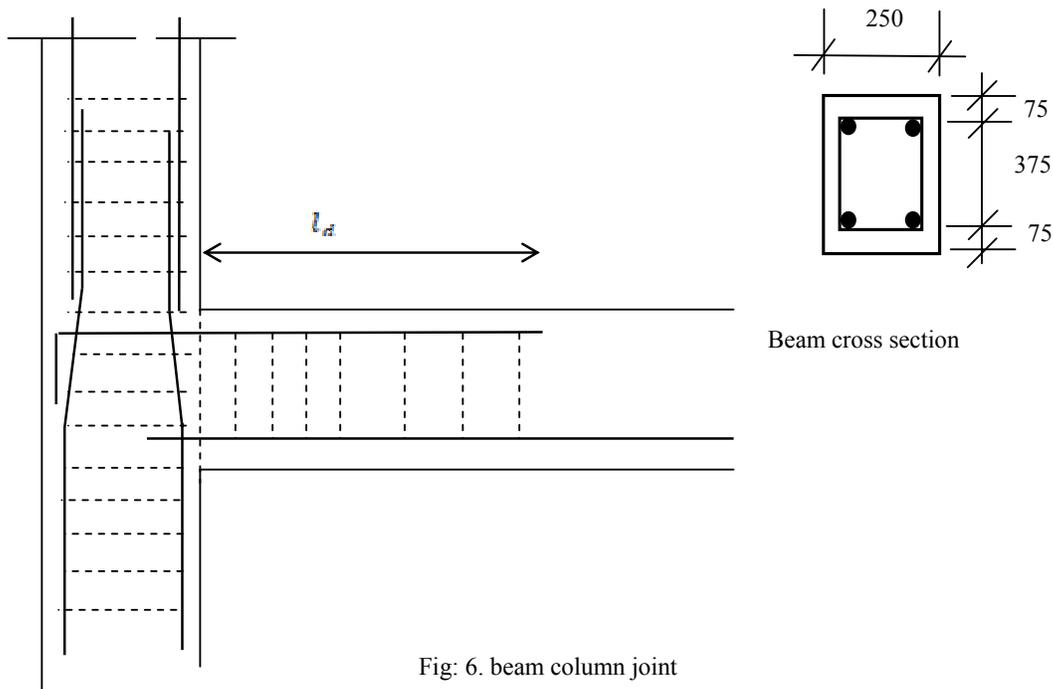


Fig. 6. beam column joint

Parameters

Ultimate compressive strength of concrete	10 MPa, 15 MPa, 20.5 MPa, 23.9 MPa, 26.67 MPa, 30 MPa and 35 MPa.
Yield strength of bars	274 MPa, 410 MPa and 500 MPa.
Bar diameter	12mm, 16 mm, 20 mm, 22 mm, 25 mm, 28 mm,32 and 36 mm.

**6. Results and discussion**

The following figures demonstrate the development length required for various design code with different strength of concrete and reinforcing bars of different bar sizes. These are obtained by conducting the parametric study of concrete strength 10 MPa, 15 MPa, 20.5 MPa, 23.9 MPa, 26.67 MPa, 30MPa and 35MPa. The yield strength of reinforcing bars is 274 MPa, 410 MPa and 500MPa.

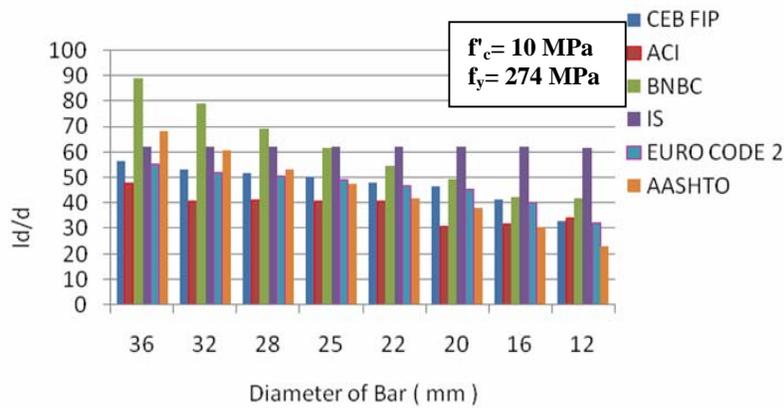


Fig. 7. Tension development length of reinforcing bar

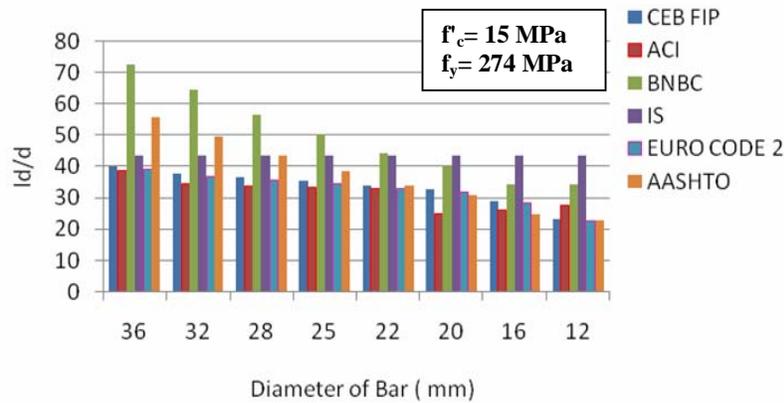


Fig. 8. Tension development length of reinforcing bar

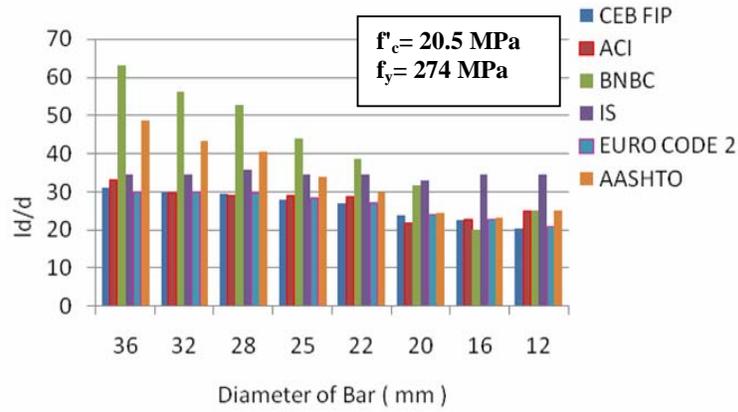


Fig. 9. Tension development length of reinforcing bar.

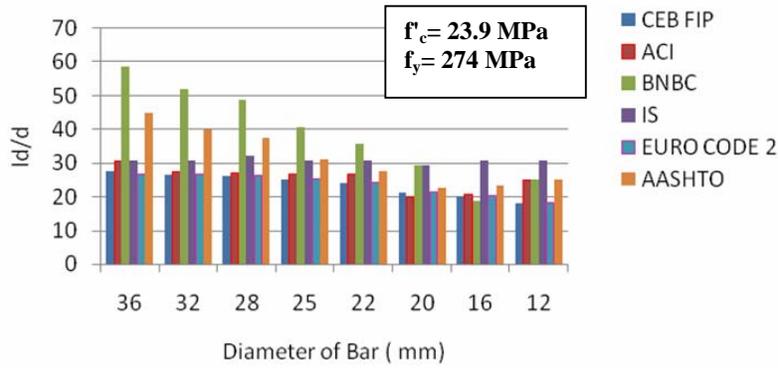


Fig. 10. Tension development length of reinforcing bar.

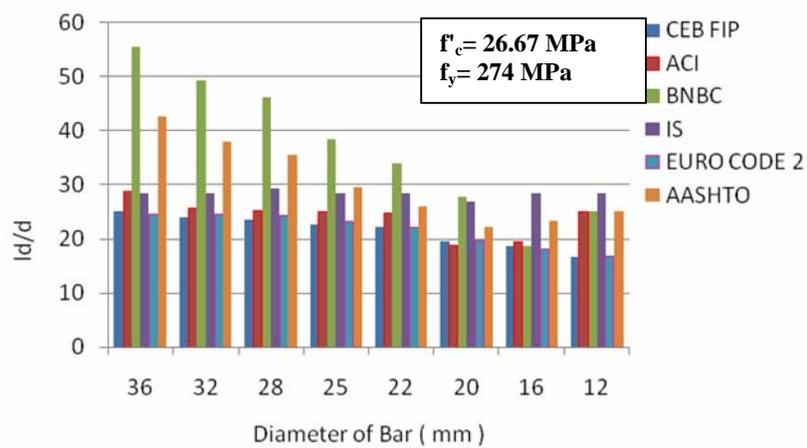


Fig. 11. Tension development length of reinforcing bar.

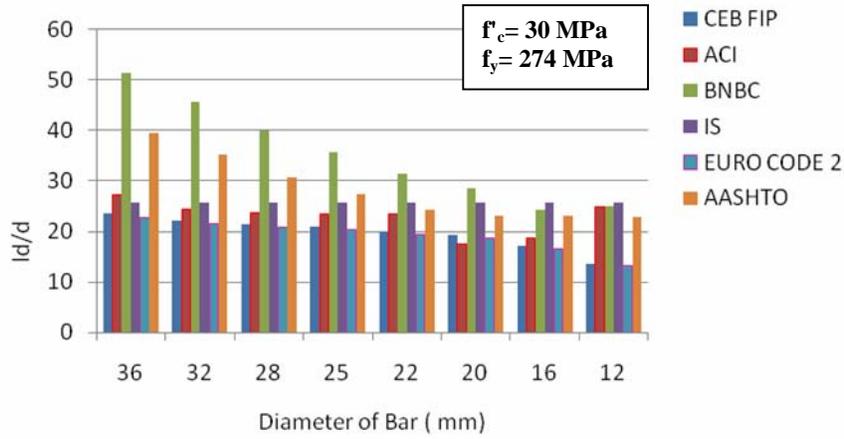


Fig. 12. Tension development length of reinforcing bar.

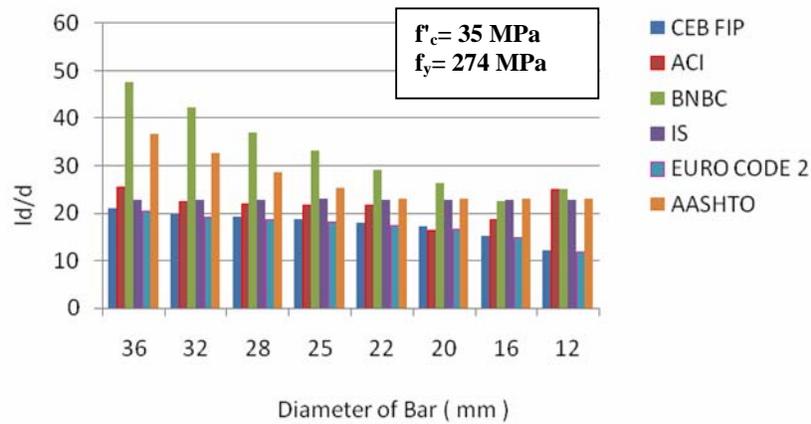


Fig. 13. Tension development length of reinforcing bar.

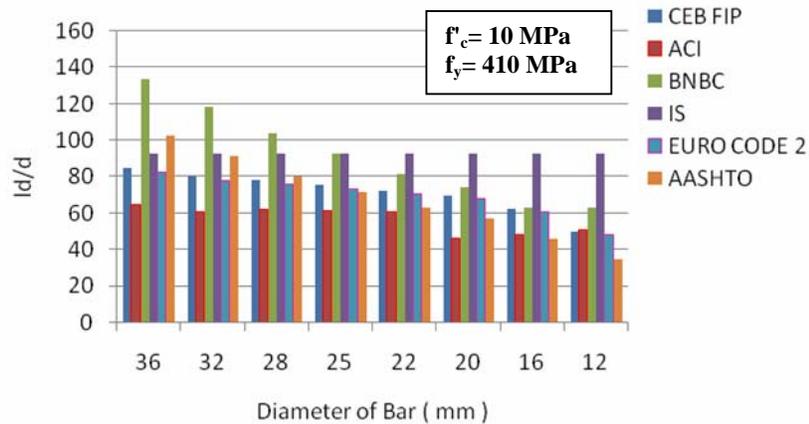


Fig. 14. Tension development length of reinforcing bar.

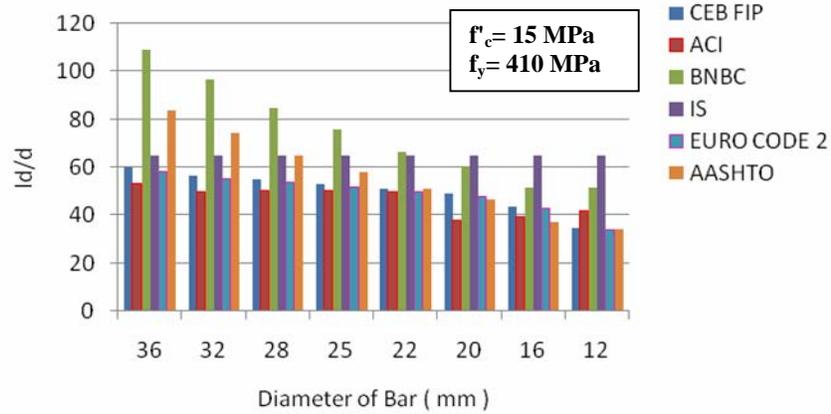


Fig. 15. Tension development length of reinforcing bar.

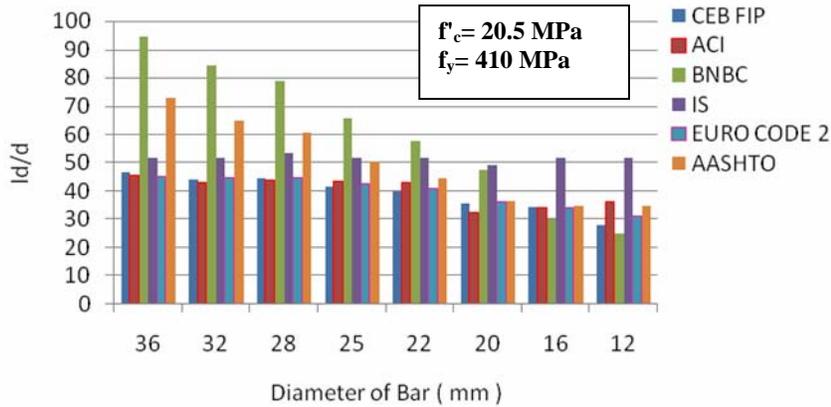


Fig. 16. Tension development length of reinforcing bar.

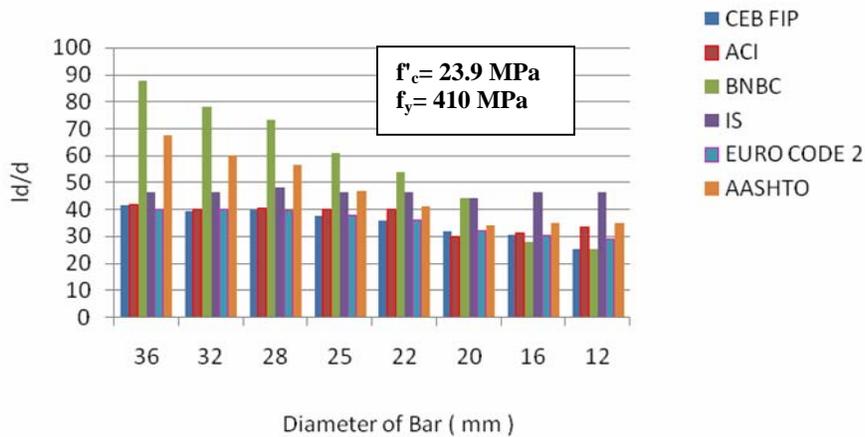


Fig. 17. Tension development length of reinforcing bar.

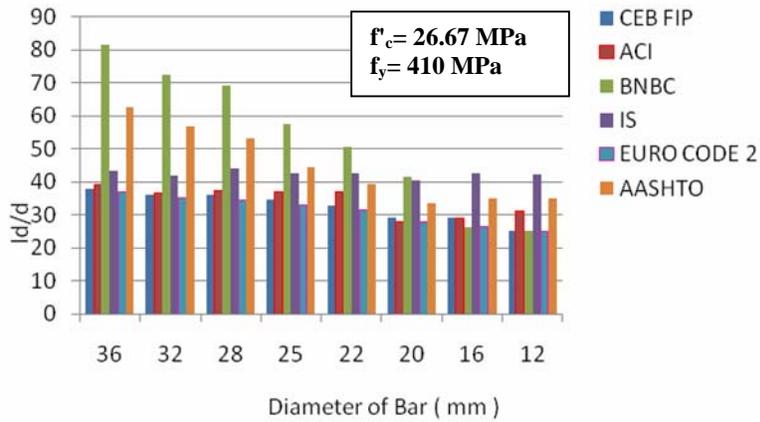


Fig. 18. Tension development length of reinforcing bar.

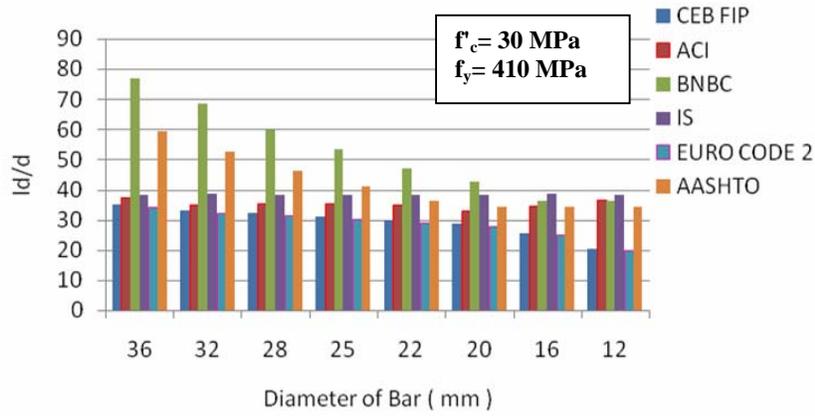


Fig. 19. Tension development length of reinforcing bar.

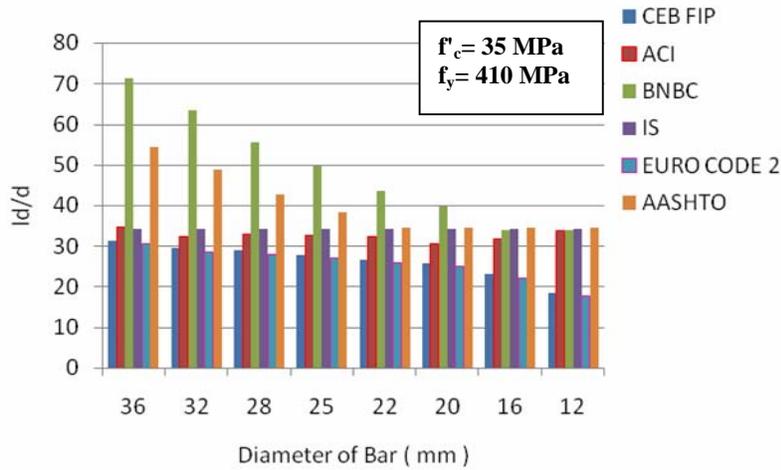


Fig. 20. Tension development length of reinforcing bar.

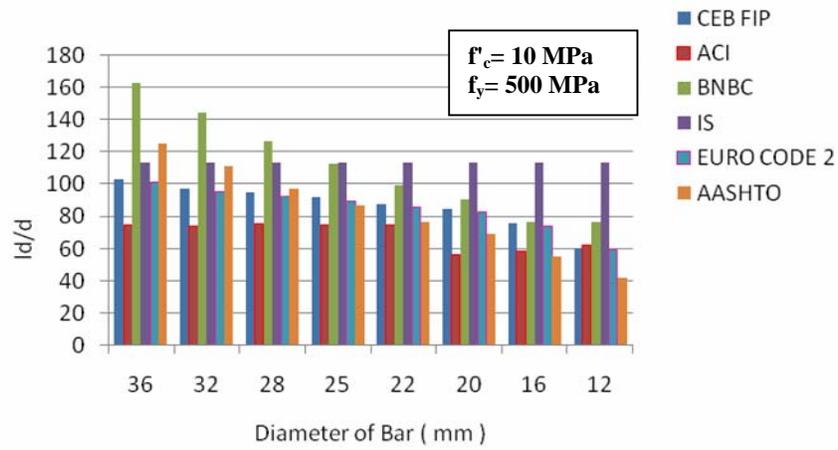


Fig. 21. Tension development length of reinforcing bar.

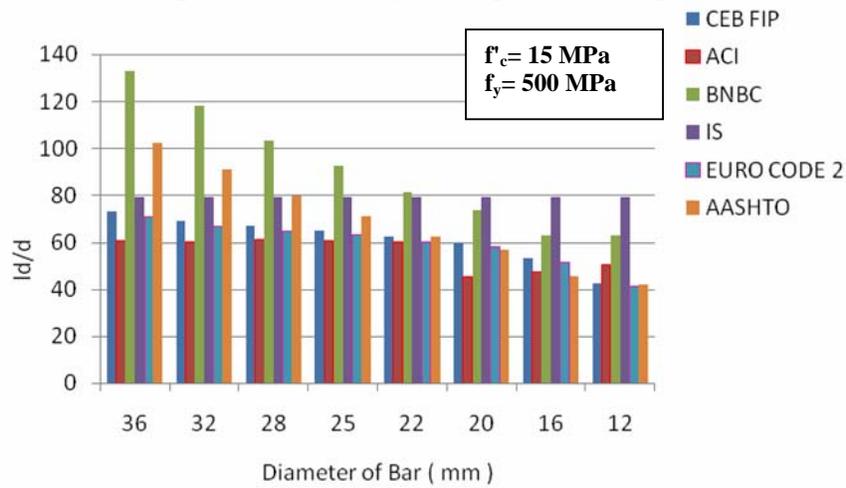


Fig. 22. Tension development length of reinforcing bar.

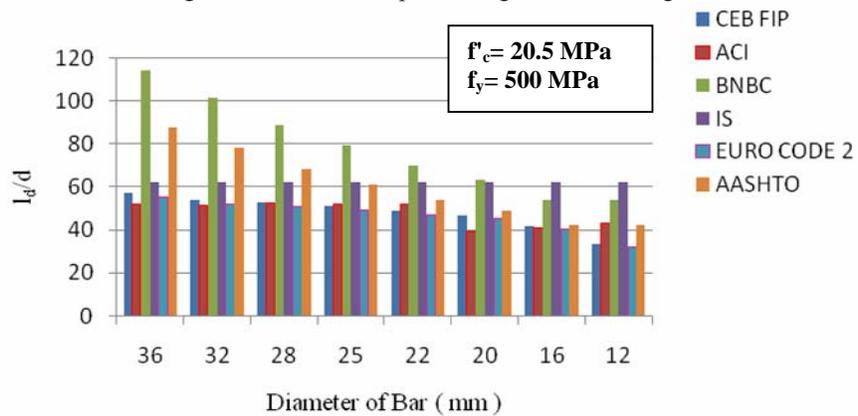


Fig. 23. Tension development length of reinforcing bar.

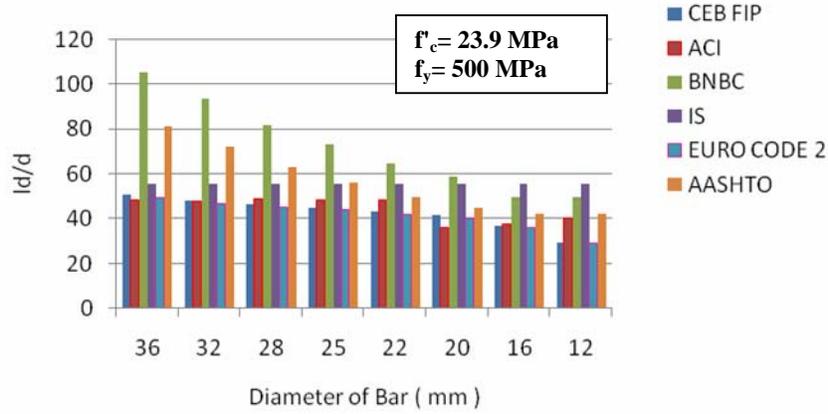


Fig. 24. Tension development length of reinforcing bar.

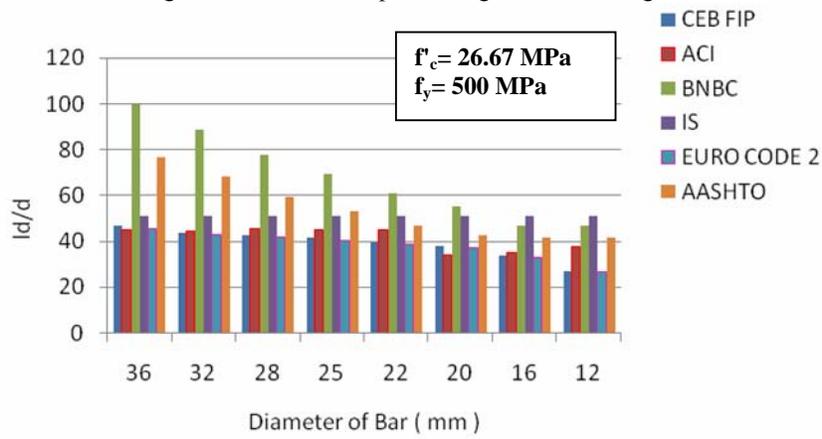


Fig. 25. Tension development length of reinforcing bar.

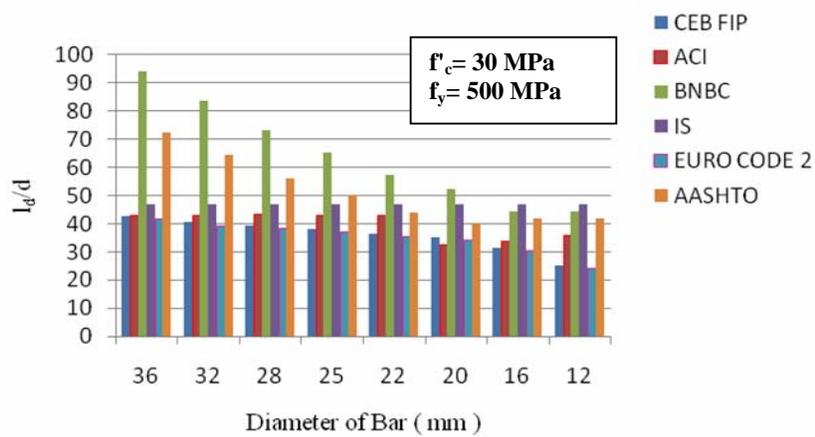


Fig. 26. Tension development length of reinforcing bar.

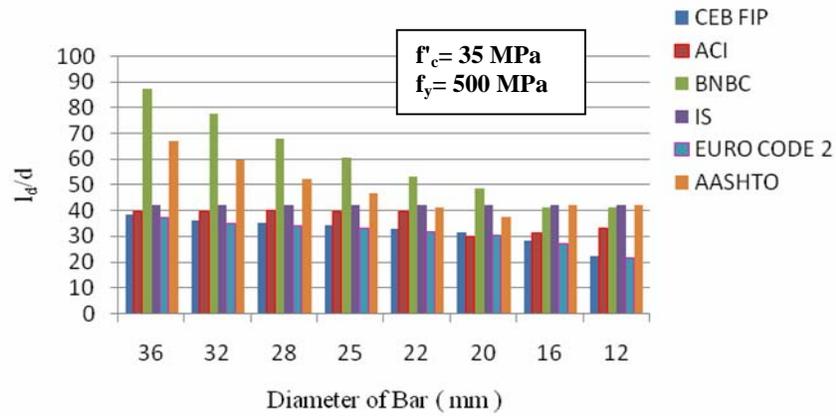


Fig. 27. Tension development length of reinforcing bar.

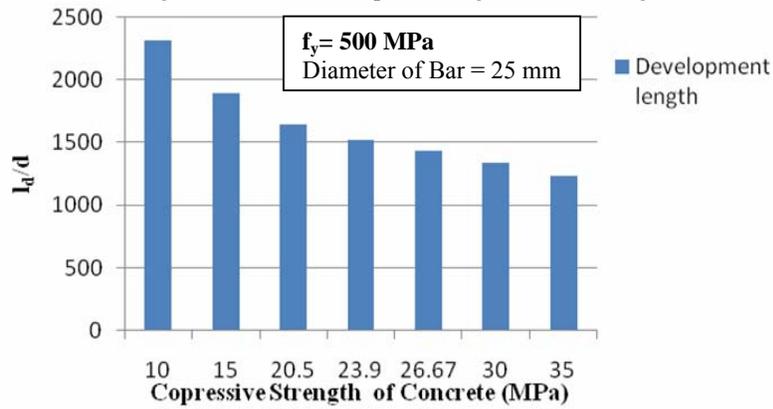


Fig. 28. Tension development length of reinforcing bar

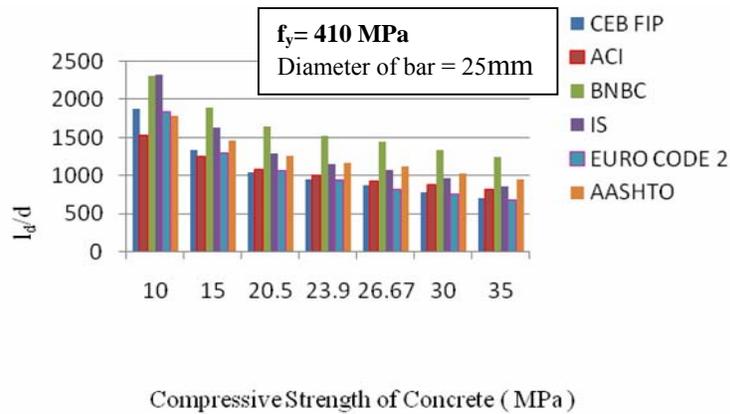


Fig. 29. Tension development length of reinforcing bar

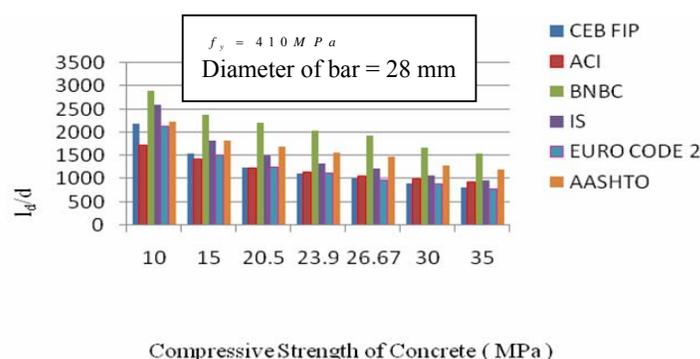


Fig. 30. Tension development length of reinforcing bar

## 6. Conclusions

The design codes ACI (2002), BNBC (1993), IS (2005), AASHTO (2007), CEB-FIP Model (1990) and EURO Code 2 have been reviewed. It has been found that BNBC (1993) recommends the largest value of development lengths for 22 mm diameter and larger diameter bars compared to other codes. The normalized development length changes with change in compressive strength of the concrete. For specific yield strength of reinforcing bars the normalized development length is gradually decreasing with increasing the compressive strength. The modification factors are used for tension development length provisions in BNBC (1993) is very large. It may be concluded that, this large modification factor may be a major concern for larger tension development length for BNBC (1993). It has been found from the study, that the CEB-FIP Model (1990) and EURO Code 2 recommends almost the same and the smallest tension development length. It has been also found that, the normalized development length for tension region is decreasing with increasing the concrete strength for specific yield strength, while the normalized development length is increases with increases of yield strength for a specific concrete strength.

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### Appendix A: Numerical example

The calculation of development length as per the ACI (2002), BNBC (1993), IS (2005), AASHTO (2007), CEB-FIP Model (1990), and EURO Code 2 .The development length requirement is calculated based on the following data.

Compressive strength of concrete is 10 MPa, 15 MPa, 20.5 MPa, 23.9 MPa, 26.67 MPa, 30 MPa, and 35MPa.  
Tensile strength of reinforcing bars is 274 MPa, 410 MPa, 500 MPa,

Diameter of bar 12mm, 16mm, 20mm,22mm, 25mm, 28mm, 32mm and 36mm.

Cover to reinforcement (top)= 75 mm

Side cover = 37.5 mm

Spacing of reinforcement = 125 mm

Area of transverse reinforcement,  $A_{tr} = 78.53 \text{ mm}^2$

#### CEB-FIP model (1990)

Calculation for 36mm bar.

$$\eta = 1.00 \text{ for } d_b \leq 32 \text{ mm, } \eta = \frac{100}{132 - d_b} \text{ for } d_b > 32 \text{ mm}$$

$$c_{\min} = \min(a/2, c_1, c_2)$$

$$c_{\min} = \min(41.5, 75, 37.5) \quad a = 250 - 2*10 - 2*36 - 2*37.5$$

$$c_{\min} = 37.5 \text{ mm} \quad a = 83 \text{ mm}$$

$$\eta = \frac{100}{132 - d_b} = \frac{100}{132 - 36} = 1.041$$

$$f_{yk} = 1.06 f_y = 1.06 * 410 = 434 \text{ MPa}$$

$$f_{yd} = \frac{f_{yk}}{1.15} = 377 \text{ MPa}$$

$$f_{ck} = f_c' - 2.75 = 26.67 - 2.75 = 23.9 \approx 24 \text{ MPa}$$

$$\sum A_{str} = 2 * 78.54 = 157 \text{ mm}^2 \quad \sum A_{str, \min} = 0.25 A_b$$

$$= 0.25 * 975 = 243.75 \text{ mm}^2.$$

$$= (1.15 - 0.15 \frac{c_{\min}}{d_b}) = (1.15 - 0.15 * \frac{37.5}{36}) = 0.99$$

$$= (1 - k \frac{\sum A_{str} - \sum A_{str, \min}}{A_b}) = (1 - 0.1 \frac{157 - 243.75}{975}) = 1.01 > 1$$

$$\approx 1.0$$

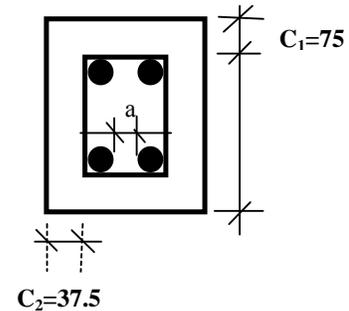
$$l_d = \frac{1}{1.228} (1.15 - 0.15 \frac{c_{\min}}{d_b}) (1 - k \frac{\sum A_{str} - \sum A_{str, \min}}{A_b}) \eta \frac{f_{yd}}{f_{ck}^{3/4}} d_b$$

$$= \frac{1}{1.228} (0.99) (1) (1.041) \frac{(377)}{(24)^{3/4}} (36) \quad (36)$$

$$l_d = 1362 \text{ (mm)}$$

Assume  $\frac{A_s \text{ (required)}}{A_s \text{ (provided)}} = 1.0$ , then

$$l_d = 1362 * 1.00 = 1362 \text{ (mm)}$$



Similarly the development lengths for bars 32 mm, 28 mm, 25 mm, 22 mm, 20 mm, 16 mm and 12 mm diameters are 1160 mm, 1013 mm, 863 mm, 723 mm, 584 mm, 469 mm, and 300 mm respectively.

**EURO Code 2**

Calculation for 36 mm diameter bar.

$$\eta = \frac{100}{132 - d_b} \quad \text{for } d_b > 32 \text{ mm}$$

$$\eta = \frac{100}{132 - 36} = \frac{100}{96} = 1.041$$

$$c_{min} = \min(a/2, c_1, c_2) \quad a = 250 - 2*10 - 2*37.5 - 2*36$$

$$c_{min} = \min(41.5, 75, 37.5) \quad a = 83 \text{ mm}$$

$$c_{min} = 37.5 \text{ mm}$$

$$f_{yk} = 1.06 f_y = 1.06 * 410 = 434 \text{ MPa}$$

$$f_{yd} = \frac{f_{yk}}{1.15} = 377 \text{ MPa}$$

$$f_{sd} = f_{yd} \text{ (As required)/(As provided)}$$

Assume  $\frac{A_s \text{ (required)}}{A_s \text{ (provided)}} = 1.0$ ,

$$f_{sd} = 377 \text{ MPa}$$

$$f_{ck} = f'_c - 2.75 = 26.67 - 2.75 = 23.9 \approx 24 \text{ MPa}$$

$$\sum A_{tr} = 2 * 78.5 = 157 \text{ mm}^2 \quad \sum A_{tr,min} = 0.25 A_b$$

$$\sum A_{tr,min} = 0.25 * 975 = 244 \text{ mm}^2$$

$$= (1.15 - 0.15 \frac{c_{min}}{d_b}) = (1.15 - 0.15 * \frac{37.5}{96}) = 0.99$$

$$= (1 - k \frac{\sum A_{tr} - \sum A_{tr,min}}{A_b}) = (1 - 0.1 \frac{157 - 244}{975}) = 1.01 > 1$$

≈ 1.0

$$l_d = \frac{1}{1.26} (1.15 - 0.15 \frac{c_{min}}{d_b}) (1 - k \frac{\sum A_{tr} - \sum A_{tr,min}}{A_b}) \eta \frac{f_{sd}}{f_{ck}^{3/4}} d_b$$

$$= \frac{1}{1.26} (0.99) (1) (1.041) \frac{(377)}{(24)^{3/4}} (36) \quad (36)$$

$$l_d = 1334 \text{ (mm)}$$

Assume  $\frac{A_s \text{ (required)}}{A_s \text{ (provided)}} = 1.0$ , then

$$l_d = 1334 * 1.00 = 1334 \text{ (mm)}$$

Similarly the development lengths for bars 32 mm, 28 mm, 25 mm, 22 mm, 20 mm, 16 mm and 12 mm diameters are 1130 mm, 969 mm, 825 mm, 694 mm, 562 mm, 425 mm, and 300 mm respectively.

**ACI Code (2002)**

Calculation for # 11 bar (36 mm).

$\alpha = 1.3$  (reinforcement location factor)

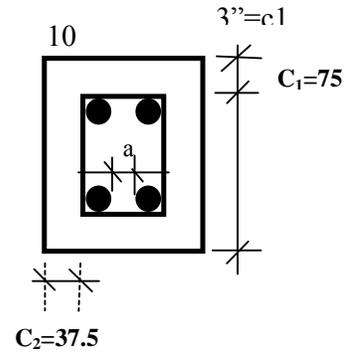
$\beta = 1.00$  reinforcement coating factor (uncoated bar)

$\gamma = 1.00$  # 7 or larger. (Reinforcement size factor)

$\lambda = 1.00$  (normal concrete is used)

$$a = 250 - 2*10 - 2*37.5 - 2*\frac{36}{2} = 119 \text{ (mm)}$$

$$a/2 = \frac{119}{2} = 59.50 \text{ (mm)}$$



$$c_1 = 75 \text{ mm (top covering)}, \quad c_2 = 37.5 + 10 + \frac{36}{2} = 65.5 \text{ (mm)}$$

$$C = \min (a/2; c_1; c_2) = \min (59.50, 75, 65.5)$$

$$C = 59.50 \text{ (mm)}$$

$$K_{cr} = \frac{A_{tr} f_{yc}}{1500 s n} = \frac{0.11 * 2 * 60000}{1500 * 5 * 2} = 0.88.$$

$$\text{So, } \frac{C + K_{cr}}{d_b} = \frac{2.42 + 0.88}{1.41} = 2.34 < 2.5 \text{ (ok)}$$

$$l_d = \frac{3}{40} \frac{f_y}{\sqrt{f'_c}} \left( \frac{\alpha \beta \gamma \lambda}{C + K_{cr}} \right) d_b$$

$$l_d = \frac{3}{40} \frac{60000}{\sqrt{4000}} \left( \frac{1.3 * 1 * 1 * 1}{2.34} \right) 1.41 = 55.7 \text{ (inch)} = 1415 \text{ mm}$$

$$l_d = 1415 * \frac{A_s \text{ (required)}}{A_s \text{ (provided)}} \quad \text{Assume } \frac{A_s \text{ (required)}}{A_s \text{ (provided)}} = 1.0,$$

$$l_d = 1415 * 1 = 1415 \text{ mm}$$

Similarly the development lengths for bars 32 mm, 28 mm, 25 mm, 22 mm, 20 mm, 16 mm and 12 mm diameters are 1175 mm, 1044 mm, 925 mm, 813 mm, 562 mm, 462 mm, and 375 mm respectively.

### BNBC (1993)

Calculation for # 11 bar (36 mm),

$$l_{db} = \frac{0.02 * A_b f_y}{\sqrt{f'_c}} \quad \text{(for 36 mm diameter bar or smaller)}$$

$$f_y = 410 \text{ MPa} \quad f'_c = 26.67 \text{ MPa}$$

$$l_{db} = \frac{0.02 * A_b f_y}{\sqrt{f'_c}} = \frac{0.02 * 1017.87 * 410}{\sqrt{26.67}} = 1616 \text{ mm}$$

Clear spacing between the bar being developed =  $250 - 2 * 37.5 - 2 * 10 - 2 * 36 = 83 \text{ mm} < 3d_b$

$$A_{tr} \geq \frac{d_b s_n}{40} A_{tr} = 2 * 78.5 = 157 \text{ mm}^2$$

$$\frac{d_b s_n}{40} = \frac{36 * (3 * 23) * 2}{40} = 225 \text{ mm}^2$$

So, condition do not satisfy, modifier = 1.4

$$l_{db} = 1616 * 1.4 = 2262 \text{ mm}$$

Further modification factor in section (8.2.3.4) in BNBC

(a) Top bar = 1.3

$$l_d = 2262 * 1.3 = 2941 \text{ mm}$$

$$l_d = 2941 * \frac{A_s \text{ (required)}}{A_s \text{ (provided)}} \quad \text{Assume } \frac{A_s \text{ (required)}}{A_s \text{ (provided)}} = 1.0,$$

$$l_d = 2941 \text{ mm}$$

Similarly the development lengths for bars 32 mm, 28 mm, 25 mm, 22 mm, 20 mm, 16 mm and 12 mm diameters are 2324 mm, 1939 mm, 1441 mm, 1116 mm, 832 mm, 421 mm, and 300 mm respectively.

### IS (2005)

Calculation for # 11 bar (36 mm),

$\sigma_s$  = stress in the bar at the section considered at design load (assume fully stressed)

$$\sigma_s = 0.87 f_y = 0.87 * 410 = 356.7 \text{ MPa}$$

$$f_{ck} = f'_c - 2.75 = 26.67 - 2.75 = 23.9 \approx 24 \text{ MPa}$$

$$\tau_{bd} = 0.16 ( \frac{f_{ck}}{24} )^{1/3} = 0.16 * ( \frac{24}{24} )^{1/3} = 1.33 \text{ MPa}$$

60% increased,  $\tau_{bd} = 2.13 \text{ MPa}$

$$l_d = \frac{d_b \sigma_s}{4 \tau_{bd}} = \frac{36 * 356.7}{4 * 2.13} = 1507 \text{ mm}$$

Similarly the development lengths for bars 32 mm, 28 mm, 25 mm, 22 mm, 20 mm, 16 mm and 12 mm diameters are 1336 mm, 1231 mm, 1066 mm, 939 mm, 812 mm, 685 mm and 508 mm respectively.

**AASHTO (2007)**

Calculation for # 11 bar (36 mm),

$$l_{db} = \frac{0.02 * d_b f_y}{\sqrt{f'_c}} = \frac{0.02 * 36 * 410}{\sqrt{26.67}} = 1616 \text{ mm}$$

But not less than  $0.06 d_b f_y = 0.06 * 36 * 410 = 885.6 \text{ mm} < 1616 \text{ mm}$

$l_{db} = 1616 \text{ mm}$

Modification factor:

1) 1.4 for top bar,

2) Assume  $\frac{l_d \text{ (required)}}{l_d \text{ (provided)}} = 1.0,$

$$l_d = 1616 * 1.4 = 2262 \text{ mm}$$

Similarly the development lengths for bars 32 mm, 28 mm, 25 mm, 22 mm, 20 mm, 16 mm and 12 mm diameters are 1816 mm, 1492 mm, 1111 mm, 864 mm, 673 mm, 558 mm and 419 mm respectively.