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

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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.

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

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 for22 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

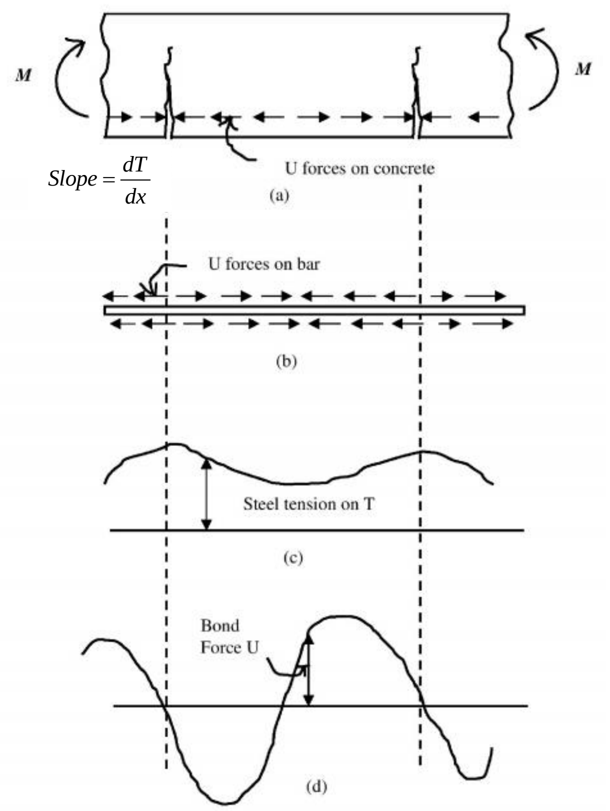


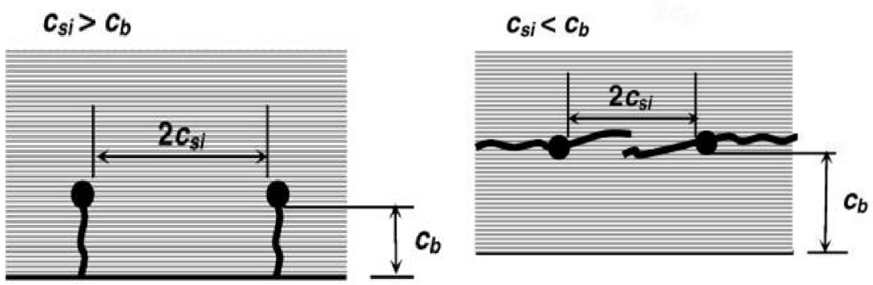
Fig. 1. (a) Cracked concrete segment, (b) bond stress acting on reinforcing bar, (c) variation of tensile force in steel; and (d) variation of bond force along bar (adapted from Nilson *et al.)*

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_{si} 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.



(a) (b)

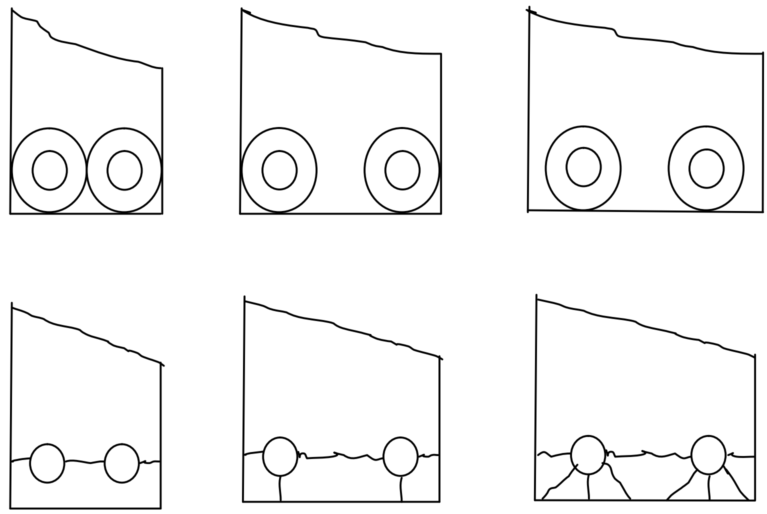
Fig. 2. Bond cracks: (a) $c_{si} > c_b$, (b) $c_{si} < c_b$

2.3 Cover distance

Cover conventionally the distance measured from the center 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.

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

(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 & 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 $f_c^{'1/4}$ in place of the more traditional $f_{ck}^{1/2}$ or $f_{ck}^{2/3}$ (where $f_c^{'}$ is the specified compressive strength and f_{ck} 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 ¼ 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 ≥ $\sqrt{f_c^{'}}$ 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.

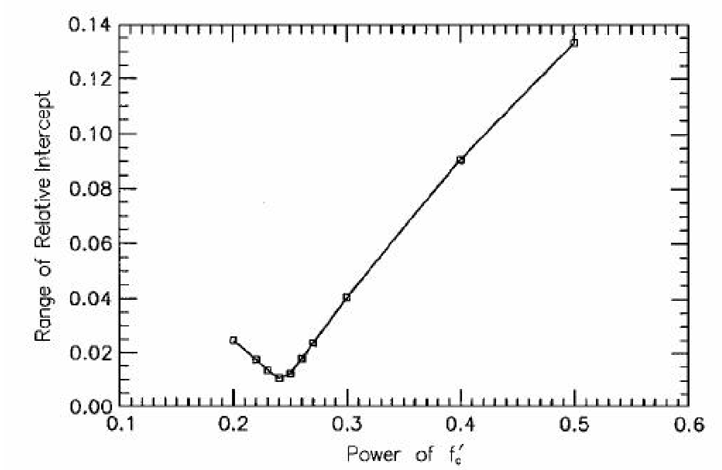


Fig. 4. Range of relative intercept obtained for dummy variables analysis for experimental bond force, normalized with respect to for optimized bond strength expressions versus the power p of for bars without confining transverse reinforcement. (Ref. David Darwin, 2005).

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)

<u>Basic equation for development of tension bars</u>

$$l_d = \frac{3}{40}\frac{f_y}{\sqrt{f_c^{'}}}\left(\frac{\sim\ \text{¥ª}}{\frac{C+K_{tr}}{d_b}}\right) \qquad (1)$$

In which the term $\frac{c+K_{tr}}{d_b}$ shall not be taken greater than 2.5. where α 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 ; β 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; γ = reinforcement size factor0.8: for No. 6 (no.19) and smaller bars and deformed wire, and 1.0: for No. 7 (no.22) and larger bars; λ 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, λ shall be permitted to be taken as $6.7\sqrt{f_c^{'}}\,/\,f_{ct}$ 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} the yield 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 $l_d = 0.03 d_b f_y / \sqrt{f_c^{'}}$, the experimentally derived limit found in earlier ACI codes equations relating to the development length.

4.2 CEB-FIP Model Code (1990)

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

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

where, d_b is diameter of bar; $\text{¦} = 1.0$ for $d_b \le 32$ mm, $\text{¦} = \frac{100}{132 - d_b}$ 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. $f_{yd} = \frac{f_{yk}}{1.15}$, where f_{yk} 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 $= 0.25A_s$ 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 ≤ (1 -0.04p) ≤ 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 (A_s required)/ (A_s provided).The development length is limited as expressed in following equation,

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

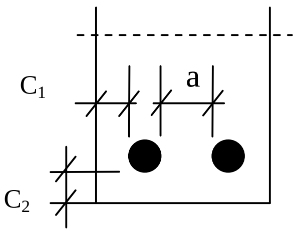


Fig.5. $c_{\min} = \min(a/2, c_1, c_2)$

2.3 EURO Code 2

The development length provisions of Euro code 2 is expressed as

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

where, f_{sd} is the design stress of the bar at the position from where anchorage is measured at the ultimate limit state = f_{yd} (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

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

2.4 BNBC (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,

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

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

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

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 mm^2.

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

For all bars satisfying any one of the following conditions:

- 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 $3d_b$
- 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, $A_{tr} \geq \frac{d_b sn}{40}$
- Bars in the inner layer of slab or wall reinforcement and with clear spacing of not less than $3d_b$
- 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 bellow 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 A_s (req.) / A_s (provided) = 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.

2.5 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,

$$l_d = \frac{d_b \pm_s}{4^{2}{}_{bd}} \quad (9)$$

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

Where, d_b nominal diameter of bar, $\pm_s$ = stress in the bar at the section considered at design load (for fully stressed bars, $\pm_s = 0.87 f_y$) and $^{2}{}_{bd}$ = 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 τ_{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.

2.6 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,

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

But not less than $0.06 d_b f_y$

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

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

where, A_b is the area of bar (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.

3. 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.

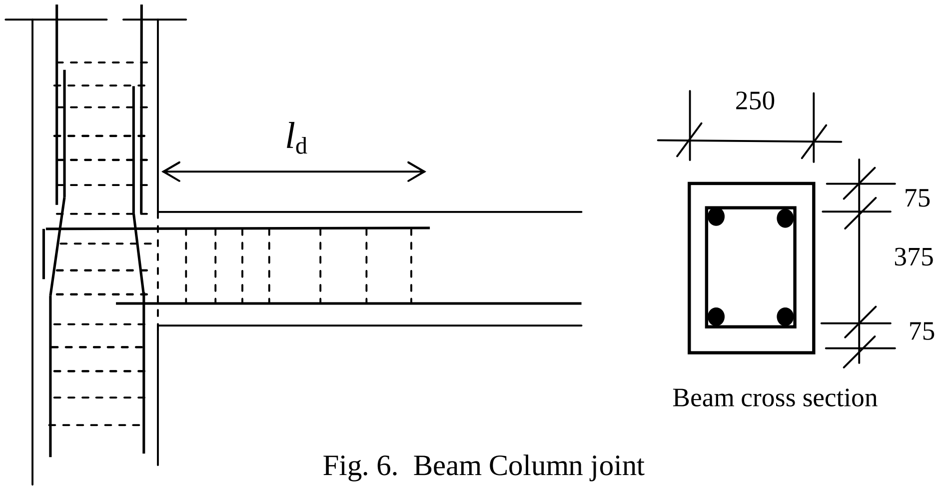


Fig. 6. Beam Column joint

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 mm and 36 mm

3.1 Results and discussion

The following table demonstrates 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.

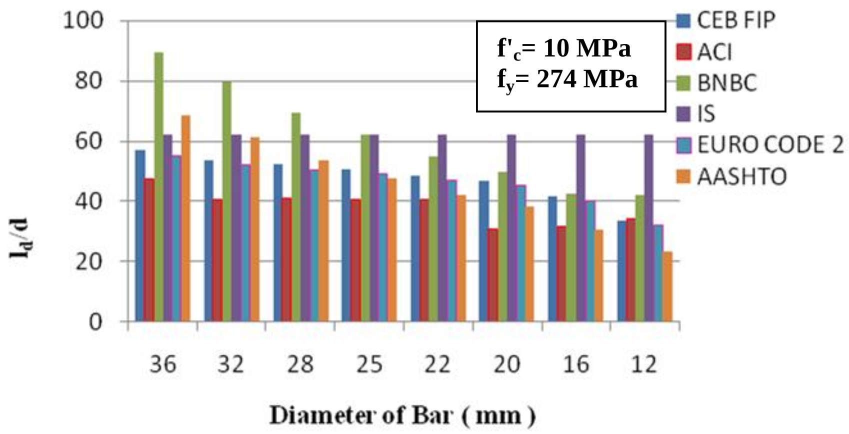


Fig. 7. Tension development length of Reinforcing bar

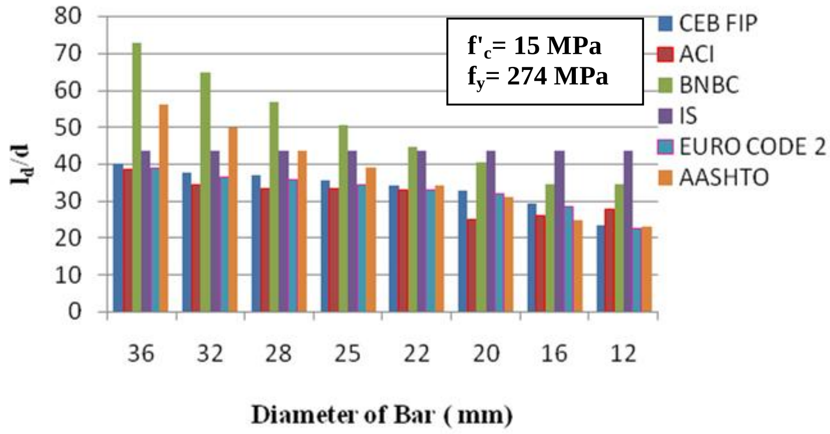


Fig. 8. Tension development length of Reinforcing bar

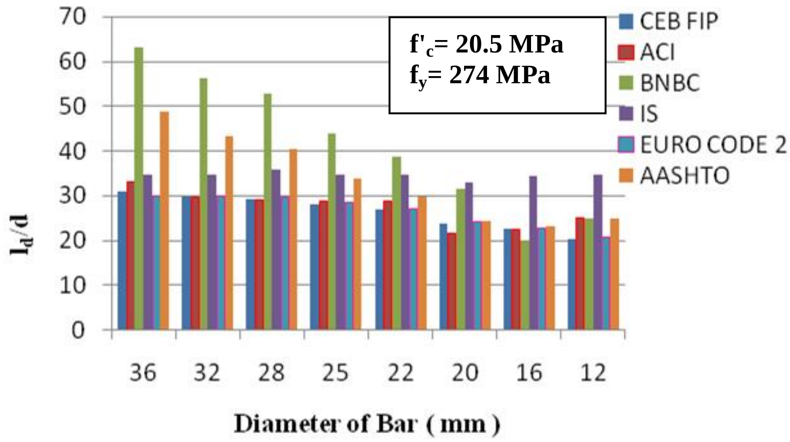


Fig. 9. Tension development length of Reinforcing bar

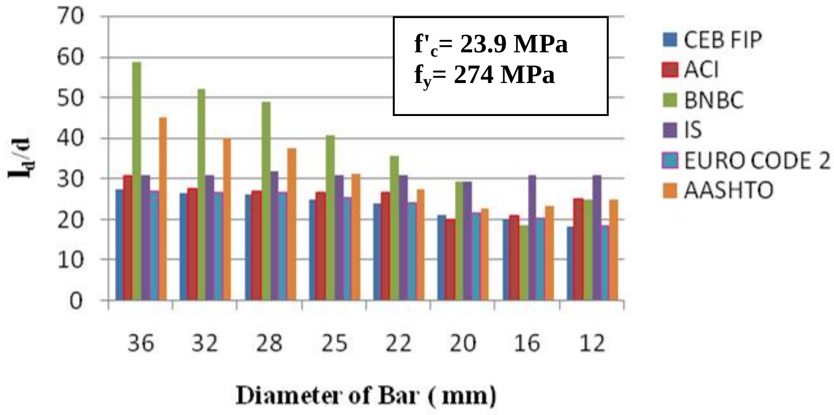


Fig. 10. Tension development length of Reinforcing bar

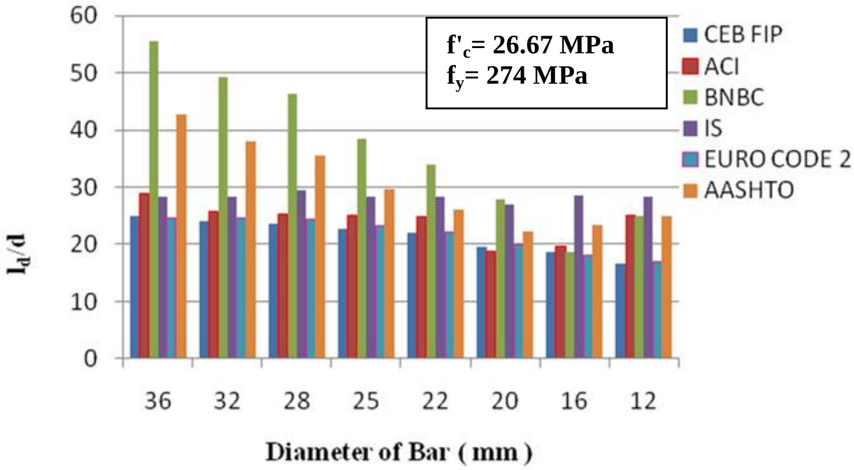


Fig. 11. Tension development length of Reinforcing bar

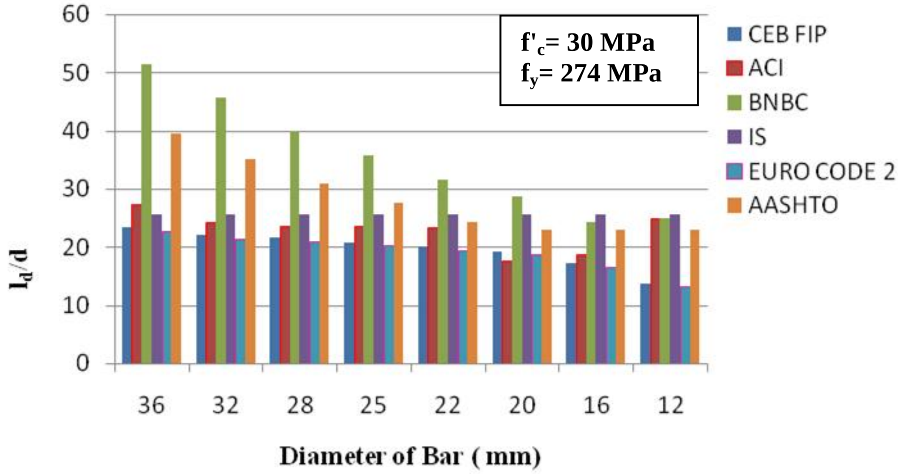


Fig. 12. Tension development length of Reinforcing bar

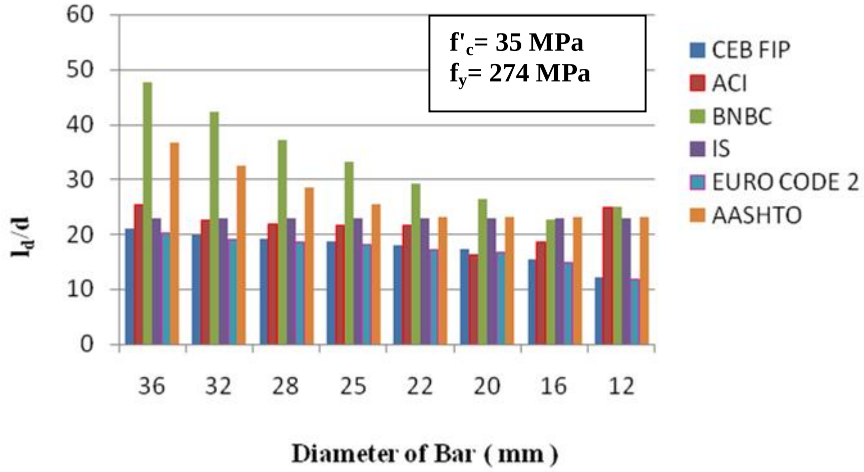


Fig. 13. Tension development length of Reinforcing bar

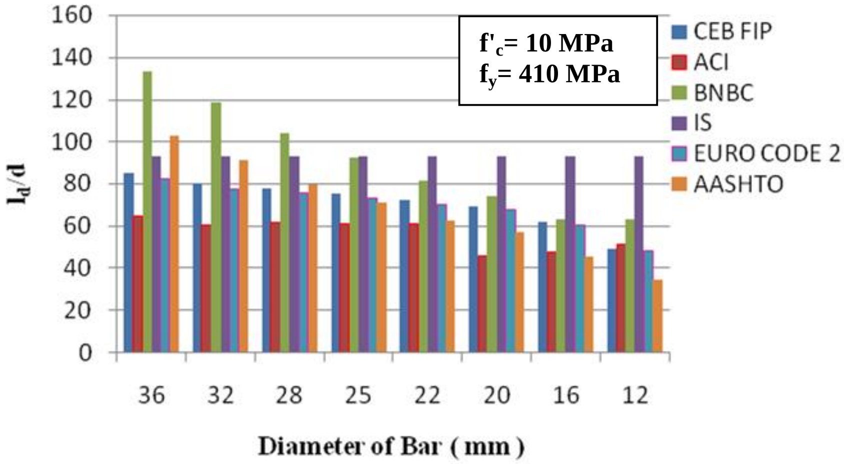


Fig. 14. Tension development length of Reinforcing bar

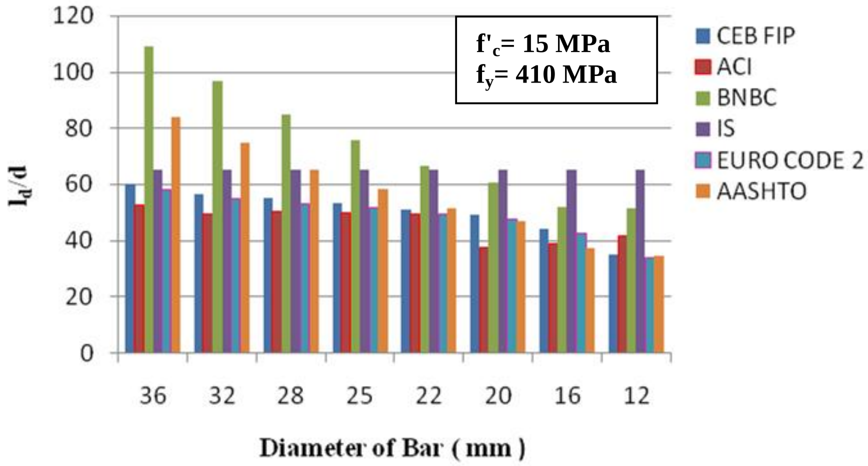


Fig. 15. Tension development length of Reinforcing bar

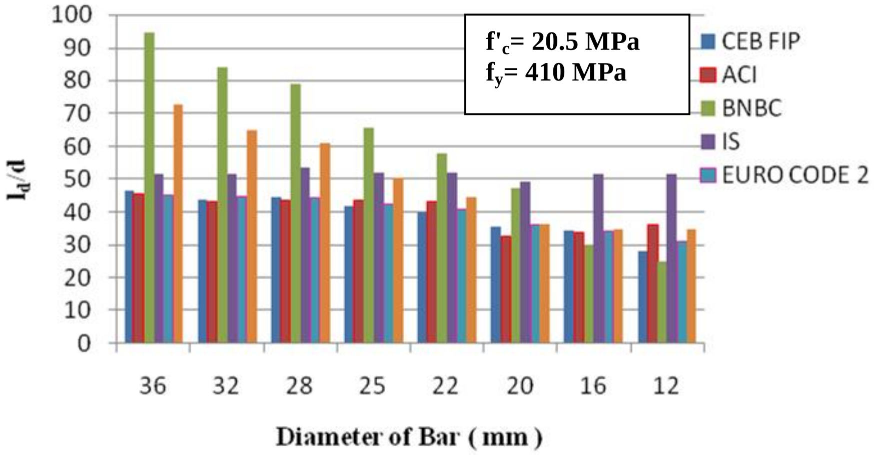


Fig. 16. Tension development length of Reinforcing bar

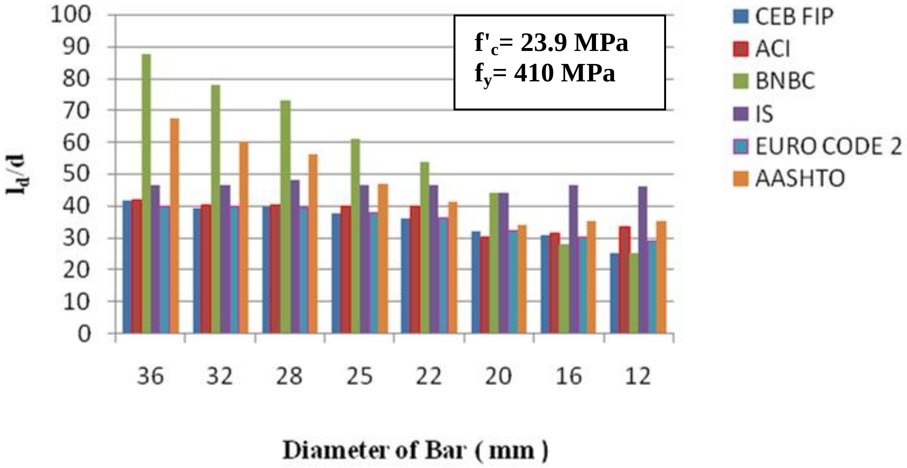


Fig. 17. Tension development length of Reinforcing bar

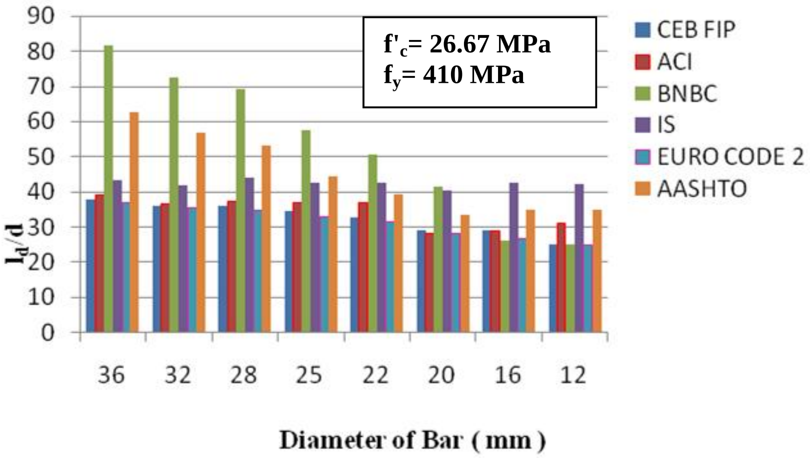


Fig. 18. Tension development length of Reinforcing bar

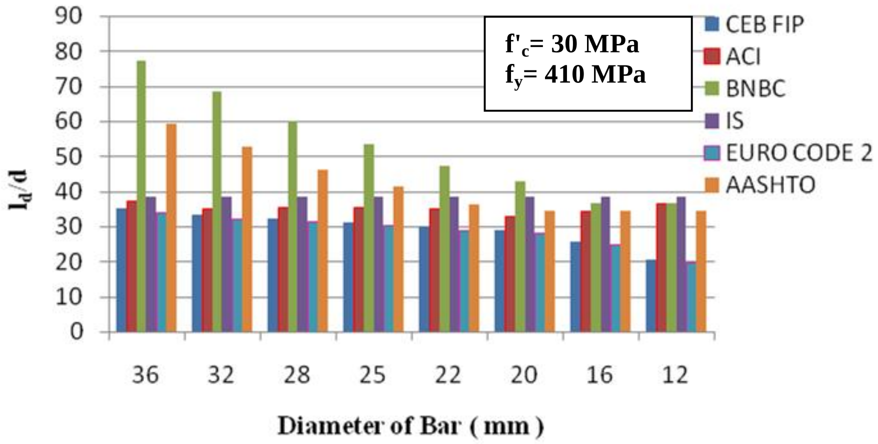


Fig. 19. Tension development length of Reinforcing bar

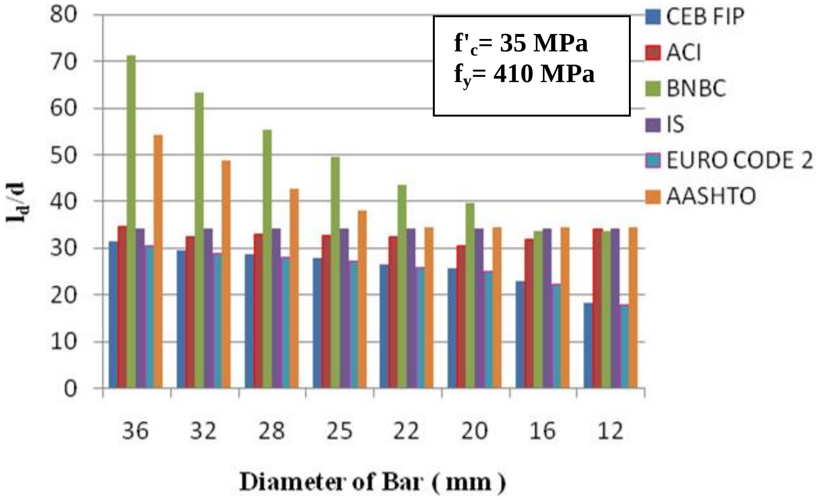


Fig. 20. Tension development length of Reinforcing bar

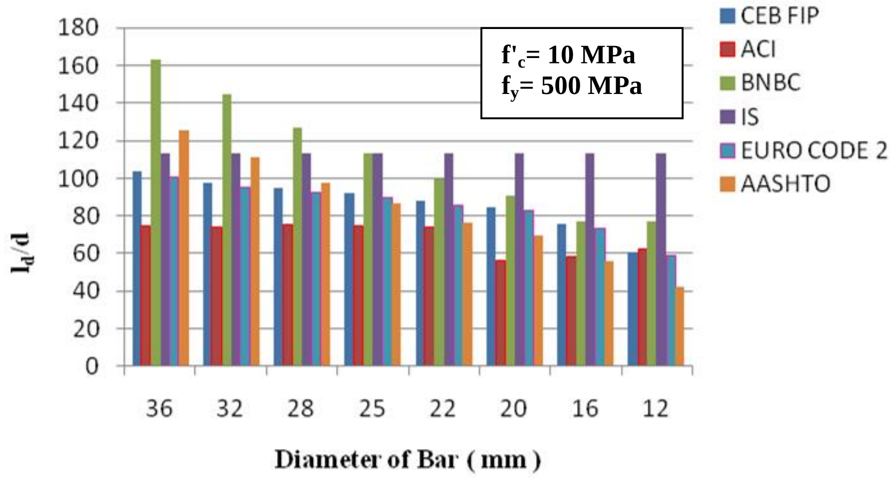


Fig. 21. Tension development length of Reinforcing bar

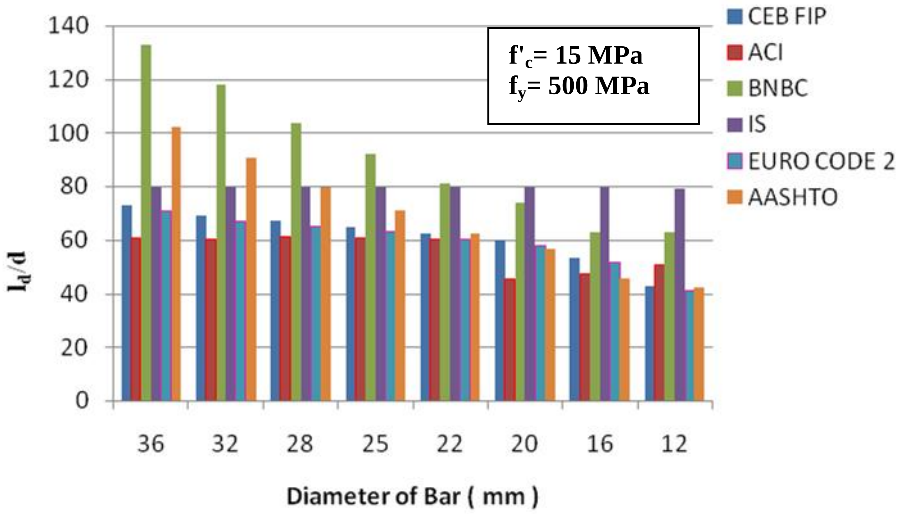


Fig. 22. Tension development length of Reinforcing bar

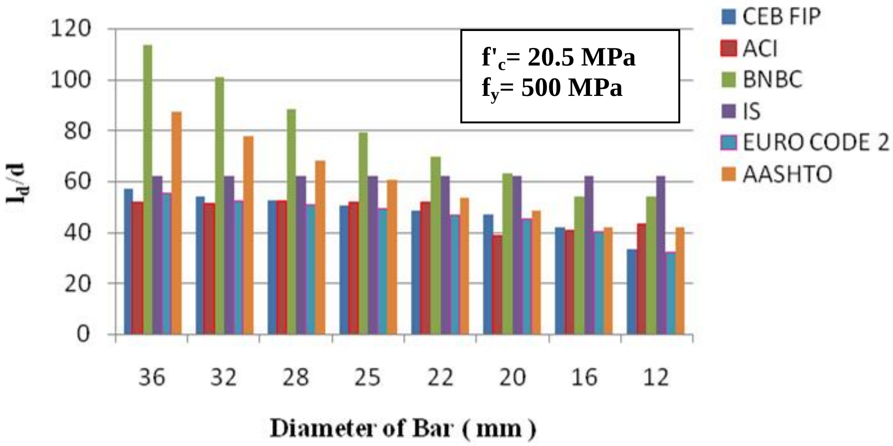


Fig. 23. Tension development length of Reinforcing bar

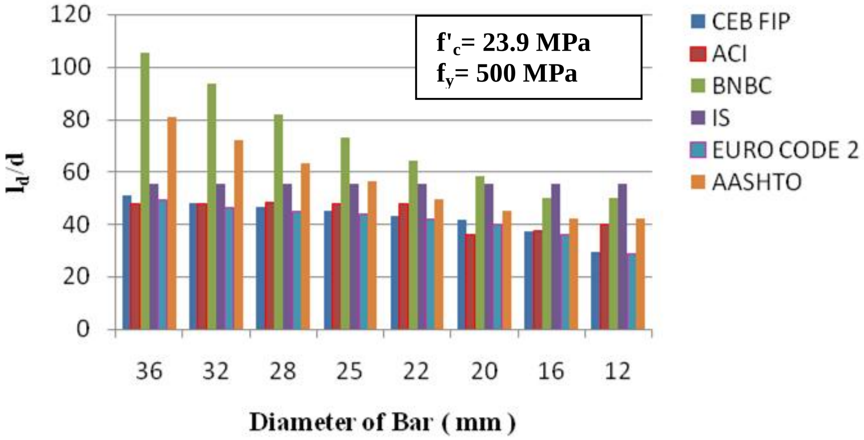


Fig. 24. Tension development length of Reinforcing bar.

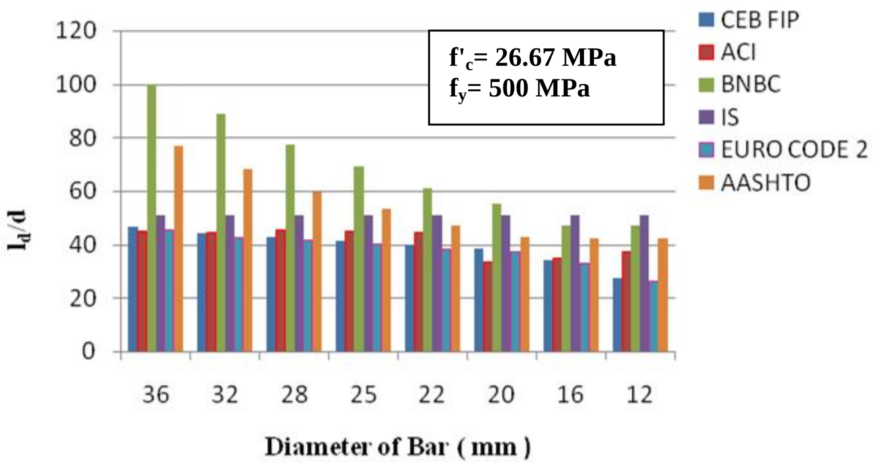


Fig. 25. Tension development length of Reinforcing bar

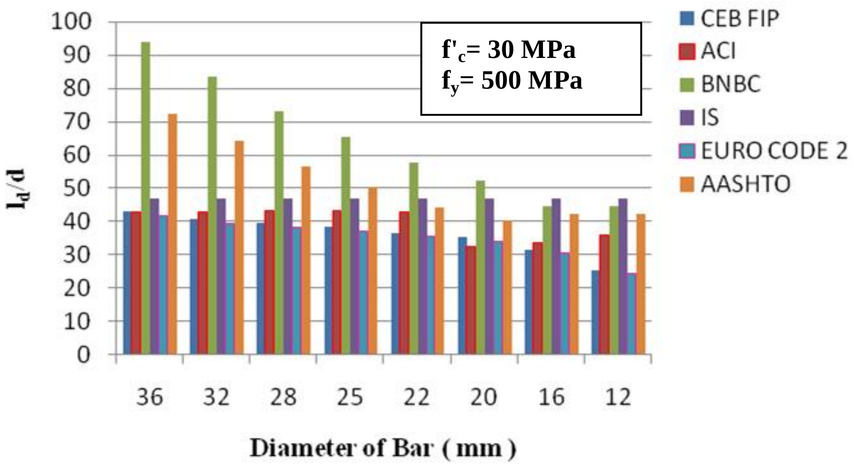


Fig. 26. Tension development length of Reinforcing bar

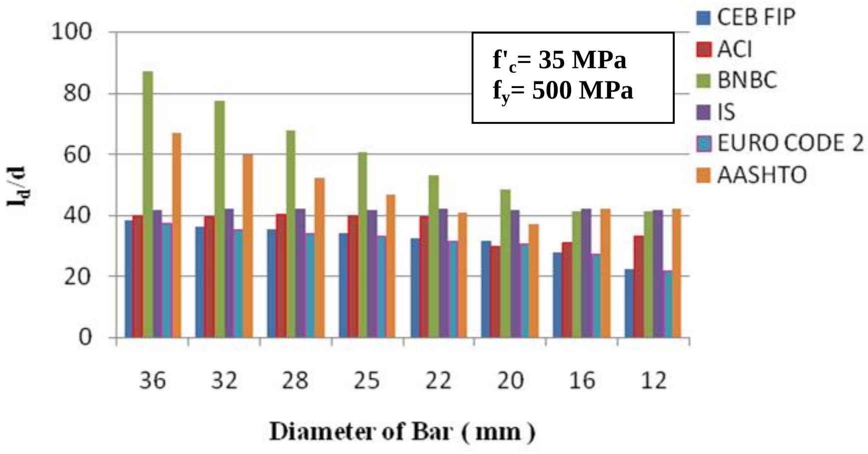


Fig. 27. Tension development length of Reinforcing bar

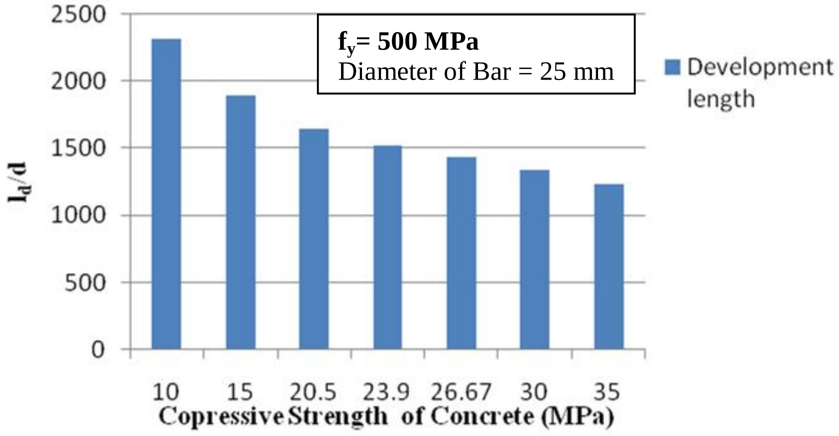


Fig. 28. Tension development length of Reinforcing bar

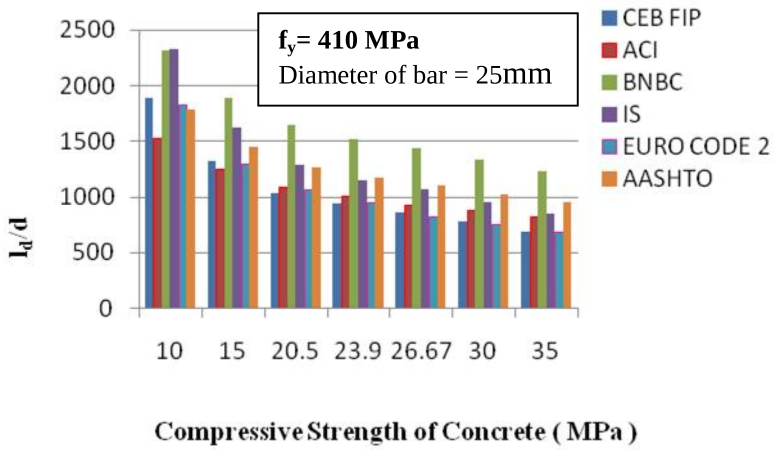


Fig. 29. Tension development length of Reinforcing bar

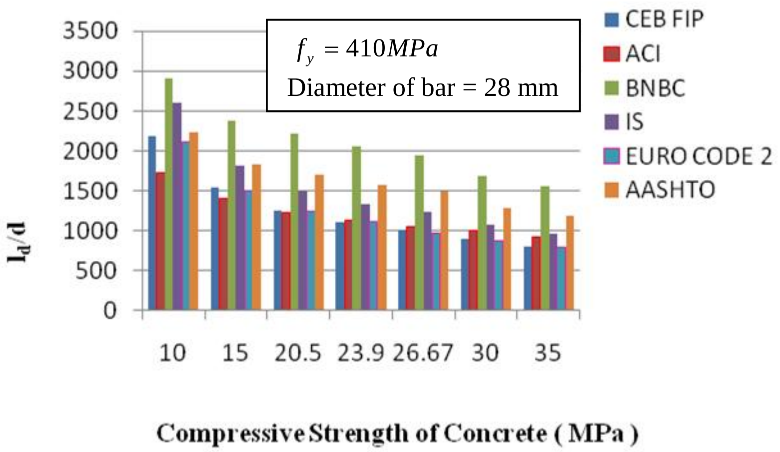


Fig. 30. Tension development length of Reinforcing bar

4. Conclusion

The design codesACI (2002), BNBC (1993), IS (2005), AASHTO (2007), CEB-FIP Model (1990) and EURO Code 2have been reviewed. It has been found that BNBC (1993) recommends the largest value of development lengths for 22 mm diameter and larger diameterbars 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 conclude that, this large modifications 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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