Development length of Tension Bars in Concrete Beams–Revisited

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Abstract

Presently development length of tension bars in reinforced concrete beams, in both codes and researches has a very wide range on the influence of major parameters. Namely, the influence of concrete compressive strength fc affects the development length of beams by varying power values: 1/2, and 1/3. It is well known that the development length of beams is essentially based on empirical or semi empirical formulae. A total of 254 NSC and HSC tested beams available from the literature are studied in this work. These includes 154 beams without transverse reinforcement and 100 with transverse reinforcement and having a different compressive strength ranged from (16.4 – 98) MPa. The best available design method obtained from the literature leads to 43.31% increase in the coefficients of variation COV compared to the proposed design method in this work, which is essentially whose COV of 14.06%.

Key Words: development length, concrete compressive strength, transverse reinforcement

طول تثبيت قضبان الشد في العتبات الخرسانية المسلحة – دراسة شاملة

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الخلاصة

ان طول تثبيت قضبان الشد في العتبات الخرسانية المسلحة في كل من المدونات والبحوث يتأثر وبشكل كبير بالاعتماد على مجموعة من المتغيرات الرئيسية. وأهم هذه المتغيرات الرئيسية هو مقاومة انضغاط الخرسانة (f'_c) حيث تاثيره يختلف باختلاف اس المتغير (power values) والذي يتراوح من ١/٢ الى ١/٣. كذلك من المعروف جدا هو ان حساب طول تثبيت قضبان الشد في العتبات الخرسانية تعتمد على المعادلات التجريبية او شبه التجريبية. تم في هذا البحث جمع ودراسة بيانات عملية مع تفاصيلها لمجموعة من العتبات الخرسانية المسلحة والبالغ عددها ٢٥٤ عتبة من بحوث سابقة. حيث شملت هذه المجموعة على دراسة ١٥٤ عتبة خرسانية غير مسلحة بحديد التسليح العرضي بالاضافة الى دراسة ١٠٠ عتبة خرسانية مسلحة بحديد التسليح العرضي وذات مقاومات انضغاط خرسانية (f'_c) مختلفة تتراوح من (16.4-98) ميغا باسكال. تم ايجاد معادلة لحساب طول تثبيت قضبان الشد في العتبات الخرسانية المسلحة ذات معامل ارتداد (COV) بقيمة (14.06) والذي هو اقل ب (43.31%) من افضل معامل ارتداد لمعادلات المدونات ومعادلات الباحثين السابقين.

1. Introduction

In reinforced concrete beams, flexural compressive forces are resisted by the concrete, while flexural tensile forces mainly are provided by reinforcing bars, so that for this process to exist, there must be a transfer of force, or bond, between concrete and the reinforcing bars. The bond between concrete and reinforcement bars is very important to develop the composite behavior of reinforced concrete beams. Therefore, the development length, is the shortest length of bar in which the bar stress can increase from zero to the yield strength.

2. Mechanism of Bond Transfer

When a deformed reinforcing bar is loaded in tension, friction and adhesion are present and quickly lost the bond-transfer mechanisms, leaving the bond to be transferred by bearing on the deformations of the tension bar as shown in the Fig. (1-a). So, these lead to equal and opposite

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bearing stresses which act on the surrounding concrete, as shown in Fig. (1-b). The forces on the surrounding concrete have radial and longitudinal components as shown in Fig. (1-c) and Fig. (1-d). The latter will cause circumferential tensile stresses which acts on the concrete around the bar. The concrete will split parallel to the tension bar, and the resulting crack will propagate towards the surface of the beam. The splitting cracks follow the reinforcing bars along the side surfaces or bottom of the beam as shown in Fig. (2). These cracks develop and the bond transfer rapidly drops unless reinforcement is provided to resist the opening of splitting crack.

3. Research Significance

Several codes and researches that estimate the development length of tension bars are investigated in this study. A large database of 254 (174 NSC and 80 HSC) tests is used in this work: 154 without transverse reinforcement and 100 with transverse reinforcement. It is found that the power of concrete compressive strength effect on this work leads to a significantly improved COV for all available 254 tests from the literature. In fact, the proposed equation leads to a COV of 14.06% compared with the best value of 20.15% from the available literature.

4. Experimental Investigations

The 254 development and splice length of tension bars tests have been taken from the literature (Chinn et al., 1955 – Darwin et al., 1996). Table (1) indicates the range of variables in all 254 tests.

Table (1) Range of Variables

Variable	Unit	Range
f'_c	N/mm^2	16.4 - 98
b	mm	91.948 - 465.83
d_b	mm	9.525 - 35.814
A_{tr}	mm^2	0-134
d_b/l	-	0.0156 – 0.2
$A_{tr}/S.d_b$	-	0 – 0.0981

where:

f'_c = cylinder compressive strength of concrete, N/mm^2

b = width of concrete section, mm

d_b = diameter of anchored bar, mm

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

S = center to center spacing of transverse reinforcement, mm

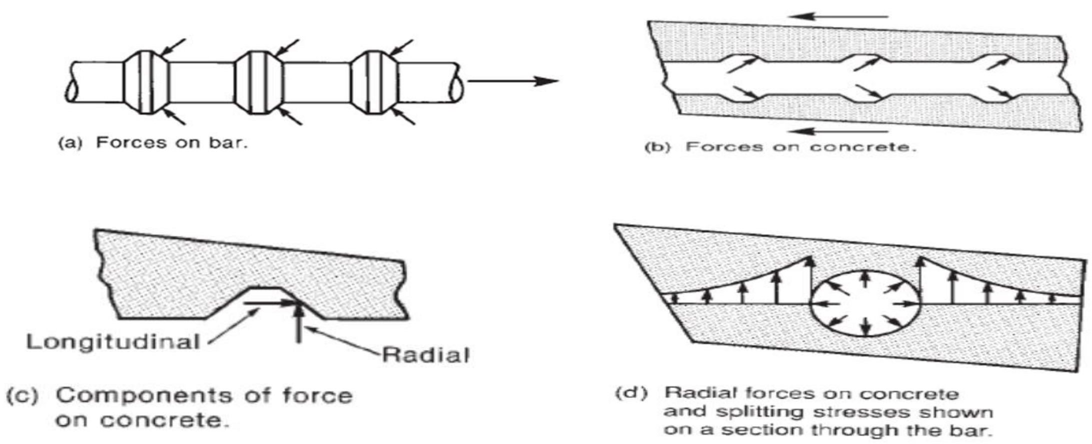

Fig. 1 Bond transfer mechanism (Wight et al., 2009)

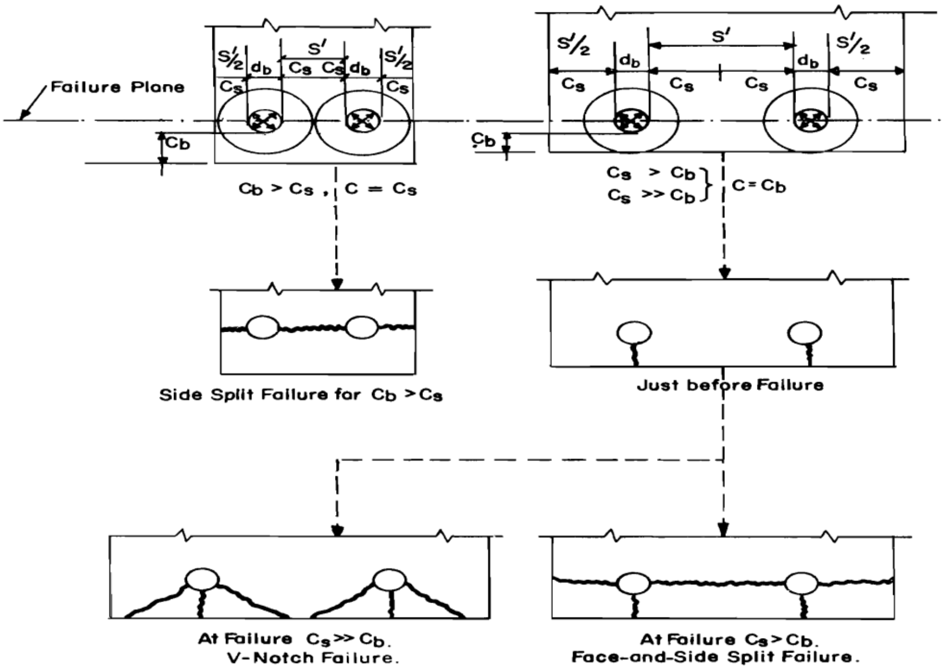

Fig. 2 Failure patterns of deformed bars (Orangun et al., 1975)

5. Some Codes Estimations of Tension Bars Development Length

i. BS 8110: 1997(BS 8110, 1997) provides the following equation for ultimate anchorage bond stress design values:

$$u = \beta\sqrt{f_{cu}} \tag{1}$$

where:

β = 0.28 for plain bars in tension

β = 0.4 for type 1 deformed bars in tension

β = 0.5 for type 2 deformed bars in tension

f_{cu} = cube compressive strength of concrete $\leq$ (40 MPa), $f_{cu} = f'_c / 0.82$

ii. ACI 318M-14 (ACI Committee 318M-14, 2014) development length equations for deformed tensioned bars are based on the following equations:

a) For bar diameter $\leq$ 19 mm

$$l_d = \frac{f_y \psi_t \psi_e}{2.1\lambda\sqrt{f'_c}} d_b \tag{2}$$

$$u = \frac{0.525\lambda\sqrt{f'_c}}{\psi_t \psi_e} \tag{3}$$

b) For bar diameter $\geq$ 22 mm

$$l_d = \frac{f_y \psi_t \psi_e}{1.7 \lambda \sqrt{f_c'}} d_b \tag{4}$$

$$u = \frac{0.425 \lambda \sqrt{f_c'}}{\psi_t \psi_e} \tag{5}$$

where:

f_c' = concrete compressive strength ≤ (68.89 MPa)

ψ_t = reinforcement location factor

ψ_e = coating factor

ψ_s = reinforcement size factor

λ = lightweight aggregate concrete factor

l_d = development or splice length, and

d_b = bar diameter

6. Existing Researches Estimations of Tension Bars Development Length

i. Orangun et al. (Orangun et al., 1975) developed an empirical equation for calculating development length for splices and anchorage of deformed bars. It is based on a non-linear regression analysis of beams test results with lap splices:

$$u = \sqrt{f_c'} \left(0.1 + 0.25 \frac{c}{d_b} + 4.15 \frac{d_b}{l_d} + \frac{A_{tr} f_{yt}}{41.52 \ S d_b} \right) \tag{6}$$

Where:

$$\frac{A_{tr} f_{yt}}{41.52 \ S d_b} \le 0.25 \quad \text{and} \quad \frac{c}{d_b} \le 2.5$$

C = smaller of minimum concrete cover or ½ of the clear spacing between bars, l_d = development or splice length, and d_b=bar diameter

ii. Zsutty (Zsutty, 1985) presented a general form of predication equation for the strength of reinforcing bar development, lapped bar splices, and hocked bar anchorages in reinforced concrete:

$$u = 5.07 \, f_c'^{1/3} \left(\frac{d_b}{l} \right)^{1/2} \left(\frac{c}{d_b} + 2r \right)^{1/2} \tag{7}$$

Where:

$$r = 100 \frac{A_{tr}}{S d_b} \quad \text{and} \quad \left(\frac{c}{d_b} + 2r \right) \le 3$$

iii. Kemp and Wilhelm (Kemp et al., 1979) indicated that the bond splitting is a complicated phenomenon involving interactions with shear and flexure and influenced by other secondary effects. They proposed the following equation for ultimate bond strength:

$$u = \sqrt{f_c'}\left(0.546 + 0.241\frac{c}{d_b}\right) + 0.191\left(\frac{A_{tr} f_{yt}}{Sd_b}\right) \tag{8}$$

Where:

$$\frac{A_{tr} f_{yt}}{Sd_b} \le 12.4 \quad \text{and} \quad \frac{c}{d_b} \le 3$$

iv. Al-Dabbous (Al-Dabbous, 1993) developed an empirical equation for calculating bond stress of deformed bars. It is based on a regression analysis of test results of beams:

$$u = 3\left(\frac{f_c' \ c^2}{d_b l_d}\right)^{1/3} + \left(\frac{A_{tr} f_{yt}}{8 \ Sd_b}\right) \tag{9}$$

Where:

$$\left(\frac{A_{tr} f_{yt}}{8 \ Sd_b}\right) \le 1.3$$

7. Evaluation of Experimental Results

From the methods used in codes and researches proposals, a comparison was made for the ratio of (U_{exp}/U_{cal}), where:

U_{exp} = bond stress of tested beam

U_{cal} = calculated bond stress based on different methods of prediction

Table (2) gives a comparison of the results of the different methods, based on the ratio of (U_{exp}/U_{cal}). Regression analysis was performed on all of 254 tests obtained from the literature. This leads to the following equation:

$$u = f_c'^{\,0.35}\left(0.5 + 0.2\frac{c}{d_b} + 7\frac{d_b}{l_d} + \frac{A_{tr} f_{yt}}{40Sd_b}\right) \tag{10}$$

Where:

$$\frac{A_{tr} f_{yt}}{40Sd_b} \le 0.26 \quad \text{and} \quad \frac{c}{d_b} \le 2.5$$

In testing all of 254 results, this lead to a COV of 14.06% where equation (10) was applied. Therefore, this equation is recommended in this work. Solving Eq.(10) for l_d which lead to the following equation:

$$l_d = \frac{d_b\left[f_y - 28 f_c'^{\,0.35}\right]}{4 f_c'^{\,0.35}\left(0.5 + 0.2\frac{c}{d_b} + \frac{A_{tr} f_{yt}}{40Sd_b}\right)} \tag{11}$$

The last column in Table (2) indicates the various ratios of (U_{exp}/U_{cal}) for the proposed method Eq. (10). As can be seen from this table, the COV values range from (20.15% - 33.66%). The proposed method has improved significantly the COV to a value of 14.06%.

Table (2) Comparison of the ratio of (U_{exp}/U_{cal}) for all 254 beam tests

Detail	BS	ACI	Orangun et al.	Zsutty	Kemp et al.	Al-Dabbous	Proposed method
Equation used	1	3&5	6	7	8	9	10
Mean	2.11	1.955	1.248	1.189	0.917	1.173	1.232
Standard deviation	0.71	0.57	0.251	0.252	0.214	0.302	0.173
COV%	33.66	29.15	20.15	21.23	23.36	25.77	14.06
Min. ratio	0.965	0.774	0.792	0.711	0.484	0.698	0.802
Max. ratio	4.59	4.227	2.337	2.491	2.046	2.86	1.691
Range (max/min)	4.76	5.45	2.94	3.5	4.22	4.095	2.108
Number < 1	1	4	35	55	177	91	10

Number <1 indicates the number of specimens (out of 254) for which ($U_{exp}<U_{cal}$)

8. Discussion

Using data bank listed in the literature (Chinn et al., 1955 – Darwin et al., 1996) a regression analysis was made and various parameters were investigated with the aim of obtaining a simple equation with small coefficient of variation (COV). This equation is intended for application to NSC and HSC without loss of accuracy.

The test results of concrete beams indicate that the bond stress (u), for tension bars in concrete beams depends on some parameters. These parameters are (c, d_b, l_d, f_c), which were used in many equations and can be arranged to form dimensionless parameters such as (c/d_b, d_b/l).

Figures 3-6 shows the trend of the influence of major parameters on the predication of bond stress for tension bars in concrete beams of five methods: Orangun et al., Zsutty, Kemp et al., Al-Dabbus, and the proposed method. Fig.3 shows the effect of concrete compressive strength (f'_c) ranged from (16.4 – 98) MPa on the predicted bond strength. Fig.4 shows the effect of (c/d_b) on the predicted bond strength. Also, Fig.5 shows the effect of (d_b/l) ranged from (0.0156 – 0.20) on the predicted bond strength, and Fig.6 shows the effect of ($A_{tr}/S.d_b$) ranged from (0 – 0.0981) on the predicated bond strength.

The BS-97 method is very conservative and shows a highest COV among other existing methods, which is (33.66%). It can be seen that this method did not taken into account the transverse reinforcement and the ratio of (c/d_b) as a direct parameters the concrete compressive strength f_{cu} is limited to (40MPa). ACI method also, shows a high COV of (29.15%) due to the limitation of f'_c, which is limited by (69 MPa). From Table (2) it can be seen that Orangun et al equation is the best among all existing methods, because it gives lower COV of (20.15%). Zsutty equation did not take into account the yield strength of transverse reinforcement (f_{yt}) and used the parameter of ($A_{tr}.f_{yt}/S.d_b$) as transverse contributing with (f_c) of power (1/2).

Research indicates that beyond a certain limit, transverse reinforcement will no longer be effective and an upper limit is needed (Orangun et al., 1975, Azizinamini et al., 1993, Al-Dabbous, 1993, Darwin et al., 1996, and Kemp et al., 1979). However the proposed method gives that the upper limit of ($A_{tr}f_{yt}/40Sd_b$) is (0.26).

In addition, the strength of bar increases as the concrete cover to bar diameter ratio increases. Also, it is obvious that at some concrete cover to diameter ratio the mode of failure will not involve splitting. For large values of (c/d_b), direct pullout could occur with the bar deformation, therefore the limitation of (c/d_b) is (2.5).

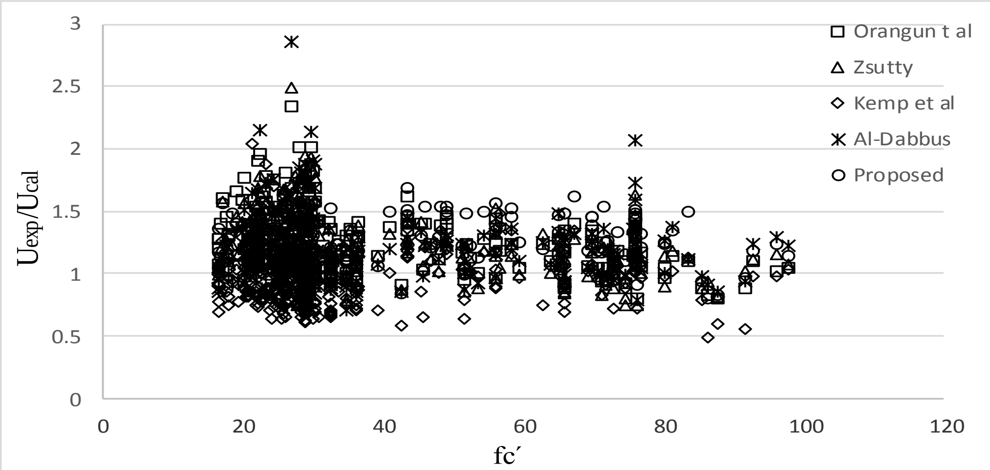

Fig.3 Influence of concrete compressive strength fc on the ratio of U_{exp}/U_{cal}

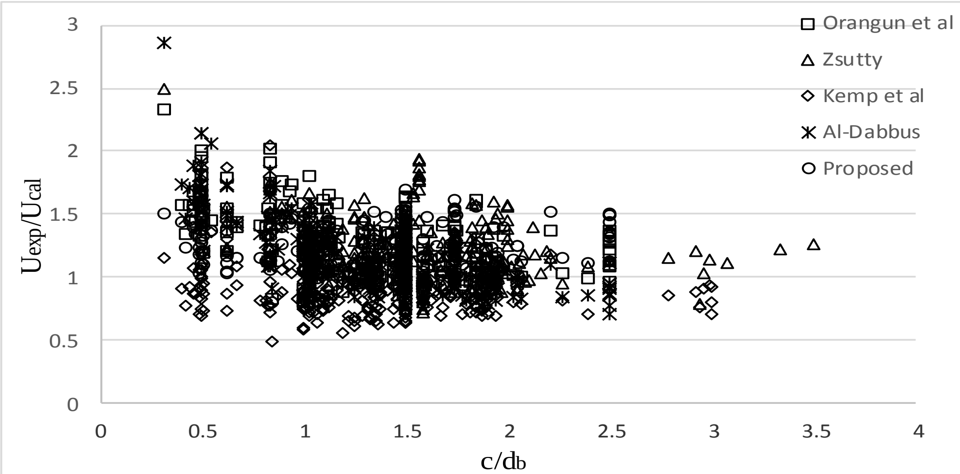

Fig.4 Influence of c/d_b on the ratio of U_{exp}/U_{cal}

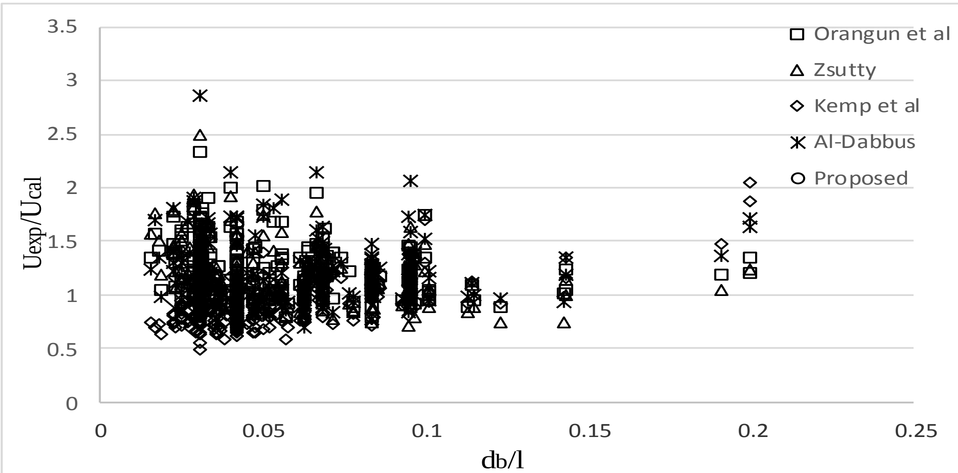

Fig.5 Influence of d_b/l on the ratio of U_{exp}/U_{cal}

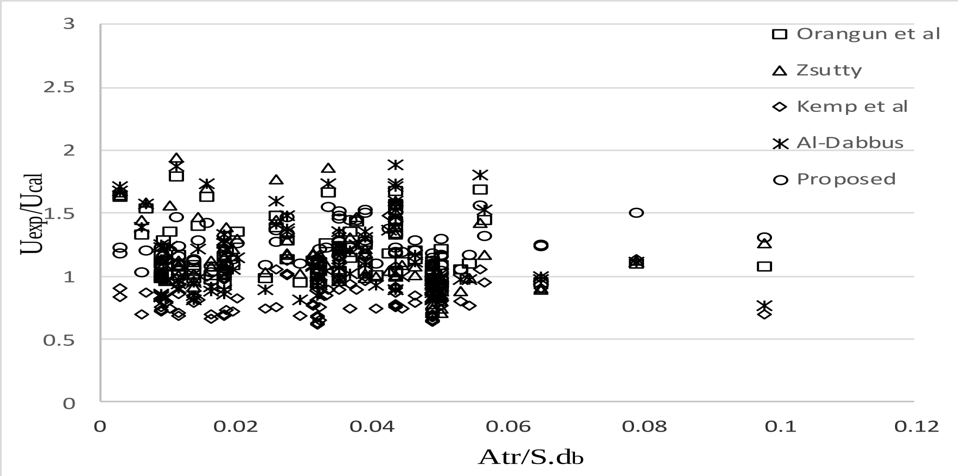

Fig.6 Influence of $A_{tr}/S.d_b$ on the ratio of U_{exp}/U_{cal}

9. Conclusions

Based on 254 tests of development tension bars obtained from the literature, the following conclusions are made:

1. Regression analysis of all tests indicates that the proposed Eq. (10) has lower COV (14.06 %) than other existing proposed methods with mean value of U_{exp}/U_{cal} of (1.23).
2. Orangun et al. empirical equation gives the lowest COV of all existing methods (20.15%), and the proposed method significantly improved the COV for bond stress predication.
3. From the codes methods, the BS 97 gives highest COV of (33.66%). This is because this method did not take into account the transverse reinforcement and the concrete compressive strength f_{cu} is limited to (40MPa).
4. The proposed method simulates that the parameter of ($A_{tr}f_{yt}/40Sd_b$) in Eq.(10) is limited to (0.26), and the transverse reinforcement will be no longer effective beyond this limit.
5. Using the concrete compressive strength (fc) of power (0.35) for bond stress gives a better representation of bond than the power of (1/2) or (1/3).

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