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Proposed Design Provisions for Development Length Considering Effects of Confinement

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Abstract: Confinement is major contribution to bond strength between reinforcement steel bars and concrete. Cover thickness, bar spacing and transverse reinforcement are the key confinement factors of current provisions for the development and splices of reinforcement. However, current provisions are still too complicated to determine the values of the confinement, which need to be well delineated in the process of design. In this study, an experimental work using beam-end and splice specimens was performed to examine the effect of concrete cover on bond strength. The results of this experiment and previously available data are analyzed to identify the effects of confinement on bond strength. From this reevaluation, new provisions for the development and splices of reinforcement are proposed. The provisions suggest some limitations in the confinement index. The new provisions will allow the engineers to use a simple and yet satisfactory and appropriate method or a precise approach for design to determine the values of confinement on the calculation of development and splice lengths.

Keywords: bond, development length, confinement, concrete cover, transverse reinforcement.

1. Introduction

The provisions that are proposed for Chapter 12 of the ACI Building Code[1] have been based, in part, on a statistical analysis carried out 30 years ago[2] and on recommendations based on that analysis provided by ACI Committee 408. Current design standard for development and splice lengths in Korea (Architectural Institute of Korea, Korea Concrete Institute) is typically based on ACI 318 Building Code Requirement for Structural Concrete. In the 1989 (ACI 318-89) code, major changes were made in the procedures for calculating development lengths. In the 1995 and 2005 codes, the provisions for determining the development lengths have been continuously revised with a view of formulating a more "user friendly" format, while maintaining general agreement with research results and professional judgments. However, many of those applying the 2005 provisions in design, detailing and fabrication in Korea found them to be overly complex in application.

The major influencing factors to bond strength between reinforcing bars and concrete can be largely classified into 1) confinement, ie. the structural characteristics of concrete cover and transverse reinforcing steel and 2) material characteristics of the interface between the steel bars and concrete.[3,4] When cover distance or bar spacing is insufficient to resist lateral concrete tension resulting from the wedging action of the bar deformations, the concrete along the bar splits. The transverse reinforcement provided by stirrups improves the resistance of tensile bars to splitting failure. In the 2005 ACI Code, the required development length for deformed bars in tension is based on a basic equation that includes all the influences of confinement and thus appears highly complex because of its inclusiveness. The ACI Code also includes simplified equations that can be used for most cases in ordinary design, provided that some restrictions are accepted on bar spacing, cover values, and minimum transverse reinforcement.

This study carried out an experiment on bond strength and analyzed the behavior of confinement to delineate the influence of such confinement, using existing experimental data. The results are then analyzed and compared to current design standards to propose an improved design format and procedures for calculating development lengths in reinforced concrete structures.

2. Design standard for development and splice length

The code 12.2.2 of ACI 318 established in 2005 is the simple procedure for calculating the development length, l_d, depending on the size of the bar and transverse confinement (spacing, cover, or stirrups). In this simpler development length equation, there is no need to compute the factors of c_b (spacing or cover dimension) or K_{tr}(transverse reinforcement index) as indicated in the following Eq. (1). However, this design method has its shortcomings in that it requires a discreet judge of the appropriate case to apply and it often returns higher values than those reported in the field.

The Code 12.2.3 is a time-consuming but more accurate computational method for the c_b and K_{tr} factors described above. The development length is determined by the strength of the materials, location of the reinforcing bars, coating, reinforcement size, light-weight

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concrete, and confinement and is shown in Eq. (1) below.

$$l_d = \frac{9}{10}\frac{f_y}{\sqrt{f'_{ck}}}\frac{\psi_t\psi_e\psi_s\lambda}{\left(\frac{c_b+K_{tr}}{d_b}\right)}d_b,\ \text{MPa} \qquad (1)$$

Where,

ψ_t = *reinforcement location factor,*

ψ_e = *coating factor,*

ψ_s = *reinforcement size factor,*

λ = *lightweight aggregate concrete factor.*

In which, the term, $(c_b + K_{tr}) / d_b$ should be 2.5 or less. Where, c_b = smaller of (a) the distance from center of the bars or wires to nearest concrete surface, and (b) one-half the center-to-center spacing of the bars or wires being developed.

When the cover or spacing is small, a splitting failure can occur. In this case, transverse bars across the plane of splitting can be added to increase the confinement and to restrain splitting crack. In this perspective, K_{tr}, the transverse reinforcement index, can be defined as in the following equation.

$$K_{tr} = \frac{A_{tr}f_{yt}}{10sn} \qquad (2)$$

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, MPa.

s = maximum center-to-center spacing of transverse reinforcement within l_d, mm.

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

The code permits to set K_{tr} = 0 as a design simplification even if transverse reinforcement is present. The logic behind this simplified design method is that having to calculate K_{tr} all the time may be a waste of time and expense even if it means a slight increase in the design of development length.

From the above discussion, a proper reevaluation of c_b (spacing or cover dimension) and K_{tr} (transverse reinforcement index) may be in order, and a more practical computation equation for the development and splice length should be proposed based on the results of such reevaluation.

3. Experiment

This research experimented with the change in concrete cover thickness as the main variable for the influence of confinement on bond strength in an effort to evaluate the bond performance between the concrete and reinforcing steel bars. The experiment varied the clear cover thickness as the direct variable of splitting failure of the concrete into 0.5, 1.0, 2.0, 3.0d_b (nominal diameter of bar) to see the effect of the change on the splitting bond failure.

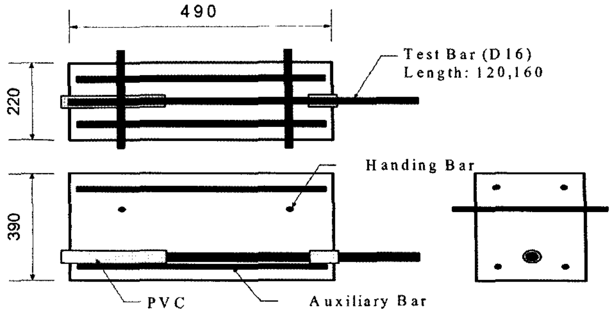

Fig. 1 Beam end specimen(unit:mm).

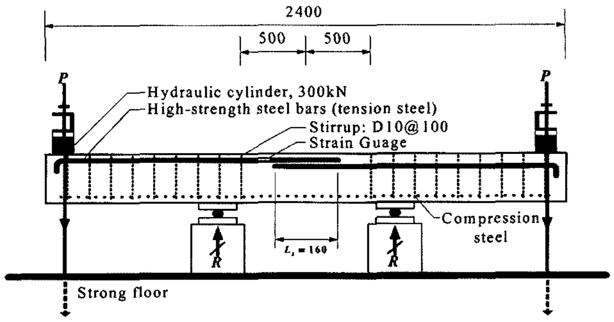

Fig. 2 Splice test specimen(unit:mm).

The bond strength experiment was carried out on beam end specimens and splice test specimens. The test specimens were grouped into four. The first and second group consisted of beam end specimens. The splice specimens were made and grouped as the third and fourth group for the experiment[5,6] (Figs. 1, 2).

1st group : beam end specimens of design strength of 34.3 MPa.

2nd group : beam end specimens of design strength of 58.8 MPa.

3rd group : splice specimens of design strength of 34.3 MPa.

4th group : splice specimens of design strength of 58.8 MPa.

Table 1 shows the experimental values, predicted values by a prediction equation,[2] and values computed by ACI standard equations for the bond strength.

4. Influence of concrete cover thickness

The results of experiment on beam end specimens and splice specimens for each cover thickness are compared with Orangun equation (OJB equation)[2] and ACI equation. In addition to the

Table 1 Bond strength computed by tests, OJB equation and ACI.

Specimens	d_b(mm)	A_b(mm^2)	C_b/d_b	l_d(mm)	test1*	test2**	OJBEq.	ACI 12.2.3	ACI 12.2.2
Beam end	16	199	1	120	7134	6377	4655	2096	2096
			1.5	120	7619	7138	5406	3144	3144
			2.5	120	9689	7495	6908	5240	3144
			3.5	120	10870	8932	8410	7336	3144
Splice			1	160	8157	7756	5106	2795	2795
			1.5	160	9197	9263	6107	4192	4192
			1.9	160	10465	10315	6908	5310	4192

*test1: Beam end specimen, f_{ck}' = 36.8 MPa, Splice specimen, f_{ck}' = 35.3 MPa

** test2: Beam end specimen, f_{ck}' = 63.7 MPa, Splice specimen, f_{ck}' = 59.1 MPa

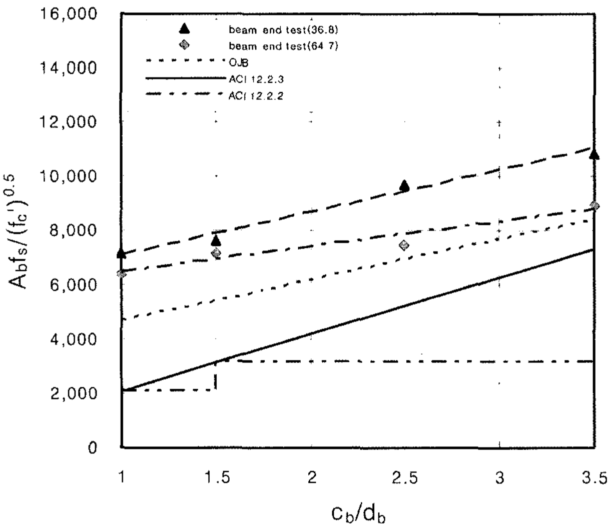

Fig. 3 Bond forces of beam end specimens versus ratio of cover thickness to bar diameter.

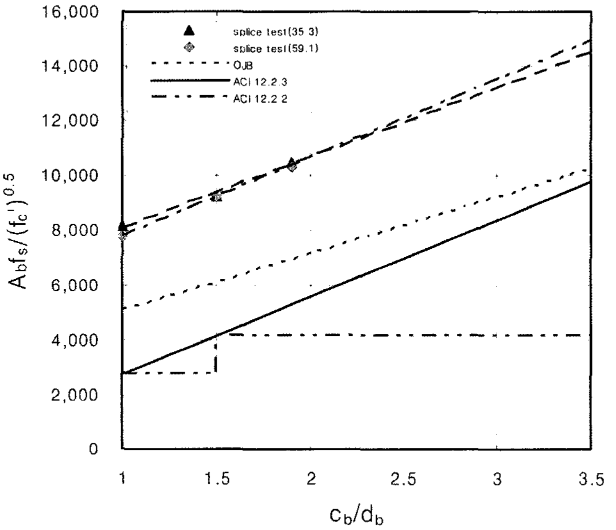

Fig. 4 Bond forces of splice specimens versus ratio of cover thickness to bar diameter.

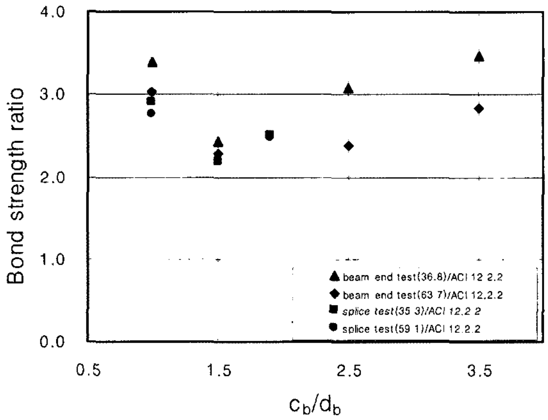

Fig. 5 Bond strength ratio of test results and ACI 12.2.2 equation versus ratio of cover thickness to bar diameter.

OJB equation, ACI standard equations of 12.2.3 and 12.2.2 were applied.

The formula for converting the OJB equation and ACI equation in terms of the load (SI unit) follows below.[7]

$$\frac{A_bf_s}{\sqrt{f_{ck}'}} = 0.249\pi l_d(C + 0.4d_b + K_{tr}) + 16.6A_b,\ \text{MPa} \tag{3}$$

$$\frac{A_bf_s}{\sqrt{f_{ck}'}} = 0.278\frac{\pi(c_b + K_{tr})}{\psi_t\psi_e\psi_s\lambda}l_d,\ \text{MPa} \tag{4}$$

Where, C = minimum cover thickness

Figs. 3 and 4 depict the relationship of cover thickness and bond force and show that, as the cover thickness increases, the bond force increases. The experimental values and the values computed by OJB equation exhibit more reasonable behavior than those of ACI equations (both more exact and simpler equations). The experimental values show that the bond forces between 1.0 and $1.5d_b$ were not significantly smaller than the bond force at $2.0d_b$. However, the ACI equations underestimated the bond force at $1.0d_b$ compared to the force at $2.0d_b$. The ACI equation 12.2.3 overestimates the bond force above $2.0d_b$, meaning that the development length predicted by ACI equations may be significantly shorter.

This troublesome results were analyzed in a slightly different angle. The experimental values of bond force were divided by the bond force predicted by each standard equation of ACI. This ratio would be known as bond strength ratio and has the implication of relative safety. Figs. 5 and 6 show such ratio. In case of ACI equation 12.2.2 (the simpler version), the bond strength ratio has the value around 3.0 as shown in Fig. 5. Fig. 6 show that the ACI equation 12.2.3 (the more exact formula) predicted the bond strength ratio of the cover thickness above $2.0d_b$ was below 2.0, meaning that the ACI equation 12.2.3 overestimates the bond force above $2.0d_b$ as explained above. Additionally, the bond strength ratio was above 3.0 when the cover thickness was below $1.0d_b$, meaning that the relative safety was rather higher and that the standard equations underestimated the bond strength. Thus, it is found that the minimum and maximum value for the cover thickness ratio, C_b/d_b, should be 1 and 2, respectively.

5. Influence of transverse reinforcement

In order to examine the influence of transverse reinforcement bars, the OJB equation and ACI 318-05 12.2.3 equation were compared as to their predictive power against existing research data. For this analysis, the researchers used the data on transverse reinforcement bars among the experimental data of Rezansoff et al. (1993)[8] for the reevaluation of ACI 318 standard equation on spliced bars and the data on transverse reinforcement bars among Darwin et al.'s (1996)[9] paper.

To obtain the bond strength of transverse bars for the analysis of the effect of transverse bars, the cover thickness was subtracted from the values of experimental results in bond strength equation. When the term of cover thickness in OJB equation is subtracted, the bond strength of transverse reinforcement bars can be expressed as in the following equation.

$$\frac{A_bf_s'}{\sqrt{f_{ck}'}} = \frac{A_bf_s}{\sqrt{f_{ck}'}} - 0.249\pi l_d(C + 0.4d_b + K_{tr}) + 16.6A_b \tag{5}$$

In addition, when the terms of cover thickness in ACI equation is subtracted, the bond strength of transverse reinforcement bars is

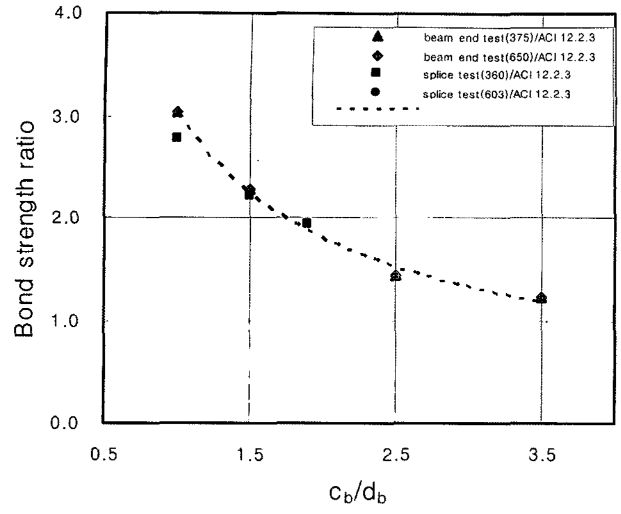

Fig. 6 Bond strength ratio of test results and ACI 12.2.3 equation. versus ratio of cover thickness to bar diameter.

shown as in the following equation.

$$\frac{A_b f_s'}{\sqrt{f_{ck}'}} = \frac{A_b f_s}{\sqrt{f_{ck}'}} - 0.278\frac{\pi \cdot c_b \cdot l_d}{\psi_t \psi_e \psi_s \lambda} \qquad (6)$$

Table 2 shows the analysis results of previous experimental data. Figs. 7 and 8 show the relationship between bond strength of transverse reinforcement in relation to the diameter of the reinforcement bar. As shown in the figures, the bond strength increases as the transverse reinforcement bar increases. Another prediction equation was derived by subtracting the effect of cover thickness on bond strength from he experimental values (bond strength determined by cover thickness and transverse reinforcement), and the result is shown in the figures. It can be seen that the dispersion of data is rather widespread and that the increase in bond strength is rather slight even if some K_{tr}, the transverse reinforcement index, are large.

As shown in the Figs. 7 and 8, since the ACI equation excluded a constant term ($16.6A_b$) in consideration of the safety factor, the

Table 2 Bond strength of transverse reinforcement from previous test data.

Label	n	l_d	d_b	A_b (mm)	c_b (mm)	f'_c (MPa)	A_{tr} (mm)	f_{yt} (MPa)	s (mm)	f_s (MPa)	K_{tr}	Test	OJB*	ACI**	ACI***	K_{tr}**** ratio
		(mm)														
8C0	3	711	25	507	24.5	26.3	71	482	88.9	359	25.7	35470	7865	12494	15928	0.78
8C0	2	610	25	507	35.7	28.3	71	482	152.4	320	22.4	30505	282	4826	11957	0.40
8C0	2	406	25	507	34.1	29.1	71	445	203.2	253	15.5	23766	1344	7243	5510	1.31
8N0	3	610	25	507	11.5	26.4	127	584	76.2	480	64.8	47387	28711	34601	34547	1.00
8N0	2	610	25	507	46.2	29.1	71	445	304.8	381	10.4	35755	521	4482	5520	0.81
8N0	2	660	25	507	45.7	29.3	71	445	330.2	406	9.6	37994	820	4446	5513	0.81
8N0	2	508	25	507	47.6	29.3	127	584	101.6	427	73.0	40015	8709	13350	32366	0.41
8N0	2	457	25	507	46.8	30.2	127	584	114.3	427	64.8	39394	10673	15726	25882	0.61
5N0	4	254	16	199	13.2	28.4	127	584	127	313	29.2	11691	4493	5812	8092	0.72
5N0	3	254	16	199	26.4	28.4	71	445	254	334	8.3	12488	2668	2950	2298	1.28
5N0	3	305	16	199	32.2	28.3	71	445	304.8	387	6.9	14457	1944	1072	2300	0.47
5N0	2	305	16	199	30.7	28.9	71	445	152.4	415	20.7	15334	3179	2448	6899	0.35
11N0	2	686	35	957	37.3	36.2	127	584	76.2	433	97.3	68955	25540	36123	58276	0.62
11N0	2	1016	35	957	38.5	36.2	71	445	101.6	428	31.1	68056	10444	18365	27580	0.67
11B0	2	1016	35	957	46.8	35.7	71	445	254	422	12.4	67540	3331	10484	11032	0.95
11B0	2	965	35	957	47.3	32.5	71	445	120.6	455	26.2	76377	14217	21764	22068	0.99
11B0	2	762	35	957	48.4	32.5	127	584	108.9	405	68.1	67972	14891	24115	45295	0.53
11B0	2	1016	35	957	47.5	32.4	71	445	169.4	457	18.6	76865	12100	19188	16541	1.16
1a	2	749	25	507	25.8	27.3	32	440	124.9	488	11.3	47328	17936	22274	7368	3.02
3a	3	749	25	507	25.4	27.3	32	450	124.9	454	7.7	44030	14873	19238	5021	3.83
4a	3	889	30	693	29.5	27.8	32	440	225	409	4.2	53743	13379	19192	3236	5.93
1b	2	749	25	507	25.8	26.2	32	440	124.9	462	11.3	45745	16353	20691	7368	2.81
3b	3	749	25	507	25.4	26.2	32	440	124.9	411	7.5	40693	11535	15900	4912	3.24
4b	3	1125	30	693	29.5	27.8	32	440	225	452	4.2	59387	11361	15664	4095	3.82
6	3	560	25	507	25.4	24.9	49	580	70.1	353	27.0	35780	11856	17244	13207	1.31
7	3	375	25	507	25.4	24.9	199	470	93.7	324	66.5	32837	14037	20425	21775	0.94
8	3	300	25	507	37.9	24.9	199	470	100	239	62.3	24226	4569	11021	16323	0.68
9	3	850	30	693	29.5	26.8	103	475	85	488	38.3	65291	26194	32256	28460	1.13
10	3	560	30	693	29.5	28.2	199	470	80	464	77.9	60551	30867	38786	38086	1.02

C : Clear cover thickness

n : Number of spliced bars

*Bond strength of transverse reinforcement, Eq. (5)

**Bond strength of transverse reinforcement, Eq. (6)

***Bond strength of K_{tr} by ACI provision, $0.278\frac{\pi K_{tr} l_d}{\psi_t \psi_e \psi_s \lambda}$

****Ratio of bond strength of K_{tr} by test results to bond strength of K_{tr} by ACI provision (relative safety)

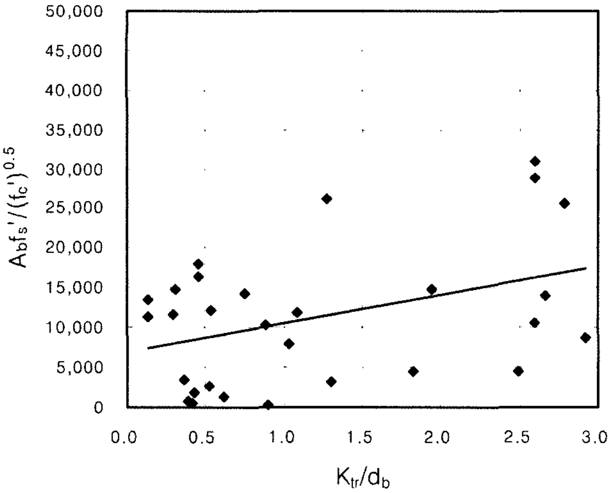

Fig. 7 Bond strength of transverse reinforcement versus K_{tr}/d_b by Orangun equation.

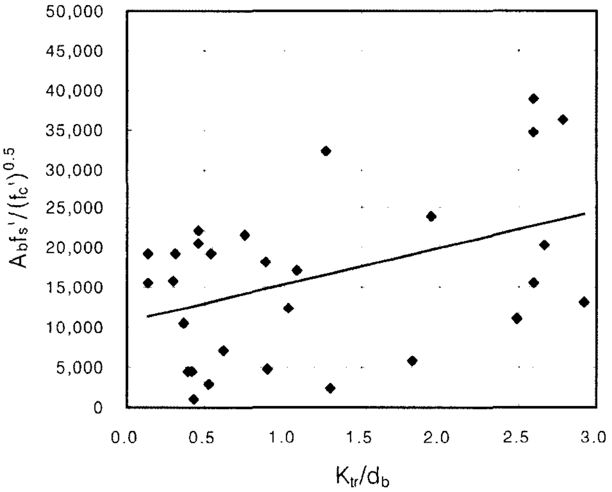

Fig. 8 Bond strength of transverse reinforcement versus K_{tr}/d_b by ACI 12.2.3.

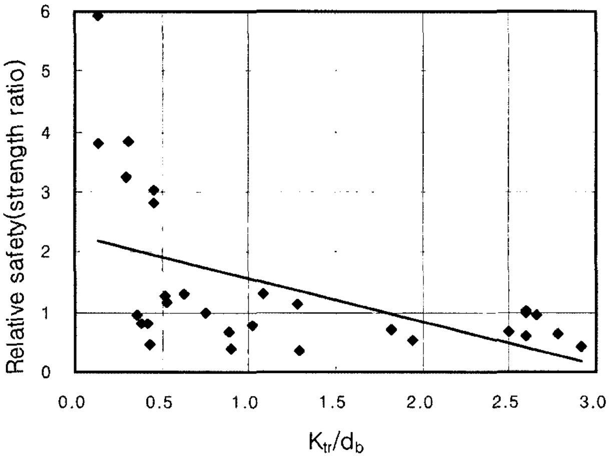

Fig. 9 Bond strength ratio of test results to ACI 12.2.3 equation. versus K_{tr}/d_b.

values of ACI equation pertaining to the bond strength due to K_{tr} show higher values than those of OJB equation.

Fig. 9 shows the relative safety ratio which is the bond strength ratio obtained by dividing the bond strength of K_{tr}, ie. $A_b\, f_s'/\sqrt{f_s'}$, computed from the experimental result, by the bond strength of K_{tr} based on the current ACI standard, ie., $0.278\pi\, l_d K_{tr}/\ \psi_t \psi_e \psi_s \lambda$.

As shown in the Fig. 9, the relative safety (bond strength ratio) takes the value around 2.0 when the value of K_{tr}/d_b is rather low around 0.5. However, when K_{tr}/d_b exceeds 1.0, the bond strength ratio drops rapidly below 1.75. Thus, when K_{tr}/d_b is low and high, underestimation and overestimation, respectively, become the problem. When all the minimum requirements are met, the value of 0.5 for K_{tr}/d_b can be proposed as the minimum value, and this proposition affirms the first item of the design method of current ACI standard 12.2.2 (simpler) equation. In addition, the value of 1.0 can be proposed as the maximum value for K_{tr}/d_b.

The current standard is that 2.5 is the maximum value for $(c_b + K_{tr})/d_b$, but there is no minimum value specified for $(c_b + K_{tr})/d_b$. In section 4 of this paper, the minimum and maximum value for c_b/d_b of 1.0 and 2.0, respectively, has been proposed. Considering all these findings, the minimum and maximum values for c_b/d_b, K_{tr}/d_b, $(c_b + K_{tr})/d_b$ can be proposed as follows.

$$1.0 \le \frac{c_b}{d_b} \le 2.0 \tag{7}$$

$$1.5 \le \frac{K_{tr}}{d_b} \le 1.0 \tag{8}$$

$$1.0 \le \frac{(c_b + K_{tr})}{d_b} \le 2.5 \tag{9}$$

6. Proposed design provisions for development length

The methods for computing the development length have been specified by ACI 318-05 Code. The first method is a simpler method to select the range of $(c_b + K_{tr})/d_b$ before computing the development length in general cases. For the cases of transverse bars like stirrups and cases of ensuring main bar space and cover thickness among others, the value of $(c_b + K_{tr})/d_b$ is set to 1.5, otherwise the value is 1.0 in computation of the development length. To be more specific, the value of 1.5 is used for $(c_b + K_{tr})/d_b$ when 1) clear spacing of 2.0 d_b and clear cover 1.0 d_b for the spliced and development bars and guaranteed or 2) clear spacing of 1.0 d_b and clear cover of 1.0 d_b and stirrups or tie through l_d not less than the code are ensured. Otherwise, the $(c_b + K_{tr})/d_b$ is set to 1.0.

The second method is to compute the actual value for $(c_b + K_{tr})/d_b$ in the determination of development length. From each variable of cover thickness, spacing, and transverse reinforcement bars, $(c_b + K_{tr})/d_b$ is computed, and this value can be used in more accurate computation of development length, especially for the risky section or places in need of a more careful analysis. In this case, however, the effect of K_{tr} can be ignored in the computation of development length for simplicity.

The second method can design the development length to be shorter than the first method, and the limit, that $(c_b + K_{tr})/d_b$ should be at or below 2.5, implies that the proposed maximum value of 2.5 is included to safeguard against pullout type failures.

Any one of the two methods discussed so far can be used to compute the development length. However, the first method has its shortcoming in that it is hard to determine the appropriate case to apply. The second method may not need to compute K_{tr}, but it is not easy when the values of c_b and K_{tr} must be computed. In addition, when K_{tr} is set to zero in case of no transverse reinforcement bars, the maximum value of 2.5 set for c_b/d_b is somewhat in the unsafe side.

This study sets aside the two complex methods of the above and combines them into one equation to propose the following design provisions for the development length.

The development length, of deformed bars and wires in tension can be computed by the following equation.

$$l_d = \frac{9}{10}\frac{f_y}{\sqrt{f_{ck}'}}\frac{\psi_t\psi_e\psi_s\lambda}{\left(\frac{c_b+K_{tr}}{d_b}\right)}d_b, \text{MPa} \qquad (10)$$

Where, $1.0 \le \frac{(c_b+K_{tr})}{d_b} \le 2.5$

When transverse stirrups or ties satisfy the minimum requirement, set $K_{tr} = 0.5d_b$. Otherwise, K_{tr} can be set to zero.

Additionally, when $K_{tr} = 0$, $c_b/d_b \le 2.0$.

From the above stipulations, the designer may compute the development length discretionarily in the following three steps.

The first step is to assume the value of 1.0 for $(c_b+K_{tr})/d_b$ in determination of the development length. This method generally satisfies the design requirements such as the minimum spacing of the steel but does not satisfy the other requirements regarding transverse reinforcement bars. It is the most rudimentary computational step.

The second step is to assume the value of 0.5 d_b for K_{tr} to compute the term, $(c_b+K_{tr})/d_b$, easily. The requirements regarding transverse reinforcement bars is satisfied and is adequately considered to design a short development length appropriately. This method is intermediate in terms of computational complexity in that only the value of c_b needs to be determined for simplified computation of the development length. When K_{tr} is set to zero for the case of no transverse reinforcement bars, the constraint that c_b/d_b can not exceed 2.0 must be observed.

The third step is a special case, and the value of K_{tr} is computed directly and same as the second method of ACI 318 Code. The computation is complex, but it is the most accurate computational step, which can design the development length the shortest possible and yet satisfies all the necessary requirements.

7. Conclusions

This study carried out analyses of existing experimental data to examine the influence of confinement on bond strength and to propose new design provisions for development length. The following conclusions are drawn.

1) The provisions of ACI 318 Code overestimated and underestimated the development length depending on the cover thickness and the effect of transverse reinforcement bars. Thus, the maximum and minimum values for such variables were proposed.

2) A new design provisions were proposed against existing computational equations for the development and splice length. It set aside the two methods of current design standards and integrated them into one equation as an improved design method.

3) This proposed design method can compute the development and splice lengths easily and yet appropriately or time-consumingly and accurately depending on the given situation.

Acknowledgements

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