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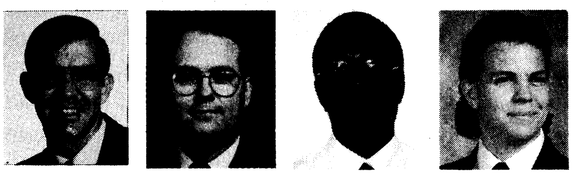
Development Length Criteria: Bars Not Confined by Transverse Reinforcement



by David Darwin, Steven L. McCabe, Emmanuel K. Idun, and Steven P. Schoenekase

An expression that accurately represents development and splice strength as a function of concrete cover and bar spacing is developed. The expression is then used to establish and evaluate modifications to the bond and development provisions of the ACI Building Code (ACI 318-89) for bars in concrete members that are not confined by transverse reinforcement. The expression for development and splice strength is similar in form to expressions developed by Orangun, Jirsa, and Breen (1975, 1977) but is obtained using techniques that limit the effects of unintentional bias in the test data. The resulting expression provides a more accurate representation of development and splice strength than do the earlier expressions, and it provides better guidance when there is a significant difference between the concrete cover and one-half of the clear spacing between bars. Proposals for new design criteria, including one under study by ACI Committee 318, are compared. Each of the new proposals contains design criteria that are superior to the current development length provisions (ACI 318-89); however, the criteria differ in terms of relative safety, economy, and ease of application. Side-by-side comparisons in design offices are recommended. In all cases, an additional development length modification factor of 1.1 is recommended for reinforcing steels with specified yield strengths in excess of 60,000 psi (414 MPa).

Keywords: bond (concrete to reinforcement); bridge specifications; building codes; deformed reinforcement; development; lap connections; reinforcing steels; splicing; structural engineering.

Work is underway on a large-scale study at the University of Kansas to substantially improve the development characteristics of reinforcing bars. At the initiation of the study, it became clear that an accurate characterization of the development and splice strength of current bars was needed to provide input for the design of test specimens and, even more important, to establish a baseline to determine the degree of improvement in bond strength provided by new bar geometries. Such a characterization must accurately account for the effects of concrete cover, bar spacing, and confining reinforcement, since these parameters play a critical role in bond strength. This paper describes the efforts of this initial work.

The development of an accurate characterization of development/splice strength also offers the opportunity to simultaneously investigate simplifications of the development and splice length provisions in the ACI Building Code (ACI 318-89). This opportunity is important because changes made to Section 12.2 in the 1989 revision of ACI 318 have raised objections from individuals in the design community because of added complications in bond and development design, compared to earlier versions of the ACI Building Code.

Several approaches to simplification have been proposed, including variations on current code procedures, proposed by the authors (and described in this paper), and new expressions, under consideration by ACI Committee 318,* that give the designer the option of using simplified procedures or a more accurate representation of development length requirements.

RESEARCH SIGNIFICANCE

The research is significant because the new representation for development and splice strength captures the effects of development/splice length, bar size, concrete cover, bar spacing, and steel stress more accurately than earlier representations and because the paper provides the engineering community with the opportunity to evaluate proposed changes in the development length criteria in the ACI Building Code (ACI 318-89) while they are under active consideration by ACI Committee 318. Full details of the study are presented by Darwin, McCabe, Idun, and Schoenekase (1992).

*Balloted as proposed Code Change CB-23. Available from ACI headquarters.

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David Darwin, FACI, is the Deane E. Ackers Professor of Civil Engineering and Director of the Structural Engineering and Materials Laboratory at the University of Kansas. He is a past member of the Board of Direction and the Technical Activities Committee and is Past President of the Kansas Chapter of ACI. Professor Darwin is Chairman of the Publications Committee and the Concrete Research Council and is Past Chairman and a member of ACI Committee 224, Cracking. He is also a member of ACI Committees 408, Bond and Development of Reinforcement; and 446, Fracture Mechanics; and joint ACI-ASCE Committees 445, Shear and Torsion; and 447, Finite Element Analysis of Reinforced Concrete Structures.

*ACI member **Steven L. McCabe** is an associate professor of civil engineering at the University of Kansas. He is active in research involving reinforced concrete, structural analysis/design for dynamic loading, and finite element techniques. He is Chairman of ACI Committee 439, Steel Reinforcement; and is a member of ACI Committees 408, Bond and Development of Reinforcement; and 446, Fracture Mechanics; and joint ACI-ASCE Committee 447, Finite Element Analysis of Reinforced Concrete Structures. He is currently President of the Kansas Chapter of ACI.*

*ACI member **Emmanuel K. Idun** is a graduate research assistant in civil engineering at the University of Kansas. He holds a BSc (Eng.) in civil engineering and a M.Phil. in structures from the University of Science and Technology in Ghana. He is currently pursuing his PhD degree.*

*ACI member **Steven P. Schoenekase** is a graduate research assistant in civil engineering at the University of Kansas. He holds a BS in architectural engineering from the University of Kansas and is currently pursuing his MSCE degree.*

For the current effort, the effects of transverse reinforcement are neglected. Even without considering transverse reinforcement, however, the relationships developed here are important because, historically, the expressions for bond and development in the ACI Building Code have been based on test results that have de-emphasized the role of transverse reinforcement. The effects of transverse reinforcement will be considered in a future paper.

DEVELOPMENT AND SPLICE STRENGTH

The goal of the first phase of the study is to establish an accurate expression for development and splice strength. This phase consists of first evaluating an existing expression that provides close agreement with test data for bond and splice strength; next, developing an improved expression using an expanded database; and finally, demonstrating the accuracy of the new expression.

Orangun, Jirsa, and Breen's equation

In their well-known statistical study of the bond strength of reinforcing bars, Orangun, Jirsa, and Breen (1975, 1977) developed an expression for the average bond stress at failure u, normalized with respect to the square root of the concrete strength f_c'

$$\frac{u}{\sqrt{f_c'}} = 1.22 + \frac{3.23C}{d_b} + \frac{53d_b}{l_d} \qquad (1)$$

in which $C = \min(C_s, C_b)$; $C_s = \min$ (one half of clear spacing, side cover); C_b = cover; d_b = bar diameter; and l_d = development length or splice length (all units in psi or in.).

Eq. (1) was based on a total of 62 test specimens. This expression was modified by rounding the coefficients to obtain a somewhat more conservative value for u, denoted as u_{cal}

$$\frac{u_{cal}}{\sqrt{f_c'}} = 1.2 + \frac{3C}{d_b} + \frac{50d_b}{l_d} \qquad (2)$$

Orangun et al. (1975, 1977) compared the bond stresses calculated using Eq. (2) to test results obtained from a total of nine studies of splice and development strength for bars not confined by transverse reinforcement. The predicted strengths gave a close match with the test results.

The close agreement of the predicted strengths with the test data is the reason that the expressions by Orangun, Jirsa, and Breen (1975, 1977) were selected for further evaluation in this study. In the process of evaluating the accuracy of their predictions, Orangun et al. observed that their predicted results became progressively more conservative as the transverse spacing between the reinforcing bars, normalized to the bar diameter, increased relative to the concrete cover. They compared the ratio of the bond strength from the test u_t to the calculated bond stress u_{cal} with the ratio $C_s/(C_b\, d_b)$, where C_s, C_b, and d_b are defined following Eq. (1). The ratio u_t/u_{cal} increased as $C_s/(C_b d_b)$ increased.

The approach used in this study differs from the approach used in the Orangun et al. study. Foremost among the changes is a switch from bond stress to bond force as the measure of strength. The switch is made because bond stress is usually expressed as an average value at failure, when, in fact, bond stress varies significantly over the length of a bar at failure (Mains 1951). Since bond strength is a structural, rather than material property, bond force provides a better measure of member response than bond stress.

To help remove the effects of differences in concrete strength, the bond force $A_b f_s$ (A_b = bar area, f_s = steel stress at failure) is normalized with respect to the square root of the concrete strength f_c'. $\sqrt{f_c'}$ serves as a measure of the tensile strength or, perhaps more appropriately, the fracture energy of the concrete. While it is not clear that $\sqrt{f_c'}$ provides the best measure of the tensile properties of concrete (Gettu et al. 1990), it has been used with success for many years over limited ranges of concrete strength, and, thus, is adopted here.

If Eq. (1) and (2) are modified to express bar force at failure normalized with respect to $\sqrt{f_c'}$, the following equations are obtained

$$\frac{A_b f_s}{\sqrt{f_c'}} = 3.23\pi\, l_d(C + 0.378d_b) + 212A_b \qquad (3)$$

$$\frac{A_b f_s}{\sqrt{f_c'}} = 3\pi\, l_d(C + 0.4d_b) + 200A_b \qquad (4)$$

The values of $A_b f_s/\sqrt{f_c'}$ from tests are plotted versus the strengths predicted by Eq. (3) (the more accurate of the two expressions) in Fig. 1 for 53 of the 62 data points used by Orangun et al. (1975) to establish Eq. (1). These 53 data points are for No. 6, No. 8, and No. 11 bars (for clarity, test results for two No. 3 bars, three No. 4 bars, one No. 5 bar, one No. 14 bar, and two No. 18 bars are not shown) (each bar size represents an increment in nominal diameter of 3.175 mm). The four lines plotted in the figure represent the individual regression (best fit) lines for each of the three bar sizes illustrated, as well as the best-fit line for all of the data. Fig. 1 shows that Eq. (3) does a good job of representing the overall data—for the overall best-fit line, the slope is close to 1.0 and the intercept is close to zero. However, Fig. 1 also shows that when the No. 6, No. 8, and No. 11 bars are considered separately, the individual best-fit lines differ significantly from the overall trend—for No. 6, No. 8, and No. 11 bars, the slopes are 0.81, 0.59, and 0.98, and the intercepts are

38.9, 343.5, and 143.1, respectively. These differences indicate that the influence of one or more of the controlling parameters is not adequately represented in Eq. (1) through (4), and that improvements need to be made to obtain accurate predictions of development and splice strength.

To accomplish this goal, a more detailed study is carried out using additional data from Orangun et al. (1975). The resulting expression is checked against all data for bars in members without confining transverse reinforcement in that report and more recent test results from the University of Texas (Treece and Jirsa 1987, 1989; Hamid and Jirsa 1990) and the University of Kansas (Choi et al. 1990, 1991; Hester et al. 1991). The recent results are from studies of the bond strength of epoxy-coated bars; only results for uncoated bars tested in those studies are used here.

Improved expression

Eq. (4) expresses the splice or development strength, normalized with respect to $\sqrt{f_c'}$, as the sum of two terms, $3\pi l_d (C + 0.4 d_b)$ and $200 A_b$. In the first term, $l_d (C + 0.4 d_b)$ represents an area, with $l_d C$ representing an area of fractured concrete. The fact that an $l_d d_b$ term also appears is not surprising, since measurable bond strength should be present, even for bars with zero cover. The $200 A_b$ term has been interpreted as representing an additional fracture area at the end of the reinforcing bar (Losberg and Olsson 1979). Under any circumstances, the expression includes one term that depends on the development length, cover or clear spacing, and bar size and another term that depends solely on the bar size.

For statistically based expressions like Eq. (1) through (4) to be fully reliable, the test data upon which they are based must be totally unbiased with respect to other aspects that may affect the principal dependent variable, in this case bond strength. A study of the tests used to develop Eq. (1) through (4) (Orangun et al. 1975, 1977; Darwin et al. 1992) shows that this criterion may have been unintentionally violated. The larger reinforcing bars [No. 8 and No. 11 bars tested by Ferguson and Breen (1965)] used for the analysis had a larger lateral spacing than the smaller bars [No. 6 bars tested by Chinn, Ferguson, and Thompson (1955)], without an increase in cover, which results in an increased C_s/C_b ratio. As Orangun et al. (1975, 1977) noted, an increase in C_s/C_b should result in an increase in the value of bond stress. This effect was not filtered out of the data prior to carrying out the original regression analysis that produced Eq. (1).

Bias also may have entered the analysis because of a disparity in the size of the coarse aggregate used in the studies. The No. 6 bar specimens tested by Chinn, Ferguson, and Thompson (1955) were fabricated using a maximum aggregate size of only ¼ in. (6 mm). Small coarse aggregate is likely to produce concrete with lower fracture energy, and thus a lower bond strength, than concrete of the same compressive strength containing larger aggregate (Van Mier 1991). Finally, higher strength steel was used for the larger bars than for the smaller bars, resulting in test specimens designed to produce higher values of steel stress at failure for No. 8 and No. 11 bars than for No. 6 bars. Thus, it should be expected that the statistically derived coefficients in Eq. (1) through (4) would reflect some of these biases.

Overall, these biases cause Eq. (1) through (4) to overestimate bond strength when $C_s/C_b \cong 1$, and to underestimate

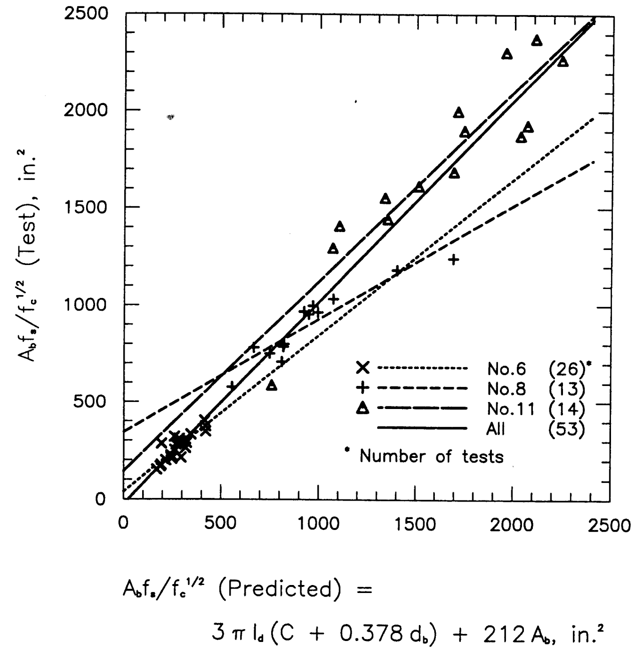

Fig. 1—$A_b f_s/\sqrt{f_c'}$ (test) versus $A_b f_s/\sqrt{f_c'}$ (predicted) $= 3.23\pi l_d (C + 0.378 d_b) + 212 A_b$ [Orangun, Jirsa, and Breen (1975, 1977)]—best-fit lines for individual bar sizes and all bars (1 in. = 25.4 mm)

bond strength when C_s/C_b differs greatly from 1.0 (i.e., when $C_s \gg C_b$ and when $C_b \gg C_s$). Not accounting for bias in the data is the principal reason why Eq. (3) predicts higher strengths at the higher values of bond force than predicted by the individual trends for No. 6 and No. 8 bars in Fig. 1. In spite of these observations, the authors do not suggest that the form of Eq. (1) through (4) is wrong, only that the analysis requires additional scrutiny if the effects of bias in the data are to be minimized.

Modified equation

To help reduce the effects of bias in the data, and to isolate the effects of development length, cover, and bar diameter, the first approximation of bond and splice strength uses the following expression

$$\frac{A_b f_s}{\sqrt{f_c'}} = 10 l_d (C + f d_b) \tag{5}$$

in which f is a factor that accounts for the portion of the bar diameter that contributes to the bond strength along length l_d. After some study, a value of 0.5 was selected for the factor f. This value was selected for two reasons. First, $f = 0.5$ in Eq. (5) provides a better correlation with the data than 0.4 [as used in Eq. (4)]. Second, from a practical point of view, $C + 0.5 d_b$ equals the smaller of one-half of the center-to-center bar spacing or the cover measured to the center of the bar. With $f = 0.5$, Eq. (5) becomes

$$\frac{A_b f_s}{\sqrt{f_c'}} = 10 l_d (C + 0.5 d_b) \tag{6}$$

To improve the accuracy of the analysis for bar spacing and cover, 147 tests are used, representing both splice and de-

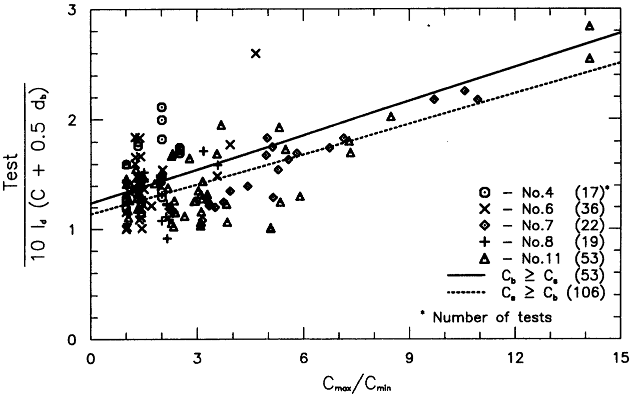

Fig. 2—Test/[10 ld (C + 0.5 db] versus ratio of C_{max} *to* C_{max} *for 147 development and splice specimens without transverse reinforcement*

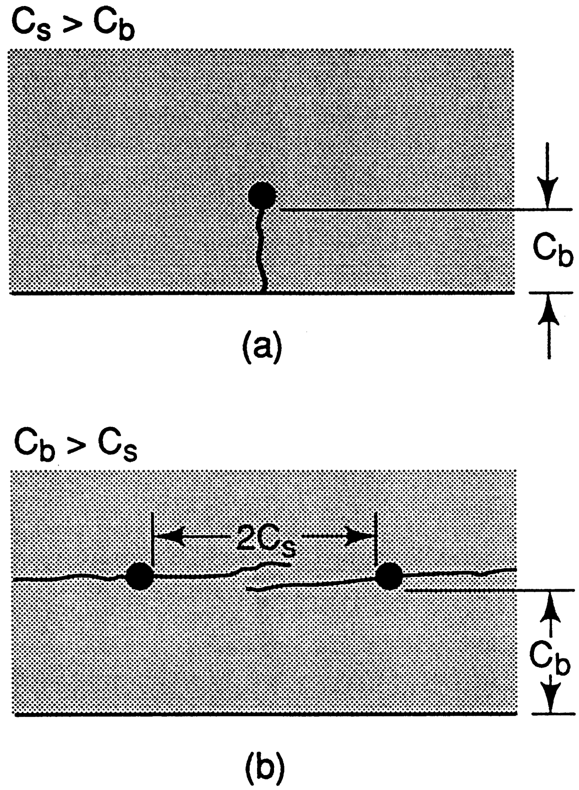

Fig. 3—Bond cracks: (a) $C_s > C_b$ *and (b)* $C_b > C_s$

velopment tests by Chinn, Ferguson, and Thompson (1955), Chamberlin (1956, 1958), Ferguson and Thompson (1962, 1965), Ferguson and Breen (1965), Ferguson and Briceno (1969), and Thompson, Jirsa, Breen and Meinheit (1975), using No. 4, No. 6, No. 7, No. 8, and No. 11 bars. Only results for specimens with a clear spacing of at least one bar diameter or 1 in. (25 mm), whichever is greater, are used.

Using Eq. (6) as the "predicted bond strength," the next step is to determine the effect of $C_s/C_b \neq 1.0$. To do this, the ratio of the test strength to the strength predicted by Eq. (6) is plotted versus C_{max}/C_{min} in Fig. 2, in which C_{max} and C_{min}, respectively, equal the larger and smaller of C_s and C_b. The results are plotted versus C_{max}/C_{min}, rather than versus $C_s/(C_b\, d_b)$ as done by Orangun et al. (1975, 1977), because a study of the data shows that the statistical correlation with the test/prediction ratio improves when 1) the bar diameter is removed from the analysis, and 2) the two cases, $C_s \geq C_b$ and $C_b \geq C_s$, are treated separately. The results provide best-fit expressions for *Test/[10* l_d *(C +* 0.5 d_b)] versus C_{max}/C_{min} as follows:

For $C_s \geq C_b$

$$\frac{Test}{10 l_d (C + 0.5 d_b)} = 1.144 + 0.091 \frac{C_{max}}{C_{min}} \tag{7a}$$

For $C_b \geq C_s$

$$\frac{Test}{10 l_d (C + 0.5 d_b)} = 1.238 + 0.103 \frac{C_{max}}{C_{min}} \tag{7b}$$

The higher value of the ratio, *Test*/[10 l_d (C + 0.5 d_b)] in Eq. (7b) ($C_b \geq C_s$), in all likelihood, reflects the greater fracture surface area that is produced by cracking between bars than by cracking between the bar and the concrete surface. When $C_s > C_b$, the principal bond cracks propagate from the bar to the concrete surface [Fig. 3(a)]. Therefore, the crack length is closely approximated by the cover. When $C_b > C_s$, however, the principal bond cracks propagate between bars [Fig. 3(b)]. Because cracks in concrete are not perfectly planar, it is unlikely that cracks propagating between adjacent bars or splices will line up exactly. Thus, when cracks from adjacent bars or splices coalesce, their effective half-lengths are greater than C_s. A greater half-length means that using $C = C_s$, as is the case when $C_b > C_s$, underestimates the strength more than using $C = C_b$, when $C_s > C_b$.

For the next step in the analysis, the coefficients in Eq. (7a) and (7b) are modified to provide a ratio of 1.0 when C_s/C_b = 1.0.

For $C_s \geq C_b$

$$\frac{Test}{10 l_d (C + 0.5 d_b)} = 0.923 + 0.077 \frac{C_{max}}{C_{min}} \tag{8a}$$

For $C_b \geq C_s$

$$\frac{Test}{10 l_d (C + 0.5 d_b)} = 0.926 + 0.074 \frac{C_{max}}{C_{min}} \tag{8b}$$

Eq. 8(a) and 8(b) are quite similar, so that a single approximation can be used when $C_s \neq C_b$

$$\frac{Test}{10 l_d (C + 0.5 d_b)} = 0.92 + 0.08 \frac{C_{max}}{C_{min}} \tag{9}$$

Combining Eq. (6) and (9) gives an expression for bond strength corrected for bar spacing and cover

$$\frac{A_b f_s}{\sqrt{f_c'}} = 10 l_d (C + 0.5 d_b)\left(0.92 + 0.08 \frac{C_{max}}{C_{min}}\right) \tag{10}$$

A plot of the test results versus the values predicted by Eq. (10) shows that, like the original Orangun et al. equation (Fig. 1), the overall trend in the data is closely represented by the single expression (Darwin et al. 1992). But it also shows that, as observed in Fig. 1, the trends obtained for individual bar sizes do not coincide with the overall trend.

Table 1 — Results of dummy variable analysis of $\left(\frac{A_b f_s}{\sqrt{f_c'}}\right)_{test}$ versus $l_d\,(C+0.5d_b)\left(0.92+0.08\frac{C_{max}}{C_{min}}\right)$

Best - fit equation:

$$\frac{A_b f_s}{\sqrt{f_c'}} = 6.73\, l_d\,(C + 0.5d_b)\left(0.92 + 0.08\,\frac{C_{max}}{C_{min}}\right) + K$$

Value of intercept K, based on bar size

Bar size	K (in.^{2})	$\frac{K}{A_b}$
No. 4	60	299
No. 6	127	290
No. 7	298	496
No. 8	327	414
No.11	650	417

To improve the match with the data, the results are reanalyzed using the technique of dummy variables (Draper and Smith 1981). This analysis is based on the assumption that Eq. (10) accurately represents all aspects of bond performance except bar size. The expression obtained from the dummy variable regression analysis is

$$\frac{A_b f_s}{\sqrt{f_c'}} = 6.73 l_d (C+0.5d_b)\left(0.92+0.08\frac{C_{max}}{C_{min}}\right)+K \quad (11)$$

with $K = 60$ for No. 4 bars, 127 for No. 6 bars, 298 for No. 7 bars, 327 for No. 8 bars, and 650 for No. 11 bars.

With increasing bar size, the value of K increases more rapidly than the bar diameter or even the bar area. However, as shown in Table 1, K can be represented conservatively as $300\,A_b$, except for the No. 6 bars where $300\,A_b$ slightly overpredicts the value of K ($290\,A_b$).

As will be demonstrated in the next section, replacing the K-term with $300\,A_b$ in Eq. (11) results in an expression that is slightly conservative overall. To simplify later calculations, the coefficient 6.73 in Eq. (11) is rounded to two-thirds of 10, or 6.67, to give the final expression

$$\frac{A_b f_s}{\sqrt{f_c'}} = 6.67 l_d (C+0.5d_b)\left(0.92+0.08\frac{C_{max}}{C_{min}}\right)+300A_b \quad (12)$$

Test results are compared to strengths predicted by Eq. (12) in Fig. 4, which presents the individual and overall best-fit lines. The conservative nature of Eq. (12) is demonstrated by the slope of the best-fit line, 1.14; the intercept is –8.6. The slopes of the individual best-fit lines are 1.17, 1.23, 1.05, 0.89 and 1.01 for No. 4, No. 6, No. 7, No. 8, and No. 11 bars, respectively. The intercepts are –18, –63, 92, 173, and 171, respectively. Fig. 4 shows that the trends for the individual bars closely match the overall trend—a significant improvement over the match obtained in Fig. 1 and an indication that Eq. (12) does a better job than Eq. (3) of capturing the effects of the parameters that control bond strength.

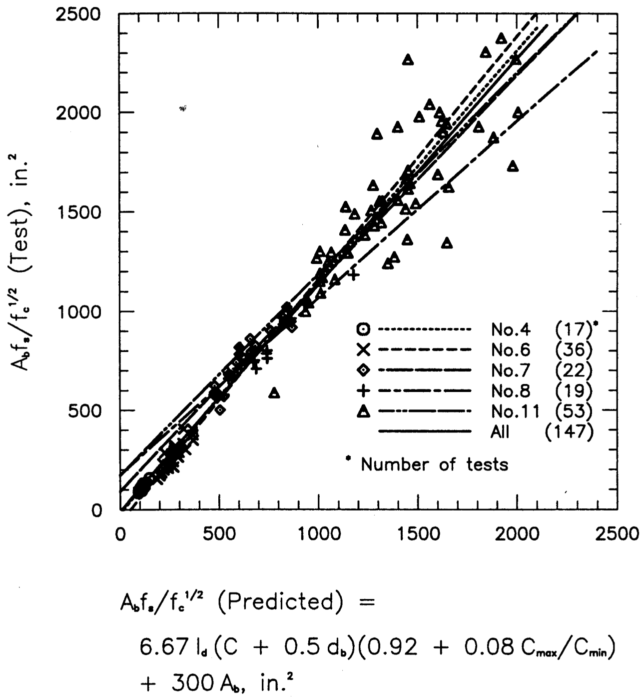

Fig. 4—$A_b f_s/\sqrt{f_c'}$ (test) versus $A_b f_s/\sqrt{f_c'}$ (predicted) = 6.67 l_d (C + 0.5 d_b) (0.92 + 0.08 C_{max}/C_{min}) + 300 A_b. Note improved agreement between best-fit lines for individual bar sizes and best-fit line for all bars compared to agreement obtained in Fig. 1 (1 in. = 25.4 mm)

Comparison with data

A detailed comparison of predictions obtained using Eq. (3), (4), and (12) was made (Darwin et al. 1992) with the test results used in the 1975 Orangun et al. paper (Chinn, Ferguson, and Thompson 1955; Ferguson and Breen 1965; Chamberlin 1956, 1958; Ferguson and Krishnaswamy 1971; Ferguson and Briceno 1969; Thompson et al. 1975; Tepfers 1973; and Ferguson and Thompson 1962, 1965) (Appendixes A through I).* Comparisons were also made with tests by Hester et al. (1991), Choi et al. (1990, 1991), Treece and Jirsa (1987, 1989), and Hamad and Jirsa (1990) (Appendix J). The comparisons are summarized in Table 2, which presents the mean test/prediction ratios, the maximum and minimum test prediction ratios, and the coefficients of variation (COV) for the 62 specimens used by Orangun et al. to develop Eq. (1) and (2), and for each of the test series covered in Appendixes A through J. Table 2 also presents a summary of the results for the 257 test specimens without transverse reinforcement evaluated in the Orangun et al. (1975) report, a summary for all data, and a summary that excludes the 90 specimens tested by Tepfers (1973). The latter summary is of interest since 20 of Tepfers specimens had very low covers and bar spacings, which do not meet current ACI Code provisions (ACI 318-89), and are well outside the ranges used to develop Eq. (3), (4), and (12).

As illustrated by the comparisons in Table 2, overall Eq. (12) provides a better match with the test data than Eq. (3). Eq. (12) produces the lowest coefficient of variation for 11 of the 14 test series, with Eq. (3) and (4) producing lower and nearly equal COVs for the other three series.

Eq. (12) generally produces smaller ranges of the test/prediction ratio. This is particularly evident for the 90 specimens tested by Tepfers (1973) for which the test/prediction ratios range from 0.634 to 2.854 for Eq. (3) versus 0.642 to 1.802 for Eq. (12). For all 290 specimens, Eq. (3), (4), and

*Because of space limitations, Appendixes A through L are not presented here but will be kept permanently on file at ACI headquarters where photocopies will be available at cost of reproduction and handling.

Table 2 — Test/prodiction ratios — Summary

		Eq.(3)	Eq. (4)	Eq. (12)			Eq. (3)	Eq. (4)	Eq. (12)
Orangun, Jirsa, and Breen (1975)	MEAN	1.006	1.069	1.060	Chamberlin (1956)	MEAN	1.014	1.074	0.964
62 specimens	COV	0.142	0.142	0.129	23 specimens (I)*	COV	0.079	0.079	0.106
	MIN	0.720	0.767	0.753		MIN	0.817	0.862	0.715
	MAX	1.460	1.546	1.398		MAX	1.164	1.228	1.119
Chinn, Ferguson, and Thompson	MEAN	0.960	1.020	0.980	Hester, Salamizavaregh,	MEAN	0.950	1.011	0.999
(1955)	COV	0.165	0.164	0.147	Darwin, McCabe (1991)	COV	0.078	0.078	0.069
35 specimens (A)*	MIN	0.720	0.767	0.753	Beams	MIN	0.887	0.943	0.919
	MAX	1.463	1.550	1.398	7 specimens (J)*	MAX	1.089	1.158	1.128
Ferguson and Breen (1965)	MEAN	1.031	1.096	1.125	Hester, Salamizavaregh,	MEAN	0.782	0.834	0.861
26 specimens (B)*	COV	0.116	0.115	0.081	Darwin, McCabe (1991)	COV	0.090	0.090	0.094
	MIN	0.733	0.781	0.884	Slabs	MIN	0.678	0.724	0.737
	MAX	1.277	1.353	1.277	7 specimens (J)*	MAX	0.854	0.912	0.938
Chamberlin (1958)	MEAN	0.977	1.040	0.989	Choi, Hadje-Ghaffari,	MEAN	1.032	1.097	1.065
6 specimens (C)*	COV	0.153	0.153	0.127	Darwin, and McCabe (1990)	COV	0.157	0.158	0.156
	MIN	0.819	0.873	0.855	8 specimens (J)*	MIN	0.813	0.865	0.856
	MAX	1.141	1.215	1.130		MAX	1.278	1.360	1.340
Ferguson and Krishnaswamy	MEAN	1.378	1.355	1.202	Treece and Jirsa (1987)	MEAN	0.932	0.990	0.981
(1971)	COV	0.261	0.258	0.097	9 specimens (J)*	COV	0.116	0.115	0.127
12 specimens (D)*	MIN	0.928	0.985	1.048		MIN	0.758	0.806	0.853
	MAX	1.947	2.053	1.459		MAX	1.104	1.174	1.213
Ferguson and Briceno (1969)	MEAN	1.081	1.147	1.175	Hamad and Jirsa (1990)	MEAN	1.268	1.344	1.262
20 specimens (E)*	COV	0.142	0.140	0.117	2 specimens (J)*	COV	0.361	0.360	0.299
	MIN	0.885	0.936	0.938		MIN	0.810	0.861	0.885
	MAX	1.468	1.552	1.559		MAX	1.726	1.828	1.639
Thompson, Jirsa, Breen, and	MEAN	1.064	1.132	1.173	Summary for 257 tests —	MEAN	1.095	1.163	1.126
Meinheit (1975)	COV	0.070	0.070	0.063	OJB (Appendixes A-I)	COV	0.233	0.230	0.167
11 specimens (F)*	MIN	0.897	0.952	1.031		MIN	0.634	0.674	0.642
	MAX	1.179	1.253	1.288		MAX	2.854	2.970	1.802
Tepfers (1973)	MEAN	1.133	1.201	1.195	Summary for 290 tests —	MEAN	1.079	1.145	1.112
90 specimens (G)*	COV	0.282	0.276	0.181	All (Appendixes A-J)	COV	0.235	0.232	0.172
	MIN	0.634	0.674	0.642		MIN	0.634	0.674	0.642
	MAX	2.854	2.970	1.802		MAX	2.854	2.970	1.802
Ferguson and Thompson	MEAN	1.210	1.288	1.157	Summary for 200 tests —	MEAN	1.054	1.120	1.073
(1962, 1965)	COV	0.211	0.209	0.140	(Appendixes A-J)	COV	0.202	0.201	0.154
34 specimens (H)*	MIN	0.839	0.892	0.815	Except Tepfers	MIN	0.678	0.724	0.715
	MAX	1.873	1.983	1.656		MAX	1.947	2.053	1.656

*Letter in parentheses designates Appendix containing detailed comparisons.

(12) give mean test/prediction ratios of 1.079, 1.145, and 1.112, respectively, with corresponding coefficients of variation of 0.235, 0.232, and 0.172. When the test data of Tepfers is excluded, the remaining 200 test specimens provide mean test/prediction ratios of 1.054, 1.120, and 1.074, for Eq. (3), (4), and (12), with corresponding coefficients of variation of 0.202, 0.201, and 0.154. The higher mean test/prediction ratios produced by Eq. (12), compared to those produced by Eq. (3), are the result of the conservative modifications to the best-fit equations described in the previous section. The lower coefficients of variation produced by Eq. (12), compared to the other equations, attest to its improved accuracy.

DEVELOPMENT LENGTH EXPRESSION

The development length design criteria in Section 12.2 of ACI 318-89 are structured so that the selection criteria for modification factors are expressed in terms of bar diameter. This approach comes from the usual way of interpreting the Orangun, Jirsa, Breen equation [Eq. (2)] for development length

$$l_d = \frac{\left(\dfrac{f_s}{4\sqrt{f_c'}} - 50\right)d_b}{3(C/d_b)+1.2} \qquad (13)$$

Since Eq. (13) is formulated in terms of d_b, the cover/bar spacing term in the denominator is expressed in multiples of bar diameter $C/_d b$. This has led to the conclusion that cover/spacing criteria should change as a function of bar diameter—a correct interpretation only if the basic expression (i.e., without regard for cover and bar spacing) is also in terms of bar diameter.

If Eq. (13) is modified so that the numerator includes the area of the bar A_b, then the cover/bar spacing term in the denominator is expressed in units of absolute length rather than in multiples of the bar diameter

$$l_d = \frac{\left(\dfrac{f_s}{\sqrt{f_c'}} - 200\right)A_b}{\pi(3C+1.2d_b)} = \frac{0.106\left(\dfrac{f_s}{\sqrt{f_c'}} - 200\right)A_b}{(C+0.4d_b)} \qquad (14)$$

In this form, Eq. (14) indicates that the development length must increase with the bar area but decrease with a number $(C+0.4\,d_b)$ that is very close to the smaller of one-half of the center-to-center bar spacing or the cover measured to the center of the bar.

If the proposed equation for $A_b f_s/\sqrt{f_c'}$, Eq. (12), also is solved for the development length l_d, an expression is obtained that is similar in form to the Orangun, Jirsa, Breen (1975, 1977) expression in Eq. (14)

$$l_d = \frac{0.15\left(\dfrac{f_s}{\sqrt{f_c'}} - 300\right)A_b}{(C+0.5d_b)(0.92+0.08C_{max}/C_{min})} \qquad (15)$$

A direct comparison of Eq. (14) and (15), with $C_s = C_b$, shows that for $f_s = f_y$ = 60,000 psi (414 MPa) and f_c' = 4500 psi (31 MPa), Eq. (14) provides an estimate of l_d that is about 15 percent lower than that provided by Eq. (15). The two equations provide approximately equal predictions when $C_{max} \cong 3\ C_{min}$. For $C_{max} > 3\ C_{min}$, Eq. (15) provides a lower estimate of the required development length.

Eq. (12) and (15) have several advantages over test results as a basis for evaluating design expressions. First, the equations reflect the observed nonproportional relationship between l_d and f_s. Since l_d is proportional to f_s in most design expressions, an equation that appears to be safe for tests with f_s < 60,000 psi (414 MPa) will not necessarily be safe for $f_s \geq$ 60,000 psi (414 MPa). This is important because the vast majority of the test results available for comparison (Orangun et al. 1975, Darwin et al. 1992) represent development and splice failures with f_s < 60,000 psi (414 MPa). Second, Eq. (12) and (15) cover the full range of design variables, while test results have gaps in the variables covered. This point is particularly important if design criteria are discontinuous.

DESIGN CRITERIA

In the 1989 revision of ACI 318, changes were made in Section 12.2 to reflect the fact that closely spaced bars and bars with low cover exhibit lower bond strengths than predicted by ACI 318-83. Unlike earlier versions of ACI 318, the current provisions require that every bar must be categorized, not just the exceptions or the best and worst cases. Also, under ACI 318-89, the spacing and cover criteria used to select the modification factors are expressed as multiples of bar diameter. Thus, not only must every bar be categorized, but the spacing and cover criteria for each category change with bar size, resulting in significant extra effort in the design process compared to earlier codes.

The goal of the second phase of this study is to use the improved expressions developed in Phase 1 to help simplify the design rules found in ACI 318-89. To achieve this goal in a straightforward manner, one approach, referred to as Proposal A, is to make changes within the framework of the 1989 code format. Another approach, proposed code change CB-23, under study by ACI Committee 318, is to change the code format to express the basic development length in terms of d_b rather than A_b. Both approaches, along with a suggested modification to CB-23 (referred to as Proposal B), are addressed in the following sections.

Proposal A—Changes within the framework of ACI 318-89

Using current code format, basic development length expressions similar to those used in ACI 318-89 are used in conjunction with Eq. (15) to develop provisions that correlate well with the test data. Under Proposal A, the basic development lengths l_{db} provided in Section 12.2 of ACI 318-89 are modified as follows:

For No. 11 bars and smaller

$$l_{db} = \frac{0.06 A_b f_y}{\sqrt{f_c'}} \tag{16a}$$

For No. 14 bars

$$l_{db} = \frac{0.125 f_y}{\sqrt{f_c'}} = \frac{0.0556 A_b f_y}{\sqrt{f_c'}} \tag{16b}$$

For No. 18 bars

$$l_{db} = \frac{0.175 f_y}{\sqrt{f_c'}} = \frac{0.0438 A_b f_y}{\sqrt{f_c'}} \tag{16c}$$

in which f_y = yield strength of steel. The coefficients in Eq. (16a) through (16c) are increased about 50 percent compared to those in ACI 318-89 because of the unconservative nature of the current code provisions for closely spaced bars with low cover.

To calculate development length modification factors that account for the effects of cover and bar spacing, the basic development lengths calculated using Eq. (16a) through (16c) were compared (Darwin et al. 1992) with those obtained using Eq. (15), for $f_s = f_y$ = 60,000 psi (414 MPa) and f_c'= 4500 psi (31 MPa) (Appendix K). The calculated modification factors range from 2.32, for No. 3 bars with ¾-in. (19-mm) cover and 1⅜-in. (35-mm) center-to-center spacing, to 0.42, for No. 11 bars with 3-in. (76-mm) cover and 12-in. (305-mm) center-to-center spacing.

Based on an analysis of these modification factors, the following code provisions are further suggested under Proposal A:

1. The basic development length criteria presented in Eq. (16a) through (16c) should be adopted.

2. The appropriate modification factors based on cover and bar spacing should be:

   1.5 for bars with cover < 1½ in. (38 mm) or spaced laterally < 3 in. (75 mm), except 2.0 for bars with center-to-center bar spacing < 2 in. (50 mm)

   0.8 for bars spaced at least 8 in. (200 mm) on center

   0.9 for bars with cover of at least 3 in. (75 mm)

3. The 1.5 and 2.0 factors should be mandatory; the 0.8 and 0.9 factors would be permitted.

4. The current minimum values of l_d, 0.03 $d_b f_y/\sqrt{f_c'}$ and 12 in. (305 mm), should be retained.

These provisions are compared with development lengths calculated using Eq. (15) in Table 3 for bars with covers of 0.75, 1.5, and 3.0 in. (19, 38, and 75 mm) and center-to-center spacings ranging from the minimum provided for flexural members (ACI 318-89) up to 12 in. (305 mm). The comparisons in Table 3 have the additional condition that the minimum value used for l_d from Eq. (15) is 12 in. (305 mm).

Discussion—The l_d ratios in Table 3 show that, in all but a few cases, Proposal A provides a close but conservative match when compared to either Eq. (15) or a minimum development length of 12 in. (305 mm). The proposed provisions are least conservative for bars with minimum spacing and minimum [¾-in. (19-mm)] cover and for bars with 3-in. center-to-center spacing and cover > 1½ in. (38 mm), producing a ratio of Eq. (15) to the proposed code provision as high as 1.14, for No. 3 bars with a ¾-in. (19-mm) cover and minimum spacing. The results are most conservative for No. 7 through No. 14 bars with a cover of 2 in. (51 mm) and center-to-center spacings

Table 3 — l_d [Eq. (15) ≥ 12 in.]/l_d (Proposal A) for f_y = 60,000 psi and f_c'4500 psi*
[values greater than 1.0 (in bold) are unconservative]

Bar	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11	No. 14	No. 18
C-C spacing	¾ in. cover										
Minimum	**1.14**	**1.07**	0.98	0.91	0.85	**1.07**	0.96	0.86	0.78	—	—
2.50	1.00	**1.08**	**1.02**	0.97	0.93	0.89	0.88	0.87	—	—	—
3.00	1.00	**1.05**	1.00	0.95	0.90	0.86	0.83	0.79	0.76	—	—
4.00	1.00	1.00	0.95	0.90	0.86	0.82	0.79	0.75	0.72	—	—
5.00	1.00	0.95	0.90	0.86	0.82	0.78	0.75	0.71	0.68	—	—
6.00	1.00	0.91	0.86	0.82	0.78	0.75	0.71	0.68	0.65	—	—
8.00	1.00	**1.01**	0.99	0.94	0.90	0.86	0.82	0.78	0.75	—	—
12.00	1.00	0.89	0.85	0.81	0.77	0.74	0.70	0.67	0.64	—	—
	1½ in. cover										
Minimum	**1.02**	0.95	0.88	0.82	0.76	0.95	0.87	0.79	0.72	1.00	0.98
2.50	1.00	0.85	0.85	0.84	0.83	0.82	0.81	0.79	—	—	—
3.00	1.00	0.89	**1.08**	**1.08**	**1.07**	**1.07**	**1.06**	**1.04**	**1.03**	—	—
4.00	1.00	0.89	0.90	0.88	0.85	0.83	0.83	0.82	0.82	0.89	—
5.00	1.00	0.89	0.88	0.86	0.83	0.81	0.79	0.76	0.74	0.76	0.90
6.00	1.00	0.89	0.86	0.84	0.81	0.79	0.77	0.74	0.72	0.74	0.85
8.00	1.00	0.89	0.81	0.93	0.97	0.94	0.91	0.88	0.86	0.88	**1.01**
12.00	1.00	0.89	0.74	0.85	0.88	0.86	0.83	0.81	0.78	0.80	0.92
	3 in. cover										
Minimum	1.00	0.88	0.81	0.75	0.70	0.88	0.81	0.75	0.69	0.98	0.99
2.50	1.00	0.85	0.84	0.82	0.81	0.79	0.77	0.75	—	—	—
3.00	1.00	0.89	0.98	**1.09**	**1.07**	**1.06**	**1.05**	**1.02**	**1.01**	—	—
4.00	1.00	0.89	0.78	0.86	0.86	0.85	0.85	0.84	0.84	0.89	—
5.00	1.00	0.89	0.72	0.71	0.71	0.71	0.71	0.70	0.70	0.75	0.92
6.00	1.00	0.89	0.72	0.61	0.61	0.61	0.60	0.60	0.60	0.65	0.80
8.00	1.00	0.89	0.72	0.60	0.65	0.65	0.64	0.63	0.62	0.65	0.79
12.00	1.00	0.89	0.72	0.60	0.62	0.62	0.61	0.60	0.59	0.61	0.73

1000 psi = 6.895 MPa; 1 in. = 25.4 mm.

between 4 and 8 in. (102 and 203 mm) (not shown in Table 3), and No. 7 through No. 14 bars with 3-in. (76-mm) cover and center-to-center spacings in excess of 5 in. (127 mm). The ratios drop as low as 0.59 for No. 11 bars with a 3-in. (76-mm) cover and 12-in. (305-mm) center-to-center spacing.

In general, the comparisons are good, however, and Proposal A has two very practical advantages over the current provisions. First, all bars need not be categorized—only those that have low cover or close spacing, or (if desired) high cover or high spacing. This is a return to the philosophy used in the 1983 provisions (ACI 318-83) in that only the exceptions, not every bar, must be categorized. Second, and probably more important, the new criteria depend only on specific absolute values of cover and center-to-center bar spacing; they do not change with bar size. This last point, the use of actual cover and bar spacing, not multiples of bar diameter, could aid greatly the designer in selecting factors to modify the basic development length expressions.

CB-23—Currently under consideration by ACI Committee 318

ACI Committee 318 is currently considering a revision to Section 12.2 of the ACI Building Code, designated as CB-23. The revision is summarized in Table 4.

Discussion—The provisions of CB-23 effectively contain two expressions for the basic development length $l_{db} = 0.05\, d_b f_y/\sqrt{f_c'}$ in Section 12.2.2.1 and $l_{db} = 0.04\, d_b f_y/\sqrt{f_c'}$ in Section 12.2.2.2, rather than three expressions, as used in the current code and in Proposal A.

The principal changes offered by CB-23 involve the use of expressions in which the basic development length is expressed in terms of the bar diameter (Section 12.2.2), rather than the bar area; the use of simplified modification factors (1.0 and 1.5) for cover, bar spacing, and confining reinforcement (Section 12.2.3.1); and the ability to use an alternate expression that more accurately accounts for the effects of cover, bar spacing, and confining reinforcement than the basic expression and modification factors (Section 12.2.2 combined with Section 12.2.3.2). The development of Eq. (12) and (15) provides a useful tool for evaluating CB-23 for members without transverse reinforcement.

CB-23 (Section 12.2.2 plus Section 12.2.3.1) is compared to Eq. (15) in Table 5. As with Table 3, the comparisons represent the ratio of l_d from Eq. (15) to the proposed l_d, with a minimum value of 12 in. (305 mm) used for l_d from Eq. (15).

The l_d ratios in Table 5 show that CB-23 produces generally conservative results, except for No. 4 bars at minimum spacing, No. 5 bars with ¾-in. (19-mm) cover at spacings of 2½, 3, and 4 in. (64, 76, and 102 mm), and No. 6 bars with ¾-in. (19-mm) cover at spacings up through 6 in. (152 mm), for which the results are quite unconservative. The highest (and most unconservative) ratio in Table 5 is 1.28, for No. 4 bars with ¾-in. (19-mm) cover and minimum spacing, and No. 6 bars with ¾-in. (19-mm) cover and 2.5-in. (64-mm) center-to-center spacing. In contrast, at higher covers the provisions become progressively more conservative, especially for bar sizes up through No. 11. The lowest ratio is 0.37 [l_d required by Eq. (15) is just 37 percent of that required by the proposed provisions] for No. 7 bars with 3-in. (76-mm) cover and 12-in. (305-mm) center-to-center spacing, but the ratios for No. 4, No. 5, and No. 6 bars are also quite conservative, except for low covers or close spacings.

The conservative comparisons for bars below No. 7 have prompted consideration of the use of an even smaller value

Table 4 — Proposed code change CB-23

12.0 Notation: Add:

K = the smaller of $C_c + K_{tr}$ or $C_s + K_{tr}$ (the units of K are inches)

$K_{tr} = A_{tr} f_{yt}/1500\, s\, N$ but not greater than $2d_b$ (The units of the constant are psi. The units of A_{tr} are square inches, of f_{yt} are psi, and of s are inches. Thus, the units of K_{tr} are inches.)

C_c = Thickness of concrete cover measured from extreme tension fiber to center of bar in. [= $C_b + 0.5d_b$].

C_s = Smaller of side cover to center of outside bar measured along the line through the layer of bars or half the center-to-center distance of adjacent bars in the layer, in. For splices, Cs shall be the smaller of the side cover to the center of the outside bar or half the smaller center-to-center distance of the bars coming from one direction and being spliced at the same section [= $C_s + 0.5d_b$].

N = Number of bars in a layer being spliced or developed at a critical section [no change].

Replace: 12.2.2 and 12.2.3 with the following:

12.2.2 — Basic development length l_{db} shall be:

12.2.2.1 #7 deformed bars and larger, the basic development length shall be:

$$l_{db} = 0.05\, d_b \frac{f_y}{\sqrt{f_c'}} \qquad \text{Eq. (12.X)}$$

12.2.2.2 For #6 deformed bars and smaller and for deformed wire, the basic development length shall be taken as 80 percent of Eq. 12.X.

12.2.3 — To account for bar spacing, amount of cover, and enclosing transverse reinforcement, the basic development length shall be multiplied by a factor from 12.2.3.1 or 12.2.3.2.

12.2.3.1 — (a) Bars or wires with minimum clear cover not less than d_b and either:

Minimum clear spacing not less than d_b and enclosed within transverse reinforcement satisfying tie requirements of 7.10.5 or minimum stirrup requirements of 11.5.4 and 11.5.5.3 along the development length 1.0

or

Minimum clear spacing not less than $2d_b$ 1.0

(b) All other conditions 1.5

12.2.3.2 Any condition:

For #7 deformed bars and larger .... $1.5\, d_b/K$

For #6 deformed bars and smaller and for deformed wire .... $1.5\, d_b/0.8K$

However, K shall not be greater than $2.5\, d_b$.

Table 5 — l_d [Eq. (15) ≥ 12 in.]/l_d (CB23-sections 12.2.2 and 12.2.3.1) for f_y = 60,000 psi and f_c' = 4500 psi

[values greater than 1.0 (in bold) are unconservative]

Bar	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11	No. 14	No. 18
C-C spacing						¾ in. cover					
Minimum	**1.02**	**1.28**	0.98	**1.07**	0.93	**1.01**	**1.02**	**1.03**	**1.04**	—	—
2.50	0.89	0.97	**1.14**	**1.28**	0.76	0.84	0.93	1.04	—	—	—
3.00	0.89	0.95	**1.11**	**1.25**	0.74	0.82	0.88	0.95	**1.01**	—	—
4.00	0.89	0.90	**1.06**	**1.19**	0.71	0.78	0.84	0.90	0.96	—	—
5.00	0.89	0.86	**1.01**	**1.13**	0.67	0.74	0.80	0.86	0.91	—	—
6.00	0.89	0.82	0.96	**1.08**	0.64	0.71	0.76	0.82	0.87	—	—
8.00	0.89	0.76	0.89	0.99	0.59	0.65	0.70	0.75	0.79	—	—
12.00	0.89	0.67	0.76	0.86	0.51	0.56	0.60	0.64	0.68	—	—
						1½ in. cover					
Minimum	0.92	**1.15**	0.87	0.96	0.84	0.91	0.92	0.94	0.96	0.98	**1.02**
2.50	0.89	0.77	0.94	**1.11**	0.68	0.78	0.86	0.94	—	—	—
3.00	0.89	0.67	0.81	0.95	0.88	**1.01**	0.75	0.83	0.92	—	—
4.00	0.89	0.67	0.68	0.77	0.70	0.79	0.88	0.98	0.73	0.87	—
5.00	0.89	0.67	0.66	0.75	0.69	0.77	0.84	0.92	0.98	0.75	0.94
6.00	0.89	0.67	0.64	0.74	0.67	0.75	0.82	0.89	0.96	0.73	0.88
8.00	0.89	0.67	0.61	0.70	0.64	0.71	0.78	0.85	0.91	0.69	0.83
12.00	0.89	0.67	0.56	0.64	0.58	0.65	0.71	0.77	0.83	0.63	0.76
						3 in. cover					
Minimum	0.89	0.95	0.72	0.80	0.69	0.75	0.78	0.81	0.83	0.87	0.92
2.50	0.89	0.69	0.84	0.98	0.60	0.68	0.74	0.81	—	—	—
3.00	0.89	0.67	0.73	0.86	0.80	0.91	0.67	0.74	0.80	—	—
4.00	0.89	0.67	0.58	0.68	0.64	0.73	0.81	0.91	0.67	0.79	—
5.00	0.89	0.67	0.54	0.57	0.53	0.61	0.68	0.76	0.84	0.66	0.86
6.00	0.89	0.67	0.54	0.48	0.45	0.52	0.58	0.65	0.72	0.86	0.75
8.00	0.89	0.67	0.54	0.45	0.39	0.44	0.49	0.54	0.59	0.69	0.88
12.00	0.89	0.67	0.54	0.45	0.37	0.42	0.47	0.52	0.56	0.65	0.82

1000 psi = 6.895 MPa; 1 in. = 25.4 mm.

of l_{db} for the small bar sizes than is currently embodied in CB-23. The problem with reducing the value for l_{db} will be that the development lengths will be highly unconservative for bars with low covers and low spacings.

Proposal B—Modified version of CB-23

With these points in mind, two modifications are recommended for CB-23 that will improve both safety and economy. These recommendations are to 1) use a single de-

Table 6 — l_d [Eq. (15) ≥ 12 in.]/l_d (Proposal B) for f_y = 60,000 psi and f_c' = 4500 psi
[values greater than 1.0 (in bold) are unconservative]

Bar	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11	No. 14	No. 18
C-C spacing					¾ in. cover						
Minimum	0.82	**1.02**	0.78	0.86	0.93	**1.01**	**1.02**	**1.03**	**1.04**	—	—
2.50	0.72	0.78	0.91	**1.03**	0.76	0.84	0.93	**1.04**	—	—	—
3.00	0.72	0.76	0.89	1.00	0.74	0.82	0.88	0.95	**1.01**	—	—
4.00	0.72	0.72	0.85	0.95	0.71	0.78	0.84	0.90	0.96	—	—
5.00	0.72	0.69	0.81	0.91	0.67	0.74	0.80	0.86	0.91	—	—
6.00	0.72	0.66	0.77	0.87	0.64	0.71	0.76	0.82	0.87	—	—
8.00	0.72	0.60	0.71	0.80	0.59	0.65	0.70	0.75	0.79	—	—
12.00	0.72	0.54	0.61	0.68	0.51	0.56	0.60	0.64	0.68	—	—
					1½ in. cover						
Minimum	0.73	0.92	0.70	0.77	0.84	0.91	0.92	0.94	0.96	0.98	**1.02**
2.50	1.00	**1.02**	0.75	0.89	0.68	0.78	0.86	0.94	—	—	—
3.00	1.00	0.89	0.65	0.76	0.88	**1.01**	0.75	0.83	0.92	—	—
4.00	1.00	0.89	0.90	**1.03**	0.70	0.79	0.88	0.98	0.73	0.87	—
5.00	1.00	0.89	0.88	**1.01**	0.69	0.77	0.84	0.92	0.98	0.75	0.94
6.00	1.00	0.89	0.86	0.98	0.67	0.75	0.82	0.89	0.96	0.73	0.88
8.00	1.00	0.89	0.81	0.93	0.64	0.71	0.78	0.85	0.91	0.69	0.83
12.00	1.00	0.89	0.74	0.85	0.58	0.65	0.71	0.77	0.83	0.63	0.76
					3 in. cover						
Minimum	0.72	0.76	0.58	0.64	0.69	0.75	0.78	0.81	0.83	0.87	0.92
2.50	1.00	0.92	0.67	0.78	0.60	0.68	0.74	0.81	—	—	—
3.00	1.00	0.89	0.59	0.69	0.80	0.91	0.67	0.74	0.80	—	—
4.00	1.00	0.89	0.78	0.91	0.64	0.73	0.81	0.91	0.67	0.79	—
5.00	1.00	0.89	0.72	0.75	0.88	**1.01**	0.68	0.76	0.84	0.66	0.86
6.00	1.00	0.89	0.72	0.64	0.75	0.86	0.96	0.65	0.72	0.86	0.75
8.00	1.00	0.89	0.72	0.60	0.65	0.74	0.82	0.91	0.98	0.69	0.88
12.00	1.00	0.89	0.72	0.60	0.62	0.70	0.78	0.86	0.94	0.65	0.82

1000 psi = 6.895 MPa; 1 in. = 25.4 mm.

velopment length expression for all bar sizes, i.e., that given in Code Change CB-23 in Eq. (12.X) (Table 4), with no special provisions (Section 12.2.2.2) for smaller bar sizes; and 2) add an additional modification factor of 0.6 for bars with cover ≥ $2d_b$ and clear spacing > $4d_b$.

Discussion—The adoption of Proposal B as a modification to CB-23 results in a reduction in basic development length equations from two to one, and an increase in modification factors from two (1.0 and 1.5) to three (0.60, 1.0, and 1.5). In addition, only a single criterion is needed in Section 12.2.3.2. Proposal B is compared to Eq. (15) in Table 6. The l_d ratios, which range from 1.04 to 0.51, show that the modified recommendations are generally more conservative for the smaller bars with low covers and close spacings and more economical for all bars with at least a 2-bar diameter cover and a 4-bar diameter clear spacing.

Ease of application

Both CB-23 and Proposal B have a major advantage over the current provisions (ACI 318-89) and Proposal A in that basic development lengths can be expressed as multiples of the bar diameter. This is appealing to many engineers, since the basic provisions can be remembered easily and, in most cases, depend only on the concrete strength, since Grade 60 steel is the standard for most applications. CB-23 and Proposal B, however, also retain one of the disadvantages of the current code (ACI 318-89), in that the cover and bar spacing criteria depend upon multiples of bar diameter, not on the cover or bar spacing expressed in inches. Thus, the designer is faced with cover and spacing criteria that change with bar size.

The complications involved in having to evaluate cover and bar spacing criteria in terms of bar diameters must be balanced with the reduced number of rules necessary to describe the development length provisions. CB-23 has two basic development length criteria and two cover/bar spacing modification factors. Proposal B has a single development length equation and three modification factors. In contrast, Proposal A has three development length equations and four modification factors. CB-23 and Proposal B require that every bar be categorized, whereas Proposal A requires only the exceptions—bars with low covers and close spacings or high covers and high spacings—to be categorized. Any of the new recommendations provide advantages over the current code (ACI 318-89). In deciding which of the new recommendations to use, it would seem wise to conduct a series of side-by-side comparisons in design and detailing offices to ascertain which of the methods is easiest to use.

More on CB-23

To complete the evaluation of CB-23, the development lengths obtained from Eq. (15) were compared to those obtained from Sections 12.2.2 and 12.2.3.2 (Appendix L). The purpose of the combination of these two sections is to provide the designer with development length criteria that are more accurate than those obtained with the use of Sections 12.2.2 and 12.2.3.1. The comparison shows that the more exact procedures provide a good, generally conservative match with experimental data. The highest, and least conservative ratio is 1.06. The lowest ratio is 0.60. The proposed code revisions are slightly unconservative when $C_b = C_s$ and become progressively more conservative as the difference between C_b and C_s increases.

Effect of steel strength

As described earlier in this paper, Eq. (14) and (15) show the widely known fact that development length must increase more rapidly than the steel stress f_s (Orangun et al. 1975, 1977).

A comparison of Eq. (14) and (15) with the design equations [Eq. (16a) through (c) and Eq. (12.X) in Table 4] shows that the design equations become successively less conservative as the steel stress increases, since they provide for an increase in l_d that is proportional to f_y. ACI 318-83 included a modification factor 2-60,000/f_y (f_y in psi), based on Eq. (14), to account for the use of reinforcement with $f_y >$ 60,000 psi (414 MPa). ACI 318-89 and Code Change CB-23 include no factor to account for $f_y >$ 60,000 psi (414 MPa). The current analysis shows that the term used in ACI 318-83 is somewhat overconservative. For $f_c' \cong$ 4500 psi (31 MPa), the factor obtained using Eq. (15) for application with Eq. (16) or (12.X) (Table 4) is 1.5-30,000/f_y (f_y in psi) or 1.1 for Grade 75 (517 MPa) steel (ASTM A 615-91). If a Grade 80 steel were used [although Grade 80 (552 MPa) steel is not presently a standard grade], the calculated factor would go up to only 1.125, not enough of a change from 1.1 to be of concern.

Thus, it is recommended that a factor of 1.1 be applied to basic development length expressions in the form given in Eq. (16) or (12.X) (Table 4) for specified steel strengths in excess of Grade 60 (414 MPa) to account for the fact that the required development length increases more rapidly than the stress in the bar being developed. The extra 10 percent in development length required by a Grade 75 (517 MPa) bar should not be ignored.

Meaning of l_d ratios

The l_d ratios presented in Tables 3, 5, and 6 represent factors needed to modify the design provisions to produce l_d from Eq. (15) [or 12 in. (305 mm), whichever is greater]. Therefore, they do not represent the inverse of strength ratios based on Eq. (12). A strength ratio can be calculated only by substituting the "code value" of l_d into Eq. (12) and determining the corresponding bar force. For example, for f_y = 60,000 psi (414 MPa) and f_c = 4500 psi (31 MPa), an l_d ratio of 1.1 represents a strength ratio of 0.940, rather than 1/1.1 = 0.909. Likewise, an l_d ratio of 0.9 represents a strength ratio of 1.074 rather than 1/0.9 = 1.111. The highest l_d ratio, 1.28 in Table 5, corresponds to an unconservative strength ratio of 0.85 (but not as bad as indicated by 1/1.28 = 0.78). Thus, the strength ratios represented by l_d ratios $\neq$ 1.0 are always closer to 1.0 than would be suggested by the inverse of the l_d ratio.

CONCLUSIONS AND RECOMMENDATIONS

The study described in this paper is aimed at: 1) establishing an expression that accurately represents development and splice strength as a function of development/splice length, bar size, concrete strength, concrete cover, and bar spacing; and 2) using that expression to establish and evaluate simplified criteria for use with the bond and development provisions of the ACI Building Code (ACI 318-89) for bars without transverse reinforcement. The conclusions and recommendations that follow are based on this work.

Conclusions

1. Eq. (12) provides a more accurate representation of development and splice strength than the Orangun, Jirsa, and Breen (1975, 1977) equation, and inherently provides better guidance when there is a significant difference between one-half of the clear spacing between bars C_s, and the concrete cover C_b. Eq. (12) indicates that bar force increases in a linear but nonproportional manner with development length and bar area and in a nearly linear manner with concrete cover and spacing between bars.

2. The new expression is obtained primarily by recognizing and limiting the effects of unintentional bias in the test data.

3. Each of three new proposals for modifying the development length criteria in ACI 318-89, Proposal A, Proposal B, and CB-23 provide significant advantages over the current provisions.

4. The criteria presented under Proposals A and B and under combined Sections 12.2.2 and 12.2.3.2 of CB-23 are generally conservative and economical.

5. The criteria presented under combined Sections 12.2.2 and 12.2.3.1 of CB-23 provide both the least conservative development lengths (for No. 4 through No. 6 bars with minimum covers) and the least economical development lengths (for No. 3 through No. 11 bars with higher covers) of the provisions considered.

6. The observed nonproportional relationship between bar force and development length means that the required development length must increase more rapidly than the steel stress f_s. Development length increases an extra 10 percent as f_s increases from 60,000 to 75,000 psi (414 to 517 MPa).

Recommendations

1. Due to the nonproportional relationship between bar force and development length, Eq. (12) and (15), or future improvements to Eq. (12) and (15), should be used as the basis for evaluating the safety and economy of development length criteria.

2. Proposals A and B and CB-23 should be evaluated in design offices to determine relative ease of application.

3. If proposed code change CB-23 is adopted by ACI Committee 318, modifications should be made, such as those presented in Proposal B, to improve the relative safety of development lengths for No. 4 through No. 6 bars with low covers and the relative economy of development lengths for No. 3 through No. 11 bars with higher covers.

4. An additional development length modification factor of 1.1 should be used for steels with specified yield strengths in excess of 60,000 psi (414 MPa). Without this modification factor, development and splice lengths provided for Grade 75 (517 MPa) bars will be 10 percent under length.

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NOTATION

A_b = bar area
C = $C_{min} = min\ (C_s, C_b)$
C_b = cover
$\mathbf{C}_c$ = see Table 4
$C_{max} = (C_s, C_b)$
C_s = min (one half of clear spacing, side cover)
$\mathbf{C}_s$ = see Table 4
d_b = bar diameter
f_c' = concrete compressive strength
f_y = yield strength of steel
l_d = development length or splice length
l_{db} = basic development length
u = average bond stress at failure
u_{cal} = calculated average bond stress at failure
u_t = experimental average bond stress at failure

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