DEVELOPMENT LENGTH CRITERIA:
BARS WITHOUT TRANSVERSE REINFORCEMENT

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DEVELOPMENT LENGTH CRITERIA: BARS WITHOUT TRANSVERSE REINFORCEMENT

ABSTRACT

An expression that accurately represents development and splice strength as a function of concrete cover and bar spacing is developed and used to establish and evaluate modifications to the bond and development provisions of the ACI Building Code (ACI 318-89) for bars without 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 provides better guidance when there is a significant difference between the concrete cover and one-half of the clear spacing between bars.

The expression for development and splice strength is used to establish new criteria that follow the format of ACI 318-89 and to evaluate design criteria that are currently under review by ACI Subcommittee 318-B. The new criteria that follow the format of ACI 318-89 are generally conservative and economical. The provisions under study by Subcommittee 318-B are unconservative for No. 6 bars and smaller with minimum covers and close spacings, and are over-conservative for most bars with higher covers and wider spacings. Modifications are recommended that increase both the safety and the economy provided by the provisions under study by ACI Subcommittee 318-B.

INTRODUCTION

Work is now underway on a large-scale study at the University of Kansas designed 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 importantly, 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 report 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 provisions in ACI 318-89. Such a step is important because modifications made to Section 12.2 in the 1989 revision of the ACI Building Code (ACI 318-89) have raised objections from individuals in the design community because of added complications in bond and development design, compared to earlier versions of the Building Code. 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. To address this problem, new criteria were added to the Code. These criteria established categories of bars based on cover, clear spacing between bars, and the amount of confining reinforcement. Based on the category, development length modification factors, 0.75, 0.8, 1.0, 1.4, and/or 2.0, are applied to a basic development length, that is itself a function of bar size, steel yield stress, and concrete strength. Unlike earlier versions of ACI 318, the current provisions require that every bar must be categorized, even if the modification factor is 1.0 (i.e., not just the best and worst cases). 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.

Several approaches to simplification have been proposed, including variations on current code procedures, proposed by the authors (and described fully in this report), and new expressions, proposed by Breen (1991), that give the designer the option of using simplified procedures or a more accurate representation of development length requirements. The Breen proposal is embodied in Code Change CB-23 that is now under consideration by ACI Subcommittee 318-B (1992).

Faced with both the need to characterize the bond strength of current reinforcing bars and the opportunity to significantly simplify current design criteria, the goals of this study are to select an accurate representation for development and splice strength, to use that representation to develop simple, accurate design provisions modeled after current Code provisions, and to evaluate and suggest modifications to the proposals now under consideration by ACI Subcommittee 318-B (1992).

PLAN OF ATTACK

The work consists of two phases. The goal of the first phase is to establish 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. This phase consists of evaluating the expression developed by Orangun, Jirsa, and Breen (1975, 1977), which provides close agreement with test data for bond and splice strength; developing an improved expression using an expanded data base; and demonstrating the accuracy of the new expression. The goals of the second phase are to use the expression to establish simplified design criteria for bond and development and to evaluate the provisions of Code Change CB-23 that is now under study by ACI Subcommittee 318-B (1992). For the current effort, the effects of transverse reinforcement are neglected. These will be considered in a future report.

ANALYSIS

Orangun, Jirsa, Breen 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.

$$\frac{u}{\sqrt{f'_c}} = 1.22 + \frac{3.23\ C}{d_b} + \frac{53\ d_b}{l_d} \tag{1}$$

in which $C = \min(C_s, C_b)$

$C_s = \min$ ($1/2$ of clear spacing, side cover)

C_b = cover

d_b = bar diameter

l_d = development length or splice length

Eq. 1 was based on a total of 62 test specimens, summarized in Table 1 [also in Table 1 of Orangun et al. (1975)]. This expression was modified by rounding the coefficients to obtain a somewhat more conservative value for u, denoted as u_{cal}.

$$\frac{u_{cal}}{\sqrt{f'_c}} = 1.2 + \frac{3\ C}{d_b} + \frac{50\ d_b}{l_d} \tag{2}$$

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 without 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 et al. (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. As illustrated in Fig. 1, 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 and C_b are defined following Eq. 1.

The approach used in this study differs somewhat from the approach used in the Orangun study: Principal among the changes is a switch from bond stress to bond force as the measure of strength. Although bond stress has been the traditional measure of development and splice strength, the switch was 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 the time of bond failure (Mains 1951). Thus, at failure, bond stress, as the term is usually applied, is no more than a term that is derived from the ultimate bond force.

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 Eqs. 1 and 2 are modified to express bar force at failure normalized with respect to $\sqrt{f'_c}$, the following equations are obtained.

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

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

Eq. 3 represents the expression obtained from the Orangun et al. (1975, 1977) regression analysis, and Eq. 4 represents the smoothed, conservative form of the equation.

The values of $A_b f_s/\sqrt{f'_c}$ from the tests are plotted versus the strengths predicted by Eqs. 3 and 4 in Figs. 2 and 3, respectively, 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). Figs. 2 and 3 show that Eqs. 3 and 4 do a good job of representing the overall data – for the best fit line, the slope is close to 1.0 and the intercept is close to zero. However, Figs. 2 and 3 also show that when the No. 6, No. 8, and No. 11 bars are considered individually, the individual best fit lines differ significantly from the overall trend.

For Eq. 3 (the expression obtained by Orangun et al. using regression analysis), the best fit lines based on bar size have slopes of 0.81, 0.59 and 0.98 for No. 6, No. 8 and No. 11 bars, respectively. The intercepts are 38.9, 343.5 and 143.1, respectively.

For Eq. 4 (the smoothed, conservative version of Eq. 3), the best fit lines based on bar size have slopes of 0.86, 0.62 and 1.04 for No. 6, No. 8 and No. 11 bars, respectively. The intercepts are 37.9, 343.2 and 139.3, respectively.

The differences between the overall trends, Eq. 3 or Eq. 4, and the trends for the individual bar sizes indicate that the influence of one or more of the controlling parameters is not correctly represented in Eqs. 1-4, and that some improvements need to be made to obtain an accurate prediction 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 without 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, Hadje-Ghaffari, Darwin and McCabe 1990, 1991, Hester, Salimazavaregh, Darwin and McCabe 1991).

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 Eqs. 1-4 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 Eqs. 1-4 (Table 1) shows that this criterion may have been unintentionally violated. Probably the most striking observation is the fact that the larger reinforcing bars [No. 8 and No. 11 bars tested by Ferguson and Breen (1965)] have 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. An increase in C_s/C_b, in turn, should result in an increase in the value of bond stress, as illustrated in Fig. 1. The effect of C_s/C_b 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 $1/4$ in. 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 Eqs. 1-4 would reflect some of these biases. Overall, these biases cause Eqs. 1-4 to overestimate bond strength when $C_s/C_b \cong 1$, and to underestimate bond strength when C_s/C_b differs greatly from 1.0. [The second point, as noted earlier, was observed by Orangun et al. (1975, 1977).] Not accounting for bias in the data is the principal reason why Eqs. 3 and 4 predict higher strengths at the higher values of bond force than predicted by the individual trends for No. 6 and No. 8 bars in Figs. 2 and 3.

In spite of these observations, the authors do not suggest that the *form* of Eqs. 1-4 is wrong – only that the analysis requires additional scrutiny if the effects of bias in the data are to be limited.

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, 147 tests are used, representing both splice and development 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 et al. (1975), using No. 4, No. 6, No. 7, No. 8, and No. 11 bars. Only tests of specimens that provided a clear spacing of one bar diameter or 1 in., 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. 4, 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 in Fig. 1 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) when 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 $C_s \geq C_b$,

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

For $C_b \geq C_s$,

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

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 crack surface area that is produced by cracking between bars than by cracking between a bar and the concrete surface. When $C_s > C_b$, the principal bond cracks propagate from the bar to the concrete surface (Fig. 5a). Therefore, the crack length is closely approximated by the cover. When $C_b > C_s$, however, the principal bond cracks propagate between bars (Fig. 5b). 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 use in the next step in the analysis, the coefficients in Eqs. 7a and 7b are modified to provide a ratio of 1.0 when $C_s/C_b = 1.0$.

For $C_s \geq C_b$,

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

For $C_b \geq C_s$,

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

Eqs. 8a and 8b are close enough that a single approximation can be used when $C_s \neq C_b$.

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

Combining Eqs. 6 and 9 gives

$$\frac{A_b\ f_s}{\sqrt{f'_c}} = 10\ l_d\ (C + 0.5\ d_b)\ (0.92 + 0.08\ \frac{C_{max}}{C_{min}}) \qquad (10)$$

Plotting the test results versus the values predicted by Eq. 10 (Fig. 6) shows that, like the original Orangun et al. equation (Figs. 2 and 3), the overall trend in the data is closely represented by Eq. 10. It also shows that, as observed in Figs. 2 and 3, the trends obtained for individual bar sizes do not coincide with the overall trend. The best fit lines for the individual bar sizes illustrated in Fig. 6 are as follows.

For No. 4 bars,

$$\frac{A_b\ f_s}{\sqrt{f'_c}} = 7.84\ l_d\ (C + 0.5\ d_b)\ (0.92 + 0.08\ \frac{C_{max}}{C_{min}}) + 43.0 \qquad (10a)$$

For No. 6 bars,

$$\frac{A_b\ f_s}{\sqrt{f'_c}} = 7.46\ l_d\ (C + 0.5\ d_b)\ (0.92 + 0.08\ \frac{C_{max}}{C_{min}}) + 108.3 \qquad (10b)$$

For No. 7 bars,

$$\frac{A_b\ f_s}{\sqrt{f'_c}} = 6.98\ l_d\ (C + 0.5\ d_b)\ (0.92 + 0.08\ \frac{C_{max}}{C_{min}}) + 280.0 \qquad (10c)$$

For No. 8 bars,

$$\frac{A_b\ f_s}{\sqrt{f'_c}} = 6.36\ l_d\ (C + 0.5\ d_b)\ (0.92 + 0.08\ \frac{C_{max}}{C_{min}}) + 338.5 \qquad (10d)$$

For No. 11 bars,

$$\frac{A_b\ f_s}{\sqrt{f'_c}} = 6.71\ l_d\ (C + 0.5\ d_b)\ (0.92 + 0.08\ \frac{C_{max}}{C_{min}}) + 637.1 \tag{10e}$$

To improve the match with the data, the results in Fig. 6 are reanalyzed using the technique of dummy variables (Draper and Smith 1981). This analysis is based on the assumption that Eqs. 10a-10e accurately represent all aspects of bond performance except bar size. The expression obtained from the dummy variable regression analysis is

$$\frac{A_b\ f_s}{\sqrt{f'_c}} = 6.73\ l_d\ (C + 0.5\ d_b)\ (0.92 + 0.08\ \frac{C_{max}}{C_{min}}) + K \tag{11}$$

with K = 59.7 for No. 4 bars, 127.4 for No. 6 bars, 297.5 for No. 7 bars, 327.1 for No. 8 bars, and 650.1 No. 11 bars (Fig. 7).

With increasing bar size, the value of K increases more rapidly than the bar diameter and more rapidly than even the area of the bar. However, as shown in Table 2, K can be conservatively represented 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, adding the term 300 A_b to Eq. 11 results in an expression that is slightly conservative overall. To simplify later calculations, the coefficient, 6.73, in Eq. 11 is modified slightly to give:

$$\frac{A_b\ f_s}{\sqrt{f'_c}} = 6.67\ l_d\ (C + 0.5\ d_b)\ (0.92 + 0.08\ \frac{C_{max}}{C_{min}}) + 300\ A_b \tag{12}$$

Test results are compared to strengths predicted by Eq. 12 in Fig. 8, 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 –18.3, –63.1, 91.6, 173.4, and 171.2, respectively.

Eq. 12 has the same general form as Eq. 4. However, it includes the effects of $C_s/C_b \neq 1$ and more accurately represents the effects of bar size than do the Orangun et al. (1975, 1977) expressions. This is demonstrated in the next section where the predictions obtained using Eq. 12 are compared with those obtained using Eqs. 3 and 4.

Comparison with Data

A detailed comparison with the individual test results used in the Orangun et al. (1975) report (Chinn et al. 1955, Ferguson and Breen 1965, Chamberlin 1956, 1958, Ferguson and Krishnaswamy 1971, Ferguson and Briceno 1969, Thompson et al. 1975, Tepfers 1973, Ferguson and Thompson 1962, 1965) is presented in Appendices A through I. Additional comparisons with tests by Hester et al. (1991), Choi et al. (1990, 1991), Treece and Jirsa (1987, 1989), and Hamad and Jirsa (1990) are presented in Appendix J. In each case, the test results are compared with the predictions obtained using Eqs. 3, 4 and 12. The comparisons are summarized in Table 3, which presents the mean test prediction ratios for the 62 specimens used by Orangun et al. to develop Eqs. 3 and 4, and each of the test series covered in Appendices A through J. In addition to the mean test/prediction ratios, Table 3 presents the maximum and minimum test prediction ratios and the coefficient of variation (COV) for each series. Table 3 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 summary excluding the results of Tepfers 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 Eqs. 3, 4 and 12.

As illustrated by a comparison of Fig. 8 with Figs. 2 and 3, overall, Eq. 12 provides a better match with the test data than Eqs. 3 or 4. In Fig. 8, the trends for the individual bars closely match the overall trend. The comparisons in Table 3 show that Eq. 12 produces the lowest coefficient of variation for 11 of the 14 test series, with Eqs. 3 and 4 producing lower and nearly equal COV's 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, Eqs. 3, 4, and 12 give mean test/prediction ratios of 1.078, 1.145, and 1.111, 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 1.053, 1.119, and 1.073, for Eqs. 3, 4, and 12, with corresponding coefficients of variation of 0.202, 0.201, and 0.153. 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, attests 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.

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

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. This interpretation is correct, however, 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 length rather than in multiples of the bar diameter.

$$l_d = \frac{\left(\frac{f_s}{\sqrt{f'_c}} - 200\right) A_b}{\pi\,(3C + 1.2\,d_b)} = \frac{0.106\left(\frac{f_s}{\sqrt{f'_c}} - 200\right) A_b}{(C + 0.4\,d_b)} \tag{14}$$

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, 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.

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

A direct comparison of Eq. 14 and Eq. 15, with $C_s = C_b$, shows that for $f_s = f_y = 60{,}000$ psi, 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.

Eqs. 12 and 15 can be used to both characterize development and splice strength of existing reinforcing bars and serve as a framework for modifying development length design criteria. These expressions provide more accurate representations of development and splice strength than do the earlier expressions and inherently provide better guidance when there is a significant difference between the values of C_s and C_b. Table 4 presents a summary of development lengths calculated using Eq. 15 for No. 3-No. 18 bars with covers ranging from $^3/_4$ in. to 3 in. and center-to-center spacings ranging from the minimum allowed by ACI 318-89 to 12 in., for $f_s = f_y =$ 60,000 psi and $f'_c = 4500$ psi.

DESIGN CRITERIA

One of the key goals of this study is to simplify the design rules found in ACI 318-89. To achieve this goal in a straightforward manner, one approach is to make changes within the framework of the 1989 code format. Such an approach is offered in this report. Another approach has been developed by Breen (1991) as part of his work on a Task Committee of ACI Subcommittee 318-B. Both approaches are addressed in the following sections.

Criteria Following Current Code Format

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. The basic development lengths, l_{db}, provided in Section 12.2 of ACI 318-89 are:

For No. 11 bars and smaller,

$$l_{db} = \frac{0.04\ A_b\ f_y}{\sqrt{f'_c}} \tag{16a}$$

For No. 14 bars,

$$l_{db} = \frac{0.085\ f_y}{\sqrt{f'_c}} = \frac{0.0378\ A_b\, f_y}{\sqrt{f'_c}} \qquad (16b)$$

For No. 18 bars,

$$l_{db} = \frac{0.125\ f_y}{\sqrt{f'_c}} = \frac{0.313\ A_b\, f_y}{\sqrt{f'_c}} \qquad (16c)$$

in which f_y = yield strength of steel.

For the current proposal, Eqs. 16a-16c are modified as follows:

For No. 11 bars and smaller,

$$l_{db} = \frac{0.06\ A_b\, f_y}{\sqrt{f'_c}} \qquad (17a)$$

For No. 14 bars,

$$l_{db} = \frac{0.125\ f_y}{\sqrt{f'_c}} = \frac{0.0556\ A_b\, f_y}{\sqrt{f'_c}} \qquad (17b)$$

For No. 18 bars,

$$l_{db} = \frac{0.175\ f_y}{\sqrt{f'_c}} = \frac{0.0438\ A_b\, f_y}{\sqrt{f'_c}} \qquad (17c)$$

The coefficients in Eqs. 17a-17c are increased compared to those in Eqs. 16a-16c 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 Eqs. 17a-17c are compared in

Table 5a with those obtained using Eq. 15 (Table 4), for $f_s = f_y = 60{,}000$ psi and $\sqrt{f'_c} = 4500$ psi.

The calculated modification factors range from 2.32, for No. 3 bars with $^3/_4$ in. cover and $1^3/_8$ in. center-to-center spacing, to 0.42, for No. 11 bars with 3 in. cover and 12 in. center-to-center spacing.

Based on an analysis of the modification factors presented in Table 5a, the following code provisions are suggested:

The basic development length criteria presented in Eqs. 17a-17c should be adopted.

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

1.5 for bars with cover < $1^1/_2$ in. or spaced laterally < 3 in., except 2.0 for bars with center-to-center bar spacing < 2 in.

0.8 for bars spaced at least 8 in. on center

0.9 for bars with cover of at least 3 in.

The 1.5 and 2.0 factors would be mandatory; the 0.8 and 0.9 factors would be permitted. The current minimum value of $l_d = 0.03\ d_b\ f_y/\sqrt{f'_c}$ should be retained.

These provisions are compared with development lengths calculated using Eq. 15 in Table 5b. The comparisons in Table 5b have the additional proviso that the minimum value used for l_d from Eq. 15 is 12 in.

A review of the comparisons presented in Table 5b shows that in all but a few cases the proposed provisions provide a close but conservative match when compared to either Eq. 15 or a minimum development length of 12 in. The proposed provisions are least conservative for bars with minimum spacing and minimum ($^3/_4$ in.) cover, producing a ratio of Eq. 15 to the proposed code provision as high as 1.14, for No. 3 bars with a $^3/_4$ in. cover and minimum spacing. The results are most conservative for No. 7 through No. 14 bars with a cover of 2 in. and center-to-center spacings between 4 and 8 in., and No. 7 through No. 14 bars with 3 in. cover and center-to-center spacings in excess of 5 in. The ratios drop as low as 0.59 for No. 11 bars with a 3 in.

cover and 12 in. center-to-center spacing. Overall, however, the comparisons are good, and the proposed criteria have 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 basic change in philosophy from the current (ACI 318-89) provisions 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 greatly aid the designer in selecting factors to modify the basic development length expressions.

ACI Subcommittee 318-B Recommendations

ACI Subcommittee 318-B currently has under consideration the following revision to Section 12.2 of the ACI Building Code (designated as Code Change CB-23).

12.2.1 Development length, l_d, in inches for deformed bars and deformed wire in tension shall be computed as the product of the basic development length l_{db} of 12.2.2 and the applicable modification factors of 12.2.3 through 12.2.5, but l_d shall not be less than 12 in.

12.2.2 Basic development length l_{db} shall be:

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

$$l_{db} = 0.05\, d_b \frac{f_y}{\sqrt{f'_c}} \qquad \text{(Eq. 12.X)} \qquad (18)$$

12.2.2.2 For #6 deformed bars and smaller and for deformed wire, the basic development shall be taken as 80 percent of Eq. 12.X [Eq. 18].

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

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

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

$\boldsymbol{C_c}$ = Thickness of concrete cover measured from extreme tension fiber to center of bar, in.

$\boldsymbol{C_s}$ = 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 $\boldsymbol{C_s}$ 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.

N = Number of bars in a layer being spliced or developed at a critical section.

$\boldsymbol{C_c}$ and $\boldsymbol{C_s}$ are equivalent to (C_b + 0.5 d_b) and (C_s + 0.5 d_b), respectively.

These provisions 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 in place of the three expressions used in the current code (Eqs. 16a-16c) and the proposal made earlier in this report (Eqs. 17a-17c).

The principal changes offered by CB-23 involve the use of an expression 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 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 Eqs. 12 and 15 provides a useful tool for evaluating the proposed criteria. As with the earlier discussions in this report, this evaluation will be limited to members without transverse reinforcement.

The proposed simplified criteria (Section 12.2.2 plus Section 12.2.3.1) are compared to Eq. 15 in Table 6a. As with Table 5b, the comparisons represent the ratio of l_d from Eq. 15 to l_d

based on CB-23, with a minimum value of 12 in. used for l_d from Eq. 15.

The comparisons made in Table 6a show that CB-23 produces generally conservative results, except for No. 4 bars at minimum spacing, No. 5 bars with 3/4 in. cover at spacings of 2 1/2, 3 and 4 in., and No. 6 bars with 3/4 in. cover at spacings up through 6 in. for which the results are quite unconservative. The highest (and most unconservative) ratio in Table 6a is 1.28, for No. 4 bars with 3/4 in. cover and minimum spacing and No. 6 bars with 3/4 in. cover and 2.5 in. 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. cover and 12 in. 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 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.

With this in mind, two modifications are recommended for CB-23 that will improve both safety and economy. These recommendations are to 1) use a single development length expression for all bar sizes, i.e., that given in CB-23 in Eq. 18, with no special provisions for smaller bar sizes, and 2) add an additional modification factor of 0.6 for bars with cover $\geq 2d_b$ and a clear spacing $\geq 4d_b$. The trade-off is a reduction in basic development length equations from 2 to 1, and an increase in modification factors from 2 (1.0 and 1.5) to 3 (0.60, 1.0, and 1.5). In addition, only a single criterion is needed in Section 12.2.3.2. The modified provisions are compared to Eq. 15 in Table 6b. The comparisons, with a range of ratios from 1.06 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.

The proposed provisions, whether as originally recommended in Code Change CB-23 or as modified here, have a major advantage over current provisions and recommendations made earlier in this report in that basic development lengths can be expressed as multiples of the bar diameter. This has a strong appeal for many engineers, since the basic provisions can be easily remembered and, in most cases, depend only on the concrete strength, since Grade 60 steel is the standard for most applications. These provisions, however, also retain one of the main 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. The modified version of those provisions (suggested here) has a single development length equation and three modification factors. In contrast, the provisions offered under the current code format have three development length equations and four modification factors. The two versions of the CB-23 require that every bar be categorized, whereas the provisions offered under the current format require only the exceptions – bars with low covers and close spacings or high covers and high spacings – to be categorized. Any of the new recommendations provides generally safe development length criteria, and all provide advantages over the current code (ACI 318-89). In making a decision as to 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.

To complete the evaluation of CB-23, the development lengths obtained from Eq. 15 are compared to those obtained from Sections 12.2.2 and 12.2.3.2 in Table 7. 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.

As demonstrated in Table 7, 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 $C_b \cong C_s$ and become progressively more conservative as the difference between C_b and C_s increases.

Effect of Steel Strength

Eqs. 14 and 15 show the widely known fact (Orangun et al. 1975, 1977) that development length must increase more rapidly than the steel stress, f_s.

A comparison of Eqs. 14 and 15 with Eqs. 16a-c, 17a-c, and 18 shows that Eqs. 16-18 become successively less conservative as the steel stress increases, since Eqs. 16-18 provide for an increase in l_d that is proportional to f_y. ACI 318-83 included a modification factor for Eqs. 16a-16c, based on Eq. 14, $2-60{,}000/f_y$, to account for the use of reinforcement when $f_y > 60{,}000$ psi. ACI 318-89 and Code Change CB-23 include no factor to account for $f_y > 60{,}000$ psi. The current analysis shows that the term used in ACI 318-83 is somewhat overconservative. For $f'_c \cong 4500$ psi, the factor obtained using Eq. 15 for application with Eqs. 16, 17 or 18 is $1.5-30{,}000/f_y$, or 1.1 for Grade 75 steel (ASTM A 615-91). If a Grade 80 steel were used (although Grade 80 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 Eqs. 16-18 for steel strength in excess of Grade 60 to account for the fact that the required development length goes up more rapidly than the stress in the bar being developed. The extra 10 percent development length required by a Grade 75 bar should not be ignored.

Additional Comments

ϕ-Factors.– The reader is reminded that the basis for comparison used in this report, Eq.

12, produces a slightly conservative prediction of development and splice strength. The exact degree of conservatism is not clear, but it ranges from about 14 percent, based on the best fit lines in Fig. 8, to 7.3 percent, based on the comparison with data from the 200 test results that exclude the Tepfers (1973) specimens (Table 3). Thus, a ratio of l_d from Eq. 15 to l_d from design provisions of 1.0 will produce development/splice strengths that are, on the average, 7.3 to 14 percent higher than test results. A simple approach to calculating a capacity reduction factor, ϕ, suggests that these values correspond to a capacity reduction factor in the range of $1/1.073 = 0.935$ to $1/1.14 = 0.877$.

As pointed out by Breen (1991), flexural design in ACI 318-89 already includes a ϕ-factor of 0.9, which should be considered as part ϕ for development and splice strength. Therefore, an l_d ratio of 1.0 corresponds to a range in ϕ for development and splice strength from $0.9 \times 0.935 = 0.84$ to $0.9 \times 0.877 = 0.79$.

Meaning of l_d ratios.–The l_d ratios presented in Tables 5-7 represent factors needed to modify the design provisions to produce l_d from Eq. 15 (or 12 in., 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 and $f'_c = 4500$ psi, 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 6a, 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.

SUMMARY AND CONCLUSIONS

The study described in this report is aimed at 1) establishing an expression that accurately represents development and splice strength as a function of 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 (1989) for bars without transverse reinforcement.

The process of establishing an expression to represent development and splice strength involves the evaluation of the expressions developed by Orangun, Jirsa and Breen (1975, 1977) and obtaining an improved version of those expressions using analysis techniques that limit the effects of unintentional bias in the test data. The resulting expression can be used to both characterize the development and splice strength of existing reinforcing bars and serve as a framework for evaluating and modifying development length design criteria. The expression provides a more accurate representation of development and splice strength than do the earlier expressions, and inherently provides better guidance when there is a significant difference between one-half of the clear spacing between the bars, C_s, and the concrete cover, C_b.

The improved expression to represent development and splice strength is used to establish simplified bond and development criteria that follow the format of the current ACI Building Code (ACI 318-89) and to evaluate the provisions of Code Change CB-23, now under study by ACI Subcommittee 318-B.

The proposed criteria that follow the format of ACI 318-89 are generally conservative and economical. These provisions include three equations for basic development length (Eqs. 17a-17c) and four development length modification factors, based on cover and bar spacing. The proposed modifications to ACI 318-89 are summarized in Table 8.

CB-23 includes two approaches to development length design. One approach includes design expressions that are based on bar diameter rather than bar area (as used in ACI 318-89) and simplified modification factors to account for confining reinforcement, cover and bar spacing. The other approach is more complex, but allows the designer to more accurately account for confining reinforcement and member geometry. The first approach is unconservative for No. 6 bars and smaller with low cover and close spacing and overconservative for most bars with covers of $1^1/_2$ in. or more. The more complex approach gives realistic and generally conservative results for most bar sizes. CB-23 includes two expressions for basic development length and two development length modification factors. Overall, safety and economy are improved by reducing the number of expressions for basic development length to one and increasing the simplified development length modification factors to three. The modified version of CB-23 is summarized in Table 9.

The proposed provisions that follow the current code format (Table 8) have a number of advantages over the current ACI Building Code (ACI 318-89) and CB-23 (original and as modified), in that not all bars need to be categorized and the criteria for selecting development length modification factors depend only on specific values of cover and center-to-center bar spacing, not on bar size. Both the original and modified versions of CB-23 have a major advantage over the current provisions and the recommendations that follow the format of the current provisions, in that the basic development length can be expressed as a multiple of the bar diameter; the original and modified versions of CB-23 also include fewer expressions for basic development length, two and one, respectively, and fewer simplified modification factors, two and three, respectively. The two versions of the CB-23 have a major disadvantage, in that the cover and bar spacing criteria for selection of development length modification factors depend on multiples of bar diameter, not on the cover and bar spacing expressed in inches. Thus, a change in bar size may require a change in the modification factor, even if the cover and bar spacing do not change. It is recommended that side-by-side comparisons be carried out in design offices to determine which format is easiest to apply.

The analyses described in this report also address the effect of high yield strength on the required development length, and an additional development length modification factor of 1.1 is recommended for steels with yield strengths in excess of 60,000 psi. Without the proposed modification factor, development lengths and splices provided for Grade 75 bars will be 10 percent under-length. Thus, the use of the 1.1 factor is included in both sets of recommendations (Tables 8 and 9).

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TABLE 1

COMPARISONS WITH DATA FROM ORANGUN, JIRSA AND BREEN (1975) TABLE 1 – 62 SPECIMENS

							$A_bf_s/f'^{1/2}_c$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	A_bf_s kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
D15	11.00	0.75	0.62	2.88	4290	18.61	284.12	194.59	183.74	226.83	1.46	1.55	1.25
D40	16.00	0.75	0.75	2.94	5280	23.22	319.59	261.14	246.28	280.03	1.22	1.30	1.14
D24	16.00	0.75	0.81	2.88	4450	18.85	282.57	270.89	255.32	284.24	1.04	1.11	0.99
11R30a	41.25	1.41	1.31	4.65	4030	89.35	1407.51	1102.46	1040.31	1135.15	1.28	1.35	1.24
11R60a	82.50	1.41	1.41	4.63	2690	119.50	2304.07	1957.95	1846.33	1843.77	1.18	1.25	1.25
11F36b	49.50	1.41	1.47	4.63	3350	89.90	1553.23	1337.21	1260.57	1309.18	1.16	1.23	1.19
11F42a	57.75	1.41	1.48	4.63	3530	95.93	1614.60	1510.82	1424.11	1452.46	1.07	1.13	1.11
11R48a	66.00	1.41	1.50	4.67	5620	126.59	1688.63	1692.80	1595.42	1602.23	1.00	1.06	1.05
11F36a	49.50	1.41	1.50	4.65	4570	97.57	1443.37	1352.28	1274.56	1317.90	1.07	1.13	1.10
11F60b	82.50	1.41	1.50	4.63	4090	119.87	1874.29	2033.33	1916.27	1883.20	0.92	0.98	1.00
11F48a	66.00	1.41	1.53	4.64	3140	111.97	1998.24	1712.90	1614.07	1611.31	1.17	1.24	1.24
11F48b	66.00	1.41	1.58	4.66	3330	109.63	1899.87	1746.40	1645.15	1630.19	1.09	1.15	1.17
11F60a	82.50	1.41	1.59	4.62	2610	121.33	2374.88	2108.70	1986.21	1922.68	1.13	1.20	1.24
11R24a	33.00	1.41	1.67	4.65	3720	78.94	1294.21	1068.71	1006.55	1065.09	1.21	1.29	1.22
11R60b	82.50	1.41	1.75	4.62	3460	133.39	2267.66	2242.70	2110.56	1995.40	1.01	1.07	1.14
4a	6.00	0.50	1.00	2.50	4370	8.42	127.32	114.82	107.83	116.00	1.11	1.18	1.10
4c	6.00	0.50	1.00	2.50	4370	8.55	129.31	114.82	107.83	116.00	1.13	1.20	1.11
4b	6.00	0.50	1.00	2.50	4370	8.66	131.02	114.82	107.83	116.00	1.14	1.22	1.13
8F36a	36.00	1.00	1.41	3.29	4650	54.51	799.42	820.91	771.88	744.30	0.97	1.04	1.07
8F36b	36.00	1.00	1.40	3.24	3770	48.18	784.68	817.25	768.49	740.95	0.96	1.02	1.06
11R48b	66.00	1.41	2.06	4.68	3100	107.30	1927.08	2068.00	1943.58	1808.39	0.93	0.99	1.07
8F42b	42.00	1.00	1.45	3.27	3830	58.98	953.03	946.87	890.02	837.83	1.01	1.07	1.14
8R48a	48.00	1.00	1.48	3.26	3040	57.00	1033.83	1072.83	1008.16	931.56	0.96	1.03	1.11
8F42a	42.00	1.00	1.50	3.30	2660	51.46	997.76	968.18	909.80	850.76	1.03	1.10	1.17
8R80a	80.00	1.00	1.50	3.25	3740	75.90	1241.11	1692.63	1590.00	1403.22	0.73	0.78	0.88
8R64a	64.00	1.00	1.52	3.27	3550	70.37	1181.09	1400.59	1315.66	1178.25	0.84	0.90	1.00
8F39a	39.00	1.00	1.53	3.27	3650	58.44	967.36	922.87	867.12	812.82	1.05	1.12	1.19
8R30a	30.00	1.00	1.53	3.27	3030	41.28	749.94	748.55	703.48	679.94	1.00	1.07	1.10
8R42a	42.00	1.00	1.56	3.30	3310	55.42	963.24	993.77	933.54	865.27	0.97	1.03	1.11
D13	11.00	0.75	1.44	2.91	4820	21.43	308.74	285.74	268.32	275.97	1.08	1.15	1.12
D21	11.00	0.75	1.47	2.91	4480	18.97	283.45	289.09	271.42	277.90	0.98	1.04	1.02
D36	5.50	0.38	0.56	1.10	4410	5.53	83.23	62.50	58.79	62.52	1.33	1.42	1.33
8R24a	24.00	1.00	1.67	3.28	3530	46.37	780.46	666.44	626.03	610.98	1.17	1.25	1.28
D32	11.00	0.75	1.47	2.88	4700	20.16	294.13	289.09	271.42	277.68	1.02	1.08	1.06
8R18a	18.00	1.00	1.75	3.26	3470	33.99	576.94	556.32	522.59	525.64	1.04	1.10	1.10
D19	16.00	0.75	1.70	2.91	4230	26.24	403.43	415.45	389.46	365.94	0.97	1.04	1.10
18S15	93.00	2.25	2.63	4.50	2860	205.10	3835.20	4133.88	3892.91	3660.53	0.93	0.99	1.05
18S12	60.00	2.25	3.00	4.56	3160	179.83	3198.95	3193.28	3004.55	2918.64	1.00	1.06	1.10
SP40	15.00	0.63	0.83	1.25	3220	13.19	232.53	228.08	214.62	211.88	1.02	1.08	1.10
D26	24.00	0.75	0.75	1.10	5100	23.64	330.99	345.08	325.42	318.72	0.96	1.02	1.04
14S1	45.00	1.69	2.38	3.46	2710	102.26	1964.31	1856.04	1745.59	1677.62	1.06	1.13	1.17
D17	16.00	0.75	0.80	1.10	3580	16.70	279.12	269.27	253.82	261.09	1.04	1.10	1.07
D22	7.00	0.75	0.80	1.10	4480	10.11	151.05	170.27	160.54	188.48	0.89	0.94	0.80
D23	16.00	0.75	0.78	1.06	4450	16.59	248.66	266.02	250.80	258.74	0.93	0.99	0.96

TABLE 1, continued

							$A_bf_s/f'^{1/2}_c$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	A_bf_s kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
D5	11.00	0.75	1.50	2.00	4180	19.05	294.65	292.44	274.53	273.17	1.01	1.07	1.08
D14	11.00	0.75	0.83	1.10	4820	13.79	198.61	217.62	205.11	222.67	0.91	0.97	0.89
D31	5.50	0.38	0.83	1.10	4700	6.83	99.62	77.58	72.78	71.28	1.28	1.37	1.40
D33	20.25	1.41	1.55	2.03	4830	40.81	587.26	758.91	715.31	779.97	0.77	0.82	0.75
8F36k	36.00	1.00	1.38	1.42	3460	41.62	707.56	809.94	761.71	689.25	0.87	0.93	1.03
D38	11.00	0.75	1.52	1.56	3160	11.92	212.09	294.67	276.60	271.26	0.72	0.77	0.78
D7	11.00	0.75	1.27	1.06	4450	14.31	214.47	243.30	228.94	238.90	0.88	0.94	0.90
D20	7.00	0.75	1.42	1.13	4230	11.38	174.98	193.72	182.30	203.68	0.90	0.96	0.86
D29	11.00	0.75	1.39	1.10	7480	19.10	220.86	247.77	233.08	242.45	0.89	0.95	0.91
D9	11.00	0.75	1.44	1.06	4380	14.75	222.83	243.30	228.94	240.25	0.92	0.97	0.93
D27	11.00	0.75	1.50	1.10	4550	14.46	214.40	247.77	233.08	243.31	0.87	0.92	0.88
D35	24.00	0.75	1.45	1.06	3800	23.07	374.28	420.60	395.50	368.36	0.89	0.95	1.02
D10	7.00	0.75	1.48	1.06	4370	11.08	167.66	188.75	177.69	201.09	0.89	0.94	0.83
D34	12.50	0.75	1.49	1.06	3800	15.46	250.84	263.76	248.16	255.46	0.95	1.01	0.98
D39	11.00	0.75	1.56	1.10	3160	11.56	205.63	247.77	233.08	243.79	0.83	0.88	0.84
D30	16.00	0.75	1.56	1.10	7480	22.62	261.54	317.99	299.03	294.60	0.82	0.87	0.89
D12	16.00	0.75	1.62	1.13	4530	19.30	286.78	322.86	303.55	298.10	0.89	0.94	0.96
D25	24.00	0.75	1.53	1.06	5100	24.77	346.83	420.60	395.50	369.74	0.82	0.88	0.94
										MEAN	1.006	1.069	1.060
										COV	0.142	0.142	0.129
										MIN	0.720	0.767	0.753
										MAX	1.460	1.546	1.398

TABLE 2

RESULTS OF DUMMY VARIABLE ANALYSIS OF

$\left(\frac{A_b f_s}{\sqrt{f'_c}}\right)_{test}$ VERSUS $l_d\ (C + 0.5d_b)(0.92 + 0.08\ \frac{C_{max}}{C_{min}})$

Best Fit Equation:

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

Value of Intercept, K, Based on Bar Size:

Bar Size	K (in.^{2})	$\frac{K}{A_b}$
No. 4	59.7	299
No. 6	127.4	290
No. 7	297.5	496
No. 8	327.1	414
No. 11	650.1	417

TABLE 3

TEST/PREDICTION RATIOS – SUMMARY

		Eq.3	Eq.4	Eq.12
Orangun, Jirsa and Breen (1975)	MEAN	1.006	1.069	1.060
62 specimens	COV	0.142	0.142	0.129
	MIN	0.720	0.767	0.753
	MAX	1.460	1.546	1.398
Chinn, Ferguson and Thompson	MEAN	0.960	1.020	0.980
(1955)	COV	0.165	0.164	0.147
35 specimens	MIN	0.720	0.767	0.753
	MAX	1.463	1.550	1.398
Ferguson and Breen (1965)	MEAN	1.031	1.096	1.125
26 specimens	COV	0.116	0.115	0.081
	MIN	0.733	0.781	0.884
	MAX	1.277	1.353	1.277
Chamberlin (1958)	MEAN	0.977	1.040	0.989
6 specimens	COV	0.153	0.153	0.127
	MIN	0.819	0.873	0.855
	MAX	1.141	1.215	1.130
Ferguson and Krishnaswamy (1971)	MEAN	1.278	1.355	1.202
12 specimens	COV	0.261	0.258	0.097
	MIN	0.928	0.985	1.048
	MAX	1.947	2.053	1.459
Ferguson and Briceno (1969)	MEAN	1.081	1.147	1.175
20 specimens	COV	0.142	0.140	0.117
	MIN	0.885	0.936	0.938
	MAX	1.468	1.552	1.559
Thompson, Jirsa, Breen and	MEAN	1.064	1.132	1.173
Meinheit (1975)	COV	0.070	0.070	0.063
11 specimens	MIN	0.897	0.952	1.031
	MAX	1.179	1.253	1.288
Tepfers (1973)	MEAN	1.133	1.201	1.195
90 specimens	COV	0.282	0.276	0.181
	MIN	0.634	0.674	0.642
	MAX	2.854	2.970	1.802
Ferguson and Thompson	MEAN	1.210	1.288	1.157
(1962, 1965)	COV	0.211	0.209	0.140
34 specimens	MIN	0.839	0.892	0.815
	MAX	1.873	1.983	1.656

TABLE 3, continued

		Eq.3	Eq.4	Eq.12
Chamberlin (1956)	MEAN	1.014	1.074	0.964
23 specimens	COV	0.079	0.079	0.106
	MIN	0.817	0.862	0.715
	MAX	1.164	1.228	1.119
Hester, Salamizavaregh,	MEAN	0.950	1.011	0.999
Darwin and McCabe (1991)	COV	0.078	0.078	0.069
-Beams	MIN	0.887	0.943	0.919
7 specimens	MAX	1.089	1.158	1.128
Hester, Salamizavaregh,	MEAN	0.782	0.834	0.861
Darwin and McCabe (1991)	COV	0.090	0.090	0.094
-Slabs	MIN	0.678	0.724	0.737
7 specimens	MAX	0.854	0.912	0.938
Choi, Hadje-Ghaffari,	MEAN	1.032	1.097	1.065
Darwin and McCabe (1990)	COV	0.157	0.158	0.156
8 specimens	MIN	0.813	0.865	0.856
	MAX	1.278	1.360	1.340
Treece and Jirsa (1987)	MEAN	0.932	0.990	0.981
9 specimens	COV	0.116	0.115	0.127
	MIN	0.758	0.806	0.853
	MAX	1.104	1.174	1.213
Hamad and Jirsa (1990)	MEAN	1.268	1.344	1.262
2 specimens	COV	0.361	0.360	0.299
	MIN	0.810	0.861	0.885
	MAX	1.726	1.828	1.639
SUMMARY FOR 257 TESTS	MEAN	1.095	1.162	1.126
- OJB (APPENDICES A-I)	COV	0.233	0.230	0.167
	MIN	0.634	0.674	0.642
	MAX	2.854	2.970	1.802
SUMMARY FOR 290 TESTS	MEAN	1.078	1.145	1.111
- ALL (APPENDICES A-J)	COV	0.235	0.232	0.172
	MIN	0.634	0.674	0.642
	MAX	2.854	2.970	1.802
SUMMARY FOR 200 TESTS	MEAN	1.053	1.119	1.073
- (APPENDICES A-J)	COV	0.202	0.201	0.153
EXCEPT TEPFERS	MIN	0.678	0.724	0.715
	MAX	1.947	2.053	1.656

TABLE 4

DEVELOPMENT LENGTHS CALCULATED USING EQ. 15 FOR $f_y = 60,000$ psi AND $f'_c = 4500$ psi

BAR	#3	#4	#5	#6	#7	#8	#9	#10	#11	#14	#18
C-C SPACING						0.75 in. COVER					
Minimum	13.72	22.86	32.71	43.11	54.87	67.73	77.10	87.89	98.15	-	-
2.50	10.12	17.37	25.50	34.41	44.75	56.35	70.73	88.46	-	-	-
3.00	9.87	16.93	24.86	33.53	43.60	54.89	66.53	80.68	95.14	-	-
4.00	9.40	16.11	23.65	31.90	41.46	52.18	63.22	76.65	90.35	-	-
5.00	8.97	15.37	22.56	30.41	39.52	49.72	60.24	73.07	86.01	-	-
6.00	8.58	14.70	21.56	29.06	37.75	47.49	57.51	69.68	82.07	-	-
8.00	7.89	13.51	19.81	26.69	34.65	43.57	52.74	63.88	75.19	-	-
12.00	6.79	11.63	17.04	22.94	29.77	37.40	45.24	54.75	64.38	-	-
C-C SPACING						1.00 in. COVER					
Minimum	13.21	22.02	31.50	41.52	52.84	65.22	74.51	85.24	95.45	-	-
2.50	8.22	14.27	22.00	31.03	42.02	54.89	68.75	85.24	-	-	-
3.00	8.06	13.99	20.75	28.25	37.03	46.96	59.07	74.14	90.86	-	-
4.00	7.76	13.46	19.96	27.17	35.61	45.15	55.08	67.24	79.70	-	-
5.00	7.47	12.97	19.23	26.18	34.30	43.48	53.04	64.78	76.70	-	-
6.00	7.21	12.51	18.55	25.25	33.08	41.93	51.13	62.40	73.92	-	-
8.00	6.74	11.69	17.33	23.58	30.88	39.13	47.71	58.20	68.93	-	-
12.00	5.96	10.34	15.32	20.83	27.26	34.53	42.07	51.30	60.72	-	-
C-C SPACING						1.50 in. COVER					
Minimum	12.30	20.50	29.33	38.65	49.19	60.72	69.84	80.40	90.49	111.61	153.97
2.50	7.60	13.72	21.10	29.69	40.09	52.18	65.09	80.40	-	-	-
3.00	6.46	11.70	18.05	25.48	34.53	45.15	56.66	70.94	86.59	-	-
4.00	5.72	10.06	15.10	20.79	27.52	35.22	44.39	55.93	68.68	99.12	-
5.00	5.57	9.80	14.71	20.25	26.81	34.31	42.22	52.03	62.10	84.80	141.60
6.00	5.43	9.55	14.34	19.74	26.13	33.44	41.14	50.67	60.52	82.74	133.03
8.00	5.17	9.10	13.66	18.79	24.88	31.83	39.15	48.22	57.57	78.68	126.42
12.00	4.73	8.31	12.47	17.15	22.69	29.03	35.70	43.96	52.46	71.65	114.99
C-C SPACING						2.00 in. COVER					
Minimum	11.51	19.18	27.44	36.16	46.02	56.81	65.72	76.08	86.01	106.85	148.83
2.50	7.33	13.21	20.27	28.46	38.32	49.72	61.81	76.08	-	-	-
3.00	6.28	11.34	17.47	24.62	33.31	43.48	54.45	68.00	82.70	-	-
4.00	4.86	8.82	13.62	19.26	26.16	34.31	43.20	54.36	66.65	95.80	-
5.00	4.43	7.85	11.86	16.44	21.89	28.18	35.57	45.03	55.13	78.92	137.62
6.00	4.34	7.69	11.63	16.12	21.47	27.62	34.18	42.34	50.82	70.13	118.12
8.00	4.18	7.41	11.20	15.51	20.66	26.58	32.88	40.73	48.89	67.44	110.15
12.00	3.89	6.89	10.42	14.43	19.21	24.72	30.57	37.86	45.43	62.65	102.24
C-C SPACING						3.00 in. COVER					
Minimum	10.19	16.98	24.30	32.03	40.76	50.31	58.78	68.70	78.27	98.46	139.51
2.50	6.85	12.30	18.80	26.28	35.21	45.44	56.14	68.70	-	-	-
3.00	5.93	10.69	16.42	23.08	31.13	40.48	50.50	62.79	75.89	-	-
4.00	4.66	8.43	13.01	18.37	24.92	32.61	40.98	51.47	62.92	89.79	-
5.00	3.83	6.95	10.74	15.19	20.65	27.09	34.16	43.19	52.80	75.34	130.29
6.00	3.25	5.90	9.13	12.93	17.59	23.11	29.17	36.85	45.25	65.36	113.31
8.00	3.01	5.38	8.19	11.43	15.33	19.86	24.73	30.84	37.25	51.98	88.78
12.00	2.86	5.11	7.79	10.86	14.57	18.87	23.49	29.30	35.38	49.36	82.28

TABLE 5a

RATIO OF DEVELOPMENT LENGTHS CALCULATED USING EQ. 15 TO DEVELOPMENT LENGTHS CALCULATED USING EQ. 17a, 17b and 17c

BAR	#3	#4	#5	#6	#7	#8	#9	#10	#11	#14	#18
C-C SPACING						0.75 in. COVER					
Minimum	2.32	2.13	1.97	1.83	1.70	1.60	1.44	1.29	1.17	-	-
2.50	1.72	1.62	1.53	1.46	1.39	1.33	1.32	1.30	-	-	-
3.00	1.67	1.58	1.49	1.42	1.35	1.29	1.24	1.18	1.14	-	-
4.00	1.59	1.50	1.42	1.35	1.29	1.23	1.18	1.12	1.08	-	-
5.00	1.52	1.43	1.36	1.29	1.23	1.17	1.12	1.07	1.03	-	-
6.00	1.45	1.37	1.30	1.23	1.17	1.12	1.07	1.02	0.98	-	-
8.00	1.34	1.26	1.19	1.13	1.08	1.03	0.98	0.94	0.90	-	-
12.00	1.15	1.08	1.02	0.97	0.92	0.88	0.84	0.80	0.77	-	-
C-C SPACING						1.00 in. COVER					
Minimum	2.24	2.05	1.89	1.76	1.64	1.54	1.39	1.25	1.14	-	-
2.50	1.34	1.33	1.32	1.31	1.31	1.29	1.28	1.25	-	-	-
3.00	1.37	1.30	1.25	1.20	1.15	1.11	1.10	1.09	1.09	-	-
4.00	1.31	1.25	1.20	1.15	1.11	1.07	1.03	0.99	0.95	-	-
5.00	1.27	1.21	1.16	1.11	1.07	1.03	0.99	0.95	0.92	-	-
6.00	1.22	1.17	1.12	1.07	1.03	0.99	0.95	0.92	0.88	-	-
8.00	1.14	1.09	1.04	1.00	0.96	0.92	0.89	0.85	0.82	-	-
12.00	1.01	0.96	0.92	0.88	0.85	0.81	0.78	0.75	0.73	-	-
C-C SPACING						1.50 in. COVER					
Minimum	2.08	1.91	1.76	1.64	1.53	1.43	1.30	1.18	1.08	1.00	0.98
2.50	1.29	1.28	1.27	1.26	1.24	1.23	1.21	1.18	-	-	-
3.00	1.10	1.09	1.08	1.08	1.07	1.07	1.06	1.04	1.03	-	-
4.00	0.97	0.94	0.91	0.88	0.85	0.83	0.83	0.82	0.82	0.89	-
5.00	0.94	0.91	0.88	0.86	0.83	0.81	0.79	0.76	0.74	0.76	0.90
6.00	0.92	0.89	0.86	0.84	0.81	0.79	0.77	0.74	0.72	0.74	0.85
8.00	0.88	0.85	0.82	0.80	0.77	0.75	0.73	0.71	0.69	0.70	0.81
12.00	0.80	0.77	0.75	0.73	0.70	0.68	0.67	0.64	0.63	0.64	0.73
C-C SPACING						2.00 in. COVER					
Minimum	1.95	1.79	1.65	1.53	1.43	1.34	1.22	1.12	1.03	0.96	0.95
2.50	1.24	1.23	1.22	1.21	1.19	1.17	1.15	1.12	-	-	-
3.00	1.06	1.06	1.05	1.04	1.03	1.03	1.01	1.00	0.99	-	-
4.00	0.82	0.82	0.82	0.82	0.81	0.81	0.80	0.80	0.80	0.86	-
5.00	0.75	0.73	0.71	0.70	0.68	0.66	0.66	0.66	0.66	0.71	0.88
6.00	0.74	0.72	0.70	0.68	0.67	0.65	0.64	0.62	0.61	0.63	0.75
8.00	0.71	0.69	0.67	0.66	0.64	0.63	0.61	0.60	0.58	0.60	0.70
12.00	0.66	0.64	0.63	0.61	0.60	0.58	0.57	0.56	0.54	0.56	0.65
C-C SPACING						3.00 in. COVER					
Minimum	1.73	1.58	1.46	1.36	1.27	1.19	1.10	1.01	0.93	0.88	0.89
2.50	1.16	1.15	1.13	1.11	1.09	1.07	1.05	1.01	-	-	-
3.00	1.00	1.00	0.99	0.98	0.97	0.95	0.94	0.92	0.91	-	-
4.00	0.79	0.79	0.78	0.78	0.77	0.77	0.76	0.76	0.75	0.80	-
5.00	0.65	0.65	0.65	0.64	0.64	0.64	0.64	0.63	0.63	0.67	0.83
6.00	0.55	0.55	0.55	0.55	0.55	0.55	0.54	0.54	0.54	0.58	0.72
8.00	0.51	0.50	0.49	0.48	0.48	0.47	0.46	0.45	0.44	0.46	0.57
12.00	0.48	0.48	0.47	0.46	0.45	0.45	0.44	0.43	0.42	0.44	0.53

TABLE 5b

RATIO OF DEVELOPMENT LENGTHS CALCULATED USING EQ. 15 $\geq$ 12.0 IN. TO DEVELOPMENT LENGTHS CALCULATED USING PROPOSED REVISIONS TO SECTION 12.2 OF ACI 318-89 FOLLOWING CURRENT CODE FORMAT

BAR	#3	#4	#5	#6	#7	#8	#9	#10	#11	#14	#18
C-C SPACING						0.75 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	-	-
C-C SPACING						1.00 in. COVER					
Minimum	1.10	1.03	0.95	0.88	0.82	1.03	0.93	0.83	0.76	-	-
2.50	1.00	0.89	0.88	0.88	0.87	0.86	0.85	0.83	-	-	-
3.00	1.00	0.87	0.83	0.80	0.77	0.74	0.73	0.73	0.72	-	-
4.00	1.00	0.84	0.80	0.77	0.74	0.71	0.68	0.66	0.63	-	-
5.00	1.00	0.81	0.77	0.74	0.71	0.68	0.66	0.63	0.61	-	-
6.00	1.00	0.78	0.74	0.71	0.68	0.66	0.64	0.61	0.59	-	-
8.00	1.00	0.89	0.87	0.83	0.80	0.77	0.74	0.71	0.69	-	-
12.00	1.00	0.89	0.77	0.74	0.71	0.68	0.65	0.63	0.60	-	-
C-C SPACING						1.50 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
C-C SPACING						2.00 in. COVER					
Minimum	1.00	0.89	0.82	0.77	0.71	0.89	0.82	0.74	0.68	0.96	0.95
2.50	1.00	0.82	0.81	0.80	0.79	0.78	0.77	0.74	-	-	-
3.00	1.00	0.89	1.04	1.04	1.03	1.03	1.01	1.00	0.99	-	-
4.00	1.00	0.89	0.81	0.82	0.81	0.81	0.80	0.80	0.80	0.86	-
5.00	1.00	0.89	0.72	0.70	0.68	0.66	0.66	0.66	0.66	0.71	0.88
6.00	1.00	0.89	0.72	0.68	0.67	0.65	0.64	0.62	0.61	0.63	0.75
8.00	1.00	0.89	0.72	0.77	0.80	0.78	0.77	0.75	0.73	0.75	0.88
12.00	1.00	0.89	0.72	0.72	0.75	0.73	0.71	0.69	0.68	0.70	0.82
C-C SPACING						3.00 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

TABLE 6a

RATIO OF DEVELOPMENT LENGTHS CALCULATED USING EQ. 15 ≥ 12.0 IN. TO DEVELOPMENT LENGTHS CALCULATED USING SECTIONS 12.2.1, 12.2.2 AND 12.2.3.1 OF CODE CHANGE CB-23

BAR	#3	#4	#5	#6	#7	#8	#9	#10	#11	#14	#18
C-C SPACING						0.75 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	-	-
C-C SPACING						1.00 in. COVER					
Minimum	0.98	1.23	0.94	1.03	0.90	0.97	0.98	1.00	1.01	-	-
2.50	0.89	0.80	0.98	1.16	0.72	0.82	0.91	1.00	-	-	-
3.00	0.89	0.78	0.93	1.05	0.95	1.05	0.78	0.87	0.96	-	-
4.00	0.89	0.75	0.89	1.01	0.91	1.01	0.73	0.79	0.84	-	-
5.00	0.89	0.73	0.86	0.98	0.88	0.97	0.70	0.76	0.81	-	-
6.00	0.89	0.70	0.83	0.94	0.85	0.94	0.68	0.73	0.78	-	-
8.00	0.89	0.67	0.78	0.88	0.79	0.88	0.63	0.68	0.73	-	-
12.00	0.89	0.67	0.68	0.78	0.70	0.77	0.56	0.60	0.64	-	-
C-C SPACING						1.50 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
C-C SPACING						2.00 in. COVER					
Minimum	0.89	1.07	0.82	0.90	0.78	0.85	0.87	0.89	0.91	0.94	0.98
2.50	0.89	0.74	0.91	1.06	0.65	0.74	0.82	0.89	-	-	-
3.00	0.89	0.67	0.78	0.92	0.85	0.97	0.72	0.80	0.87	-	-
4.00	0.89	0.67	0.61	0.72	0.67	0.77	0.86	0.96	0.70	0.84	-
5.00	0.89	0.67	0.54	0.61	0.56	0.63	0.71	0.79	0.87	0.69	0.91
6.00	0.89	0.67	0.54	0.60	0.55	0.62	0.68	0.75	0.81	0.93	0.78
8.00	0.89	0.67	0.54	0.58	0.53	0.59	0.65	0.72	0.78	0.89	0.73
12.00	0.89	0.67	0.54	0.54	0.49	0.55	0.61	0.67	0.72	0.83	0.68
C-C SPACING						3.00 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

TABLE 6b

RATIO OF DEVELOPMENT LENGTHS CALCULATED USING EQ. 15 ≥ 12.0 IN. TO DEVELOPMENT LENGTHS CALCULATED USING MODIFIED VERSIONS OF SECTIONS 12.2.1, 12.2.2 AND 12.2.3.1 OF CODE CHANGE CB-23

BAR	#3	#4	#5	#6	#7	#8	#9	#10	#11	#14	#18
C-C SPACING						0.75 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	-	-
C-C SPACING						1.00 in. COVER					
Minimum	0.79	0.98	0.75	0.83	0.90	0.97	0.98	1.00	1.01	-	-
2.50	1.00	1.06	0.79	0.93	0.72	0.82	0.91	1.00	-	-	-
3.00	1.00	1.04	0.74	0.84	0.95	1.05	0.78	0.87	0.96	-	-
4.00	1.00	1.00	0.71	0.81	0.91	1.01	0.73	0.79	0.84	-	-
5.00	1.00	0.97	0.69	0.78	0.88	0.97	0.70	0.76	0.81	-	-
6.00	1.00	0.93	0.66	0.75	0.85	0.94	0.68	0.73	0.78	-	-
8.00	1.00	0.89	0.62	0.70	0.79	0.88	0.63	0.68	0.73	-	-
12.00	1.00	0.89	0.55	0.62	0.70	0.77	0.56	0.60	0.64	-	-
C-C SPACING						1.50 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	1.19	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
C-C SPACING						2.00 in. COVER					
Minimum	0.72	0.86	0.65	0.72	0.78	0.85	0.87	0.89	0.91	0.94	0.98
2.50	1.00	0.98	0.73	0.85	0.65	0.74	0.82	0.89	-	-	-
3.00	1.00	0.89	0.63	0.73	0.85	0.97	0.72	0.80	0.87	-	-
4.00	1.00	0.89	0.81	0.96	0.67	0.77	0.86	0.96	0.70	0.84	-
5.00	1.00	0.89	0.72	0.82	0.93	1.05	0.71	0.79	0.87	0.69	0.91
6.00	1.00	0.89	0.72	0.80	0.91	1.03	0.68	0.75	0.81	0.93	0.78
8.00	1.00	0.89	0.72	0.77	0.88	0.99	0.65	0.72	0.78	0.89	0.73
12.00	1.00	0.89	0.72	0.72	0.82	0.92	0.61	0.67	0.72	0.83	0.68
C-C SPACING						3.00 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

TABLE 7

RATIO OF DEVELOPMENT LENGTHS CALCULATED USING EQ. 15 ≥ 12.0 IN. TO DEVELOPMENT LENGTHS CALCULATED USING SECTIONS 12.2.1, 12.2.2 AND 12.2.3.2 OF CODE CHANGE CB-23

BAR	#3	#4	#5	#6	#7	#8	#9	#10	#11	#14	#18
C-C SPACING						0.75 in. COVER					
Minimum	1.00	1.02	1.01	1.00	1.00	1.01	1.02	1.03	1.04	-	-
2.50	1.00	1.04	1.03	1.03	1.03	1.05	1.04	1.03	-	-	-
3.00	1.00	1.01	1.01	1.00	1.01	1.02	1.02	1.03	1.04	-	-
4.00	1.00	0.96	0.96	0.95	0.96	0.97	0.97	0.98	0.99	-	-
5.00	1.00	0.92	0.91	0.91	0.91	0.93	0.93	0.94	0.94	-	-
6.00	1.00	0.88	0.87	0.87	0.87	0.88	0.89	0.89	0.90	-	-
8.00	1.00	0.81	0.80	0.80	0.80	0.81	0.81	0.82	0.82	-	-
12.00	1.00	0.72	0.69	0.68	0.69	0.70	0.70	0.70	0.70	-	-
C-C SPACING						1.00 in. COVER					
Minimum	0.96	0.98	0.98	0.96	0.96	0.97	0.98	1.00	1.01	-	-
2.50	1.00	1.06	1.05	1.03	1.02	1.02	1.01	1.00	-	-	-
3.00	1.00	1.04	1.04	1.03	1.04	1.05	1.04	1.03	1.02	-	-
4.00	1.00	1.00	1.00	0.99	1.00	1.01	1.01	1.02	1.02	-	-
5.00	1.00	0.97	0.96	0.95	0.96	0.97	0.97	0.98	0.98	-	-
6.00	1.00	0.93	0.93	0.92	0.93	0.94	0.94	0.94	0.95	-	-
8.00	1.00	0.89	0.87	0.86	0.86	0.88	0.87	0.88	0.88	-	-
12.00	1.00	0.89	0.77	0.76	0.76	0.77	0.77	0.78	0.78	-	-
C-C SPACING						1.50 in. COVER					
Minimum	0.90	0.92	0.91	0.90	0.90	0.91	0.92	0.94	0.96	0.98	1.02
2.50	1.00	1.02	1.01	0.98	0.98	0.97	0.95	0.94	-	-	-
3.00	1.00	0.89	1.03	1.01	1.01	1.01	1.00	0.99	0.97	-	-
4.00	1.00	0.89	0.90	1.03	1.04	1.05	1.04	1.04	1.03	1.02	-
5.00	1.00	0.89	0.88	1.01	1.01	1.02	1.02	1.03	1.03	1.03	1.04
6.00	1.00	0.89	0.86	0.98	0.99	1.00	0.99	1.00	1.00	1.01	1.02
8.00	1.00	0.89	0.81	0.93	0.94	0.95	0.95	0.95	0.95	0.96	0.97
12.00	1.00	0.89	0.74	0.85	0.86	0.87	0.86	0.87	0.87	0.87	0.88
C-C SPACING						2.00 in. COVER					
Minimum	0.87	0.86	0.85	0.84	0.84	0.85	0.87	0.89	0.91	0.94	0.98
2.50	1.00	0.98	0.97	0.94	0.93	0.93	0.91	0.89	-	-	-
3.00	1.00	0.89	1.00	0.98	0.97	0.97	0.96	0.95	0.93	-	-
4.00	1.00	0.89	0.81	0.96	1.02	1.02	1.01	1.01	1.00	0.98	-
5.00	1.00	0.89	0.72	0.82	0.93	1.05	1.04	1.04	1.03	1.03	1.01
6.00	1.00	0.89	0.72	0.80	0.91	1.03	1.03	1.03	1.03	1.04	1.04
8.00	1.00	0.89	0.72	0.77	0.88	0.99	0.99	0.99	0.99	1.00	1.01
12.00	1.00	0.89	0.72	0.72	0.82	0.92	0.92	0.92	0.92	0.93	0.94
C-C SPACING						3.00 in. COVER					
Minimum	0.87	0.76	0.75	0.74	0.74	0.75	0.78	0.81	0.83	0.87	0.92
2.50	1.00	0.92	0.90	0.87	0.86	0.85	0.82	0.81	-	-	-
3.00	1.00	0.89	0.94	0.92	0.91	0.91	0.89	0.88	0.85	-	-
4.00	1.00	0.89	0.78	0.91	0.97	0.97	0.96	0.96	0.94	0.92	-
5.00	1.00	0.89	0.72	0.75	0.88	1.01	1.00	1.00	0.99	0.98	0.95
6.00	1.00	0.89	0.72	0.64	0.75	0.86	0.96	1.03	1.02	1.01	1.00
8.00	1.00	0.89	0.72	0.60	0.65	0.74	0.82	0.91	0.98	1.04	1.04
12.00	1.00	0.89	0.72	0.60	0.62	0.70	0.78	0.86	0.94	0.99	0.99

TABLE 8

PROPOSED MODIFICATIONS TO ACI 318-89 FOLLOWING CURRENT CODE FORMAT

12.2 – Development of Deformed Bars and Deformed Wire in Tension

12.2.1 – No change

12.2.2 – Basic development length, l_{db} shall be:

#11 bar and smaller and deformed wire	$0.06\,A_b f_y/\sqrt{f'_c}$*
#14 bar	$0.125\,f_y/\sqrt{f'_c}$†
#18 bar	$0.175\,f_y/\sqrt{f'_c}$†

12.2.3 – To account for bar spacing, amount of cover and enclosing reinforcement, the basic development length shall be multiplied, if applicable, by a factor in 12.2.3.1 or 12.2.3.2 which may be modified by 12.2.3.3, 12.2.3.4 and/or 12.2.3.5, but shall not be less than provided by 12.2.3.6.

12.2.3.1 - For bars with cover less than $1\frac{1}{2}$ in. or spaced laterally less than 3 in. on center or with less than $1\frac{1}{2}$ in. from edge of member to center of bar measured in the plane of the bars 1.5

12.2.3.2 - For bars spaced laterally less than 2 in on center 2.0

12.2.3.3 – For bars spaced at least 8 in. on center with at least 4 in. from the edge of the member to the center of the bar, measured in the plane of the bars, the basic development length, modified as applicable by 12.2.3.1 or 1.2.2.3.2, may be multiplied by 0.8.

12.2.3.4 – For bars with cover of at least 3 in., the basic development length, modified as applicable by 12.2.3.1 or 1.2.2.3.2, may be multiplied by 0.9.

12.2.3.5, 12.2.3.6 – No change.

12.2.4 – Add:

12.2.4.4 – Reinforcement with f_y greater than 60,000 psi 1.1

12.2.5 – No change.

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*The constant carries the unit of one/in.

†The constant carries the unit of in.

TABLE 9

MODIFIED VERSION OF CODE CHANGE CB-23

12.2.1 - Development length, l_d, in inches for deformed bars and deformed wire in tension shall be computed as the product of the basic development length l_{db} of 12.2.2 and the applicable modification factors of 12.2.3 through 12.2.5, but l_d shall not be less than 12 in.

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

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

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 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) Bars or wires with minimum cover not less than $2d_b$ and minimum clear spacing not less than $4d_b$. 0.6

(c) All other conditions 1.5

12.2.3.2 - Any condition . . . .$1.5\, d_b/K$

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

12.2.4 – Add:

12.2.4.4 – Reinforcement with f_y greater than 60,000 psi 1.1

12.2.5 – No change.

Add to notation:

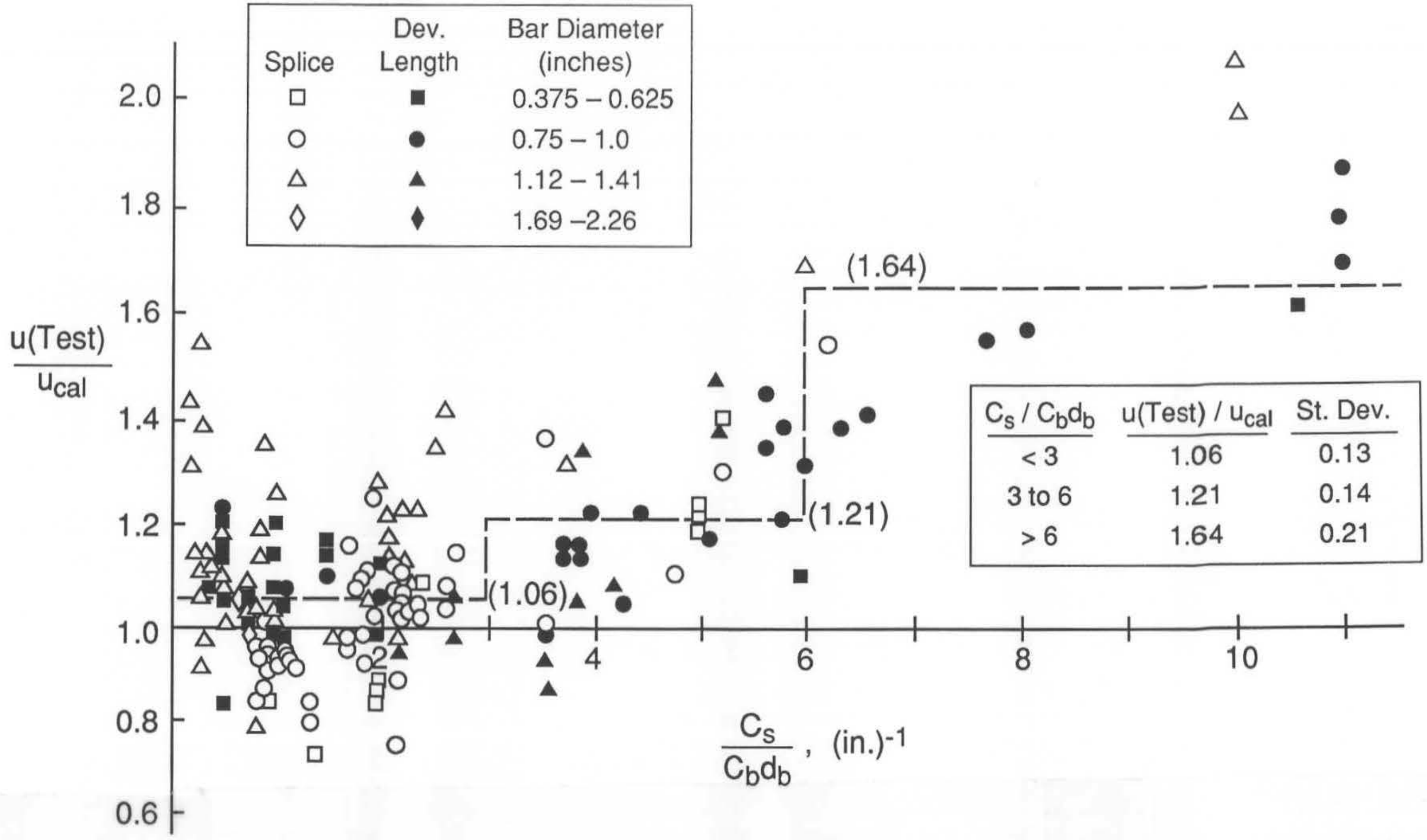
K = the smaller of $C_c + K_{tr}$ or $C_s + K_{tr}$ (the units of K are inches)

TABLE 9, continued

$K_{tr} = \dfrac{A_{tr}\, f_{yt}}{1500\, s\, N}$ (The units of the constant are psi. The units of A_{tr} are sq. in. 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_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 C_s 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.



Splice	Dev. Length	Bar Diameter (inches)
□	■	0.375 – 0.625
○	●	0.75 – 1.0
△	▲	1.12 – 1.41
◊	♦	1.69 –2.26

$C_s / C_b d_b$	$u(Test) / u_{cal}$	St. Dev.
< 3	1.06	0.13
3 to 6	1.21	0.14
> 6	1.64	0.21

Fig. 1. $u(Test)/u_{cal}$ versus $C_s/(C_b\ d_b)$
(Orangun, Jirsa and Breen 1975, 1977)

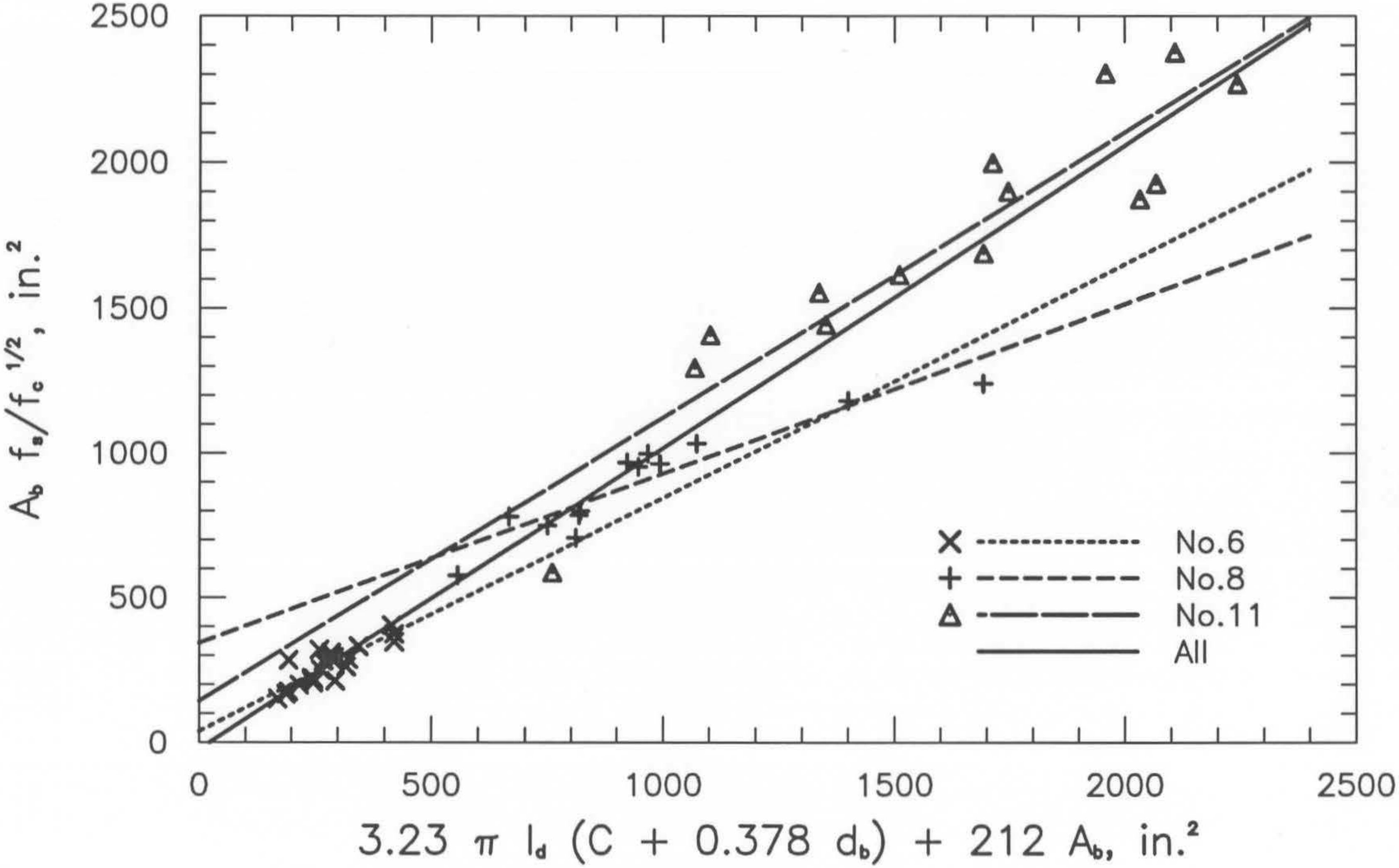


Fig. 2. $A_b f_s/f_c^{1/2}$(Test) versus $3.23 \pi l_d (C + 0.378 d_b) + 212 A_b$ (Orangun, Jirsa and Breen 1975, 1977)

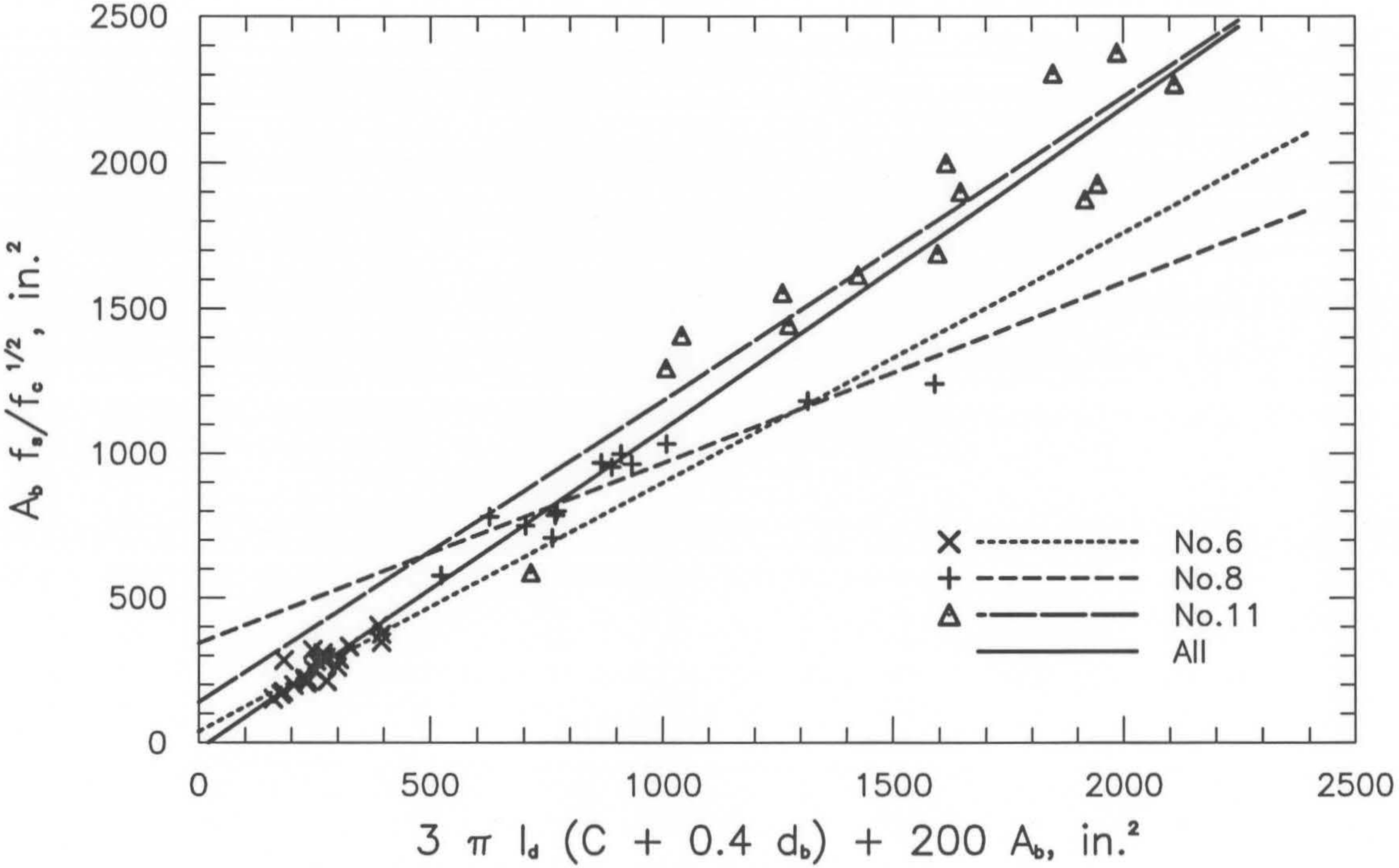


Fig. 3. $A_b\ f_s/f_c^{1/2}$(Test) versus $3\ \pi\ l_d\ (C + 0.4\ d_b) + 200\ A_b$ (Orangun, Jirsa and Breen 1975, 1977)

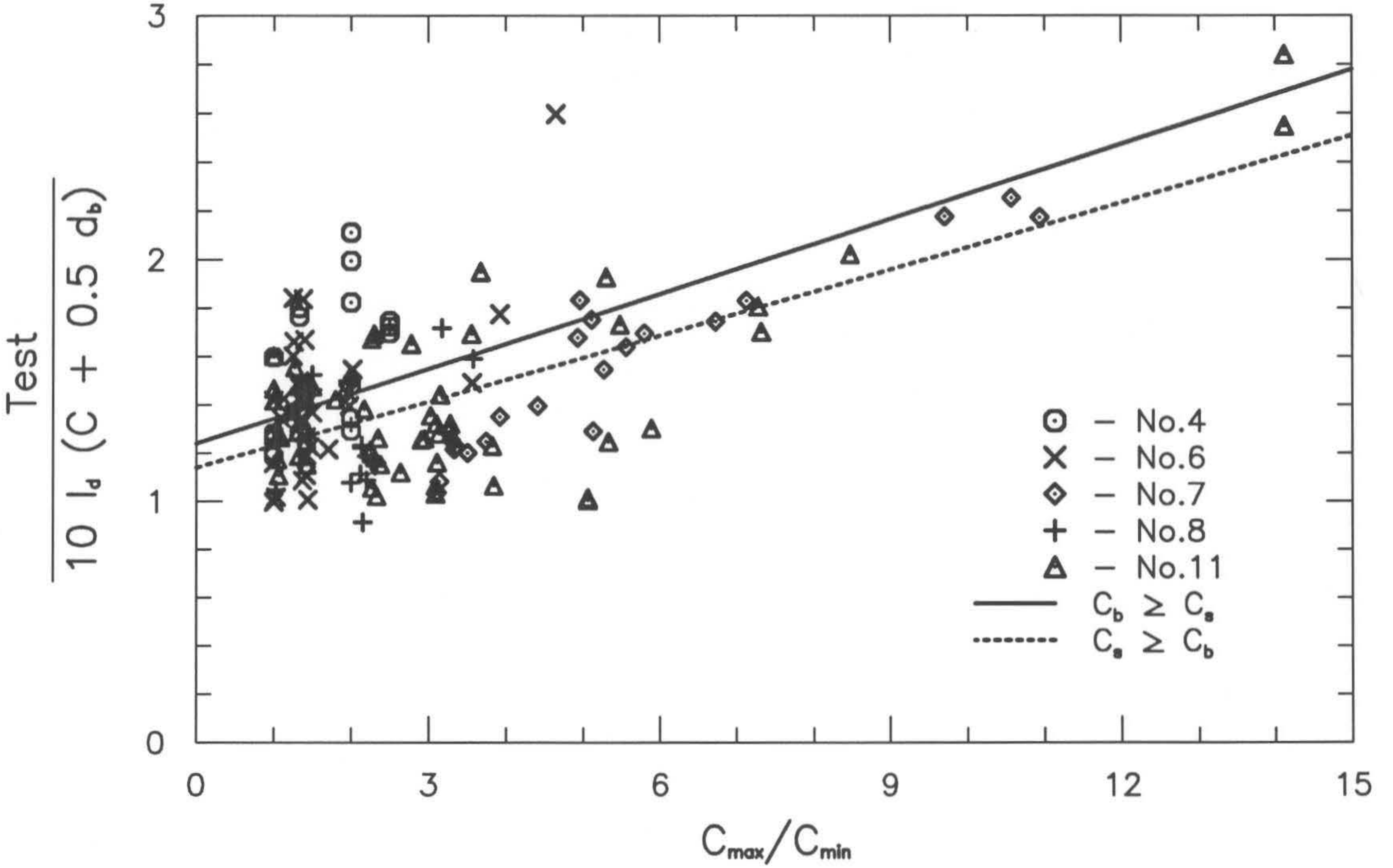


Fig. 4. Test/[10 l_d (C + 0.5 d_b)] versus ratio of C_{max} to C_{min} for 147 development and splice specimens without transverse reinforcement

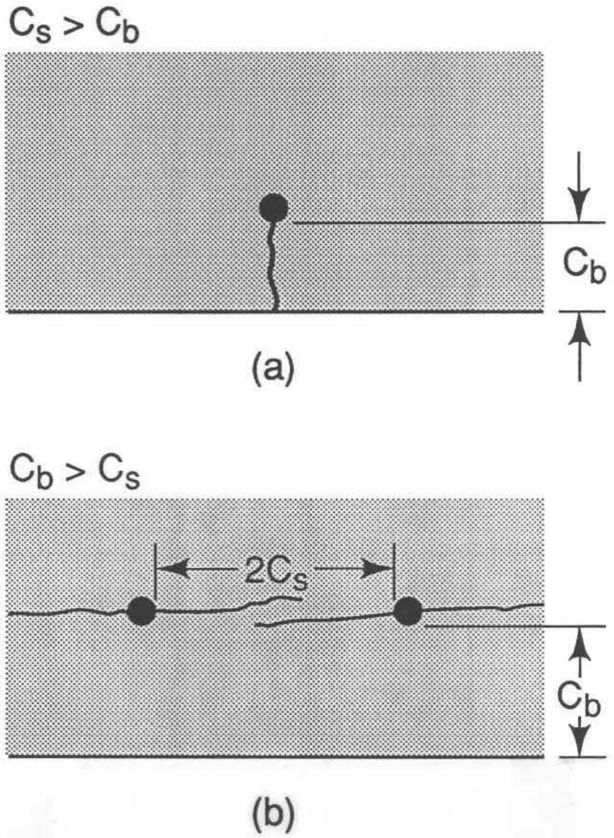


Fig. 5. Bond cracks (a) $C_s > C_b$ and (b) $C_b > C_s$

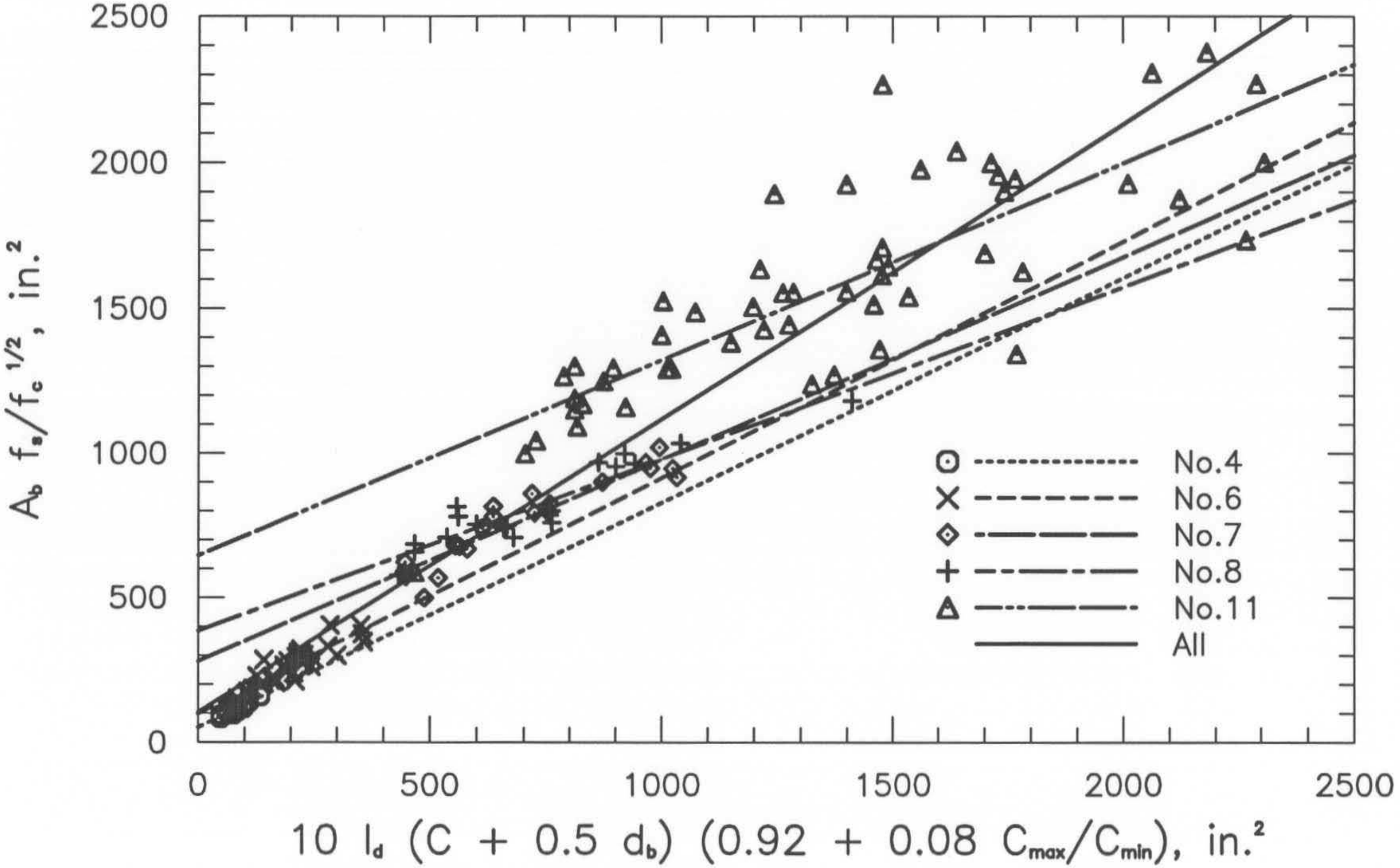


Fig. 6. $A_b\ f_s/f_c^{\ 1/2}$(Test) versus 10 l_d (C + 0.5 d_b) (0.92 + 0.08 C_{max}/C_{min}). Best fit lines for individual bar sizes and all bars

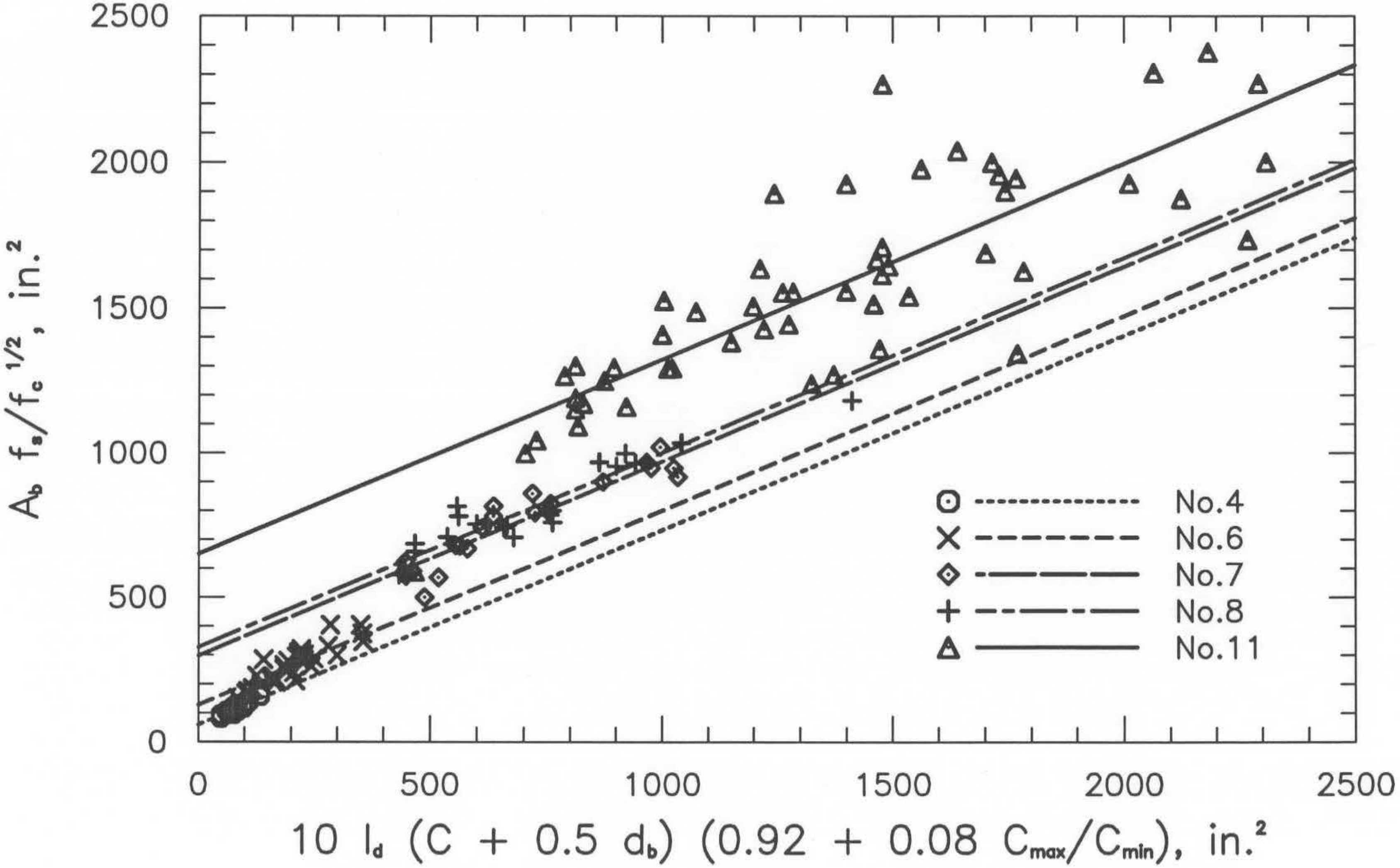


Fig. 7. $A_b\ f_s/f_c^{\ 1/2}$(Test) versus $10\ l_d\ (C + 0.5\ d_b)\ (0.92 + 0.08\ C_{max}/C_{min})$. Dummy variable analysis

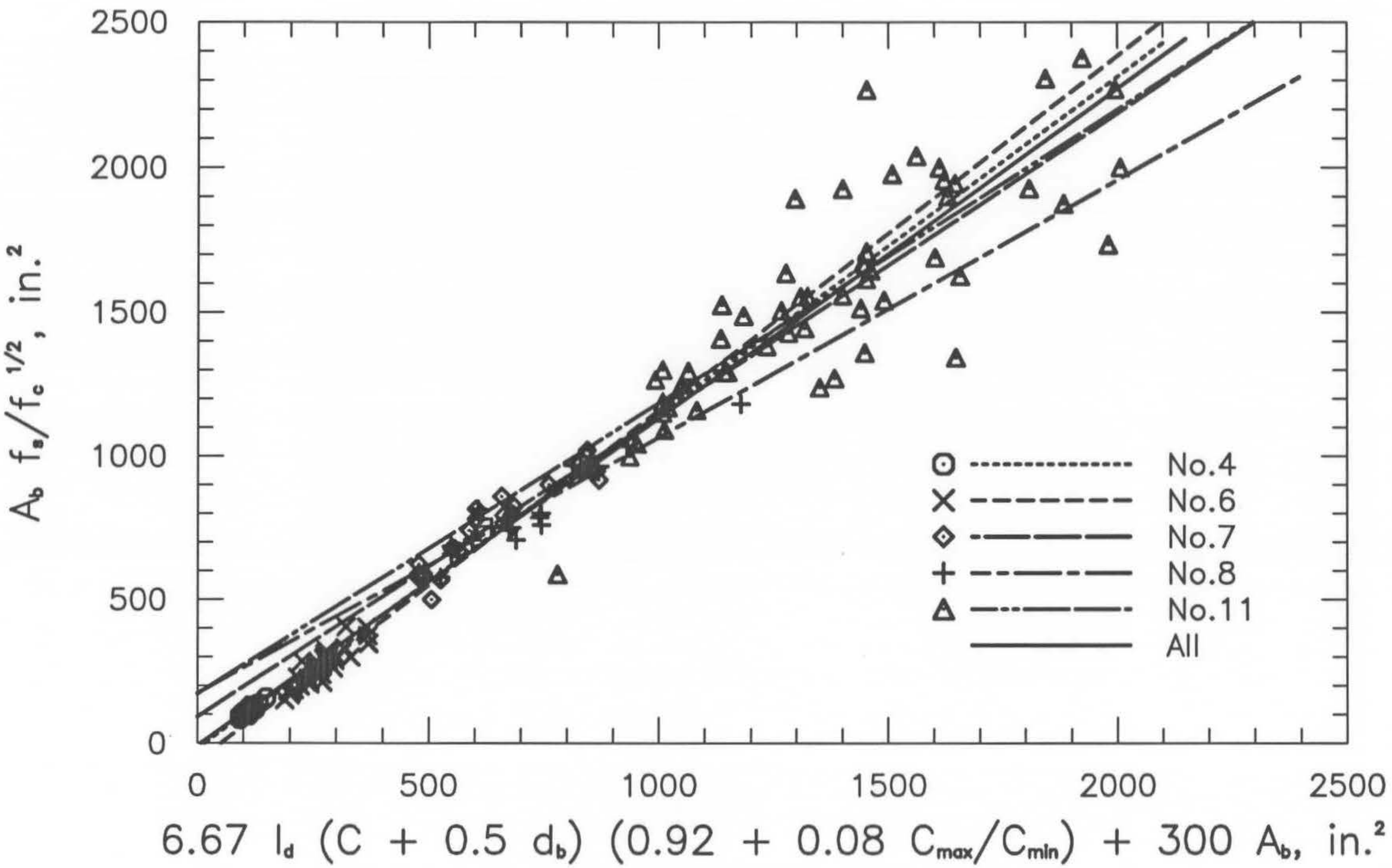


Fig. 8. $A_b f_s/f_c^{1/2}$(Test) versus 6.67 l_d (C + 0.5 d_b) (0.92 + 0.08 C_{max}/C_{min}) + 300 A_b. Best fit lines for individual bar sizes and all bars

APPENDIX A

COMPARISONS WITH DATA FROM CHINN, FERGUSON AND THOMPSON (1955) – 35 SPECIMENS

							$A_b f_s / f'^{1/2}_c$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	$A_b f_s$ kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
D15	11.00	0.75	0.62	2.88	4290	18.61	284.12	194.17	183.35	226.24	1.46	1.55	1.26
D40	16.00	0.75	0.75	2.94	5280	23.22	319.59	261.14	246.28	280.03	1.22	1.30	1.14
D24	16.00	0.75	0.81	2.88	4450	18.85	282.57	270.89	255.32	284.24	1.04	1.11	0.99
D13	11.00	0.75	1.44	2.91	4820	21.43	308.74	285.74	268.32	275.97	1.08	1.15	1.12
D21	11.00	0.75	1.47	2.91	4480	18.97	283.45	289.09	271.42	277.90	0.98	1.04	1.02
D36	5.50	0.38	0.56	1.10	4410	5.53	83.23	62.50	58.79	62.52	1.33	1.42	1.33
D32	11.00	0.75	1.47	2.88	4700	20.16	294.13	289.09	271.42	277.68	1.02	1.08	1.06
D19	16.00	0.75	1.70	2.91	4230	26.24	403.43	415.45	389.46	365.94	0.97	1.04	1.10
D26	24.00	0.75	0.75	1.10	5100	23.64	330.99	345.08	325.42	318.72	0.96	1.02	1.04
D22	7.00	0.75	0.80	1.10	4480	10.11	151.05	170.27	160.54	188.48	0.89	0.94	0.80
D17	16.00	0.75	0.80	1.10	3580	16.70	279.12	269.27	253.82	261.09	1.04	1.10	1.07
D23	16.00	0.75	0.78	1.06	4450	16.59	248.66	266.02	250.80	258.74	0.93	0.99	0.96
D5	11.00	0.75	1.50	2.00	4180	19.05	294.65	292.44	274.53	273.17	1.01	1.07	1.08
D31	5.50	0.38	0.83	1.10	4700	6.83	99.62	77.58	72.78	71.28	1.28	1.37	1.40
D14	11.00	0.75	0.83	1.10	4820	13.79	198.61	217.62	205.11	222.67	0.91	0.97	0.89
D33	20.25	1.41	1.55	2.03	4830	40.81	587.26	758.91	715.31	779.97	0.77	0.82	0.75
D2	10.25	0.75	0.75	0.94	4820	12.82	184.72	200.82	189.40	210.43	0.92	0.98	0.88
D1	11.00	0.75	0.75	0.94	3880	14.20	228.02	208.69	196.82	216.17	1.09	1.16	1.05
D38	11.00	0.75	1.52	1.56	3160	11.92	212.09	294.67	276.60	271.26	0.72	0.77	0.78
D4	16.00	0.75	1.50	1.50	4470	20.02	299.41	382.96	359.32	332.00	0.78	0.83	0.90
D3	11.00	0.75	1.50	1.50	4350	15.76	238.93	292.44	274.53	269.50	0.82	0.87	0.89
D6	11.00	0.75	1.16	1.06	4340	14.00	212.45	243.30	228.94	238.03	0.87	0.93	0.89
D7	11.00	0.75	1.27	1.06	4450	14.31	214.47	243.30	228.94	238.90	0.88	0.94	0.90
D20	7.00	0.75	1.42	1.13	4230	11.38	174.98	193.72	182.30	203.68	0.90	0.96	0.86
D29	11.00	0.75	1.39	1.10	7480	19.10	220.86	247.77	233.08	242.45	0.89	0.95	0.91
D9	11.00	0.75	1.44	1.06	4380	14.75	222.83	243.30	228.94	240.25	0.92	0.97	0.93
D27	11.00	0.75	1.50	1.10	4550	14.46	214.40	247.77	233.08	243.31	0.87	0.92	0.88
D35	24.00	0.75	1.45	1.06	3800	23.07	374.28	420.60	395.50	368.36	0.89	0.95	1.02
D10	7.00	0.75	1.48	1.06	4370	11.08	167.66	188.75	177.69	201.09	0.89	0.94	0.83
D8	11.00	0.75	1.48	1.06	4570	15.21	225.05	243.30	228.94	240.57	0.92	0.98	0.94
D34	12.50	0.75	1.49	1.06	3800	15.46	250.84	263.76	248.16	255.46	0.95	1.01	0.98
D39	11.00	0.75	1.56	1.10	3160	11.56	205.63	247.77	233.08	243.79	0.83	0.88	0.84
D30	16.00	0.75	1.56	1.10	7480	22.62	261.54	317.99	299.03	294.60	0.82	0.87	0.89
D12	16.00	0.75	1.62	1.13	4530	19.30	286.78	322.86	303.55	298.10	0.89	0.94	0.96
D25	24.00	0.75	1.53	1.06	5100	24.77	346.83	420.60	395.50	369.74	0.82	0.88	0.94
										MEAN	0.960	1.020	0.980
										COV	0.165	0.164	0.147
										MIN	0.720	0.767	0.753
										MAX	1.463	1.550	1.398

APPENDIX B

COMPARISONS WITH DATA FROM FERGUSON AND BREEN (1965) – 26 SPECIMENS

							$A_bf_s/f'_c{}^{1/2}$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	A_bf_s kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
11R30a	41.25	1.41	1.31	4.65	4030	89.35	1407.51	1102.46	1040.31	1135.15	1.28	1.35	1.24
11R60a	82.50	1.41	1.41	4.63	2690	119.50	2304.07	1957.95	1846.33	1843.77	1.18	1.25	1.25
11F36b	49.50	1.41	1.47	4.63	3350	89.90	1553.23	1337.21	1260.57	1309.18	1.16	1.23	1.19
11F42a	57.75	1.41	1.48	4.63	3530	95.93	1614.60	1510.82	1424.11	1452.46	1.07	1.13	1.11
11R48a	66.00	1.41	1.50	4.67	5620	126.59	1688.63	1692.80	1595.42	1602.23	1.00	1.06	1.05
11F36a	49.50	1.41	1.50	4.65	4570	97.57	1443.37	1352.28	1274.56	1317.90	1.07	1.13	1.10
11F60b	82.50	1.41	1.50	4.63	4090	119.87	1874.29	2033.33	1916.27	1883.20	0.92	0.98	1.00
11F48a	66.00	1.41	1.53	4.64	3140	111.97	1998.24	1712.90	1614.07	1611.31	1.17	1.24	1.24
11F48b	66.00	1.41	1.58	4.66	3330	109.63	1899.87	1746.40	1645.15	1630.19	1.09	1.15	1.17
11F60a	82.50	1.41	1.59	4.62	2610	121.33	2374.88	2108.70	1986.21	1922.68	1.13	1.20	1.24
11R24a	33.00	1.41	1.67	4.65	3720	78.94	1294.21	1068.71	1006.55	1065.09	1.21	1.29	1.22
11R60b	82.50	1.41	1.75	4.62	3460	133.39	2267.66	2242.70	2110.56	1995.40	1.01	1.07	1.14
8F36a	36.00	1.00	1.41	3.29	4650	54.51	799.42	820.91	771.88	744.30	0.97	1.04	1.07
8F36b	36.00	1.00	1.40	3.24	3770	48.18	784.68	817.25	768.49	740.95	0.96	1.02	1.06
11R48b	66.00	1.41	2.06	4.68	3100	107.30	1927.08	2068.00	1943.58	1808.39	0.93	0.99	1.07
8F42b	42.00	1.00	1.45	3.27	3830	58.98	953.03	946.87	890.02	837.83	1.01	1.07	1.14
8R48a	48.00	1.00	1.48	3.26	3040	57.00	1033.83	1072.83	1008.16	931.56	0.96	1.03	1.11
8F42a	42.00	1.00	1.50	3.30	2660	51.46	997.76	968.18	909.80	850.76	1.03	1.10	1.17
8R80a	80.00	1.00	1.50	3.25	3740	75.90	1241.11	1692.63	1590.00	1403.22	0.73	0.78	0.88
8R64a	64.00	1.00	1.52	3.27	3550	70.37	1181.09	1400.59	1315.66	1178.25	0.84	0.90	1.00
8R30a	30.00	1.00	1.53	3.27	3030	41.28	749.94	748.55	703.48	679.94	1.00	1.07	1.10
8F39a	39.00	1.00	1.53	3.27	3650	58.44	967.36	922.87	867.12	812.82	1.05	1.12	1.19
8R42a	42.00	1.00	1.56	3.30	3310	55.42	963.24	993.77	933.54	865.27	0.97	1.03	1.11
8R24a	24.00	1.00	1.67	3.28	3530	46.37	780.46	666.44	626.03	610.98	1.17	1.25	1.28
8R18a	18.00	1.00	1.75	3.26	3470	33.99	576.94	556.32	522.59	525.64	1.04	1.10	1.10
8F36k	36.00	1.00	1.38	1.42	3460	41.62	707.56	809.94	761.71	689.25	0.87	0.93	1.03
										MEAN	1.031	1.096	1.125
										COV	0.116	0.115	0.081
										MIN	0.733	0.781	0.884
										MAX	1.277	1.353	1.277

APPENDIX C

COMPARISONS WITH DATA FROM CHAMBERLIN (1958) – 6 SPECIMENS

							$A_bf_s/f'_c{}^{1/2}$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	A_bf_s kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
4a	6.00	0.50	1.00	2.50	4370	8.42	127.32	114.82	107.83	116.00	1.11	1.18	1.10
4b	6.00	0.50	1.00	2.50	4370	8.66	131.02	114.82	107.83	116.00	1.14	1.22	1.13
4c	6.00	0.50	1.00	2.50	4370	8.55	129.31	114.82	107.83	116.00	1.13	1.20	1.11
3a	6.00	0.50	1.00	1.00	4450	6.28	94.09	114.82	107.83	110.00	0.82	0.87	0.86
3b	6.00	0.50	1.00	1.00	4450	6.32	94.80	114.82	107.83	110.00	0.83	0.88	0.86
3c	6.00	0.50	1.00	1.00	4450	6.42	96.21	114.82	107.83	110.00	0.84	0.89	0.87
										MEAN	0.977	1.040	0.989
										COV	0.153	0.153	0.127
										MIN	0.819	0.873	0.855
										MAX	1.141	1.215	1.130

APPENDIX D

COMPARISONS WITH DATA FROM FERGUSON AND KRISHNASWAMY (1971) – 12 SPECIMENS

							$A_bf_s/f'_c{}^{1/2}$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	A_bf_s kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
SP34	36.00	1.41	0.75	10.59	3280	85.16	1486.88	799.59	757.71	1183.72	1.86	1.96	1.26
SP33	55.00	1.41	0.75	10.59	3360	118.16	2038.47	1047.04	992.94	1561.46	1.95	2.05	1.31
SP32	50.00	1.41	1.25	10.59	3280	113.18	1976.17	1235.71	1166.54	1509.21	1.60	1.69	1.31
SP35	20.00	1.41	2.00	10.59	3310	59.98	1042.50	844.99	795.11	952.59	1.23	1.31	1.09
SP36	24.00	1.41	2.00	7.34	3440	74.21	1265.19	947.84	891.74	993.25	1.33	1.42	1.27
18S15	93.00	2.25	2.63	4.50	2860	205.10	3835.20	4133.88	3892.91	3660.53	0.93	0.99	1.05
18S12	60.00	2.25	3.00	4.56	3160	179.83	3198.95	3193.28	3004.55	2918.64	1.00	1.06	1.10
SP40	15.00	0.63	0.83	1.25	3220	13.30	234.39	228.37	214.91	212.14	1.03	1.09	1.10
14S1	45.00	1.69	2.38	3.46	2710	102.26	1964.31	1856.04	1745.59	1677.62	1.06	1.13	1.17
SP37	45.00	1.41	2.00	2.54	3260	108.04	1892.23	1487.82	1399.01	1297.03	1.27	1.35	1.46
SP39	45.00	1.41	2.00	2.09	3120	79.73	1427.46	1487.82	1399.01	1282.42	0.96	1.02	1.11
SP38	40.00	1.41	2.00	1.41	2970	68.04	1248.48	1119.68	1055.92	1050.88	1.12	1.18	1.19
										MEAN	0.977	1.040	0.989
										COV	0.153	0.153	0.127
										MIN	0.819	0.873	0.855
										MAX	1.141	1.215	1.130

APPENDIX E

COMPARISONS WITH DATA FROM FERGUSON AND BRICENO (1969) – 20 SPECIMENS

							$A_b f_s / f'^{1/2}_c$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	$A_b f_s$ kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
17	50.00	1.41	2.00	2.86	3550	92.84	1558.17	1619.57	1519.79	1400.68	0.96	1.03	1.11
22	50.00	1.41	2.00	2.86	3900	120.31	1926.55	1619.57	1519.79	1400.68	1.19	1.27	1.38
14	33.00	1.41	2.00	2.84	3050	64.05	1159.80	1181.36	1109.14	1083.10	0.98	1.05	1.07
13	44.00	1.41	2.00	2.17	3380	87.55	1505.86	1464.91	1374.85	1266.86	1.03	1.10	1.19
16	44.00	1.41	2.00	2.12	3060	85.99	1554.44	1464.91	1374.85	1265.28	1.06	1.13	1.23
15	65.00	1.41	2.00	2.12	3340	112.34	1943.79	2006.23	1882.12	1645.79	0.97	1.03	1.18
28	44.00	1.41	3.00	2.48	3290	93.79	1635.10	1679.84	1573.80	1417.94	0.97	1.04	1.15
12	65.00	1.41	2.00	1.51	4250	111.47	1709.91	1682.10	1582.09	1452.75	1.02	1.08	1.18
2a	32.00	1.00	2.00	1.50	3920	46.36	740.51	779.05	730.80	675.04	0.95	1.01	1.10
27	42.30	1.41	2.00	1.11	3270	62.42	1091.58	1037.97	979.15	1012.66	1.05	1.11	1.08
1a	47.00	1.00	2.00	1.00	2775	40.03	759.91	826.58	777.93	744.60	0.92	0.98	1.02
7	57.50	1.41	2.00	0.92	2920	69.82	1292.02	1180.94	1115.97	1149.42	1.09	1.16	1.12
11	85.00	1.41	2.00	0.89	3200	93.04	1644.69	1561.61	1476.46	1462.01	1.05	1.11	1.12
19	57.50	1.41	2.00	0.88	3720	93.00	1524.87	1157.53	1094.30	1137.45	1.32	1.39	1.34
20	85.00	1.41	2.00	0.87	3250	129.20	2266.29	1544.31	1460.44	1453.24	1.47	1.55	1.56
1	85.00	1.41	2.00	0.86	2800	71.94	1359.62	1535.66	1452.44	1448.88	0.89	0.94	0.94
9	85.00	1.41	2.00	0.85	3060	92.28	1668.28	1527.01	1444.43	1444.54	1.09	1.15	1.15
5	85.00	1.41	2.00	0.84	3900	94.54	1513.92	1518.36	1436.42	1440.22	1.00	1.05	1.05
3a	42.00	1.00	2.00	0.63	3750	49.90	814.80	598.32	565.59	608.44	1.36	1.44	1.34
4a	42.00	1.00	2.00	0.56	4350	46.73	708.49	568.40	537.90	594.86	1.25	1.32	1.19
										MEAN	1.081	1.147	1.175
										COV	0.142	0.140	0.117
										MIN	0.885	0.936	0.938
										MAX	1.468	1.552	1.559

APPENDIX F

COMPARISONS WITH DATA FROM THOMPSON, JIRSA, BREEN AND MEINHEIT (1975) – 11 SPECIMENS

							$A_bf_s/f'_c{}^{1/2}$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	A_bf_s kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
11.45a	45.00	1.41	1.00	2.00	3520	69.37	1169.20	1031.01	975.11	1020.42	1.13	1.20	1.15
11.25a	25.00	1.41	2.00	3.00	3920	62.46	997.58	973.55	915.89	936.87	1.02	1.09	1.06
14.60a	60.00	1.69	2.00	2.00	2865	100.03	1868.77	2084.27	1962.68	1813.00	0.90	0.95	1.03
8.24a	24.00	1.00	2.00	2.00	3105	42.00	753.68	746.84	700.64	637.00	1.01	1.08	1.18
14.60b	60.00	1.69	2.00	2.00	3200	120.42	2128.66	2084.27	1962.68	1813.00	1.02	1.08	1.17
11.30a	30.00	1.41	2.00	2.00	2865	61.53	1149.50	1102.12	1036.67	1009.00	1.04	1.11	1.14
11.30b	30.00	1.41	2.00	2.00	3350	68.84	1189.32	1102.12	1036.67	1009.00	1.08	1.15	1.18
11.30c	30.00	1.41	2.00	2.00	4420	86.38	1299.25	1102.12	1036.67	1009.00	1.18	1.25	1.29
6.12a	12.00	0.75	2.00	2.00	3730	24.68	404.16	371.45	348.01	322.00	1.09	1.16	1.26
8.18a	18.00	1.00	3.00	2.00	4710	47.05	685.55	602.00	564.98	549.00	1.14	1.21	1.25
8.18b	18.00	1.00	3.00	2.00	2920	35.57	658.24	602.00	564.98	549.00	1.09	1.17	1.20
										MEAN	1.081	1.147	1.175
										COV	0.142	0.140	0.117
										MIN	0.885	0.936	0.938
										MAX	1.468	1.552	1.559

APPENDIX G

COMPARISONS WITH DATA FROM TEPFERS (1973) – 90 SPECIMENS

							$A_bf_s/f'_c{}^{1/2}$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	A_bf_s kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
732-46	20.49	0.63	0.04	1.89	3880	17.60	282.56	123.57	118.73	320.92	2.29	2.38	0.88
732-49	20.49	0.63	0.04	0.95	2400	17.28	352.64	123.57	118.73	229.75	2.85	2.97	1.53
715-56a	20.49	0.63	0.20	1.28	3920	21.86	349.12	156.85	149.61	193.74	2.23	2.33	1.80
732-48	20.49	0.63	0.67	2.31	2880	19.91	371.04	254.62	240.33	253.90	1.46	1.54	1.46
732-73	20.49	0.63	0.99	2.82	3370	19.59	337.42	321.18	302.10	297.62	1.05	1.12	1.13
732-47	20.49	0.63	0.71	1.89	2570	16.10	317.58	262.94	248.05	251.63	1.21	1.28	1.26
732-72	20.49	0.63	0.95	2.32	3280	22.67	395.83	312.86	294.38	285.73	1.27	1.34	1.39
657-14	28.37	0.63	0.39	0.95	3200	19.60	346.42	246.62	233.95	241.66	1.40	1.48	1.43
732-70	20.49	0.47	0.47	1.10	2620	10.86	212.19	170.76	161.72	157.63	1.24	1.31	1.35
715-56b	20.49	0.63	0.59	1.32	4060	24.86	390.15	237.98	224.89	228.86	1.64	1.73	1.70
732-71	20.49	0.63	0.91	1.82	2990	18.53	338.93	304.54	286.66	273.72	1.11	1.18	1.24
732-69	16.55	0.47	0.55	1.08	2620	10.09	197.17	158.29	149.77	144.29	1.25	1.32	1.37
732-68	12.61	0.47	0.55	1.08	2770	6.96	132.31	129.19	122.38	122.08	1.02	1.08	1.08
732-67	8.67	0.47	0.59	1.10	2770	5.85	111.16	103.60	98.25	101.98	1.07	1.13	1.09
732-65	16.55	0.47	0.63	1.10	2400	9.60	196.04	171.73	162.24	152.13	1.14	1.21	1.29
732-41	12.61	0.93	0.59	1.02	3320	25.38	440.55	264.69	250.15	297.86	1.66	1.76	1.48
747-6	52.01	0.99	1.42	2.44	4360	72.95	1104.86	1110.54	1043.78	933.15	0.99	1.06	1.18
747-1	20.49	0.99	1.46	2.46	3600	30.02	500.26	544.76	512.23	512.69	0.92	0.98	0.98
747-4	20.49	0.99	1.46	2.46	2920	33.07	612.07	544.76	512.23	512.69	1.12	1.19	1.19
732-64	12.61	0.47	0.67	1.10	1780	8.73	206.98	144.55	136.63	130.99	1.43	1.51	1.58
747-3	36.25	0.99	1.58	2.46	3180	44.76	793.73	882.37	828.78	754.80	0.90	0.96	1.05
747-2	28.37	0.99	1.58	2.46	3650	45.09	746.31	726.05	682.09	640.94	1.03	1.09	1.16
732-5	20.49	0.63	0.63	0.97	8120	30.37	337.08	246.30	232.61	227.66	1.37	1.45	1.48
732-54	20.49	0.63	0.67	0.99	5700	20.85	276.10	254.62	240.33	232.69	1.08	1.15	1.19
747-8	36.25	1.26	1.50	2.17	2850	55.39	1037.51	992.25	932.76	908.14	1.05	1.11	1.14
732-6	20.49	0.63	0.67	0.97	9095	27.46	287.89	254.62	240.33	232.37	1.13	1.20	1.24
732-63	8.67	0.47	0.75	1.08	2410	6.95	141.60	117.69	111.31	109.94	1.20	1.27	1.29
732-37	20.49	0.63	0.71	0.99	12540	19.87	177.45	262.94	248.05	237.43	0.67	0.72	0.75
732-55	20.49	0.63	0.71	0.99	7490	21.37	246.95	262.94	248.05	237.43	0.94	1.00	1.04
732-66	20.49	0.47	0.79	1.10	2400	11.77	240.23	237.32	223.49	195.41	1.01	1.07	1.23
732-3	20.49	0.63	0.71	0.97	5060	22.35	314.13	262.94	248.05	237.12	1.19	1.27	1.32
732-40	12.61	0.39	0.71	0.96	3180	8.79	155.89	135.20	126.77	114.22	1.15	1.23	1.36
732-51	20.49	0.63	0.75	0.98	3730	17.68	289.51	271.26	255.77	242.05	1.07	1.13	1.20
732-35	20.49	0.63	0.75	0.98	5290	25.02	344.03	271.26	255.77	242.05	1.27	1.35	1.42
732-1	20.49	0.63	0.75	0.97	2440	16.59	335.79	271.26	255.77	241.89	1.24	1.31	1.39
732-36	20.49	0.63	0.75	0.97	13300	26.08	226.11	271.26	255.77	241.89	0.83	0.88	0.93
732-52	20.49	0.63	0.75	0.95	3550	17.28	289.95	271.26	255.77	241.58	1.07	1.13	1.20
747-5	36.25	0.99	1.93	2.44	3800	62.46	1013.24	1011.17	948.30	829.43	1.00	1.07	1.22
732-53	20.49	0.63	0.79	0.98	1620	10.71	266.00	279.58	263.49	246.85	0.95	1.01	1.08
657-4	52.01	0.63	0.79	0.95	3180	27.48	487.39	608.55	572.92	482.35	0.80	0.85	1.01
657-2	28.37	0.63	0.79	0.95	3230	21.00	369.51	361.82	340.85	305.38	1.02	1.08	1.21
657-1	20.49	0.63	0.79	0.95	3230	17.28	303.98	279.58	263.49	246.39	1.09	1.15	1.23
657-3	40.19	0.63	0.79	0.95	3180	25.53	452.79	485.19	456.89	393.86	0.93	0.99	1.15
732-17	20.49	0.63	0.83	0.98	6620	21.86	268.65	287.90	271.21	251.67	0.93	0.99	1.07
732-4	20.49	0.63	0.83	0.96	6570	26.77	330.21	287.90	271.21	251.37	1.15	1.22	1.31
732-11	20.49	0.63	0.83	0.96	2270	17.68	371.11	287.90	271.21	251.37	1.29	1.37	1.48

APPENDIX G, continued

							$A_bf_s/f'^{1/2}_c$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	A_bf_s kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
732-12	20.49	0.63	0.83	0.95	1100	9.57	288.57	287.90	271.21	251.22	1.00	1.06	1.15
732-10	20.49	0.63	0.87	0.96	3920	23.24	371.15	296.22	278.93	256.21	1.25	1.33	1.45
747-7	20.49	1.26	2.01	2.17	3480	39.42	668.21	782.15	734.67	737.92	0.85	0.91	0.91
732-61	28.37	0.75	0.75	0.80	2300	15.84	330.34	390.92	369.01	345.91	0.85	0.90	0.95
732-15	20.49	0.63	0.91	0.97	4050	18.65	293.13	304.54	286.66	261.22	0.96	1.02	1.12
732-9	20.49	0.63	0.91	0.96	3055	22.14	400.61	304.54	286.66	261.07	1.32	1.40	1.53
732-7	20.49	0.63	0.91	0.96	1300	9.33	258.70	304.54	286.66	261.07	0.85	0.90	0.99
732-28	20.49	0.63	0.91	0.95	6200	28.96	367.74	304.54	286.66	260.92	1.21	1.28	1.41
657-25	14.18	0.77	0.79	0.81	3190	19.90	352.25	255.26	239.82	252.30	1.38	1.47	1.40
657-23	4.73	0.77	0.79	0.81	3530	10.37	174.48	151.55	142.06	178.13	1.15	1.23	0.98
657-24	9.46	0.77	0.79	0.81	4050	18.22	286.23	203.46	190.99	215.25	1.41	1.50	1.33
657-25A	26.00	0.77	0.79	0.81	4150	26.35	409.08	384.97	362.09	345.08	1.06	1.13	1.19
657-22	2.36	0.77	0.79	0.81	3090	5.84	105.06	125.54	117.55	159.52	0.84	0.89	0.66
732-2	20.49	0.63	0.95	0.97	3310	17.84	310.15	312.86	294.38	266.09	0.99	1.05	1.17
732-62	12.61	0.75	0.83	0.80	2530	8.44	167.76	231.98	219.04	231.07	0.72	0.77	0.73
715-56c	20.49	0.63	1.38	1.33	3960	24.86	395.04	391.90	367.72	318.38	1.01	1.07	1.24
732-16	20.49	0.63	1.02	0.98	4675	19.99	292.41	319.10	300.17	270.47	0.92	0.97	1.08
123-S7	37.82	0.63	0.99	0.95	4400	27.62	416.40	521.88	490.62	413.02	0.80	0.85	1.01
123-S4	28.37	0.63	0.99	0.95	4170	23.98	371.29	407.90	383.61	333.06	0.91	0.97	1.11
123-S3	22.06	0.63	0.99	0.95	4340	21.66	328.73	331.79	312.15	279.67	0.99	1.05	1.18
123-S2	15.76	0.63	0.99	0.95	4320	19.37	294.71	255.81	240.81	226.36	1.15	1.22	1.30
123-S1	9.46	0.63	0.99	0.95	3250	12.60	221.03	179.82	169.47	173.05	1.23	1.30	1.28
732-14	20.49	0.63	1.02	0.96	1860	11.72	271.75	314.94	296.31	268.04	0.86	0.92	1.01
732-30	20.49	0.63	1.02	0.95	6270	29.16	368.24	312.86	294.38	266.82	1.18	1.25	1.38
732-13	20.49	0.63	1.02	0.95	1420	9.73	258.29	312.86	294.38	266.82	0.83	0.88	0.97
732-42	20.49	0.75	1.42	1.22	4880	30.46	436.09	406.01	381.77	352.73	1.07	1.14	1.24
732-59	28.37	0.75	0.95	0.81	2270	17.45	366.18	408.20	385.04	359.22	0.90	0.95	1.02
657-40	18.91	0.63	0.79	0.65	3900	17.10	273.88	236.21	223.04	216.75	1.16	1.23	1.26
657-40A	34.67	0.63	0.79	0.65	3740	22.23	363.54	378.30	356.97	319.89	0.96	1.02	1.14
657-38	6.30	0.63	0.79	0.65	3540	8.10	136.22	122.52	115.88	134.23	1.11	1.18	1.01
657-39	12.61	0.63	0.79	0.65	3370	14.45	248.93	179.41	169.51	175.52	1.39	1.47	1.42
657-37	3.15	0.63	0.79	0.65	3390	5.70	97.87	94.12	89.11	113.61	1.04	1.10	0.86
732-60	12.61	0.75	1.02	0.81	2270	10.79	226.37	233.26	220.23	233.69	0.97	1.03	0.97
732-43	20.49	0.75	1.54	1.21	3220	22.40	394.77	403.93	379.84	353.23	0.98	1.04	1.12
657-13	28.37	0.63	1.26	0.95	3200	24.54	433.77	407.90	383.61	338.50	1.06	1.13	1.28
715-56d	20.49	0.63	1.97	1.34	5120	27.46	383.70	393.98	369.65	327.58	0.97	1.04	1.17
732-45	20.49	0.63	1.93	0.97	2780	21.66	410.73	317.02	298.24	282.43	1.30	1.38	1.45
732-44	20.49	0.63	2.25	0.97	3150	20.84	371.40	317.02	298.24	287.06	1.17	1.25	1.29
732-74	20.49	0.63	2.60	0.94	3230	19.43	341.80	310.78	292.45	288.65	1.10	1.17	1.18
732-75	20.49	0.63	3.27	0.94	3230	20.40	358.92	310.78	292.45	298.43	1.15	1.23	1.20
732-77	20.49	0.63	3.74	0.94	2040	18.25	404.05	310.78	292.45	305.29	1.30	1.38	1.32
732-76	20.49	0.63	3.78	0.93	890	5.84	195.75	308.70	290.52	304.76	0.63	0.67	0.64
732-50	20.49	0.63	2.92	0.37	2700	14.44	277.84	192.21	182.43	238.16	1.45	1.52	1.17
732-58	20.49	0.63	0.00	0.00	2230	4.50	95.32	115.25	111.01	132.59	0.83	0.86	0.72
										MEAN	1.133	1.201	1.195
										COV	0.282	0.276	0.181
										MIN	0.634	0.674	0.642
										MAX	2.854	2.970	1.802

APPENDIX H

COMPARISONS WITH DATA FROM FERGUSON AND THOMPSON (1962, 1965) – 34 SPECIMENS

							$A_bf_s/f'_c{}^{1/2}$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	A_bf_s kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
B37	28.00	0.88	0.78	8.53	2930	40.10	740.83	442.92	418.10	587.91	1.67	1.77	1.26
B16	21.00	0.88	0.81	8.56	3910	36.89	589.92	370.39	349.51	488.33	1.59	1.69	1.21
B40	28.00	0.88	0.90	8.73	3780	50.11	814.99	477.03	449.75	603.43	1.71	1.81	1.35
C20	50.75	1.41	1.56	11.42	3600	117.35	1955.80	1408.99	1327.55	1621.81	1.39	1.47	1.21
C11	33.80	1.41	1.56	11.36	3760	84.74	1382.00	1048.86	988.37	1234.88	1.32	1.40	1.12
B4	35.00	0.88	0.78	5.56	3360	45.22	780.11	521.85	492.62	603.36	1.49	1.58	1.29
B43	35.00	0.88	0.97	6.53	3590	51.47	859.08	589.36	555.27	659.01	1.46	1.55	1.30
C1	45.00	1.41	1.41	8.31	3300	71.16	1238.78	1218.30	1148.91	1350.90	1.02	1.08	0.92
B46	21.00	0.88	1.47	8.53	4110	43.53	678.94	511.08	480.07	549.66	1.33	1.41	1.24
B27	21.00	0.88	1.53	8.50	5950	52.24	677.28	523.87	491.94	555.84	1.29	1.38	1.22
C10	33.80	1.41	1.50	8.22	3050	71.27	1290.46	1028.27	969.26	1142.93	1.25	1.33	1.13
C8	45.00	1.41	1.56	8.31	3920	79.53	1270.32	1286.82	1212.49	1382.71	0.99	1.05	0.92
B47	21.00	0.88	1.62	8.53	2580	33.94	668.26	543.06	509.74	566.34	1.23	1.31	1.18
B42	35.00	0.88	1.66	8.51	2950	51.47	947.70	834.51	782.76	830.98	1.14	1.21	1.14
B19	15.75	0.88	1.69	8.64	3000	32.17	587.31	450.29	422.69	476.88	1.30	1.39	1.23
C38	63.30	1.41	2.00	10.11	3410	101.22	1733.42	1958.38	1841.06	1979.82	0.89	0.94	0.88
C40	49.40	1.41	2.00	10.11	3310	77.25	1342.63	1600.96	1505.29	1647.84	0.84	0.89	0.81
B20	15.75	0.88	1.72	8.53	5430	45.89	622.80	455.08	427.14	478.29	1.37	1.46	1.30
B13	15.75	0.88	1.73	8.53	3800	35.33	573.11	456.68	428.63	479.15	1.25	1.34	1.20
B45	21.00	0.88	1.50	6.61	3560	33.89	567.93	517.48	486.00	525.17	1.10	1.17	1.08
A1	15.00	0.88	0.69	2.75	2470	26.31	529.32	282.63	266.98	319.68	1.87	1.98	1.66
B44	28.00	0.88	1.66	6.50	3060	43.87	793.11	693.05	650.21	662.86	1.14	1.22	1.20
C35	50.75	1.41	3.00	11.53	3430	117.12	1999.85	2150.86	2015.97	2006.66	0.93	0.99	1.00
C33	33.80	1.41	3.00	11.47	2900	82.95	1540.27	1542.95	1446.86	1491.43	1.00	1.06	1.03
B6	21.00	0.88	1.47	5.50	3980	31.52	499.61	511.08	480.07	505.62	0.98	1.04	0.99
B35	28.00	0.88	2.44	8.53	2980	52.80	967.24	914.76	855.94	824.38	1.06	1.13	1.17
B3	35.00	0.88	1.66	5.56	2810	47.72	900.23	834.51	782.76	761.40	1.08	1.15	1.18
B36	28.00	0.88	2.56	8.53	3180	57.50	1019.59	948.87	887.59	843.92	1.07	1.15	1.21
B34	21.00	0.88	2.59	8.53	2380	38.91	797.53	749.85	701.63	681.62	1.06	1.14	1.17
B38	21.00	0.88	2.62	8.53	3720	50.28	824.38	756.24	707.56	685.30	1.09	1.17	1.20
B39	28.00	0.88	2.69	8.44	3340	54.73	946.92	985.82	921.88	863.63	0.96	1.03	1.10
B1	35.00	0.88	2.09	6.50	3470	53.97	916.27	987.29	924.53	869.30	0.93	0.99	1.05
C9	45.00	1.41	2.69	8.31	3020	89.30	1625.01	1803.02	1691.50	1656.73	0.90	0.96	0.98
A4	12.00	0.88	1.25	2.81	2690	24.08	464.29	319.76	300.89	328.48	1.45	1.54	1.41
										MEAN	1.210	1.288	1.157
										COV	0.211	0.209	0.140
										MIN	0.839	0.892	0.815
										MAX	1.873	1.983	1.656

APPENDIX I

COMPARISONS WITH DATA FROM CHAMBERLIN (1956) – 23 SPECIMENS

							$A_b f_s / f'^{1/2}_c$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	$A_b f_s$ kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
SIIIh	16.00	0.75	1.00	1.50	4470	20.13	301.11	301.75	283.96	284.53	1.00	1.06	1.06
SIIIg	16.00	0.75	1.00	1.13	4470	20.96	313.51	301.75	283.96	280.19	1.04	1.10	1.12
SIIId	6.00	0.50	1.00	1.00	4470	8.01	119.82	114.82	107.83	110.00	1.04	1.11	1.09
SIId	10.66	0.50	1.00	1.00	3680	9.59	158.16	171.07	160.51	148.83	0.92	0.99	1.06
SIIIm	6.00	0.50	1.00	0.75	5870	8.27	108.01	99.59	93.70	101.07	1.08	1.15	1.07
SIIIc	6.00	0.50	1.00	0.75	4470	7.08	105.87	99.59	93.70	101.07	1.06	1.13	1.05
SIIc	10.66	0.50	1.00	0.75	3680	8.31	136.91	144.01	135.41	132.96	0.95	1.01	1.03
SIIIf	16.00	0.75	1.00	0.75	4470	17.76	265.58	261.14	246.28	255.20	1.02	1.08	1.04
SIVf	12.00	0.50	1.00	0.50	4540	7.84	116.38	126.33	119.14	124.80	0.92	0.98	0.93
SIIIb	6.00	0.50	1.00	0.50	4470	6.35	95.01	84.37	79.57	92.40	1.13	1.19	1.03
SIIb	10.66	0.50	1.00	0.50	3680	7.18	118.42	116.96	110.30	117.56	1.01	1.07	1.01
SIIIj	10.66	0.50	1.00	0.50	5870	8.24	107.53	116.96	110.30	117.56	0.92	0.97	0.91
SIIIl	6.00	0.50	1.00	0.50	5870	6.88	89.80	84.37	79.57	92.40	1.06	1.13	0.97
SIVc	6.00	0.50	1.00	0.50	4540	5.53	82.11	84.37	79.57	92.40	0.97	1.03	0.89
SIVe	12.00	0.50	1.00	0.38	4540	7.05	104.63	111.71	105.58	116.98	0.94	0.99	0.89
SIIIe	16.00	0.75	1.00	0.38	4470	15.65	234.01	201.05	190.51	223.05	1.16	1.23	1.05
SIVb	6.00	0.50	1.00	0.38	4540	5.03	74.69	77.06	72.79	88.49	0.97	1.03	0.84
SIIIi	10.66	0.50	1.00	0.25	5870	7.37	96.16	89.91	85.20	104.06	1.07	1.13	0.92
SIIa	10.66	0.50	1.00	0.25	3680	6.01	99.09	89.91	85.20	104.06	1.10	1.16	0.95
SIVa	6.00	0.50	1.00	0.25	4540	4.67	69.38	69.14	65.44	84.80	1.00	1.06	0.82
SIVd	12.00	0.50	1.00	0.25	4540	5.28	78.33	95.88	90.88	109.60	0.82	0.86	0.71
SIIIa	6.00	0.50	1.00	0.25	4470	4.58	68.51	69.14	65.44	84.80	0.99	1.05	0.81
SIIIk	6.00	0.50	1.00	0.25	5870	5.97	77.87	69.14	65.44	84.80	1.13	1.19	0.92
										MEAN	1.014	1.074	0.964
										COV	0.079	0.079	0.106
										MIN	0.817	0.862	0.715
										MAX	1.164	1.228	1.119

APPENDIX J

COMPARISONS WITH DATA FROM HESTER, SALAMIZAVAREGH, DARWIN AND McCABE (1991) - 7 BEAM SPECIMENS

							$A_bf_s/f'_c{}^{1/2}$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	A_bf_s kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
8C3220	22.75	1.00	2.15	1.50	5850	40.76	532.97	601.19	565.23	550.85	0.89	0.94	0.97
8S3160	16.00	1.00	2.10	1.50	6450	33.73	420.02	472.51	444.40	457.16	0.89	0.95	0.92
8C3160	16.00	1.00	1.84	1.50	6200	36.74	466.53	472.51	444.40	454.20	0.99	1.05	1.03
8C3160	16.00	1.00	2.12	2.00	5240	35.71	493.29	553.72	519.76	504.95	0.89	0.95	0.98
8C3160	16.00	1.00	2.05	1.50	5490	31.36	423.28	472.51	444.40	456.59	0.90	0.95	0.93
8S3160	16.00	1.00	2.04	1.50	6020	37.13	478.55	472.51	444.40	456.48	1.01	1.08	1.05
8N3160	16.00	1.00	2.00	1.50	5990	39.82	514.45	472.51	444.40	456.02	1.09	1.16	1.13
										MEAN	0.950	1.011	0.999
										COV	0.078	0.078	0.069
										MIN	0.887	0.943	0.919
										MAX	1.089	1.158	1.128

COMPARISONS WITH DATA FROM HESTER, SALAMIZAVAREGH, DARWIN AND McCABE (1991) - 7 SLAB SPECIMENS

							$A_bf_s/f'_c{}^{1/2}$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	A_bf_s kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
6C5100	10.00	0.75	2.07	3.25	5290	20.64	283.73	332.19	311.27	302.43	0.85	0.91	0.94
6S3100	10.00	0.75	2.18	3.25	5030	20.37	287.24	343.36	321.63	309.02	0.84	0.89	0.93
6C3100	10.00	0.75	2.19	3.25	5370	20.86	284.61	344.38	322.57	309.62	0.83	0.88	0.92
6C3100	10.00	0.75	2.36	3.25	5040	19.40	273.32	361.63	338.59	319.83	0.76	0.81	0.85
8C5160	16.00	1.00	2.08	3.25	5410	28.44	386.66	566.72	531.82	524.58	0.68	0.73	0.74
8C5160	16.00	1.00	2.09	3.25	5100	34.05	476.78	568.34	533.32	525.53	0.84	0.89	0.91
6C5100	10.00	0.75	2.03	3.25	5440	16.41	222.52	328.13	307.50	300.04	0.68	0.72	0.74
										MEAN	0.782	0.834	0.861
										COV	0.090	0.090	0.094
										MIN	0.678	0.724	0.737
										MAX	0.854	0.912	0.938

APPENDIX J, continued

COMPARISONS WITH DATA FROM CHOI, HADJE-GHAFFARI, DARWIN AND McCABE (1990) – 8 SPECIMENS

							$A_b f_s / f'^{1/2}_c$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	$A_b f_s$ kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
5N0120	12.00	0.63	1.00	2.00	5360	19.38	264.64	216.32	203.32	206.40	1.22	1.30	1.28
5N0120	12.00	0.63	1.00	2.00	5360	20.24	276.50	216.32	203.32	206.40	1.28	1.36	1.34
6C0120	12.00	0.75	1.00	2.00	6010	22.62	291.73	249.63	234.97	250.80	1.17	1.24	1.16
6S0120	12.00	0.75	1.00	2.00	6010	20.15	259.94	249.63	234.97	250.80	1.04	1.11	1.04
8N0160	16.00	1.00	1.50	2.00	5980	34.21	442.35	472.51	444.40	456.02	0.94	1.00	0.97
8S0160	16.00	1.00	1.50	2.00	5980	34.05	440.31	472.51	444.40	456.02	0.93	0.99	0.97
11S0240	24.00	1.41	2.00	2.00	5850	62.71	819.92	947.84	891.74	900.80	0.87	0.92	0.91
11C0240	24.00	1.41	2.00	2.00	5850	58.97	770.97	947.84	891.74	900.80	0.81	0.86	0.86
										MEAN	1.032	1.097	1.065
										COV	0.157	0.158	0.156
										MIN	0.813	0.865	0.856
										MAX	1.278	1.360	1.340

COMPARISONS WITH DATA FROM HAMAD AND JIRSA (1990) – 2 SPECIMENS

							$A_b f_s / f'^{1/2}_c$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	$A_b f_s$ kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
6P3180	18.00	0.75	2.00	0.63	3740	27.37	447.51	259.29	244.87	273.12	1.73	1.83	1.64
11P3300	30.00	1.41	2.00	2.00	3700	54.29	892.49	1102.12	1036.67	1009.00	0.81	0.86	0.88
										MEAN	1.268	1.344	1.262
										COV	0.361	0.360	0.299
										MIN	0.810	0.861	0.885
										MAX	1.726	1.828	1.639

APPENDIX J, continued

COMPARISONS WITH DATA FROM TREECE AND JIRSA (1987) – 9 SPECIMENS

							$A_bf_s/f'_c{}^{1/2}$				Test/Prediction		
Test #	l_d in.	d_b in.	C_b in.	C_s in.	f'_c psi	A_bf_s kips	Test in.^{2}	Eq.3 in.^{2}	Eq.4 in.^{2}	Eq.12 in.^{2}	Eq.3	Eq.4	Eq.12
6D0160	16.00	0.75	0.75	2.00	12600	27.85	248.13	261.14	246.28	268.00	0.95	1.01	0.93
6D0160	16.00	0.75	0.88	2.00	8040	27.85	310.62	281.45	265.12	279.05	1.10	1.17	1.11
6D0240	24.00	0.75	1.00	2.00	3860	27.85	448.29	405.98	381.94	369.60	1.10	1.17	1.21
6D0120	12.00	0.75	2.00	2.00	4250	23.36	358.39	371.45	348.01	322.00	0.96	1.03	1.11
11D0180	18.00	1.41	2.00	2.00	10510	73.16	713.67	793.56	746.80	792.60	0.90	0.96	0.90
11D0360	36.00	1.41	2.00	2.00	4290	71.60	1093.22	1256.40	1181.61	1117.20	0.87	0.93	0.98
11D0180	18.00	1.41	2.00	2.00	9600	67.08	684.63	793.56	746.80	792.60	0.86	0.92	0.86
11D0360	36.00	1.41	2.00	2.00	5030	67.55	952.42	1256.40	1181.61	1117.20	0.76	0.81	0.85
11D0180	18.00	1.41	2.13	2.00	8280	62.87	690.90	793.56	746.80	794.22	0.87	0.93	0.87
										MEAN	0.932	0.990	0.981
										COV	0.116	0.115	0.127
										MIN	0.758	0.806	0.853
										MAX	1.104	1.174	1.213