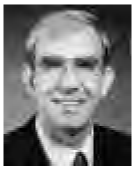
ACI STRUCTURAL JOURNAL TECHNICAL PAPER

Title no. 93-S32

Development Length Criteria for Conventional and High Relative Rib Area Reinforcing Bars




by David Darwin, Jun Zuo, Michael L. Tholen, and Emmanuel K. Idun

Statistical analyses of 133 splice and development specimens in which the bars are not confined by transverse reinforcement and 166 specimens in which the bars are confined by transverse reinforcement are used to develop an expression for the bond force at failure as a function of concrete strength, cover, bar spacing, development/splice length, transverse reinforcement, and the geometric properties of the developed/spliced bars. Results are used to formulate design criteria that incorporate a reliability-based strength reduction (ϕ) factor that allows the calculation of a single value for both development and splice length for given material properties and member geometry.

As with earlier studies, the analyses demonstrate that the relationship between bond force and development or splice length l_d *is linear but not proportional. Thus, to increase the bond force (or bar stress) by a given percentage requires more than the percentage increase in* l_d. $f'^{1/2}_c$ *does not provide an accurate representation of the effect of concrete strength on bond strength over the full range of concrete strengths in use today; development/splice strengths are underestimated for low-strength concretes and overestimated for high-strength concretes.* $f'^{1/4}_c$ *provides an accurate representation of the effect of concrete strength on bond strength for concretes with compressive strengths between 2500 and 16,000 psi (17 and 110 MPa). The most accurate representation of the effect of transverse reinforcement on bond strength obtained in the current analysis includes parameters that account for the number of transverse reinforcing bars that cross the developed/spliced bar, the area of the transverse reinforcement, the number of bars developed or spliced at one location, the relative rib area of the developed/spliced bar, and the size of the developed/spliced bar. The yield strength of transverse reinforcement does not play a role in the effectiveness of the transverse reinforcement in improving development/splice strength. Depending on the design expression selected, for conventional and high relative rib area bars that are not confined by transverse reinforcement, development lengths average 2 to 14 percent higher and splice lengths 12 to 22 percent lower than those obtained using ACI 318-95. For conventional reinforcing bars confined by transverse reinforcement, development lengths average 5 percent lower to 16 percent higher than those obtained using ACI 318-95, while splice lengths average 11 to 27 percent lower than those obtained using ACI 318-95. For high relative rib area reinforcing bars confined by transverse reinforcement, development lengths average 3 to 17 percent lower than those obtained using ACI 318-95, while splice lengths average 25 to 36 percent lower than those obtained using ACI 318-95. When confined by transverse reinforcement, high relative rib area bars require development and splice lengths that are 13 to 16 percent lower than required by conventional bars.*

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

The provisions in Chapter 12 of the 1995 ACI Building Code (ACI 318-95) will make the design process easier and reflect development and splice strength better than any previous code procedures. The new expressions are based, in part, on a statistical analysis carried out over 20 years ago (Orangun, Jirsa, and Breen 1975) and on recommendations based on that analysis provided by ACI Committee 408 (1990). As with previous versions of the ACI Code, the calculated development/splice lengths are proportional to the bar stress (the actual relationship is linear but not proportional), and most splice lengths are 30 percent greater than the corresponding development lengths.

Over the past 20 years, additional data has become available, and analyses of the expanded database (presented in this paper) have exposed a number of shortcomings in the ability of both the code expressions and the original statistically-based expressions to accurately represent the development and splice strength of reinforcing bars, as used in current practice. Specifically, the analyses demonstrate that the square root of the concrete compressive strength f'_c does not accurately characterize the effect of concrete strength on bond strength for the full range of concrete strengths in use today, and the yield strength of transverse reinforcement f_{yt} plays no measurable role in the contribution of confining steel to bond strength. In addition, the study by Orangun et al. (1975, 1977) and a more recent study by Darwin, McCabe, Idun, and Schoenekase (1992a, 1992b) have the drawback of inadvertently including top-cast and side-cast bar specimens in analyses representing bottom-cast reinforcement. Only bottom-cast bars are considered in the current study.

The current analyses were carried out in conjunction with a large-scale experimental study to improve the development characteristics of reinforcing bars (Darwin and Graham

ACI Structural Journal, V. 93, No. 3, May-June 1996.
Received Feb. 6, 1996, and reviewed under Institute publication policies. Pertinent discussion will be published in the March-April 1997 *ACI Structural Journal* if received by Nov. 1, 1996.

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1993a, 1993b, Darwin, Tholen, Idun, and Zuo 1995a, 1996a) and have several advantages over the earlier studies: 1) the database is larger (Chinn et al. 1955, Chamberlin 1956, 1958, Mathey and Watstein 1961, Ferguson and Thompson 1965, Ferguson and Breen 1965, Thompson et al. 1975, Zekany et al. 1981, Choi et al. 1990, 1991, DeVries et al. 1991, Hester et al. 1991, 1993, Rezansoff et al. 1991, 1993, Azizinamini et al. 1993, 1995, Darwin et al. 1995a, 1996a), including 133 splice and development specimens in which the bars are not confined by transverse reinforcement and 166 specimens in which the bars are confined by transverse reinforcement; 2) the concrete strengths cover a broader range than used in the earlier studies; and 3) data includes bars with a wide range of relative rib area (ratio of bearing area of ribs to shearing area between ribs) R_r, a parameter that has been demonstrated to significantly affect the added bond strength provided by transverse reinforcement (Darwin and Graham 1993a, 1993b, Darwin et al. 1995a, 1996a).

This paper describes the development of a statistically-based expression that accurately represents the development and splice strength of reinforcing bars, both with and without confining reinforcement, for values of f'_c between 2500 and 16,000 psi (17 and 110 MPa). In addition to transverse reinforcement and concrete strength, the expression takes into account cover, bar spacing, development/splice length, and the geometric properties of the developed/spliced bars. The expression is used to formulate design criteria that incorporate a reliability-based strength reduction (ϕ) factor (Darwin, Idun, Zuo, and Tholen 1995c, 1996b) that allows the calculation of a single value for both splice and development length for given material properties and member geometry. Compared to current design practice (ACI 318-95, AASHTO Highway 1992), the new design criteria permit major reductions in the development lengths of high relative rib area bars confined by transverse reinforcement and in the splice lengths of conventional and high relative rib area bars under all conditions of confinement. Additional details of the study are presented by Darwin, Zuo, Tholen and Idun (1995b).

OVERVIEW

The statistical analyses and development of design criteria that are described in this paper are based on a model in which the maximum bond force in a developed or spliced bar T_b is expressed as the sum of a "concrete contribution" T_c, which is a function of concrete strength, member geometry, and bar size, and a "steel contribution" T_s, which is a function of concrete strength, the geometric properties of the developed/spliced bar, and the geometry of the confining reinforcement in the development/splice region

$$T_b = T_c + T_s \tag{1}$$

Eq. (1) serves as the basis of the analysis that, when complete, is used to formulate design expressions that are used to calculate development/splice length l_d.

The calculation of the concrete contribution T_c builds on earlier work (Orangun et al. 1975, 1977, Darwin et al. 1992a, 1992b). The analysis initially proceeds by determining the best statistical match between the total bond force for bars not confined by transverse reinforcement $T_c = A_b f_s$, in which A_b = bar area and f_s = bar stress at development or splice failure, and the product of l_d, the development or splice length, and $c_m + 0.5\ d_b$, the smaller of the cover to the center of the bar ($c_b + 0.5\ d_b$) or half the center-to-center bar spacing ($c_s + 0.5\ d_b$), in which c_b = cover, c_s = one-half of the clear spacing between bars, and d_b = bar diameter. Next, adjustments are made to take into account the fact that bond strength increases with respect to the product $l_d(c_m + 0.5\ d_b)$ as the difference between c_b and c_s increases.

The initial analysis is carried out using (as is traditional) $f'^{1/2}_c$ to represent the effect of concrete strength on bond strength. The resulting expression is tested for f'_c between 2610 and 15,120 psi (18 and 104 MPa), and the power of f'_c is adjusted to provide an improved representation for bond strength. The new expression for T_c is then used to calculate the steel contribution T_s in development/splice tests for members containing confining reinforcement. This is done by subtracting the calculated value of the concrete contribution from the experimental bond force T_b

$$T_s = T_b - T_c \tag{2}$$

T_s is correlated with the concrete strength, the geometric properties of the transverse reinforcement, and the geometric properties of the developed/spliced bars to obtain an accurate representation of the increase in bond strength provided by the confining steel. The evaluation includes the establishment of limits within which the expressions give conservative predictions of strength.

The resulting expressions for bond force for developed/spliced bars, both with and without confining reinforcement, are then combined with a reliability-based strength reduction (ϕ) factor (Darwin et al. 1995c, 1996b) to obtain design expressions for l_d. The expressions include the effect of relative rib area R_r, and thus, can be used to take advantage of the increased bond strength obtainable with high R_r bars. The development and splice lengths obtained with the new expressions are then compared to those obtained using ACI 318-95.

Test specimens used in the analyses are limited to splice and development specimens for which concrete properties are characterized by the compressive strength of standard cylinders (ASTM C 39).

EXPRESSIONS FOR DEVELOPMENT/SPLICE STRENGTH

Bars without confining reinforcement

The work reported herein represents the final results of a series of analyses using 133 development and splice specimens containing bottom-cast bars.

Using $f'_c{}^{1/2}$ to represent the effect of concrete compressive strength on bond strength produces the following expression for total bond force for bars not confined by transverse reinforcement

$$\frac{T_c}{f'_c{}^{1/2}} = \frac{A_b f_s}{f'_c{}^{1/2}} = [8.76 l_d(c_m + 0.5d_b) + 187A_b]\left(0.14\frac{c_M}{c_m} + 0.86\right) \quad (3)$$

in which

c_m, c_M = minimum and maximum value of c_s or c_b ($c_M/c_m \leq 3.5$), in in.

c_s = min (c_{si} + 0.25 in., c_{so}), in.

c_{si} = one-half of clear spacing between bars, in.

c_{so}, c_b = side cover and bottom cover of reinforcing bars, in.

T_c is in lb, A_b is in in.^{2}, and f_s, f'_c, and $f'_c{}^{1/2}$ are in psi.

Eq. (3) is obtained following the procedures of Darwin et al. (1992a, 1992b). A best-fit is obtained between $T_c/f'_c{}^{1/2}$ and the product $l_d\,(c_m + 0.5\,d_b)$ using a dummy variable analysis (Draper and Smith, 1981) in which the data are separated based on bar size. The results of the analysis are then used to improve the fit by including a weighted average coefficient to represent the area of the bar A_b. Unlike the earlier analysis (Darwin et al. 1992a, 1992b), the effects of the differences in c_m and c_M are evaluated after the coefficient for A_b is obtained.

The term (0.14 c_M/c_m + 0.86) is obtained based on a best-fit analysis comparing the test/prediction ratios [obtained using the term in brackets on the right side of Eq. (3) as the predicted strength] with the ratio c_M/c_m. The term takes into account the increased strength observed in the tests when $c_m \neq c_M$. When determining c_s, 0.25 in. (6 mm) is added to c_{si}, one-half of the clear spacing between the bars, because the extra 0.25 in. (6 mm) gives an improved match with the test data. The fact that the effective value of c_{si} is slightly larger than one-half of the clear spacing is likely due to the longer effective crack lengths that occur when concrete splits between the bars rather than through the cover (Darwin et al. 1992a, 1992b).

When the test results used to develop Eq. (3) are re-evaluated based on categories of concrete strength, the specimens with the lowest strength concretes produce the highest relative strengths, as shown in Fig. 1. For the categories of concrete strengths evaluated, from below 3000 to over 10,000 psi (21 to 69 MPa), the intercepts on the vertical axis decrease as the concrete strength increases. The line representing concrete with compressive strengths above 10,000 psi (69 MPa) is significantly below that of the rest of the data. The comparisons show that $f'_c{}^{1/2}$ gives a good representation for concrete strengths between 4500 and 7500 psi (31 and 52 MPa). Outside of this range, $f'_c{}^{1/2}$ does not give a good representation.

Based on this observation, a series of reanalyses were carried out to determine the power of f'_c that would minimize the spread in the data. The reanalyses showed that f'_c to the 0.24 power provided the best match. For obvious reasons of convenience, the $^1/_4$ power was selected for further analysis.

Using the $^1/_4$ power, the best-fit equation is

$$\frac{T_c}{f'_c{}^{1/4}} = \frac{A_b f_s}{f'_c{}^{1/4}} = [63 l_d(c_m + 0.5d_b) + 2130A_b]\left(0.1\frac{c_M}{c_m} + 0.9\right) \quad (4)$$

in which $f'_c{}^{1/4}$ is in psi.

As illustrated in Fig. 2, Eq. (4) produces significantly less scatter as a function of compressive strength than Eq. (3). The best-fit lines for all categories of concrete strength nearly coincide, with the exception of the specimens with concrete strengths in excess of 10,000 psi (69 MPa). This deviation is largely the result of the limited amount of data for development/splice tests using high-strength concrete. Two relatively low splice strengths have a dominant effect on the results for this category. If those two tests are removed, all strength categories produce nearly coincident best-fit lines (Darwin et al. 1995b).

Table 1 provides a summary of the test/prediction ratios for the 133 specimens used to develop Eq. (3) and (4). As shown in the table, the mean test/prediction ratio for the 133 specimens without transverse reinforcement is 1.00 using both the $^1/_2$ [Eq. (3)] and the $^1/_4$ [Eq. (4)] power of f'_c, with a coefficient of variation (COV) of 0.138 using the $^1/_2$ power of f'_c and a COV of 0.107 using the $^1/_4$ power. The individual comparisons are presented by Darwin et al. (1995b) and in Appendix A.*

Bars with confining reinforcement

Eq. (2) is used to determine the additional bond strength provided by transverse reinforcement T_s. The concrete contribution to bond strength T_c, given in Eq. (4), is subtracted from the experimental bond force T_b. The results for 166 specimens in which the developed/spliced bars were confined by transverse reinforcement were initially used for this analysis. During the course of the analysis, it was established that especially low strengths, with respect to any predictive equations, were exhibited by specimens with l_d/d_b < 16. Therefore, 32 specimens with l_d/d_b < 16 have been removed

*The Appendix is available in xerographic or similar form from ACI headquarters, where it will be kept permanently on file, at a charge equal to the cost of reproduction plus handling at time of request.

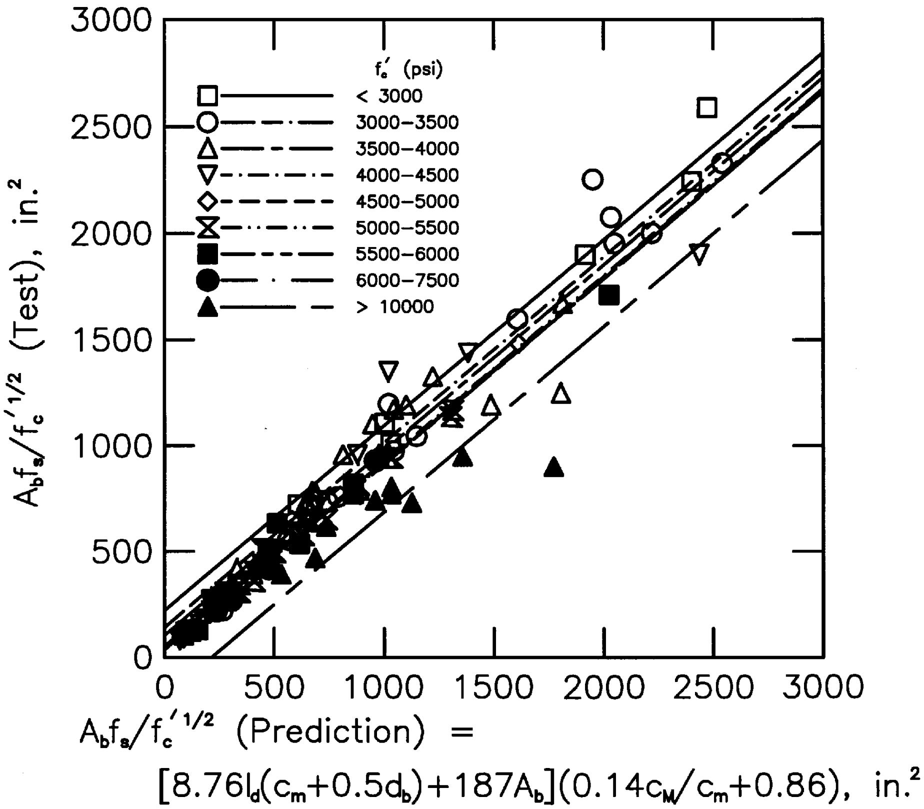

Fig. 1—Experimental bond force $T_c = A_b f_s$ normalized with respect to $f'_c{}^{1/2}$ versus predicted bond force $A_b f_s / f'_c{}^{1/2}$, as a function of concrete compressive strength for bars without confining reinforcement

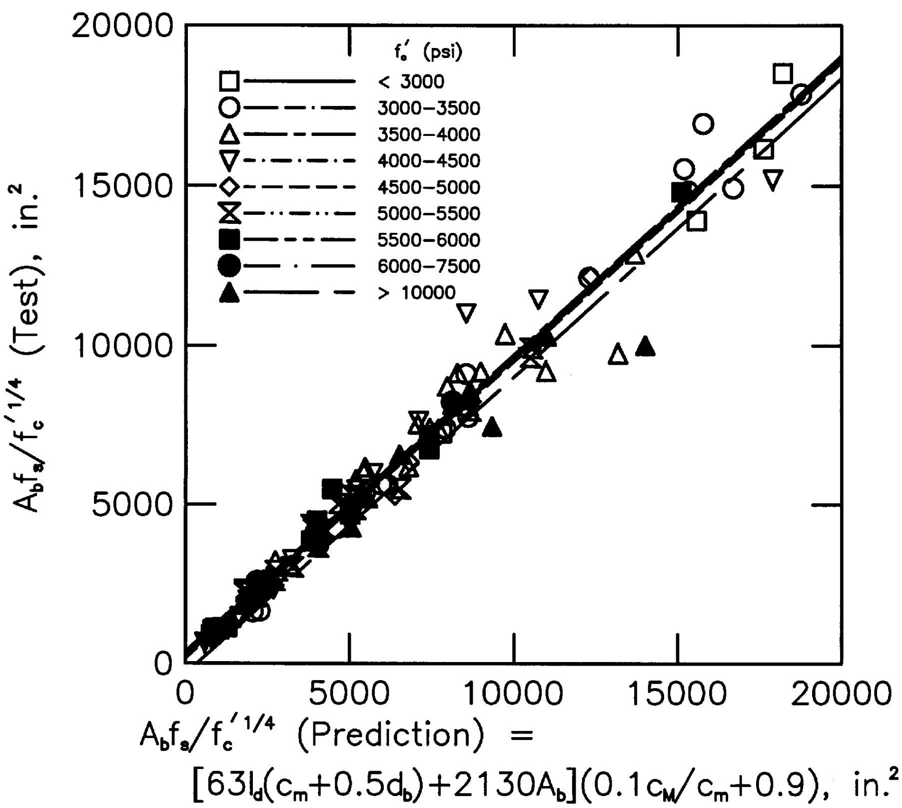

Fig. 2—Experimental bond force $T_c = A_b f_s$ normalized with respect to $f'_c{}^{1/4}$ versus predicted bond force $A_b f_s / f'_c{}^{1/4}$ as a function of concrete compressive strength for bars without confining reinforcement

from the analysis, leaving 134 specimens for the following analysis. The removal of these specimens does not hurt the overall evaluation, since members with such low values of l_d/d_b are not used in practice.

Correlations of T_s with several combinations of potential controlling parameters are evaluated. Principal among these parameters are the yield strength of the transverse reinforcement f_{yt} and the effective area of transverse reinforcement per developed/spliced bar NA_{tr}/n, in which N = the number of transverse reinforcing bars (stirrups or ties) crossing l_d; A_{tr} = area of each stirrup or tie crossing the potential plane of splitting adjacent to the reinforcement being developed or spliced, and n = number of bars being developed or spliced along the plane of splitting. The value of n is determined by the smaller of c_b or c_s. If c_b controls, the plane of splitting passes through the cover and n = 1. If c_s controls, the plane of splitting intersects all of the bars and n = the total number of bars spliced or developed at one location. Also included in the analysis are parameters t_r and t_d, representing the effects of the relative rib area and bar size, respectively, of the developed/spliced bar on T_s

$$t_r = 9.6R_r + 0.28 \tag{5}$$

$$t_d = 0.72d_b + 0.28 \tag{6}$$

Eq. (5) and (6) are based on an analysis of test results for 70 splice specimens containing No. 5, No. 8, and No. 11 (16, 25, 36-mm) bars confined by transverse reinforcement with relative rib areas R_r ranging from 0.065 to 0.14. Details of the development of Eq. (5) and (6) are presented by Darwin et al. (1995a, 1996a). For conventional reinforcement, t_r typically ranges from 0.82 to 1.11 (for R_r from 0.056 to 0.086), with an average value of 0.98 [for the average value of R_r = 0.0727 (Darwin et al. 1995b)]; t_d = 0.73, 1.00, and 1.295 for No. 5, No. 8, and No. 11 (16, 25, 36-mm) bars, respectively.

To determine the principal controlling parameters, T_s is compared to four combinations of the parameters; $NA_{tr}f_{yt}/n$, NA_{tr}/n, t_rNA_{tr}/n, and $t_rt_dNA_{tr}/n$. The first of these variables, $NA_{tr}f_{yt}/n$, is incorporated in ACI 318-95 to represent the effect of confining reinforcement on bond strength (in ACI 318-95, $N = l_d/s$, in which s = spacing of transverse reinforcement).

In carrying out the analyses, distinct differences are observed in the test results for different investigators. For example, the bond strengths obtained by Rezansoff et al. (1991, 1993) are consistently higher than those obtained by Choi et al. (1990, 1991), Hester et al. (1991, 1993), and Darwin et al. (1995a, 1996a). The differences, in all likelihood, are due to differences in concrete properties and, perhaps, testing procedures. The effect of concrete properties on bond strength is demonstrated by Darwin et al. (1995a, 1996a), who observed 35 to 45 percent changes in the effectiveness of transverse reinforcement with a change in coarse aggregate. To remove the variation caused by differences in concrete properties or other differences between test sites, the study uses a dummy variables analysis in which the data is separated based on test site and bar size.

Of the 134 specimens used in the analysis, the value of R_r is known for 85 specimens, based on measurements made on the bars or based on data provided in the original papers. For the balance of the bars, the mean values of R_r for bars of that size are used. The mean values, 0.0752 for No. 5 (16-mm) bars, 0.0748 for No. 6 (19-mm) bars, 0.0731 for No. 8 (25-mm) bars, and 0.0674 for No. 11 (36-mm) bars, are based on bar samples measured in studies dating to 1987 (Choi et al.

Table 1—Summary of test/prediction ratios for developed and spliced bars

Specimen type	Number of specimens	Power of f'_c (Eq.)	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation
Without transverse reinforcement	133	1/2 [Eq. (3)] 1/4 [Eq. (4)]	0.509 0.716	1.325 1.290	1.000 1.003	0.138 0.107	0.138 0.107
Without transverse reinforcement, $f_s > f_y$	11	1/2 [Eq. (3)] 1/4 [Eq. (4)]	0.783 0.854	1.213 1.275	0.968 0.992	0.112 0.107	0.115 0.107
With transverse reinforcement	166	1/4 [Eq. (17)]	0.571	1.387	0.979	0.138	0.141
With transverse reinforcement, l_d/d_b ŠŠŠŠŠ ≥ 16	134	1/4 [Eq. (17)]	0.664	1.352	0.989	0.135	0.137
With transverse reinforcement, l_d/d_b ŠŠŠŠŠ ≥ 16, $(c + K_{tr})/d_b \leq 4$*	119†	1/4 [Eq. (17)]	0.770	1.352	1.010	0.127	0.125
With transverse reinforcement, $f_s > f_y$, l_d/d_b ŠŠŠŠŠ ≥ 16, $(c + K_{tr})/d_b \leq 4$*	20	1/4 [Eq. (17)]	0.931	1.352	1.153	0.154	0.134
With transverse reinforcement, $f_s > f_y$, l_d/d_b ŠŠŠŠŠ ≥ 16, $(c + K_{tr})/d_b \leq 4$*	99	1/4 [Eq. (17)]	0.770	1.261	0.981	0.098	0.100

*Based on $K_{tr} = 35.3\, t_rt_dA_{tr}/sn$.
†Includes two specimens with $(c + K_{tr})/d_b > 4$: a) $(c + K_{tr})/d_b$ = 4.004, test/prediction = 0.843; b) $(c + K_{tr})/d_b$ = 4.023, test/prediction = 0.901.

1990, 1991, Hester et al. 1991, 1993, Darwin et al. 1995a), including bar samples provided by other researchers (Rezansoff et al. 1991, 1993, Azizinamini et al. 1995). The overall average value of R_r, 0.0727, represents No. 5 and larger bars. R_r = 0.0727 is used for bar sizes other than No. 5, No. 6, No. 8, and No. 11 (16, 19, 25, 36 mm), if individual data is not available. For "metric bars" (Rezansoff et al. 1991, 1993), nominal metric sizes are converted exactly to customary units for the analysis. For the analysis, T_s is in lb, f_{yt}, f'_c and $f'^{1/4}_c$ are in psi, and A_{tr} is in in.^{2} The database includes specimens with concrete strengths between 1820 and 15,760 psi (13 and 109 MPa) and bars with relative rib areas between 0.059 and 0.14.

Based on the dummy variables analyses and using the weighted mean intercepts at $T_s/f'^{1/4}_c = 0$, the best-fit expressions for the four combinations are

$$\frac{T_s}{f'^{\,1/4}_c} = 26.7\frac{NA_{tr}f_{yt}}{n} + 355 \tag{7}$$

with a coefficient of determination $r^2 = 0.757$.

$$\frac{T_s}{f'^{\,1/4}_c} = 2391\frac{NA_{tr}}{n} + 89 \tag{8}$$

with $r^2 = 0.787$.

$$\frac{T_s}{f'^{\,1/4}_c} = 2093t_r\frac{NA_{tr}}{n} + 110 \tag{9}$$

with $r^2 = 0.840$.

$$\frac{T_s}{f'^{\,1/4}_c} = 1867t_r t_d\frac{NA_{tr}}{n} + 177 \tag{10}$$

with $r^2 = 0.839$.

The closer the coefficient of determination r^2 is to 1.0, the better the correlation between $T_s/f'^{1/4}_c$ and the selected combination of parameters. r^2 is lowest (0.757) when $NA_{tr}f_{yt}/n$ is used to represent the effect of transverse reinforcement on bond strength [Eq. (7)]. Removal of f_{yt} from the controlling variable [Eq. (8)] improves r^2 to 0.787. The fact that such an improvement would occur makes sense, since it has been demonstrated that transverse reinforcement rarely yields during a splice or development failure (Maeda et al. 1991, Sakurada et al. 1993, Azizinamini et al. 1995). The addition of t_r to the analysis [Eq. (9)], as supported by the experimental work of Darwin et al. (1995a, 1996a), improves r^2 to 0.840, while the addition of t_d [Eq. (10)], also supported by Darwin et al. (1995a, 1996a), drops r^2 slightly to 0.839. For reasons that will be clear shortly, Eq. (10) is used for the next step in the analysis.

Combining Eq. (4) and Eq. (10), replacing N by l_d/s, dropping the mean intercept of 177, and solving for the development/splice length l_d gives

$$l_d = \frac{A_b\left[\dfrac{f_s}{f'^{\,1/4}_c} - 2130\left(0.1\dfrac{c_M}{c_m} + 0.9\right)\right]}{63\left[(c_m + 0.5d_b)\left(0.1\dfrac{c_M}{c_m} + 0.9\right) + \dfrac{29.6t_r t_d A_{tr}}{sn}\right]} \tag{11}$$

Modifying Eq. (11) to express l_d in terms of bar diameter d_b gives

$$\frac{l_d}{d_b} = \frac{\dfrac{f_s}{f'^{\,1/4}_c} - 2130\left(0.1\dfrac{c_M}{c_m} + 0.9\right)}{80.2\left(\dfrac{c + K_{tr}}{d_b}\right)} \tag{12}$$

in which $c = (c_m + 0.5\,d_b)(0.1\,c_M/c_m + 0.9)$ and $K_{tr} = 29.6\,t_r t_d A_{tr}/sn$.

$(c + K_{tr})/d_b$ in the denominator of Eq. (12) is a measure of the assistance provided by concrete cover, bar spacing, and transverse reinforcement (ACI 318-95), increases that result in an increase in bond strength. Increases in $(c + K_{tr})/d_b$, however, will eventually cause the mode of bond failure to switch from splitting to pullout, with bond strength limited by the strength of the concrete between the ribs of the bar rather than the clamping forces provided by surrounding concrete and steel. When this happens, bond strengths will drop in relation to the predicted strength.

Test/prediction ratios, based on the sum of Eq. (4) and (10), are compared with $(c + K_{tr})/d_b$ for the 134 tests with $l_d/d_b \geq 16$ in Fig. 3. The figure shows that the test/prediction ratios are consistently below 1.0 for values of $(c + K_{tr})/d_b > 3.75$. Based on this observation, a reanalysis was carried out using specimens with $(c + K_{tr})/d_b \leq 3.75$.

Based on the dummy variables analysis for the remaining 119 specimens and using the weighted mean intercepts at $T_s/f'^{1/4}_c = 0$, the best-fit expressions for the four combinations are

$$\frac{T_s}{f'^{\,1/4}_c} = 30.3\frac{NA_{tr}f_{yt}}{n} + 430 \tag{13}$$

with $r^2 = 0.758$.

$$\frac{T_s}{f'^{\,1/4}_c} = 2521\frac{NA_{tr}}{n} + 148 \tag{14}$$

with $r^2 = 0.783$.

$$\frac{T_s}{f'^{\,1/4}_c} = 2412t_r\frac{NA_{tr}}{n} + 71 \tag{15}$$

with $r^2 = 0.853$.

$$\frac{T_s}{f'^{\,1/4}_c} = 2226t_r t_d\frac{NA_{tr}}{n} + 66 \tag{16}$$

with $r^2 = 0.857$

In this case, $t_r t_d NA_{tr}/n$ [Eq. (16)] provides the best coefficient of determination and the lowest intercept. Combining Eq. (16) with Eq. (4) gives the final expression for T_b

$$\frac{T_b}{f'_c{}^{1/4}} = \frac{T_c + T_s}{f'_c{}^{1/4}} = \frac{A_b f_s}{f'_c{}^{1/4}} = [63 l_d (c_m + 0.5 d_b) + 2130 A_b]\left(0.1\frac{c_M}{c_m} + 0.9\right) + 2226 t_r t_d \frac{NA_{tr}}{n} + 66 \qquad (17)$$

Dropping the intercept 66 and solving for l_d in terms of A_b and d_b gives, respectively,

$$l_d = \frac{A_b\left[\frac{f_s}{f'_c{}^{1/4}} - 2130\left(0.1\frac{c_M}{c_m} + 0.9\right)\right]}{63\left[(c_m + 0.5 d_b)\left(0.1\frac{c_M}{c_m} + 0.9\right) + \frac{35.3 t_r t_d A_{tr}}{sn}\right]} \qquad (18)$$

$$\frac{l_d}{d_b} = \frac{\frac{f_s}{f'_c{}^{1/4}} - 2130\left(0.1\frac{c_M}{c_m} + 0.9\right)}{80.2\left(\frac{c + K_{tr}}{d_b}\right)} \qquad (19)$$

in which $c = (c_m + 0.5\ d_b)(0.1\ c_M/c_m + 0.9)$ and $K_{tr} = 35.3\ t_r\ t_d A_{tr}/sn$. Eq. (19) and (12) are identical, except for the coefficient in K_{tr}.

A reanalysis of the data versus $(c + K_{tr})/d_b$ using Eq. (17) and the new definition of K_{tr} is shown in Fig. 4, illustrating that Eq. (17) through (19) provide accurate predictions for specimens with $(c + K_{tr})/d_b \le 4.0$. A summary of the test/prediction ratios for all 166 specimens with transverse reinforcement in the database (c/d_b = 1.33 to 4.46, K_{tr}/d_b = 0.12 to 3.24) are presented in Table 1. For the 119 specimens used to develop Eq. (17) (c/d_b = 1.33 to 2.64, K_{tr}/d_b = 0.12 to 2.55), the mean test/prediction ratio is 1.01, with a COV of 0.125; two of the specimens have $(c + K_{tr})/d_b > 4.0$ (see Table 1). A comparison of the test results with the values predicted using Eq. (17) for the 117 specimens with $l_d/d_b \ge 16$ and $(c + K_{tr})/d_b \le 4.0$ (using $K_{tr} = 35.3\ t_r t_d A_{tr}/sn$) is shown in Fig. 5 (for completeness, it is noted that c/d_b ranges from 1.33 to 3.44 for the specimens without confining reinforcement summarized in 1). Data on the individual comparisons is presented by Darwin et al. (1995b) and in Appendix A.*

Effect of bar stress on development/splice strength

Concern has been expressed that yielding of developed/spliced bars will result in a reduction in bond strength (Orangun et al. 1975, Harajli 1994). An evaluation of the test results used in the current study shows that the concern is unwarranted.

Of the 133 test specimens without confining reinforcement, bars yielded in 11 specimens prior to bond failure. As shown in Table 1, the mean test/prediction ratio based on

*The Appendix is available in xerographic or similar form from ACI headquarters, where it will be kept permanently on file, at a charge equal to the cost of reproduction plus handling at time of request.

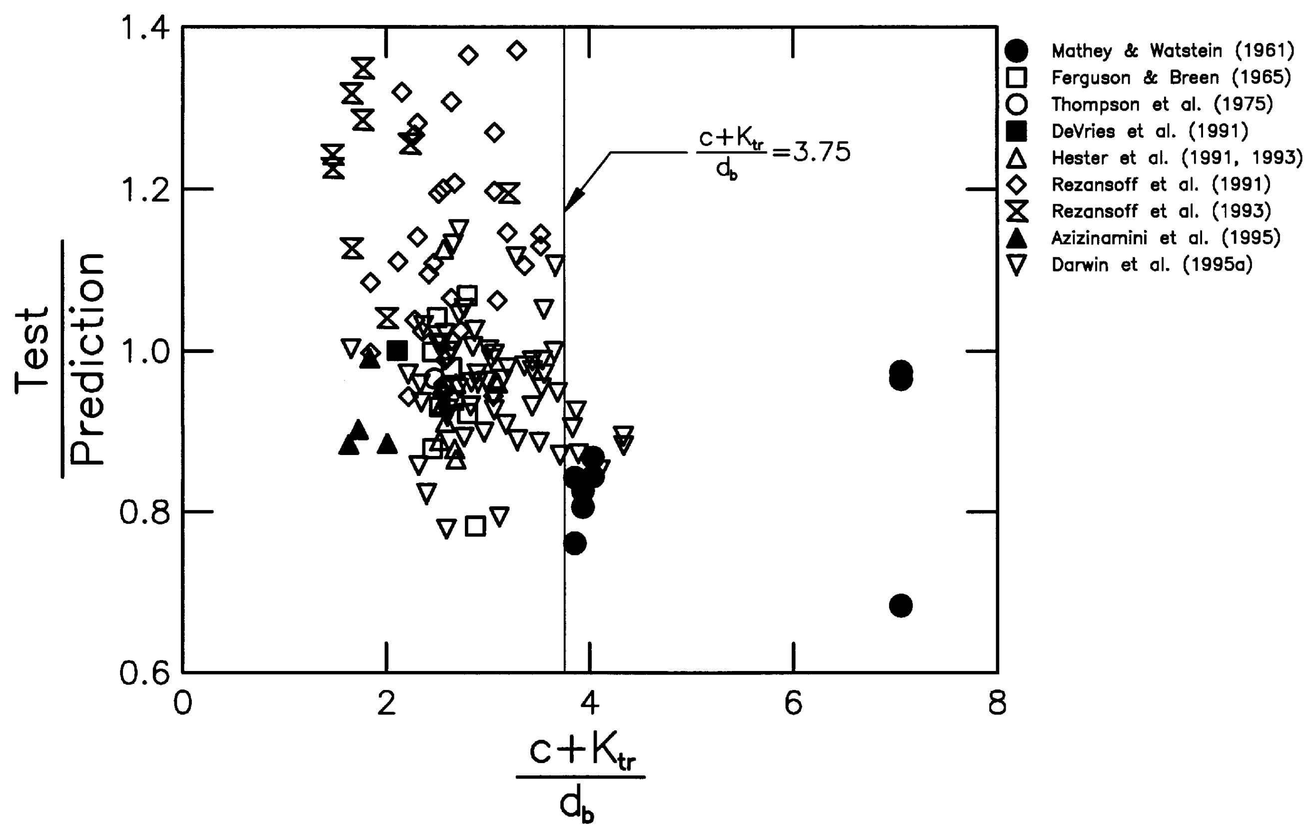

Fig. 3—Test/prediction ratio versus $(c + K_{tr})/d_b$ for 134 beams with $l_d/d_b \ge 16$ ($K_{tr} = 29.6\ t_r t_d A_{tr}/sn$)

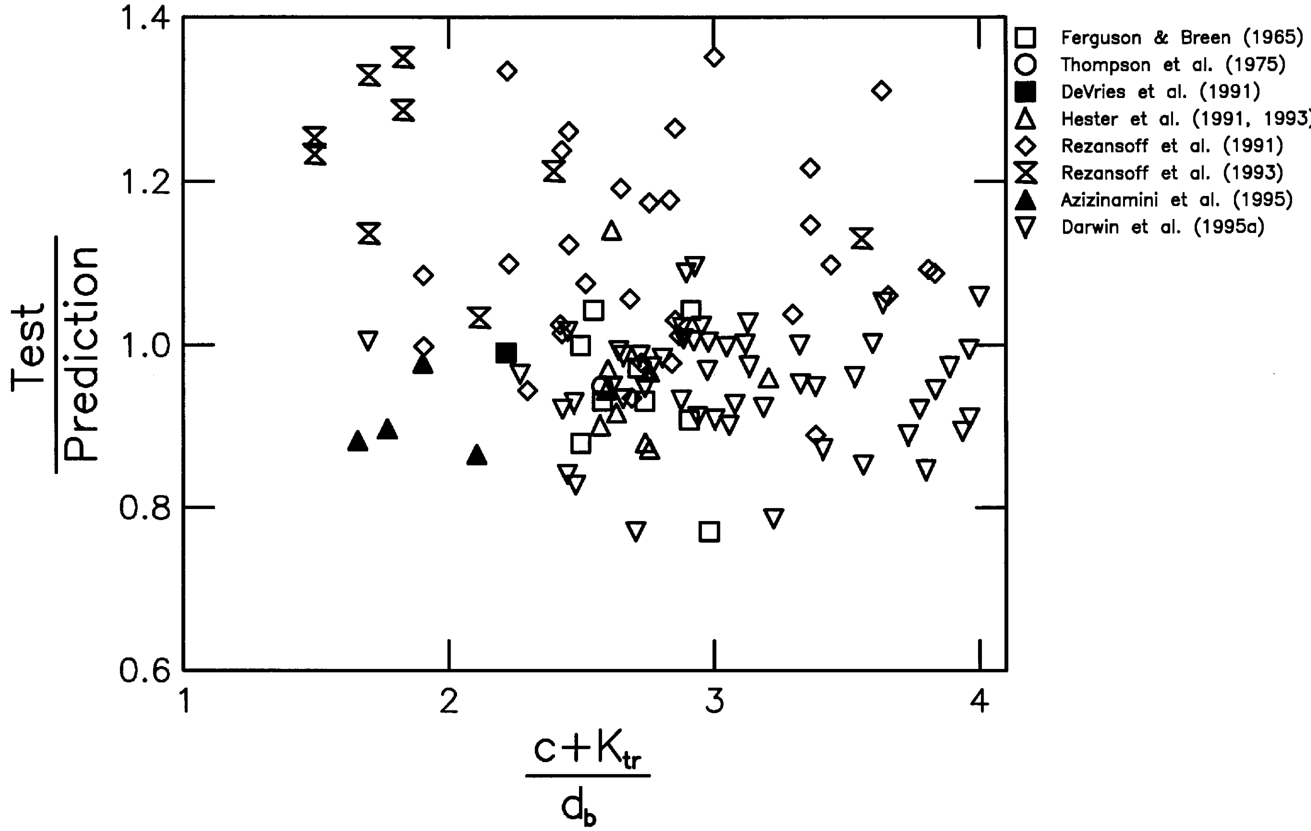

Fig. 4—Test/prediction ratio versus $(c + K_{tr})/d_b$ for 117 beams with $l_d/d_b \geq 16$ and $(c + K_{tr})/d_b \leq 4$ ($K_{tr} = 35.3\ t_r t_d A_{tr}/sn$)

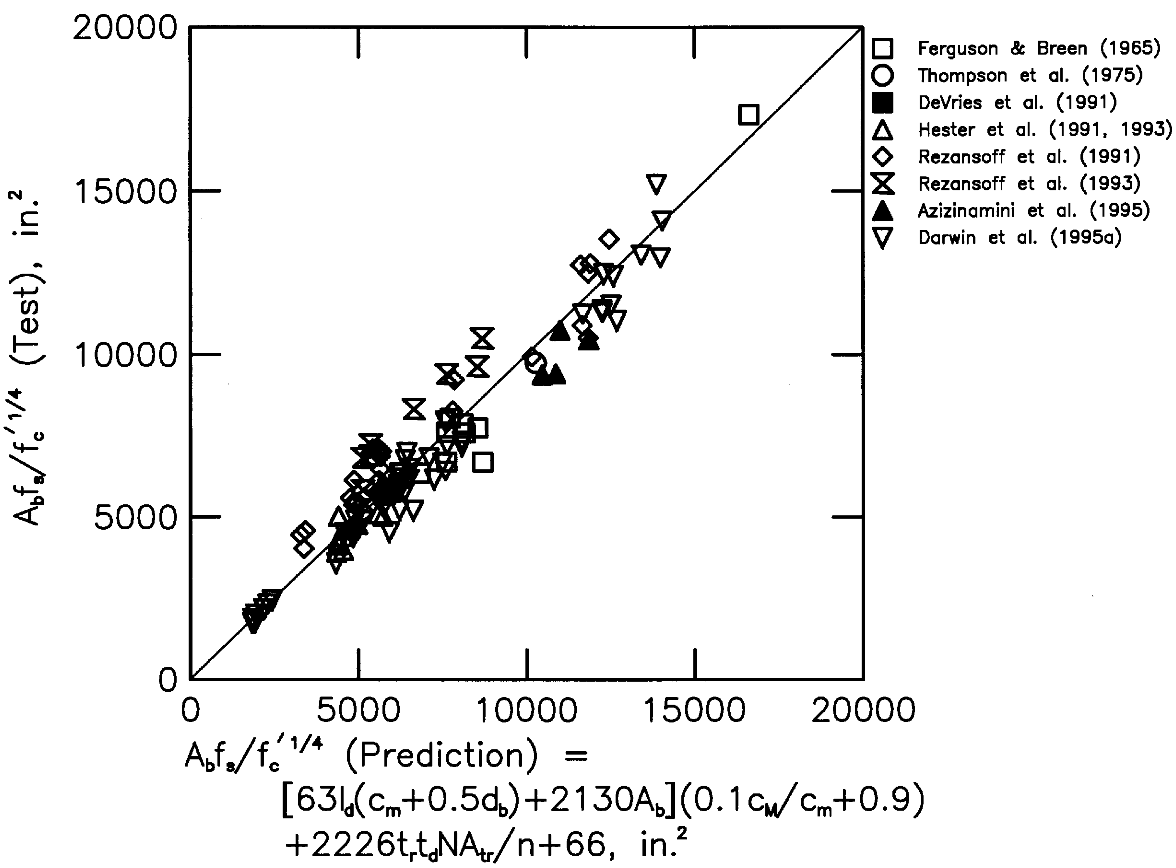

Fig. 5—Experimental bond force $T_b = A_b f_s$ normalized with respect to $f'_c{}^{1/4}$ versus predicted bond force $A_b f_s / f'_c{}^{1/4}$ for bars with confining reinforcement

Eq. (4) for the 11 tests is 0.99, with a COV of 0.107, comparing favorably to the mean of 1.00 and COV of 0.107 for the full set of data. Of the 119 bars used to develop Eq. (17), bars yielded in 20 specimens prior to bond failure. For those tests, the mean test/prediction ratio is 1.15, with a COV of 0.134, comparing very favorably with the mean of 1.01 and COV of 0.125 for the full set of 119 specimens. For the 99 tests with bars confined by transverse reinforcement that did not yield, the mean test/prediction ratio using Eq. (17) is 0.98, with a COV of 0.100.

Overall, the data indicates that, if the development/splice length is long enough to cause the bar to yield, yielding has no effect on the bond strength of bars not confined by transverse reinforcement, and results in an increase in bond strength for bars that are confined by transverse reinforcement. The increase for bars with confining reinforcement may result from a more uniform state of bond stress along the length of the bar due to greater slip that accompanies yielding. This greater slip mobilizes clamping stresses in the transverse reinforcement along a greater length of the bar.

DESIGN EXPRESSIONS FOR DEVELOPMENT/ SPLICE LENGTH

Strength reduction (ϕ) factor

Eq. (17) through (19) serve as the basis for design expressions for development/splice length. Eq. (18) and (19) cannot be used directly in design to calculate l_d because they are based on the best-fit (average) expression, Eq. (17). If used as presented, bond strength would be below the value predicted by Eq. (17) 50 percent of the time. Procedures exist, however, for insuring an adequate level of safety through the selection of a strength reduction factor (ϕ) based on the desired level of reliability.

Following the procedures of Ellingwood, Galambos, MacGregor, and Cornell (1980), Mirza and MacGregor (1986), and Lundberg (1993), a (ϕ) factor of 0.9 for development and splice strength has been obtained using a reliability index β of 3.5 (Darwin et al. 1995c, 1996b). This gives an overall probability of bond failure equal to about one-fifth of the probability of a flexural failure, for which β = 3.0 is normally obtained (Ellingwood et al. 1980). ϕ = 0.9 is obtained using Eq. (17) without the final term 66 as the design strength and Eq. (17) with the final term (if transverse reinforcement is used) as the predicted strength. Additional simplifications of Eq. (17), setting $c_M = c_m$ and dropping 0.25 in. from the definition of c_s, produce higher values of ϕ (Darwin et al. 1995c, 1996b).

ϕ = 0.9 for bond is applied in addition to the ϕ factor for the main load effect (e.g., 0.9 for flexure or 0.7 for tied columns) that is used to select the area and strength of the steel. Therefore, the total ϕ factor against a primary mode of failure in bond is the product of 0.9 and the ϕ factor for the main load effect.

In addition to allowing the selection of a desired relative probability of failure, using a reliability-based ϕ factor provides another important benefit. Since 87 percent of the tests in the database used to calculate ϕ are splice tests in which all of the bars are spliced at one location (a Class B splice in ACI 318-95 and a Class C splice in AASHTO Highway 1992), ϕ = 0.9 and Eq. (17) through (19) are already calibrated based on splice strength. Therefore, values of l_d calculated using ϕ = 0.9 apply directly to spliced bars, removing the requirement to multiply development length by 1.3 to obtain the length of a Class B splice (ACI 318-95) or by 1.7 to obtain the length of a Class C splice (AASHTO Highway 1992).

The process of obtaining the design expressions that are presented in the following starts with the incorporation of ϕ on the right side of Eq. (17) (without the final term 66) and the substitution of the bar yield strength f_y for f_s on the left side

$$\frac{A_b f_y}{f_c'^{1/4}} = \phi\left\{[63 l_d(c_m + 0.5 d_b) + 2130 A_b]\left(0.1\frac{c_M}{c_m} + 0.9\right) + 2226 t_r t_d \frac{N A_{tr}}{n}\right\} \quad (20)$$

Design expressions

Using the formulation shown in Eq. (20), a detailed design expression in the form of Eq. (19) becomes

$$\frac{l_d}{d_b} = \frac{\dfrac{f_y}{\phi f_c'^{1/4}} - 2130\left(0.1\dfrac{c_M}{c_m} + 0.9\right)}{80.2\left(\dfrac{c + K_{tr}}{d_b}\right)} \quad (21)$$

in which

c = $(c_m + 0.5\, d_b)(0.1\, c_M/c_m + 0.9)$ and c_m, c_M, c_s, c_{si}, c_{so}, and c_b are defined following Eq. (3).

$K_{tr} = K_{tr}$(conv.) = $34.5\, t_d A_{tr}/sn$ = $34.5\,(0.72\, d_b + 0.28)\, A_{tr}/sn$ for conventional bars (average $R_r = 0.0727$)

$K_{tr} = K_{tr}$(new) = $53\, t_d A_{tr}/sn$ = $53\,(0.72\, d_b + 0.28)\, A_{tr}/sn$ for high relative rib area bars (average $R_r = 0.1275$)

$(c + K_{tr})/d_b \le 4.0$

Incorporating ϕ = 0.9 into Eq. (21) and conservatively rounding the coefficients gives

$$\frac{l_d}{d_b} = \frac{\dfrac{f_y}{f_c'^{1/4}} - 1900\left(0.1\dfrac{c_M}{c_m} + 0.9\right)}{72\left(\dfrac{c + K_{tr}}{d_b}\right)} \quad (22)$$

Eq. (22) is the prototype for design equations based on Eq. (20). Different degrees of simplification are possible, depending on the application and the level of simplification desired.

One such simplification can be obtained by setting $c_M/c_m = 1$

$$\frac{l_d}{d_b} = \frac{\dfrac{f_y}{f_c'^{1/4}} - 1900}{72\left(\dfrac{c + K_{tr}}{d_b}\right)} \quad (23)$$

in which $c = (c_m + 0.5\, d_b)$.

In applying Eq. (23) to design, it would seem prudent to change the definition of c to the smaller of the cover to the center of the bar or one-half of the center-to-center bar spacing. The only change that this entails is dropping 0.25 in. from the definition of c_s that follows Eq. (3). The definitions of K_{tr} following Eq. (21) remain unchanged.

Following the lead of ACI 318-95, an alternate simplification of Eq. (22), for the case in which the clear spacing between bars being developed or spliced is not less than 2 d_b and the cover is not less than d_b [i.e., $(c + K_{tr})/d_b \geq 1.5$], is obtained by setting $(c + K_{tr})/d_b = 1.5$.

This gives

$$\frac{l_d}{d_b} = \frac{\frac{f_y}{f'^{1/4}_c} - 1900}{108} \tag{24}$$

Since, except for shells, the minimum cover c_b for cast-in-place concrete is 0.75 in. (19 mm) and the minimum clear spacing 2 c_{si} is 1 in. (25 mm) (ACI 318-95), Eq. (24) provides the maximum value of l_d for No. 6 and smaller bars.

For bars with a cover not less than d_b and a clear spacing not less than 7 d_b (principally slabs), Eq. (22) can be conservatively simplified to

$$\frac{l_d}{d_b} = \frac{\frac{f_y}{f'^{1/4}_c} - 1900}{135} \tag{25}$$

l_d from Eq. (25) is 80 percent of l_d calculated using Eq. (24). Because of the simplified format, neither Eq. (24) nor Eq. (25) takes advantage of the higher value of K_{tr} provided by high relative rib area bars. Like the simplified format in ACI 318-95 (discussed in the next section), each of the two equations provides a single value of l_d/d_b for each combination of f_y and f'_c.

Comparison with current design criteria

To illustrate the effects on development and splice lengths of both the newly proposed expressions and high relative rib area bars, values of l_d obtained with Eq. (22) through (25) are compared with development and splice lengths calculated under the provisions of ACI 318-95. Comparisons are limited to uncoated bottom-cast bars.

Eq. (22) through (25) differ from current design criteria in several important respects.

1. The relationship between l_d and the steel stress f_s or f_y is linear but nonproportional, rather than proportional, as in current design expressions. The more accurate representation provided by Eq. (22) through (25) results in values of l_d that are relatively shorter for $f_y < 60$ ksi (414 MPa) and relatively longer for $f_y > 60$ ksi (414 MPa) than obtained with ACI 318-95. Eq. (22) through (25) automatically account for the fact that, when f_y is increased by 25 percent from 60 to 75 ksi (414 to 517 MPa), l_d must be increased by more than 25 percent.

2. The effect of concrete strength on bond strength is represented by $f'^{1/4}_c$ rather than $f'^{1/2}_c$. The impact of this change is greatest for high-strength concrete. The proposed expressions apply up to at least 16,000 psi (110 MPa); the development length expressions in ACI 318-95 limit $f'^{1/2}_c$ to 100 psi (0.69 MPa), corresponding to f'_c = 10,000 psi (69 MPa).

3. Using Eq. (22) through (25), splice length and development length are identical, removing the requirement to multiply l_d by 1.3 (ACI) or 1.7 (AASHTO) to obtain the length of most splices.

The key aspects of the development/splice length criteria of ACI 318-95 are summarized next.

ACI 318-95—Under the provisions of ACI 318-95, two options are available for selecting development length. One involves a chart with selected expressions for l_d/d_b, and the other involves the use of a more detailed expression for l_d/d_b. Under Section 12.2.2 for bottom-cast uncoated reinforcement, $l_d/d_b = f_y/(25 f'^{1/2}_c)$ for No. 6 and smaller bars and $f_y/(20 f'^{1/2}_c)$ for No. 7 and larger bars if the bars have a clear spacing between bars $\geq d_b$, cover $\geq d_b$, and transverse reinforcement is not less than the code minimums, or clear spacing between bars $\geq 2\ d_b$ and cover $\geq d_b$. For all other cases, $l_d/d_b = 3 f_y/(50 f'^{1/2}_c)$ for No. 6 and smaller bars and $3 f_y/(40 f'^{1/2}_c)$ for No. 7 and larger bars.

Under Section 12.2.3

$$\frac{l_d}{d_b} = \frac{3}{40} \frac{f_y}{f'^{1/2}_c \left(\frac{c + K_{tr}}{d_b}\right)} \tag{26}$$

in which $K_{tr} = A_{tr} f_{yt}/(1500\ sn)$, $(c + K_{tr})/d_b \leq 2.5$. Although K_{tr} is the same symbol as used in this study to represent the effect of transverse reinforcement, the value includes f_{yt} and does not correspond to the value in Eq. (21) through (23).

When 50 percent or less of the reinforcement is spliced at one location and the area of steel provided is equal to or greater than twice the area required, the splice length is equal to 1.3 l_d.

Bars not confined by transverse reinforcement—For bars not confined by transverse reinforcement, it is appropriate to compare the simplified expressions in ACI 318-95 with the development and splice lengths obtained using Eq. (24) and (25). For No. 7 (22-mm) bars and larger with clear spacing $\geq$ 2 d_b and cover $\geq d_b$ and 4000 psi (28 MPa) concrete, l_d/d_b is 47.4 for developed bars and 61.7 for Class B splices, under the provisions of ACI 318-95, and 52.26 using Eq. (24) for both developed and spliced bars. Thus, using the proposed expression, the development length is 10 percent greater than under the provisions of ACI 318-95, while the splice length is 18 percent lower. The same percentages hold for the conditions under which Eq. (25) is applied. Overall, for normal-strength concretes, Eq. (24) and (25) result in greater development lengths and shorter splice lengths than do the provisions of Section 12.2.2 of ACI 318-95. The increases in development length are more than matched by the reductions in splice length.

Comparisons of development and splice lengths obtained using Eq. (22) and (23) with the more detailed provisions of ACI 318-95 [Eq. (26)] are summarized in Table 2 for the 35 beam configurations used by Darwin et al. (1995c, 1996b) to develop the reliability-based ϕ factor [the detailed comparisons are presented by Darwin et al. (1995b) and in Appendix B].* The tables cover concrete compressive strengths of 3000, 4000, and 6000 psi (21, 28, and 41 MPa) for developed or spliced No. 6, No. 8, No. 10, and No. 11 (19, 25, 32, and 36-mm) bars. Comparisons show that development lengths obtained with Eq. (23) (the more simplified of the two new expressions) are, on average, 114 percent of those obtained with ACI 318-95. Development lengths obtained with Eq. (22) are, on average, 102 percent of those obtained with the Code. The splice lengths obtained with Eq. (23) average 88 percent of those obtained with ACI 318-95, while those obtained with Eq. (22) average 78 percent of those obtained with the Code. These comparisons show that Eq. (22) and (23) result in a small increase in development length and a substantial reduction in splice length compared to values obtained under the provisions of ACI 318-95.

Bars confined by transverse reinforcement—Comparisons of development and splice lengths obtained using Eq. (22) and (23) with those obtained under the provisions of ACI 318-95 are summarized in Table 2 for the 140 beams with transverse reinforcement used to develop $\phi = 0.9$ (Darwin et al. 1995c, 1996b) [the detailed comparisons are presented by Darwin et al. (1995b) and in Appendix B].* Comparisons include development lengths obtained with both conventional and high relative rib area reinforcement. Results in Table 2 show the following.

Effect of relative rib area. Limiting consideration to the effect of using high relative rib area bars (a savings not available under ACI 318-95), the average ratios of l_d for high relative rib area bars to l_d for conventional bars are 0.87 and 0.84 using Eq. (22) and (23), respectively. Therefore, depending on the expression used for the design, average reductions of 13 to 16 percent in development and splice length can be expected with the use of high relative rib area bars.

Comparisons with ACI 318-95. For conventional reinforcement, the development lengths average 95 and 116 percent for Eq. (22) and (23), respectively, of those obtained using ACI 318-95; the splice lengths average 73 and 89 percent, respectively. For high relative rib area bars, the development lengths obtained with Eq. (22) and (23) average 83 and 97 percent, respectively, of the development lengths obtained with ACI 318-95; the splice lengths average 64 and 75 percent, respectively, of the splice lengths obtained with ACI 318-95. Overall, significant savings can be obtained with a conversion to the new expressions. Even higher savings are available when Eq. (22) and (23) are used in conjunction with high relative rib area bars.

SUMMARY AND CONCLUSIONS

Test results for 133 splice and development specimens in which the bars are not confined by transverse reinforcement and 166 specimens in which the bars are confined by transverse reinforcement are used to develop an expression for the bond force at failure as a function of concrete strength, cover, bar spacing, development/splice length, transverse reinforcement, and the geometric properties of the developed/spliced bars. The expression is valid for concrete strengths between 2500 and 16,000 psi (17 and 110 MPa). Results are used to formulate design criteria that incorporate a reliability-based strength reduction (ϕ) factor that allows the calculation of a single value for both development and splice length for given material properties and member geometry.

The following conclusions are based on the analyses and comparisons made in this paper.

1. The relationship between bond force and development or splice length l_d is linear but not proportional. Thus, to increase the bond force (or bar stress) by a given percentage requires more than the percentage increase in l_d.

2. $f'_c{}^{1/2}$ does not provide an accurate representation of the effect of concrete strength on bond strength over the full range of concrete strengths in use today. Development/splice strengths are underestimated for low-strength concretes and overestimated for high-strength concretes.

3. $f'_c{}^{1/4}$ provides an accurate representation of the effect of concrete strength on bond strength for concretes with compressive strengths between 2500 and 16,000 psi (17 and 110 MPa).

4. The most accurate representation of the effect of transverse reinforcement on bond strength obtained in the current analysis includes parameters that account for the number of transverse reinforcing bars that cross the developed/spliced bar, the area of the transverse reinforcement, the number of bars developed or spliced at one location, the relative rib area of the developed/spliced bar, and the size of the developed/spliced bar.

5. The yield strength of transverse reinforcement plays no significant role in the effectiveness of the transverse reinforcement in improving development/splice strength.

6. Depending on the design expression selected:

a. For bars that are not confined by transverse reinforcement, development lengths average 2 to 14 percent higher than those obtained using ACI 318-95, and splice lengths

Table 2—Ratios of development and splice lengths obtained using proposed expressions to development and splice lengths obtained using ACI 318-95

		Development lengths		Splice lengths	
		Eq. (22) / ACI 95	Eq. (23) / ACI 95	Eq. (22) / ACI 95	Eq. (23) / ACI 95
35 beams without transverse reinforcement	Minimum	0.785	1.036	0.604	0.797
	Maximum	1.176	1.377	0.904	1.059
	Average	1.017	1.141	0.782	0.878
140 beams with transverse reinforcement, conv. bars*	Minimum	0.776	0.832	0.597	0.640
	Maximum	1.270	1.730	0.977	1.331
	Average	0.951	1.156	0.732	0.889
140 beams with transverse reinforcement, high R_r bars†	Minimum	0.622	0.719	0.479	0.553
	Maximum	1.127	1.405	0.867	1.081
	Average	0.826	0.973	0.635	0.749

		Development and splice lengths	
		High R_r† / Conv.* [Eq. (22)]	High R_r† / Conv.* [Eq. (23)]
140 beams with transverse reinforcement	Minimum	0.779	0.753
	Maximum	1.000	1.000
	Average	0.867	0.842

*Average $R_r = 0.0727$.
†Average $R_r = 0.1275$.

*The Appendix is available in xerographic or similar form from ACI headquarters, where it will be kept permanently on file, at a charge equal to the cost of reproduction plus handling at time of request.

average 12 to 22 percent lower than those obtained with ACI 318-95 for Class B splices (i.e., for a 1.3 modification factor).

b. For conventional bars confined by transverse reinforcement, development lengths average 5 percent lower to 16 percent higher than those obtained using ACI 318-95, while splice lengths average 11 to 27 percent lower than those obtained with ACI 318-95 for Class B splices.

c. For high relative rib area bars confined by transverse reinforcement, development lengths average 3 to 17 percent lower than those obtained using ACI 318-95, while splice lengths average 25 to 36 percent lower than those obtained with ACI 318-95. When confined by transverse reinforcement, high relative rib area bars require development and splice lengths that are 13 to 16 percent lower than required by conventional bars.

ACKNOWLEDGMENTS

Support for this research was provided by the Civil Engineering Research Foundation under CERF Contract No. 91-N6002, the National Science Foundation under NSF Grants No. MSS-9021066 and CMS-9402563, the U.S. Department of Transportation, Federal Highway Administration, the Reinforced Concrete Research Council under RCRC Project 56, ABC Coating, Inc., Birmingham Steel Corp., Chaparral Steel Co., Fletcher Coating Co., Florida Steel Corp., Morton Powder Coatings, Inc., North Star Steel Co., O'Brien Powder Products, Inc., and 3M Corp. Support was also provided by Geiger Ready-Mix, Iron Mountain Trap Rock Co., and Richmond Screw Anchor Co.

NOTATION

A_b = bar area, in.^{2}
A_{tr} = area of each stirrup or tie crossing potential plane of splitting adjacent to reinforcement being developed or spliced, in.^{2}
c = $c_m + 0.5\, d_b$
c_b = bottom cover of reinforcing bars, in.
c_M = maximum value of c_s or c_b ($c_M/c_m \leq 3.5$), in.
c_m = minimum value of c_s or c_b ($c_M/c_m \leq 3.5$), in.
c_s = min (csi + 0.25 in., cso) or min (csi, cso), in.
c_{si} = one-half of clear spacing between bars, in.
c_{so} = side cover of reinforcing bars, in.
d_b = nominal bar diameter, in.
f'_c = concrete compressive strength, psi; $f'_c{}^{1/2}$ and $f'_c{}^{1/4}$, psi
$f'_c{}^p$ = concrete compressive strength to power p, psi
f_s = steel stress at failure, psi
f_y = yield strength of bars being spliced or developed, psi
f_{yt} = yield strength of transverse reinforcement, in psi
K_{tr} = term representing effect of transverse reinforcement on bond strength. Value depends on stage of analysis and design expression in which it is used. $K_{tr} = 29.6\, t_r t_d A_{tr}/sn$ based on initial analysis. $K_{tr} = 35.3\, t_r t_d/A_{tr}/sn$ based on final analysis [K_{tr} (conv.) = 34.5 (0.72 d_b + 0.28) A_{tr}/sn for conventional reinforcement (average R_r = 0.0727); K_{tr} (new) = 53 (0.72 d_b + 0.28) A_{tr}/sn for new reinforcement (average R_r = 0.1275)]
= $A_{tr} f_{yt}/(1500\, sn)$ in ACI 318-95
l_d = development or splice length, in.
N = number of transverse reinforcing bars (stirrups or ties) crossing
n = number of bars being developed or spliced along plane of splitting
R_r = ratio of projected rib area normal to bar axis to product of nominal bar perimeter and center-to-center rib spacing
s = spacing of transverse reinforcement, in.
T_b = total force in bar at splice failure, lb
T_c = concrete contribution to total force in bar at splice failure, lb
T_s = confining steel contribution to total force in bar at splice failure, in lb
t_d = 0.72 d_b + 0.28, term representing effect of bar size on T_s
t_r = 9.6 R_r + 0.28, term representing effect of relative rib area on T_s
β = reliability index
ϕ = reliability-based strength reduction factor

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93-S32

Supplement to:

ACI STRUCTURAL JOURNAL

Appendix to:

Title no. 93-S32 , *ACI Structural Journal*, V. 93, No. 3, May-June. 1996

"Development Length Criteria for Conventional and High Relative Rib Area Reinforcing Bars" by D. Darwin, J. Zuo, M. L. Tholen, and E. K. Idun

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APPENDIXES A AND B

"DEVELOPMENT LENGTH CRITERIA FOR CONVENTIONAL AND HIGH RELATIVE AREA REINFORCING BARS"

Table A.1

Data and test/prediction ratios for developed and spliced bars without confining reinforcement [t]

Test No.	n	l_d (in.)	d_b (in.)	A_b (in.^{2})	c_{so} (in.)	c_{si} (in.)	c_b (in.)	b (in.)	h (in.)	d (in.)	f'_c (psi)	f_y (ksi)	f_s (ksi)	$T_c/f'_c{}^{1/2}$ Test (in.^{2})	$T_c/f'_c{}^{1/4}$ Test (in.^{2})	$T_c/f'_c{}^{1/2}$ Eq.3* (in.^{2})	$T_c/f'_c{}^{1/4}$ Eq. 4** (in.^{2})	Test / Eq. 3	Test / Eq. 4
Chinn (1955)																			
D31	1	5.50	0.375	0.110	1.470		0.830	3.69	-	-	4700	79.00	60.35	97.23	805.07	77.20	633.14	1.260	1.272
D36	1	5.50	0.375	0.110	1.470		0.560	3.69	-	-	4410	79.00	48.95	81.41	663.38	69.56	574.58	1.170	1.155
D10	1	7.00	0.750	0.440	1.060		1.480	3.62	-	-	4370	57.00	26.27	174.82	1421.42	179.72	1632.24	0.973	0.871
D20	1	7.00	0.750	0.440	1.125		1.420	3.75	-	-	4230	57.00	26.95	182.29	1470.13	180.66	1640.62	1.009	0.896
D22	1	7.00	0.750	0.440	1.095		0.800	3.69	-	-	4480	57.00	23.89	157.04	1284.79	162.30	1509.04	0.968	0.851
D13	1	11.00	0.750	0.440	2.905		1.440	7.31	-	-	4820	57.00	48.93	310.09	2583.72	293.80	2418.31	1.055	1.068
D14	1	11.00	0.750	0.440	1.095		0.830	3.69	-	-	4820	57.00	32.63	206.77	1722.88	207.26	1828.85	0.998	0.942
D15	1	11.00	0.750	0.440	2.875		0.620	7.25	-	-	4290	57.00	42.24	283.74	2296.34	268.88	2218.39	1.055	1.035
D21	1	11.00	0.750	0.440	2.905		1.470	7.31	-	-	4480	57.00	43.35	284.97	2331.38	295.61	2432.09	0.964	0.959
D29	1	11.00	0.750	0.440	1.095		1.390	3.69	-	-	7480	57.00	44.60	226.89	2110.08	232.38	2008.60	0.976	1.051
D3	2	11.00	0.750	0.440	1.500	0.500	1.500	9.00	-	-	4350	57.00	36.86	245.92	1997.20	217.38	1888.51	1.131	1.058
D32	1	11.00	0.750	0.440	2.875		1.470	7.25	-	-	4700	57.00	46.05	295.54	2447.06	294.86	2427.57	1.002	1.008
D38	1	11.00	0.750	0.440	1.560		1.520	4.62	-	-	3160	57.00	28.16	220.41	1652.55	265.86	2256.36	0.829	0.732
D39	1	11.00	0.750	0.440	1.095		1.560	3.69	-	-	3160	57.00	27.62	216.17	1620.73	237.24	2038.97	0.911	0.795
D5	1	11.00	0.750	0.440	2.000		1.500	5.50	-	-	4180	57.00	44.34	301.77	2426.46	275.23	2311.13	1.096	1.050
D6	2	11.00	0.750	0.440	1.500	0.625	1.160	7.25	-	-	4340	57.00	33.17	221.51	1797.92	211.97	1862.19	1.045	0.965
D7	1	11.00	0.750	0.440	1.060		1.270	3.62	-	-	4450	57.00	33.85	223.29	1823.76	226.67	1969.92	0.985	0.926
D8	2	11.00	0.750	0.440	1.500	0.625	1.480	7.25	-	-	4570	57.00	35.95	234.00	1923.92	222.35	1928.15	1.052	0.998
D9	1	11.00	0.750	0.440	1.060		1.440	3.62	-	-	4380	57.00	34.98	232.59	1892.19	231.63	2000.90	1.004	0.946
D34	1	12.50	0.750	0.440	1.060		1.490	3.62	-	-	3800	57.00	36.86	263.13	2065.90	253.01	2151.12	1.040	0.960
D12	1	16.00	0.750	0.440	1.125		1.620	3.75	-	-	4530	57.00	45.70	298.73	2450.78	310.54	2556.96	0.962	0.958
D17	1	16.00	0.750	0.440	1.095		0.800	3.69	-	-	3580	57.00	39.74	292.25	2260.57	259.72	2199.83	1.125	1.028
D19*	1	16.00	0.750	0.440	2.905		1.700	7.31	-	-	4230	57.00	59.93	405.44	3269.77	410.14	3243.49	0.989	1.008
D23	1	16.00	0.750	0.440	1.060		0.780	3.62	-	-	4450	57.00	39.23	258.73	2113.16	256.44	2176.88	1.009	0.971
D24	1	16.00	0.750	0.440	2.875		0.810	7.25	-	-	4450	57.00	43.18	284.79	2326.06	337.02	2675.13	0.845	0.870
D30	1	16.00	0.750	0.440	1.095		1.560	3.69	-	-	7480	57.00	52.88	269.02	2501.88	305.46	2521.68	0.881	0.992
D4	2	16.00	0.750	0.440	1.500	0.500	1.500	9.00	-	-	4470	57.00	46.84	308.29	2520.79	273.55	2278.32	1.127	1.106
D40	1	16.00	0.750	0.440	2.940		0.750	7.38	-	-	5280	57.00	50.55	306.12	2609.42	338.06	2675.99	0.906	0.975
D25*	1	24.00	0.750	0.440	1.060		1.530	3.62	-	-	5100	57.00	58.25	358.90	3032.99	407.81	3244.68	0.880	0.935
D26	1	24.00	0.750	0.440	1.095		0.750	3.69	-	-	5100	57.00	55.87	344.22	2908.88	339.33	2759.56	1.014	1.054
D35	1	24.00	0.750	0.440	1.060		1.450	3.62	-	-	3800	57.00	54.99	392.51	3081.73	403.75	3221.23	0.972	0.957
D33	1	20.25	1.410	1.560	1.990		1.550	6.80	-	-	4830	57.00	28.20	633.04	5277.39	719.23	6375.61	0.880	0.828
Chamberlin (1956)																			
SII15	1	6.00	0.500	0.200	0.500		1.000	6.00	6.00	4.75	4470	-	34.52	103.28	844.47	87.57	780.45	1.179	1.082
SII16	1	6.00	0.500	0.200	0.750		1.000	6.00	6.00	4.75	4470	-	38.11	114.00	932.17	94.16	830.80	1.211	1.122
SIII31	1	6.00	0.500	0.200	0.500		1.000	6.00	6.00	4.75	5870	-	39.66	103.52	906.15	87.57	780.45	1.182	1.161
SIII32	1	6.00	0.500	0.200	0.750		1.000	6.00	6.00	4.75	5870	-	46.37	121.05	1059.56	94.16	830.80	1.286	1.275
SIII33	1	6.00	0.500	0.200	1.000		1.000	6.00	6.00	4.75	5870	-	48.45	126.47	1107.03	103.10	898.50	1.227	1.232
SIII1	1	10.67	0.500	0.200	0.500		1.000	6.00	6.00	4.75	3680	-	41.17	135.74	1057.23	122.53	1023.00	1.108	1.033
SIII27	1	10.67	0.500	0.200	0.500		1.000	6.00	6.00	4.75	5870	-	46.43	121.19	1060.77	122.53	1023.00	0.989	1.037
SIII28	1	10.67	0.500	0.200	0.750		1.000	6.00	6.00	4.75	5870	-	49.32	128.75	1126.92	136.95	1134.60	0.940	0.993
SIII29	1	10.67	0.500	0.200	1.000		1.000	6.00	6.00	4.75	5870	-	49.32	128.76	1127.00	154.20	1266.00	0.835	0.890
SIV53	2	12.00	0.500	0.200	2.000	0.500	1.000	6.00	6.00	4.75	4540	-	46.95	139.36	1143.90	149.17	1221.40	0.934	0.937
SII23	1	16.00	0.750	0.440	0.750		1.000	9.00	9.00	7.63	4470	-	41.89	275.72	2254.43	251.16	2140.24	1.098	1.053
Chamberlin (1958)																			
3a	2	6.00	0.500	0.200	0.500	1.500	1.000	6.00	6.00	4.75	4450	50.00	32.78	98.29	802.76	87.57	780.45	1.122	1.029
3b	2	6.00	0.500	0.200	0.500	1.000	1.000	6.00	6.00	4.75	4450	50.00	33.00	98.93	808.05	87.57	780.45	1.130	1.035
3c	2	6.00	0.500	0.200	0.500	0.500	1.000	6.00	6.00	4.75	4450	50.00	33.48	100.39	819.95	87.57	780.45	1.146	1.051
4a	1	6.00	0.500	0.200	2.500		1.000	6.00	6.00	4.75	4370	50.00	42.64	129.00	1048.88	124.75	1033.28	1.034	1.015
4b	1	6.00	0.500	0.200	2.250		1.000	6.00	6.00	4.75	4370	50.00	43.89	132.80	1079.71	121.14	1010.81	1.096	1.068
4c	1	6.00	0.500	0.200	2.000		1.000	6.00	6.00	4.75	4370	50.00	43.32	131.06	1065.58	117.53	988.35	1.115	1.078
Ferguson and Breen (1965)																			
8R18a	2	18.00	1.000	0.790	3.250	3.265	1.750	17.03	14.97	12.72	3470	99.00	41.32	554.08	4252.64	562.81	4597.13	0.984	0.925
8R24a	2	24.00	1.000	0.790	3.250	3.310	1.670	17.12	15.03	12.86	3530	99.00	58.88	782.95	6034.99	683.95	5433.36	1.145	1.111
8F30a	2	30.00	1.000	0.790	3.250	3.295	1.530	17.09	14.97	12.94	3030	74.00	52.78	757.50	5620.06	788.43	6139.88	0.961	0.915
8F36a*	2	36.00	1.000	0.790	3.250	3.330	1.410	17.16	15.00	13.09	4650	63.50	66.34	768.52	6346.24	887.10	6799.46	0.866	0.933
8F36b	2	36.00	1.000	0.790	3.250	3.220	1.400	16.94	15.03	13.13	3770	74.00	61.30	788.66	6179.78	885.09	6783.69	0.891	0.911
8F36k	2	36.00	1.000	0.790	1.420	1.425	1.380	9.69	15.09	13.21	3460	74.00	54.65	734.03	5629.69	743.61	5963.78	0.987	0.944
8F39a*	2	39.00	1.000	0.790	3.250	3.280	1.530	17.06	15.09	13.06	3650	63.50	72.90	953.29	7409.67	973.66	7420.29	0.979	0.999
8F42a*	2	42.00	1.000	0.790	3.250	3.345	1.500	17.19	15.09	13.09	2660	63.50	65.93	1009.90	7252.66	1027.89	7788.42	0.982	0.931
8F42b*	2	42.00	1.000	0.790	3.250	3.330	1.450	17.16	15.03	13.08	3830	63.50	73.54	938.77	7385.18	1015.54	7691.80	0.924	0.960
8R42a	2	42.00	1.000	0.790	3.250	3.345	1.560	17.19	15.00	12.94	3310	99.00	71.01	975.05	7395.81	1043.00	7906.25	0.935	0.935
8R48a	2	48.00	1.000	0.790	3.250	3.265	1.480	17.03	15.00	13.02	3040	99.00	72.88	1044.29	7754.22	1144.41	8587.54	0.913	0.903
8R64a	2	64.00	1.000	0.790	3.250	3.295	1.520	17.09	15.00	12.98	3550	99.00	89.71	1189.48	9181.50	1484.22	10945.85	0.801	0.839
8R80a	2	80.00	1.000	0.790	3.250	3.265	1.500	17.03	15.03	13.03	3740	99.00	96.41	1245.45	9739.65	1802.39	13135.02	0.691	0.742
11R24a	2	33.00	1.410	1.560	4.590	4.635	1.670	24.09	18.09	15.72	3720	93.00	51.81	1325.20	10349.44	1217.76	9704.76	1.088	1.066
11R30a	2	41.25	1.410	1.560	4.590	4.635	1.310	24.09	18.09	16.08	4030	93.00	58.50	1437.60	11454.22	1377.33	10702.37	1.044	1.070
11F36a	2	49.50	1.410	1.560	4.590	4.635	1.500	24.09	18.00	15.79	4570	73.00	64.16	1480.58	12173.38	1607.73	12300.11	0.921	0.990
11F36b	2	49.50	1.410	1.560	4.590	4.605	1.470	24.03	18.00	15.83	3350	65.00	59.20	1595.55	12138.65	1601.77	12250.39	0.996	0.991
11F42a	2	57.75	1.410	1.560	4.590	4.590	1.480	24.00	18.00	15.82	3530	65.00	63.61	1670.25	12874.38	1808.10	13641.10	0.924	0.944

Table A.1

Data and test/prediction ratios for developed and spliced bars without confining reinforcement (continued) [t]

Test No.	n	l_d	d_b	A_b	c_{so}	c_{si}	c_b	b	h	d	f'_c	f_y	f_s	$T_c/f'_c{}^{1/2}$ Test	$T_c/f'_c{}^{1/4}$ Test	$T_c/f'_c{}^{1/2}$ Eq.3*	$T_c/f'_c{}^{1/4}$ Eq. 4**	Test / Eq. 3	Test / Eq. 4
		(in.)	(in.)	(in.^{2})	(in.)	(in.)	(in.)	(in.)	(in.)	(in.)	(psi)	(ksi)	(ksi)	(in.^{2})	(in.^{2})	(in.^{2})	(in.^{2})		
11F48a*	2	66.00	1.410	1.560	4.590	4.620	1.530	24.16	18.03	15.80	3140	73.00	74.56	2075.59	15537.25	2027.40	15139.12	1.024	1.026
11F48b*	2	66.00	1.410	1.560	4.590	4.665	1.580	24.15	18.22	15.93	3330	65.00	72.24	1953.00	14835.85	2042.97	15266.85	0.956	0.972
11R48a	2	66.00	1.410	1.560	4.590	4.670	1.500	24.16	18.03	15.83	5620	93.00	82.22	1710.87	14813.30	2018.36	15064.38	0.848	0.983
11R48b	2	66.00	1.410	1.560	4.590	4.700	2.060	24.22	18.19	15.43	3100	93.00	71.43	2001.35	14933.60	2215.36	16639.76	0.903	0.897
11F60a*	2	82.50	1.410	1.560	4.590	4.575	1.590	23.97	18.09	15.83	2610	73.00	84.80	2589.35	18507.65	2465.49	18128.62	1.050	1.021
11F60b*	2	82.50	1.410	1.560	4.590	4.590	1.500	24.00	18.09	15.92	4090	65.00	78.02	1903.01	15218.54	2428.99	17828.64	0.783	0.854
11R60a	2	82.50	1.410	1.560	4.590	4.590	1.410	24.00	18.12	16.01	2690	93.00	74.61	2243.98	16160.60	2394.96	17544.12	0.937	0.921
11R60b	2	82.50	1.410	1.560	4.590	4.575	1.750	24.00	18.03	15.58	3460	93.00	87.80	2328.40	17857.73	2535.33	18692.65	0.918	0.955
Thompson et al. (1975)																			
6-12-4/2/2-6/6	6	12.00	0.750	0.440	2.000	2.000	2.000	33.00	13.00	10.63	3730	61.70	57.40	413.56	3232.00	331.94	2732.70	1.246	1.183
8-18-4/3/2-6/6	6	18.00	1.000	0.790	2.000	2.000	3.000	36.00	13.00	9.50	4710	59.30	56.26	647.57	5364.69	579.87	4743.59	1.117	1.131
8-18-4/3/2.5-4/6	6	18.00	1.000	0.790	2.500	2.000	3.000	36.00	13.00	9.50	2920	59.30	49.33	721.17	5301.32	608.48	4961.24	1.185	1.069
8-24-4/2/2-6/6	6	24.00	1.000	0.790	2.000	2.000	2.000	36.00	13.00	10.50	3105	59.30	50.64	717.95	5359.32	673.33	5462.70	1.066	0.981
11-25-6/2/3-5/5	5	25.00	1.410	1.560	3.000	3.000	2.000	44.06	13.01	10.30	3920	66.30	44.19	1101.17	8713.13	946.00	7962.33	1.164	1.094
11-30-4/2/2-6/6	6	30.00	1.410	1.560	2.000	2.000	2.000	40.88	13.01	10.30	2865	60.50	37.99	1107.19	8100.32	1002.59	8435.25	1.104	0.960
11-30-4/2/4-6/6	6	30.00	1.410	1.560	4.000	2.000	2.000	44.88	13.01	10.30	3350	63.40	44.39	1196.37	9101.81	1020.14	8540.69	1.173	1.066
11-30-4/2/2.7-4/6	4	30.00	1.410	1.560	2.700	2.000	2.000	44.88	13.01	10.30	4420	63.30	57.59	1351.41	11019.00	1020.14	8540.69	1.325	1.290
11-45-4/1/2-6/6	6	45.00	1.410	1.560	2.000	2.000	1.000	40.88	13.01	11.30	3520	60.50	45.28	1190.61	9170.76	1098.77	8972.12	1.084	1.022
14-60-4/2/2-5/5	5	60.00	1.693	2.250	2.000	2.000	2.000	37.50	16.15	13.30	2865	57.70	45.23	1901.10	13908.68	1916.87	15552.27	0.992	0.894
14-60-4/2/4-5/5	5	60.00	1.693	2.250	4.000	2.000	2.000	41.50	16.00	13.15	3200	57.70	56.64	2252.83	16944.03	1950.42	15746.67	1.155	1.076
Zekany 1981																			
9-53-B-N	5	16.00	1.128	1.000	2.000	1.423	2.000	27.25	16.00	13.44	5650	62.80	47.56	632.67	5485.20	514.20	4470.32	1.230	1.227
N-N-80B	4	22.00	1.410	1.560	2.000	1.849	2.000	27.25	16.01	13.30	3825	60.10	37.96	957.61	7530.89	813.03	7071.93	1.178	1.065
Choi et al. (1990, 1991)																			
1-5N0120U	2	12.00	0.625	0.310	2.000	2.000	1.000	10.50	16.00	14.69	5360	63.80	61.51	260.45	2228.55	223.37	1817.81	1.166	1.226
1-5N0120U*	3	12.00	0.625	0.310	2.000	2.000	1.000	15.75	16.00	14.69	5360	63.80	63.99	270.95	2318.38	223.37	1817.81	1.213	1.275
2-6C0120U	2	12.00	0.750	0.440	2.000	2.000	1.000	11.00	16.01	14.63	6010	69.00	51.40	291.71	2568.45	258.57	2174.37	1.128	1.181
2-6S0120U	2	12.00	0.750	0.440	2.000	2.000	1.000	11.00	16.01	14.63	6010	71.00	45.75	259.67	2286.34	258.57	2174.37	1.004	1.051
3-8N0160U	2	16.00	1.000	0.790	2.000	2.000	1.500	12.00	16.00	14.00	5980	63.80	43.02	439.52	3865.07	448.03	3821.99	0.981	1.011
3-8S0160U	2	16.00	1.000	0.790	2.000	2.000	1.500	12.00	14.00	12.00	5980	71.00	42.82	437.47	3847.05	448.03	3821.99	0.976	1.007
4-11C0240U	2	24.00	1.410	1.560	2.000	2.000	2.000	13.65	16.01	13.30	5850	69.00	37.82	771.38	6746.20	860.42	7412.76	0.897	0.910
4-11S0240U	2	24.00	1.410	1.560	2.000	2.000	2.000	13.65	16.01	13.30	5850	71.00	40.22	820.30	7173.98	860.42	7412.76	0.953	0.968
Hester et al. (1991, 1993)																			
1-8N3160U	3	16.00	1.000	0.790	2.000	1.500	2.000	16.00	16.00	13.50	5990	63.80	50.03	510.70	4492.89	472.35	4007.14	1.081	1.121
2-8C3160U	3	16.00	1.000	0.790	2.000	1.500	1.840	16.00	16.33	13.99	6200	69.00	46.24	463.97	4117.08	466.42	3971.02	0.995	1.037
3-8S3160U	3	16.00	1.000	0.790	2.000	1.500	2.040	16.09	16.23	13.69	6020	71.10	46.81	476.62	4198.27	473.83	4016.17	1.006	1.045
4-8S3160U	3	16.00	1.000	0.790	2.000	1.500	2.100	16.08	16.22	13.62	6450	71.10	42.40	417.03	3737.31	476.06	4029.71	0.876	0.927
5-8C3160U	3	16.00	1.000	0.790	2.000	1.500	2.050	16.09	16.27	13.72	5490	69.00	39.82	424.61	3654.97	474.20	4018.43	0.895	0.910
6-8C3220U	3	22.75	1.000	0.790	2.000	1.500	2.150	16.06	16.19	13.54	5850	69.00	51.85	535.52	4683.42	615.21	5019.68	0.870	0.933
7-8C3160U	2	16.00	1.000	0.790	2.000	4.000	2.120	16.03	16.20	13.58	5240	69.00	45.37	495.10	4212.40	502.31	4227.92	0.986	0.996
Rezansoff et al. (1993)																			
2a	3	29.53	0.992	0.775	1.827	0.994	2.008	13.58	12.99	10.49	3958	64.52	58.56	721.29	5721.24	646.16	5187.80	1.116	1.103
2b	3	29.53	0.992	0.775	1.827	0.994	2.008	13.58	12.99	10.49	3799	64.52	58.63	737.15	5787.23	646.16	5187.80	1.141	1.116
5a	3	35.43	1.177	1.085	1.819	1.183	2.008	15.43	20.00	17.40	4031	68.87	56.08	958.36	7636.25	877.02	7097.54	1.093	1.076
5b	3	44.29	1.177	1.085	1.819	1.183	2.008	15.43	20.00	17.40	3726	68.87	65.83	1170.12	9142.25	1042.70	8270.99	1.122	1.105
Azizinamini et al. (1993)																			
BB-8-5-23	2	23.00	1.000	0.790	1.000	1.500	1.000	9.00	14.00	12.50	5290	77.85	47.01	510.62	4354.71	449.95	3856.20	1.135	1.129
AB83-8-15-41	2	41.00	1.000	0.790	1.000	1.500	1.000	9.00	14.00	12.50	15120	77.85	73.07	469.42	5205.33	686.47	5557.20	0.684	0.937
BB-11-5-24	2	24.00	1.410	1.560	1.410	1.770	1.410	12.00	16.00	13.89	5080	70.80	29.73	650.70	5493.49	736.38	6520.68	0.884	0.842
BB-11-5-40	2	40.00	1.410	1.560	1.410	1.770	1.410	12.00	16.00	13.89	5080	70.80	43.03	941.72	7950.37	1032.82	8652.60	0.912	0.919
BB-11-12-24	2	24.00	1.410	1.560	1.410	1.770	1.410	12.00	16.00	13.89	12730	70.80	44.72	618.36	6568.21	736.38	6520.68	0.840	1.007
B-11-12-40	2	40.00	1.410	1.560	1.410	1.770	1.410	12.00	16.00	13.89	13000	70.80	58.78	804.23	8587.50	1032.82	8652.60	0.779	0.992
BB-11-11-45	3	45.00	1.410	1.560	1.410	1.680	1.410	18.00	18.00	15.89	10900	70.80	48.90	730.66	7465.74	1125.45	9318.83	0.649	0.801
BB-11-15-36	3	36.00	1.410	1.560	1.410	1.680	1.410	18.00	18.00	15.89	14550	70.80	57.34	741.57	8144.54	958.71	8119.62	0.774	1.003
BB-11-5-36	3	36.00	1.410	1.560	1.410	1.680	1.410	18.00	18.00	15.89	6170	73.72	46.75	928.44	8228.60	958.71	8119.62	0.968	1.013
BB-11-13-40	3	40.00	1.410	1.560	1.410	1.680	1.410	18.00	18.00	15.89	13600	73.72	57.70	771.88	8335.59	1032.82	8652.60	0.747	0.963
BB-11-15-13	2	13.00	1.410	1.560	1.410	1.770	1.410	12.00	16.00	13.89	14330	73.72	30.06	391.70	4285.58	532.58	5054.99	0.735	0.848
AB83-11-15-57.5	2	57.50	1.410	1.560	1.410	1.770	1.410	12.00	16.00	13.89	13870	73.72	71.66	949.21	10301.02	1357.05	10984.39	0.699	0.938
AB89-11-15-80	2	80.00	1.410	1.560	1.410	1.770	1.410	12.00	16.00	13.89	15120	73.72	71.17	902.88	10011.94	1773.91	13982.40	0.509	0.716
Darwin et al. (1995a)																			
1.1	2	16.00	1.000	0.790	2.969	2.938	2.938	16.08	17.22	13.76	5020	60.00	51.63	575.67	4845.66	630.53	5153.64	0.913	0.940
1.2	2	16.00	1.000	0.790	2.032	2.281	1.938	24.06	16.25	13.79	5020	60.00	44.60	497.29	4185.87	492.76	4160.29	1.009	1.006
1.3	3	16.00	1.000	0.790	2.032	1.438	1.938	16.07	16.21	13.75	5020	60.00	45.01	501.86	4224.35	460.64	3921.61	1.089	1.077
2.4	2	24.00	1.000	0.790	2.000	1.914	1.313	12.13	15.64	13.79	5250	75.00	54.08	589.64	5019.08	567.64	4655.43	1.039	1.078
2.5	2	24.00	1.000	0.790	2.063	1.856	1.813	12.13	16.01	13.67	5250	75.00	58.67	639.68	5445.07	646.23	5251.24	0.990	1.037
4.5	2	24.00	1.000	0.790	2.063	1.936	1.844	12.12	16.15	13.79	4090	60.00	51.06	630.73	5044.02	651.16	5288.76	0.969	0.954
6.5	2	24.00	1.000	0.790	2.000	1.906	1.969	12.10	16.13	13.63	4220	75.00	53.59	651.71	5252.70	668.28	5424.35	0.975	0.968
8.1	2	24.00	1.000	0.790	2.000	1.953	2.000	12.11	16.05	13.53	3830	79.00	61.47	784.68	6172.92	673.33	5462.70	1.165	1.130
10.2	2	26.00	1.000	0.790	2.063	1.875	1.933	12.13	16.25	13.78	4250	81.00	61.17	741.26	5985.06	708.48	5706.07	1.046	1.049
13.4	3	16.00	0.625	0.310	2.094	1.016	1.354	12.19	15.60	13.92	4110	64.00	59.96	289.94	2321.47	281.88	2266.67	1.029	1.024

Table A.1

Data and test/prediction ratios for developed and spliced bars without confining reinforcement (continued) †

Test No.	n	l_d (in.)	d_b (in.)	A_b (in.^{2})	c_{so} (in.)	c_{si} (in.)	c_b (in.)	b (in.)	h (in.)	d (in.)	f'_c (psi)	f_y (ksi)	f_s (ksi)	$T_c/f'^{1/2}_c$ Test (in.^{2})	$T_c/f'^{1/4}_c$ Test (in.^{2})	$T_c/f'^{1/2}_c$ Eq.3* (in.^{2})	$T_c/f'^{1/4}_c$ Eq. 4** (in.^{2})	Test/Eq. 3	Test/Eq. 4
14.3	3	17.00	0.625	0.310	2.032	1.031	1.295	12.14	15.51	13.89	4200	64.00	62.84	300.59	2419.83	295.75	2369.75	1.016	1.021
15.5	2	40.00	1.410	1.560	3.063	2.984	1.908	18.05	16.12	13.47	5250	81.00	54.12	1165.21	9918.42	1309.59	10507.05	0.890	0.944
16.2	2	40.00	1.410	1.560	3.016	2.969	1.895	18.07	16.28	13.64	5180	81.00	52.38	1135.34	9631.80	1302.33	10458.69	0.872	0.921

		Test/Eq. 3	Test/Eq. 4
For all 133 specimens:	Max.	1.325	1.290
	Min.	0.509	0.716
	Mean	1.000	1.003
	St. Dev.	0.138	0.107
	COV	0.138	0.107
For the 11 specimens with $f_s > f_y$:	Max.	1.213	1.275
	Min.	0.783	0.854
	Mean	0.968	0.992
	St. Dev.	0.112	0.107
	COV	0.115	0.107

† All reports describe splice tests, except Chinn (1955) which describes development tests

* Specimens with $f_s > f_y$

\- Data is not available

* Eq. 3 = $\frac{T_c}{f'^{1/2}_c} = \frac{A_b f_s}{f'^{1/2}_c} = [8.76 l_d (c_m + 0.5 d_b) + 187 A_b] \left(0.14 \frac{c_M}{c_m} + 0.86\right)$

** Eq. 4 = $\frac{T_c}{f'^{1/4}_c} = \frac{A_b f_s}{f'^{1/4}_c} = [63 l_d (c_m + 0.5 d_b) + 2130 A_b] \left(0.1 \frac{c_M}{c_m} + 0.9\right)$

1 in. = 25.4 mm; 1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

Table A.2

Data and test/prediction ratios for developed and spliced bars with confining reinforcement [t]

Specimen No.	n	l_d (in)	d_b (in)	R_r (in)	c_{so} (in)	c_{si} (in)	c_b (in)	b (in)	h (in)	d (in)	d_s (in)	N***	f'_c (psi)	f_s (ksi)	f_y (ksi)	f_{yt} (ksi)	$T_b/f'_c{}^{1/4}$ Test (in.^{2})	$T_b/f'_c{}^{1/4}$ Eq.17** (in.^{2})	Test / Prediction
Mathey and Watstein (1961)***																			
4-7-2*	1	7.00	0.500	0.096	3.750		1.750	8.00	18.00	16.00	0.500	2	4210	88.60	114.70	114.70	2200	2208	0.996
4-7-1*	1	7.00	0.500	0.096	3.750		1.750	8.00	18.00	16.00	0.500	2	4265	92.10	114.70	114.70	2279	2208	1.032
4-10.5-3**	1	10.50	0.500	0.096	3.750		1.750	8.00	18.00	16.00	0.500	3	3675	113.30	114.70	114.70	2910	3042	0.957
4-10.5-2**	1	10.50	0.500	0.096	3.750		1.750	8.00	18.00	16.00	0.500	3	4055	115.00	114.70	114.70	2882	3042	0.947
4-14-2**	1	14.00	0.500	0.096	3.750		1.750	8.00	18.00	16.00	0.500	4	3710	100.40	114.70	114.70	2573	3876	0.664
8-21-1**	1	21.00	1.000	0.088	3.500		1.500	8.00	18.00	16.00	0.500	5	4235	61.80	97.00	114.70	6052	7476	0.810
8-28-1**	1	28.00	1.000	0.088	3.500		1.500	8.00	18.00	16.00	0.500	7	4485	77.20	97.00	114.70	7453	9477	0.786
8-28-2**	1	28.00	1.000	0.088	3.500		1.500	8.00	18.00	16.00	0.500	7	3700	71.80	97.00	114.70	7273	9477	0.767
8-34-1**	1	34.00	1.000	0.088	3.500		1.500	8.00	18.00	16.00	0.500	9	3745	92.10	97.00	114.70	9301	11335	0.821
8-14-1*	1	14.00	1.000	0.088	3.500		1.500	8.00	18.00	16.00	0.500	4	3585	33.40	97.00	114.70	3410	5975	0.571
8-34-2**	1	34.00	1.000	0.088	3.500		1.500	8.00	18.00	16.00	0.500	9	3765	89.70	97.00	114.70	9046	11335	0.798
8-14-2*	1	14.00	1.000	0.088	3.500		1.500	8.00	18.00	16.00	0.500	4	4055	42.50	97.00	114.70	4207	5975	0.704
8-7-1*	1	7.00	1.000	0.088	3.500		1.500	8.00	18.00	16.00	0.500	2	4005	28.60	97.00	114.70	2840	3974	0.715
8-21-2**	1	21.00	1.000	0.088	3.500		1.500	8.00	18.00	16.00	0.500	5	3495	53.20	97.00	114.70	5466	7476	0.731
Freguson and Breen (1965)****																			
8F36c	2	36.00	1.000	0.0731	3.250	3.295	1.470	17.09	14.97	13.00	0.252	6	2740	61.33	74.00	52.00	6697	7617	0.879
8F36d*	2	36.00	1.000	0.0731	3.250	3.280	1.530	17.06	15.00	12.97	0.252	10	3580	74.31	74.00	52.00	7589	8152	0.931
8F36e*	2	36.00	1.000	0.0731	3.250	3.310	1.470	17.12	14.91	12.94	0.252	6	4170	77.44	74.00	52.00	7613	7617	1.000
8F36f*	2	36.00	1.000	0.0731	3.250	3.280	1.500	17.06	15.09	13.04	0.252	10	3780	78.15	74.00	52.00	7873	8103	0.972
8F36g*	2	36.00	1.000	0.0731	3.250	3.265	1.530	17.03	14.97	12.94	0.252	6	3070	75.78	74.00	52.00	8042	7715	1.042
8F36h	2	36.00	1.000	0.0731	3.250	3.265	1.590	17.03	15.09	13.00	0.252	14	1910	56.02	74.00	52.00	6695	8689	0.770
8F36j	2	36.00	1.000	0.0731	3.250	3.310	1.500	17.12	15.03	13.03	0.252	14	1820	64.09	74.00	52.00	7751	8540	0.908
8F30b	2	30.00	1.000	0.0731	3.250	3.270	1.500	17.04	15.03	13.03	0.252	6	2610	57.47	74.00	52.00	6352	6822	0.931
11R36a	2	49.50	1.410	0.0674	4.590	4.620	2.020	24.06	18.05	15.33	0.375	11	3020	82.35	93.00	42.00	17330	16625	1.042
Thompson et al. (1975)****																			
11-30-4/2/2-6/6-S5	6	30.00	1.410	0.0674	2.000	2.000	2.000	40.88	13.00	10.30	0.375	6	3063	46.47	65.00	68.00	9745	10265	0.949
11-20-4/2/2/-6/6-SP*	6	20.00	1.410	0.0674	2.000	2.000	2.000	40.88	13.00	10.30	0.375	7	3620	42.34	67.30	67.30	8515	8855	0.962
11-20-4/2/2-6/6-S5*	6	20.00	1.410	0.0674	2.000	2.000	2.000	40.88	13.00	10.30	0.375	4	3400	40.61	67.30	67.30	8296	7973	1.041
8-15-4/2/2-6/6-S5*	6	15.00	1.000	0.0727	2.000	2.000	2.000	36.00	13.00	10.50	0.375	3	3507	57.31	61.10	61.10	5883	4830	1.218
Zekany et al. (1981)																			
9-53-B*	5	16.00	1.128	0.0727	2.000	1.500	2.000	27.25	16.00	13.44	0.236	4	5700	57.36	62.80	70.00	6601	4759	1.387
11-40-B-A*	4	22.00	1.410	0.0674	2.000	2.000	2.000	27.25	16.00	13.30	0.236	5	5425	44.94	60.10	70.00	8168	7723	1.058
2-4.5-80-B*	4	22.00	1.410	0.0674	2.000	2.000	2.000	27.25	16.00	13.30	0.236	5	4200	42.54	60.10	74.50	8243	7723	1.067
2-5-40-B(4)*	4	22.00	1.410	0.0674	2.000	2.000	2.000	27.25	16.00	13.30	0.236	4	3850	41.59	60.10	70.00	8236	7606	1.083
3-5-53-B*	4	22.00	1.410	0.0674	2.000	2.000	2.000	27.25	16.00	13.30	0.375	4	3775	39.44	60.10	60.30	7850	8314	0.944
2-4.5-53-B*	4	22.00	1.410	0.0674	2.000	2.000	2.000	27.25	16.00	13.30	0.236	5	4125	42.00	60.10	74.50	8175	7723	1.059
11-53-B*	4	22.00	1.410	0.0674	2.000	2.000	2.000	27.25	16.00	13.30	0.236	5	4025	42.32	60.10	70.00	8289	7723	1.073
11-40-B*	4	22.00	1.410	0.0674	2.000	2.000	2.000	27.25	16.00	13.30	0.236	5	5050	45.58	60.10	70.00	8435	7723	1.092
11-53-B-D*	4	22.00	1.410	0.0674	2.000	2.000	2.000	27.25	16.00	13.30	0.236	5	4125	33.89	60.10	70.00	6597	7723	0.854
3-5-40-B*	4	22.00	1.410	0.0674	2.000	2.000	2.000	27.25	16.00	13.30	0.375	4	3750	38.21	60.10	60.30	7617	8314	0.916
DeVries et al. (1991)****																			
8G-9B-P6*	2	9.00	0.750	0.0799	1.875	2.125	1.125	11.00	16.00	14.50	0.375	3	8850	70.39	76.63	78.58	3193	2604	1.226
8N-9B-P6*	2	9.00	0.750	0.0799	1.625	2.438	1.250	11.10	16.00	14.38	0.375	3	8300	56.55	76.63	78.58	2607	2611	0.998
8G-22B-P9	2	22.00	1.128	0.0727	1.500	1.744	1.125	11.00	16.00	14.31	0.375	4	7460	52.76	66.40	78.58	5677	5732	0.990
8N-18B-P9*	2	18.00	1.128	0.0727	1.375	1.932	1.500	11.10	16.00	13.94	0.375	3	7660	51.68	70.35	78.58	5524	5219	1.058
8G-16B-P9*	2	16.00	1.128	0.0727	1.375	1.869	1.063	11.00	16.00	14.37	0.375	3	7460	42.44	66.40	78.58	4567	4731	0.965
8G-18B-P9*	2	18.00	1.128	0.0727	1.688	1.557	1.250	11.00	16.00	14.19	0.375	3	8610	52.38	70.35	78.58	5437	5184	1.049
10N-12B-P9*	2	12.00	1.128	0.0727	1.938	1.307	1.188	11.00	16.00	14.25	0.375	3	9780	37.63	70.35	78.58	3784	4412	0.858
10G-12B-P9*	2	12.00	1.128	0.0727	1.625	1.619	1.250	11.00	16.00	14.19	0.375	3	9680	37.61	70.35	78.58	3792	4457	0.851
15G-12B-P9*	2	12.00	1.128	0.0727	1.375	1.932	1.188	11.10	16.00	14.25	0.375	3	16100	49.09	70.35	78.58	4358	4359	1.000
15N-12B-P9*	2	12.00	1.128	0.0727	1.500	1.807	1.250	11.10	16.00	14.19	0.375	3	13440	50.77	70.35	78.58	4716	4422	1.066
Hester et al. (1991, 1993)***																			
7-8C3-16-3-U	2	16.00	1.000	0.0710	2.000	4.000	2.030	16.00	16.30	13.77	0.375	3	5240	51.49	69.00	54.10	4781	4981	0.960
4-8S3-16-2-U	3	16.00	1.000	0.0700	2.000	1.500	2.040	16.09	16.36	13.82	0.375	2	6450	47.06	71.10	68.90	4148	4393	0.944
4-8S3-16-3-U	3	16.00	1.000	0.0700	2.000	1.500	2.100	16.09	16.28	13.68	0.375	3	6450	50.04	71.10	68.90	4411	4562	0.967
5-8C3-16-2-U	3	16.00	1.000	0.0710	2.000	1.500	2.060	16.10	16.42	13.86	0.375	2	5490	46.51	69.00	54.10	4269	4401	0.970
6-8C3-22 3/4-3-U	3	22.75	1.000	0.0710	2.000	1.500	2.170	16.06	16.20	13.53	0.375	3	5850	56.45	69.00	54.10	5099	5562	0.917
1-8N3-16-2-U	3	16.00	1.000	0.0780	2.000	1.500	2.000	16.00	16.00	13.50	0.375	2	5990	56.00	63.80	77.30	5029	4409	1.141
6-8C3-22 3/4-4-U	3	22.75	1.000	0.0710	2.000	1.500	2.160	16.03	16.17	13.51	0.375	4	5850	55.67	69.00	54.10	5029	5716	0.880
5-8C3-16-3-U	3	16.00	1.000	0.0710	2.000	1.500	2.060	16.09	16.12	13.56	0.375	3	5490	43.31	69.00	54.10	3975	4558	0.872
3-8S3-16-2-U	3	16.00	1.000	0.0700	2.000	1.500	2.080	16.06	16.24	13.66	0.375	2	6020	46.47	71.10	68.90	4168	4402	0.947
2-8C3-16-2-U	3	16.00	1.000	0.0710	2.000	1.500	1.830	16.00	16.28	13.95	0.375	2	6200	43.99	69.00	54.10	3916	4349	0.901
Rezansoff et al. (1991)***																			
20-6-2	2	18.15	0.768	0.0799	1.000	2.980	1.000	11.02	12.99	11.61	0.313	5	4277	70.12	72.50	62.08	4032	3384	1.192
20-6-3*	2	15.39	0.768	0.0799	1.000	2.980	1.000	11.02	12.99	11.61	0.313	6	3886	75.55	72.50	62.08	4449	3292	1.351
20-6-1*	2	22.09	0.768	0.0799	1.000	2.980	1.000	11.02	12.99	11.61	0.313	3	4045	78.49	72.50	62.08	4576	3429	1.335
20-8-11*	2	16.34	0.992	0.0731	1.000	2.530	1.000	11.02	13.00	11.50	0.313	13	4466	75.00	65.54	62.08	7110	5425	1.311
20-8-9	2	18.70	0.992	0.0731	1.500	2.030	1.500	11.02	13.00	11.00	0.313	9	4205	60.05	65.54	62.08	5780	5569	1.038
20-8-10*	2	15.12	0.992	0.0731	1.500	2.030	1.500	11.02	13.00	11.00	0.313	12	4408	64.03	65.54	62.08	6090	5619	1.084
20-8-1*	2	18.70	0.992	0.0731	1.000	2.530	1.000	11.02	13.00	11.50	0.313	13	5220	71.05	65.54	62.08	6478	5647	1.147

Table A.2

Data and test/prediction ratios for developed and spliced bars with confining reinforcement (continued)[t]

Specimen No.	n	l_d (in)	d_b (in)	R_r (in)	c_{so} (in)	c_{si} (in)	c_b (in)	b (in)	h (in)	d (in)	d_s (in)	N***	f'_c (psi)	f_s (ksi)	f_y (ksi)	f_{yt} (ksi)	$T_b/f'_c{}^{1/4}$ Test (in.²)	$T_b/f'_c{}^{1/4}$ Eq.17** (in.²)	Test / Prediction
20-8-12	2	16.34	0.992	0.0731	1.500	2.030	1.500	11.02	13.00	11.00	0.313	11	4350	64.20	65.54	62.08	6126	5606	1.093
20-8-2	2	21.77	0.992	0.0731	1.000	2.530	1.000	11.02	13.00	11.50	0.313	11	5742	64.84	65.54	62.08	5773	5603	1.030
20-8-3	2	26.10	0.992	0.0731	1.000	2.530	1.000	11.02	13.00	11.50	0.313	9	5510	64.02	65.54	62.08	5759	5678	1.014
20-8-6*	2	26.10	0.992	0.0731	1.000	2.530	1.000	11.02	13.00	11.50	0.313	9	4770	75.37	65.54	62.08	7028	5678	1.238
20-8-7	2	26.10	0.992	0.0731	1.500	2.030	1.500	11.02	13.00	11.00	0.313	4	4495	61.35	65.54	62.08	5806	5666	1.025
20-8-8	2	21.77	0.992	0.0731	1.500	2.030	1.500	11.02	13.00	11.00	0.313	7	4350	59.58	65.54	62.08	5686	5622	1.011
20-8-5*	2	21.77	0.992	0.0731	1.000	2.530	1.000	11.02	13.00	11.50	0.313	11	4770	76.01	65.54	62.08	7088	5603	1.265
20-8-4*	2	18.70	0.992	0.0731	1.000	2.530	1.000	11.02	13.00	11.50	0.313	13	4335	71.94	65.54	62.08	6871	5647	1.217
20-8-21*	2	15.35	0.992	0.0731	1.260	2.270	1.500	11.02	13.00	11.00	0.313	7	3378	45.76	60.90	52.21	4652	4647	1.001
20-8-13	2	28.70	0.992	0.0731	1.180	2.350	1.000	11.02	13.00	11.50	0.313	4	3509	51.22	64.38	52.21	5158	5167	0.998
20-8-14	2	23.11	0.992	0.0731	1.180	2.350	1.000	11.02	13.00	11.50	0.313	6	3277	53.28	64.38	52.21	5458	4964	1.099
20-8-15	2	20.31	0.992	0.0731	1.180	2.350	1.000	11.02	13.00	11.50	0.313	7	3625	54.68	64.38	52.21	5462	4863	1.123
20-8-16	2	28.70	0.992	0.0731	1.180	2.350	1.000	11.02	13.00	11.50	0.313	4	3291	54.82	60.90	52.21	5609	5167	1.086
20-8-18	2	17.44	0.992	0.0731	1.180	2.350	1.000	11.02	13.00	11.50	0.313	8	3349	54.80	60.90	52.21	5582	4754	1.174
20-8-19	2	21.65	0.992	0.0731	1.260	2.270	1.500	11.02	13.00	11.00	0.313	4	3219	44.56	60.90	52.21	4584	4856	0.944
20-8-17	2	20.31	0.992	0.0731	1.180	2.350	1.000	11.02	13.00	11.50	0.313	7	3480	60.78	60.90	52.21	6133	4863	1.261
20-8-20	2	17.32	0.992	0.0731	1.260	2.270	1.500	11.02	13.00	11.00	0.313	6	3291	44.95	60.90	52.21	4599	4702	0.978
20-9-1	2	19.69	1.177	0.0727	2.000	2.140	1.500	12.99	21.72	17.91	0.444	7	3538	58.74	67.28	60.05	8264	7792	1.061
20-9-2	2	25.59	1.177	0.0727	2.000	2.140	1.500	12.99	24.03	17.91	0.444	5	3378	64.82	67.28	60.05	9225	7835	1.178
20-11-4*	2	18.90	1.406	0.0674	2.020	1.670	1.508	12.99	20.00	17.79	0.444	10	4350	47.51	66.12	83.40	9067	10291	0.881
20-11-2*	2	26.57	1.406	0.0674	2.020	1.670	2.295	12.99	20.00	17.00	0.444	11	4335	70.91	69.02	83.40	13545	12452	1.088
20-11-1	2	37.99	1.406	0.0674	2.020	1.670	2.295	12.99	20.00	17.00	0.444	5	4770	68.59	69.02	83.40	12792	11897	1.075
20-11-3	2	26.61	1.406	0.0674	2.020	1.670	1.508	12.99	20.00	17.79	0.444	7	4466	52.37	66.12	83.40	9930	10156	0.978
20-11-8	2	34.29	1.406	0.0674	2.000	1.690	1.000	12.99	22.70	18.30	0.444	10	3349	61.36	66.12	60.05	12502	11832	1.057
20-11-5	2	27.01	1.406	0.0674	2.000	1.690	2.000	12.99	21.27	17.30	0.444	9	3625	63.81	66.12	60.05	12746	11605	1.098
20-11-6	2	34.72	1.406	0.0674	2.000	1.690	2.000	12.99	24.06	17.30	0.444	6	3625	54.54	66.12	60.05	10895	11655	0.935
20-11-7	2	27.20	1.406	0.0674	2.000	1.690	1.000	12.99	21.54	18.30	0.444	12	3291	51.38	66.12	60.05	10515	11826	0.889
Rezansoff et al. (1993)***																			
6	3	22.05	0.992	0.0731	1.827	0.502	2.008	11.61	12.99	10.49	0.313	8	3625	50.77	64.52	84.10	5071	4905	1.034
1b*	2	29.53	0.992	0.0731	1.827	0.520	2.008	8.66	12.99	10.49	0.250	6	3799	69.82	64.52	63.80	6892	5356	1.287
1a*	2	29.53	0.992	0.0731	1.827	0.520	2.008	8.66	12.99	10.49	0.250	6	3958	74.05	64.52	63.80	7235	5356	1.351
7*	3	14.76	0.992	0.0731	1.827	0.502	2.008	11.61	12.99	10.49	0.630	4	3625	46.60	64.52	68.15	4654	5153	0.903
3a*	3	29.53	0.992	0.0731	1.827	0.502	2.008	11.61	12.99	10.49	0.250	6	3958	69.76	64.52	63.80	6816	5129	1.329
3b	3	29.53	0.992	0.0731	1.827	0.502	2.008	11.61	12.99	10.49	0.250	6	3799	59.03	64.52	63.80	5827	5129	1.136
8*	3	11.81	0.992	0.0731	1.827	0.994	2.008	13.58	12.99	10.49	0.630	3	3625	34.05	64.52	68.15	3401	4547	0.748
4b	3	44.29	1.177	0.0727	1.819	0.573	2.008	12.99	20.00	17.40	0.250	5	3726	67.65	68.87	63.80	9395	7617	1.233
9*	3	33.46	1.177	0.0727	1.819	0.573	2.008	12.99	20.00	17.40	0.445	10	3886	76.40	68.87	68.87	10500	8658	1.213
10*	3	22.05	1.177	0.0727	1.819	0.573	2.008	12.99	20.00	17.40	0.630	7	4089	70.99	68.87	68.15	9632	8522	1.130
4a	3	35.43	1.177	0.0727	1.819	0.573	2.008	12.99	20.00	17.40	0.250	4	4031	61.08	68.87	63.80	8318	6636	1.253
Azizinamini et al. (1995 at CTL)****																			
AB83-11-15-57.5S-50*	2	57.50	1.410	0.0674	1.410	1.770	1.410	12.00	16.00	13.89	0.252	6	15120	75.63	73.70	58.98	10639	11852	0.898
Azizinamini et al. (1995 at UNL)***																			
ABS-11-15-45S-60	3	45.00	1.410	0.0590	1.410	1.680	1.410	18.00	18.00	15.89	0.375	4	14890	67.87	70.50	71.80	9584	10459	0.916
ABS-11-15-45S-100*	3	45.00	1.410	0.0590	1.410	1.680	1.410	18.00	18.00	15.89	0.375	6	14850	77.53	70.50	71.80	10956	10995	0.996
ABS-11-15-40S-150	3	40.00	1.410	0.0590	1.410	1.680	1.410	18.00	18.00	15.89	0.375	8	15760	69.18	70.50	71.80	9632	10866	0.886
Darwin et al. (1995a)***																			
12.1	4	10.00	0.625	0.0820	1.875	0.521	1.335	12.07	15.56	13.90	0.500	2	4120	45.42	65.00	84.70	1757	1854	0.948
12.3	3	10.00	0.625	0.0820	2.032	1.039	1.291	12.14	15.50	13.88	0.375	1	4120	48.52	65.00	64.55	1877	1863	1.008
13.2	3	12.00	0.625	0.0820	1.563	1.266	1.315	12.11	15.50	13.86	0.375	1	4110	56.10	65.00	64.55	2172	2176	0.998
12.2	4	10.00	0.625	0.1090	1.953	0.516	1.297	12.12	15.57	13.94	0.500	2	4120	45.48	64.00	84.70	1760	1930	0.912
12.4	3	10.00	0.625	0.1090	2.063	1.032	1.264	12.12	15.56	13.96	0.375	1	4120	52.02	64.00	64.55	2013	1959	1.028
13.1	3	12.00	0.625	0.1090	1.532	1.289	1.303	12.18	15.51	13.88	0.375	1	4110	55.82	64.00	64.55	2161	2218	0.975
14.5	2	12.00	0.625	0.0820	1.594	3.156	1.210	12.13	15.45	13.91	0.375	2	4200	60.15	65.00	64.55	2316	2316	1.000
14.6	2	12.00	0.625	0.1090	1.532	3.188	1.277	12.05	15.49	13.89	0.375	2	4200	63.45	64.00	64.55	2443	2439	1.002
1.5	3	16.00	1.000	0.1010	2.063	1.375	1.938	16.07	16.19	13.74	0.500	5	5020	52.24	60.00	70.75	4903	5819	0.843
1.6	3	16.00	1.000	0.1010	2.063	1.438	1.938	16.05	16.19	13.74	0.500	3	5020	52.00	60.00	70.75	4881	5124	0.952
2.1	2	24.00	1.000	0.0710	2.250	1.706	1.328	12.12	15.56	13.70	0.375	7	5250	62.43	70.00	69.92	5794	6371	0.909
2.2*	2	24.00	1.000	0.1400	2.125	1.801	1.406	12.12	15.52	13.58	0.375	7	5250	77.60	75.00	69.92	7202	7624	0.945
2.3	2	24.00	1.000	0.1400	2.125	1.780	1.969	12.11	16.06	13.56	0.375	4	5250	73.45	75.00	69.92	6817	7089	0.962
3.4	2	24.00	1.000	0.0850	2.110	1.857	2.000	12.14	16.26	13.73	0.375	4	5110	55.80	-	69.92	5214	6631	0.786
3.5	3	28.00	1.000	0.0850	1.001	0.965	1.906	12.17	16.17	13.74	0.375	8	3810	52.02	-	69.92	5230	6219	0.841
4.1	2	24.00	1.000	0.0710	2.063	1.926	1.250	12.16	15.49	13.72	0.500	6	4090	62.54	70.00	70.75	6178	7245	0.853
4.2	2	24.00	1.000	0.1400	2.094	1.848	1.313	12.17	15.59	13.74	0.375	8	4090	72.34	75.00	69.92	7146	7934	0.901
4.4	2	24.00	1.000	0.1010	2.032	1.978	1.219	12.15	15.47	13.73	0.375	4	4090	58.88	60.00	69.92	5816	5857	0.993
5.1	3	24.00	1.000	0.0650	2.016	1.914	1.250	18.22	15.57	13.79	0.375	7	4190	64.62	-	69.92	6345	6209	1.022
5.2	3	24.00	1.000	0.1400	2.078	1.867	1.359	18.16	15.62	13.73	0.375	7	4190	65.41	75.00	69.92	6422	7581	0.847
5.3	2	24.00	1.000	0.1400	2.063	1.849	1.281	12.11	15.50	13.68	0.375	7	4190	67.88	75.00	69.92	6665	7492	0.890
5.4	2	24.00	1.000	0.0650	1.985	1.980	1.250	12.12	15.46	13.68	0.375	7	4190	58.87	-	69.92	5781	6199	0.933
5.5	2	24.00	1.000	0.0850	2.063	1.904	1.406	12.12	15.60	13.67	0.375	4	4190	46.43	-	69.92	4559	5917	0.770
5.6**	2	22.00	1.000	0.1400	2.094	1.807	1.313	12.11	15.69	13.84	0.500	5	4190	66.34	75.00	70.75	6514	8114	0.803

Table A.2

Data and test/prediction ratios for developed and spliced bars with confining reinforcement (continued)[t]

Specimen No.	n	l_d (in)	d_b (in)	R_r (in)	c_{so} (in)	c_{si} (in)	c_b (in)	b (in)	h (in)	d (in)	d_s (in)	N***	f'_c (psi)	f_s (ksi)	f_y (ksi)	f_{yt} (ksi)	$T_b/f'_c{}^{1/4}$ Test (in.^{2})	$T_b/f'_c{}^{1/4}$ Eq.17** (in.^{2})	Test / Prediction
6.1	3	24.00	1.000	0.0650	2.063	0.422	1.906	12.18	16.12	13.69	0.500	8	4220	63.26	-	66.42	6201	6302	0.984
6.2	3	24.00	1.000	0.1400	2.000	0.438	2.000	12.11	16.15	13.62	0.500	8	4220	74.88	75.00	66.42	7340	8064	0.910
6.3	2	16.00	1.000	0.1400	2.000	1.906	1.344	12.13	15.51	13.63	0.375	2	4220	46.09	75.00	64.55	4518	4576	0.987
6.4	2	16.00	1.000	0.0850	2.094	1.844	1.344	12.11	15.45	13.58	0.375	2	4220	36.68	-	64.55	3595	4342	0.828
7.1	2	16.00	1.000	0.1400	2.079	1.797	1.875	12.00	16.18	13.77	0.375	2	4160	46.72	75.00	64.55	4596	4975	0.924
7.2**	2	18.00	1.000	0.1010	1.469	2.531	1.313	12.06	15.45	13.72	0.500	5	4160	55.82	60.00	84.70	5491	6631	0.828
7.5	3	24.00	1.000	0.1400	2.032	0.399	2.000	11.97	16.17	13.64	0.500	8	4160	73.17	75.00	84.70	7198	8054	0.894
7.6	2	16.00	1.000	0.1010	2.032	1.969	1.938	12.01	16.22	13.77	0.375	2	4160	44.34	60.00	64.55	4362	4838	0.902
8.1	3	24.00	1.000	0.0690	2.032	0.453	1.953	12.13	16.23	13.76	0.500	8	3830	69.67	79.00	84.70	6996	6428	1.088
8.2	3	24.00	1.000	0.1190	2.047	0.430	1.969	12.16	16.20	13.69	0.500	8	3830	79.32	81.00	84.70	7965	7567	1.053
8.4	2	16.00	1.000	0.1190	2.063	1.891	1.906	12.10	16.35	13.91	0.375	2	3830	48.90	81.00	64.55	4911	4904	1.001
9.1	2	24.00	1.000	0.1190	2.032	1.875	1.954	12.14	16.19	13.70	0.375	2	4230	63.40	81.00	64.55	6211	6177	1.005
9.2	2	18.00	1.000	0.1400	2.063	1.844	1.290	12.10	15.67	13.84	0.375	6	4230	69.06	75.00	64.55	6765	6387	1.059
9.3	2	24.00	1.000	0.0690	2.094	1.907	1.818	12.19	16.12	13.78	0.375	2	4230	55.25	79.00	64.55	5412	5794	0.934
9.4	2	24.00	1.000	0.1400	2.016	1.891	1.915	12.11	16.17	13.72	0.375	2	4230	65.00	75.00	64.55	6367	6224	1.023
10.3	2	26.00	1.000	0.0690	2.094	1.844	1.798	12.11	16.09	13.77	0.375	2	4250	58.85	79.00	64.55	5758	6064	0.950
10.4**	2	20.00	1.000	0.0690	2.079	1.875	1.916	12.07	16.19	13.75	0.500	5	4250	61.98	79.00	84.70	6064	6931	0.875
11.1	3	18.00	1.000	0.1400	2.000	0.453	1.928	12.20	16.14	13.68	0.500	6	4380	66.94	75.00	84.70	6500	6536	0.995
11.2	2	18.00	1.000	0.0690	2.094	1.844	1.881	12.19	16.13	13.72	0.500	4	4380	61.94	79.00	84.70	6015	6177	0.974
11.3**	2	18.00	1.000	0.1190	2.063	1.844	1.943	12.13	16.08	13.60	0.500	4	4380	62.44	81.00	84.70	6063	7080	0.856
11.4	2	24.00	1.000	0.1400	2.094	1.844	1.928	12.15	16.23	13.77	0.375	2	4380	62.49	75.00	64.55	6068	6261	0.969
14.1	3	36.00	1.000	0.1010	2.032	0.484	1.877	12.12	16.26	13.86	0.375	3	4200	59.96	60.00	64.55	5884	5857	1.005
14.2*	3	21.00	1.000	0.1010	2.016	0.469	1.897	12.19	16.13	13.72	0.500	7	4200	62.83	60.00	84.70	6166	6498	0.949
15.1**	2	27.00	1.410	0.1270	1.516	1.500	1.902	12.11	16.11	13.46	0.500	9	5250	67.33	81.00	84.70	12339	15127	0.816
15.2	2	27.00	1.410	0.0720	1.610	1.469	1.924	12.11	16.12	13.46	0.500	9	5250	62.87	64.00	84.70	11522	12508	0.921
15.3	2	40.00	1.410	0.0720	1.516	1.531	1.820	12.04	16.19	13.63	0.375	10	5250	62.07	64.00	64.55	11375	12245	0.929
15.4	2	40.00	1.410	0.1270	1.563	1.469	1.884	12.08	16.13	13.50	0.375	10	5250	76.93	81.00	64.55	14099	14044	1.004
16.3	2	40.00	1.410	0.1270	3.047	2.969	1.791	18.03	16.16	13.62	0.375	4	5180	61.42	81.00	64.55	11294	12255	0.922
16.4	2	40.00	1.410	0.0700	3.063	3.000	1.846	18.06	16.00	13.45	0.375	4	5180	61.19	70.00	64.55	11252	11668	0.964
17.3	2	38.00	1.410	0.1270	3.047	2.984	1.888	18.03	16.12	13.48	0.375	8	4710	68.85	81.00	64.55	12965	13985	0.927
17.4	2	38.00	1.410	0.0700	3.094	3.000	1.866	18.07	16.09	13.52	0.375	8	4710	65.82	70.00	64.55	12394	12583	0.985
17.5	2	30.00	1.410	0.0700	3.079	3.000	1.907	18.09	16.09	13.48	0.500	7	4710	58.57	70.00	84.70	11029	12675	0.870
17.6**	2	30.00	1.410	0.1270	3.063	2.969	1.911	18.07	16.20	13.54	0.500	7	4710	68.92	81.00	84.70	12978	14883	0.872
18.1	2	40.00	1.410	0.1270	1.485	4.500	1.845	18.05	16.11	13.52	0.375	10	4700	80.72	81.00	64.55	15208	13876	1.096
18.3	2	40.00	1.410	0.1270	3.032	3.000	1.911	18.05	16.08	13.43	0.375	6	4700	69.33	81.00	64.55	13062	13415	0.974
18.4	2	40.00	1.410	0.0700	3.016	3.031	1.871	18.08	16.23	13.62	0.375	6	4700	66.33	70.00	64.55	12497	12292	1.017

For all 166 specimens:	Max	1.387
	Min	0.571
	Mean	0.978
	St. Dev.	0.138
	COV	0.142
For the 134 specimens with $l_d/d_b \geq 16$:	Max	1.352
	Min	0.664
	Mean	0.989
	St. Dev.	0.135
	COV	0.137
For the 119[n] specimens with $l_d/d_b \geq 16$ and $(c+K_{tr})/d_b \leq 4$ (K_{tr}=29.6$t_r t_d A_{tr}$/sn):	Max	1.352
	Min	0.770
	Mean	1.010
	St. Dev.	0.127
	COV	0.125
For the 20 specimens with $f_s > f_y$ and with $l_d/d_b \geq 16$ and $(c+K_{tr})/d_b \leq 4$:	Max	1.352
	Min	0.931
	Mean	1.153
	St. Dev.	0.154
	COV	0.134
For the 99 specimens with $f_s \leq f_y$ and with $l_d/d_b \geq 16$ and $(c+K_{tr})/d_b \leq 4$:	Max	1.261
	Min	0.770
	Mean	0.981
	St. Dev.	0.098
	COV	0.100

Table A.2

Data and test/prediction ratios for developed and spliced bars with confining reinforcement (continued)[t]

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[t] All reports describe splice tests, except Mathey and Watstein (1961) which describes development tests

[n] Includes two specimens with $(c+K_{tr})/d_b > 4$:
a) $(c+K_{tr})/d_b = 4.004$, test/prediction = 0.843
b) $(c+K_{tr})/d_b = 4.023$, test/prediction = 0.901

* Specimens with $l_d/d_b < 16$ which were removed from the 166 specimens

** Specimens with $(c+K_{tr})/d_b > 3.75$ ($K_{tr} = 29.6t_rt_dA_{tr}/sn$) with $l_d/d_b \geq 16$ which were removed from the 134 specimens
[Note: For design $K_{tr} = 35.3t_rt_dA_{tr}/sn$ and $(c+K_{tr})/d_b \leq 4$]

*** Number of transverse stirrups crossing l_d with 2 legs per stirrup, except for Thompson et al. (1975) [6 legs] and one specimen in Zekany et al. (1981) [No. 2-5-40-B(4), 4 legs]

\+ Specimens with $f_s > f_y$

++ $$\text{Eq. 17} = \frac{T_b}{f'_c{}^{1/4}} = \frac{T_c + T_s}{f'_c{}^{1/4}} = [63l_d(c_m + 0.5d_b) + 2130A_b]\left(0.1\frac{c_M}{c_m} + 0.9\right) + 2226t_rt_d\frac{NA_{tr}}{n} + 66$$

+++ R_r is known based on measurements made on the bars or based on data provided in the original papers

++++ R_r is determined based on Appendix B of Darwin, Zuo, Tholen, and Idun (1995b)

\- Data is not available

1 in. = 25.4 mm; 1 psi = 6.89 kPa; 1 ksi = 6.89 MPa

Table B.1

Data, development lengths, and splice lengths for hypothetical beams without confining reinforcement*

Beam No.	n	d_b (in.)	b (in.)	h (in.)	c_{so} (in.)	c_{si} (in.)	c_b (in.)	f'_c (psi)	ACI '95 l_d (in.)	ACI '95 l_s (in.)	Eq. 22* l_d (in.)	Eq. 23** l_d (in.)	Eq. 22* / ACI '95 l_s	Eq. 23** / ACI '95 l_s	Eq. 22* / ACI '95 l_d	Eq. 23** / ACI '95 l_d
1	2	0.75	8.0	12.0	2.00	0.50	2.00	4000	36.59	47.57	31.71	50.40	0.667	1.059	0.867	1.377
2	2	0.75	12.0	12.0	2.00	2.50	2.00	4000	17.08	22.20	18.57	18.57	0.836	0.836	1.087	1.087
3	2	1.00	12.0	12.0	2.00	2.00	2.00	4000	28.46	37.00	31.36	31.36	0.848	0.848	1.102	1.102
4	2	1.27	12.0	12.0	2.00	1.46	2.00	4000	54.78	71.21	52.72	60.36	0.740	0.848	0.962	1.102
5	2	1.41	12.0	12.0	2.00	1.18	2.00	4000	75.04	97.56	69.26	82.69	0.710	0.848	0.923	1.102
6	2	0.75	24.0	12.0	2.00	8.50	2.00	4000	17.08	22.20	18.57	18.57	0.836	0.836	1.087	1.087
7	4	0.75	24.0	12.0	2.00	2.33	2.00	4000	17.08	22.20	18.57	18.57	0.836	0.836	1.087	1.087
8	6	0.75	24.0	12.0	2.00	1.10	2.00	4000	21.71	28.22	23.99	29.90	0.850	1.059	1.105	1.377
9	8	0.75	24.0	12.0	2.00	0.57	2.00	4000	33.83	43.98	30.68	46.59	0.698	1.059	0.907	1.377
10	2	1.00	24.0	12.0	2.00	8.00	2.00	4000	28.46	37.00	31.36	31.36	0.848	0.848	1.102	1.102
11	4	1.00	24.0	12.0	2.00	2.00	2.00	4000	28.46	37.00	31.36	31.36	0.848	0.848	1.102	1.102
12	6	1.00	24.0	12.0	2.00	0.80	2.00	4000	54.73	71.15	44.97	60.31	0.632	0.848	0.822	1.102
13	2	1.27	24.0	12.0	2.00	7.46	2.00	4000	43.55	56.62	47.99	47.99	0.848	0.848	1.102	1.102
14	4	1.27	24.0	12.0	2.00	1.64	2.00	4000	50.44	65.58	49.69	55.58	0.758	0.848	0.985	1.102
15	2	1.41	24.0	12.0	2.00	7.18	2.00	4000	52.29	67.98	57.62	57.62	0.848	0.848	1.102	1.102
16	4	1.41	24.0	12.0	2.00	1.45	2.00	4000	65.54	85.20	63.24	72.21	0.742	0.848	0.965	1.102
17	2	0.75	12.0	24.0	2.00	2.50	2.00	3000	19.72	25.63	20.42	20.42	0.797	0.797	1.036	1.036
18	2	0.75	12.0	24.0	2.00	2.50	2.00	4000	17.08	22.20	18.57	18.57	0.836	0.836	1.087	1.087
19	2	0.75	12.0	24.0	2.00	2.50	2.00	6000	13.94	18.13	16.18	16.18	0.892	0.892	1.160	1.160
20	2	1.00	12.0	24.0	2.00	2.00	2.00	3000	32.86	42.72	34.48	34.48	0.807	0.807	1.049	1.049
21	2	1.00	12.0	24.0	2.00	2.00	2.00	4000	28.46	37.00	31.36	31.36	0.848	0.848	1.102	1.102
22	2	1.00	12.0	24.0	2.00	2.00	2.00	6000	23.24	30.21	27.32	27.32	0.904	0.904	1.176	1.176
23	2	1.27	12.0	24.0	2.00	1.46	2.00	3000	63.25	82.23	58.00	66.37	0.705	0.807	0.917	1.049
24	2	1.27	12.0	24.0	2.00	1.46	2.00	4000	54.78	71.21	52.72	60.36	0.740	0.848	0.962	1.102
25	2	1.27	12.0	24.0	2.00	1.46	2.00	6000	44.73	58.14	45.89	52.58	0.789	0.904	1.026	1.176
26	2	1.41	12.0	24.0	2.00	1.18	2.00	3000	86.65	112.65	76.26	90.93	0.677	0.807	0.880	1.049
27	2	1.41	12.0	24.0	2.00	1.18	2.00	4000	75.04	97.56	69.26	82.69	0.710	0.848	0.923	1.102
28	2	1.41	12.0	24.0	2.00	1.18	2.00	6000	61.27	79.65	60.22	72.03	0.756	0.904	0.983	1.176
29	4	0.75	18.0	24.0	2.00	1.33	2.00	4000	18.74	24.36	21.75	25.81	0.893	1.059	1.160	1.377
30	6	0.75	18.0	24.0	2.00	0.50	2.00	4000	36.59	47.57	31.71	50.40	0.667	1.059	0.867	1.377
31	2	1.00	18.0	24.0	2.00	5.00	2.00	4000	28.46	37.00	31.36	31.36	0.848	0.848	1.102	1.102
32	4	1.00	18.0	24.0	2.00	1.00	2.00	4000	47.43	61.66	41.41	52.26	0.672	0.848	0.873	1.102
33	2	1.27	18.0	24.0	2.00	4.46	2.00	4000	43.55	56.62	47.99	47.99	0.848	0.848	1.102	1.102
34	4	1.27	18.0	24.0	2.00	0.64	2.00	4000	90.01	117.01	70.63	99.17	0.604	0.848	0.785	1.102
35	2	1.41	18.0	24.0	2.00	4.18	2.00	4000	52.29	67.98	57.62	57.62	0.848	0.848	1.102	1.102
												Max	0.904	1.059	1.176	1.377
												Min	0.604	0.797	0.785	1.036
												Avg	0.782	0.878	1.017	1.141

* Using $\phi = 0.9$ and $f_y = 60$ ksi

* $$\text{Eq. 22} = \frac{l_d}{d_b} = \frac{\dfrac{f_y}{f_c'^{1/4}} - 1900\left(0.1\dfrac{c_M}{c_m} + 0.9\right)}{72\left(\dfrac{c + K_{tr}}{d_b}\right)}$$

** $$\text{Eq. 23} = \frac{l_d}{d_b} = \frac{\dfrac{f_y}{f_c'^{1/4}} - 1900}{72\left(\dfrac{c + K_{tr}}{d_b}\right)}$$

1 in. = 25.4 mm; 1 psi = 6.89 kPa

Table B.2a

Data, development lengths, and splice lengths for hypothetical beams with confining reinforcement*

Beam No.	n	d_b (in.)	c_{so} (in.)	c_{si} (in.)	c_b (in.)	b (in.)	h (in.)	f'_c (psi)	d_s (in.)	s (in.)	ACI '95 l_d (in.)	ACI '95 l_s (in.)	Eq. 22* l_d(Conv.**) (in.)	Eq. 22* l_d(New***) (in.)	Eq. 23** l_d(Conv.**) (in.)	Eq. 23** l_d(New***) (in.)
Group 1																
1	2	0.75	2.00	0.50	2.00	8.00	12.00	4000	0.375	4.81	17.89	23.26	21.15	18.05	28.80	23.60
2	2	0.75	2.00	2.50	2.00	12.00	12.00	4000	0.375	4.81	17.08	22.20	14.70	14.70	14.70	14.70
3	2	1.00	2.00	2.00	2.00	12.00	12.00	4000	0.375	4.75	28.46	37.00	23.68	21.03	23.68	21.03
4	2	1.27	2.00	1.46	2.00	12.00	12.00	4000	0.375	4.68	37.82	49.16	37.34	32.47	41.09	35.30
5	2	1.41	2.00	1.18	2.00	12.00	12.00	4000	0.375	4.65	49.95	64.94	46.70	39.99	52.69	44.41
6	2	0.75	2.00	8.50	2.00	24.00	12.00	4000	0.375	4.81	17.08	22.20	14.70	14.70	14.70	14.70
7	4	0.75	2.00	2.33	2.00	24.00	12.00	4000	0.375	4.81	17.08	22.20	16.31	15.36	16.31	15.36
8	6	0.75	2.00	1.10	2.00	24.00	12.00	4000	0.375	4.81	17.99	23.39	21.41	20.28	26.04	24.42
9	8	0.75	2.00	0.57	2.00	24.00	12.00	4000	0.375	4.81	27.25	35.42	27.39	25.96	39.71	36.91
10	2	1.00	2.00	8.00	2.00	24.00	12.00	4000	0.375	4.75	28.46	37.00	23.68	21.03	23.68	21.03
11	4	1.00	2.00	2.00	2.00	24.00	12.00	4000	0.375	4.75	28.46	37.00	26.98	25.18	26.98	25.18
12	6	1.00	2.00	0.80	2.00	24.00	12.00	4000	0.375	4.75	44.23	57.50	38.77	36.21	49.93	45.87
13	2	1.27	2.00	7.46	2.00	24.00	12.00	4000	0.375	4.68	36.14	46.99	34.96	30.68	34.96	30.68
14	4	1.27	2.00	1.64	2.00	24.00	12.00	4000	0.375	4.68	41.81	54.35	41.64	38.44	45.71	41.89
15	2	1.41	2.00	7.18	2.00	24.00	12.00	4000	0.375	4.65	40.13	52.17	41.26	36.00	41.26	36.00
16	4	1.41	2.00	1.45	2.00	24.00	12.00	4000	0.375	4.65	53.75	69.88	51.88	47.49	57.84	52.47
17	2	0.75	2.00	2.50	2.00	12.00	24.00	3000	0.375	10.81	19.72	25.63	18.18	17.21	18.18	17.21
18	2	0.75	2.00	2.50	2.00	12.00	24.00	4000	0.375	10.81	17.08	22.20	16.53	15.65	16.53	15.65
19	2	0.75	2.00	2.50	2.00	12.00	24.00	6000	0.375	10.81	13.94	18.13	14.40	13.64	14.40	13.64
20	2	1.00	2.00	2.00	2.00	12.00	24.00	3000	0.375	10.75	32.86	42.72	30.16	28.34	30.16	28.34
21	2	1.00	2.00	2.00	2.00	12.00	24.00	4000	0.375	10.75	28.46	37.00	27.43	25.77	27.43	25.77
22	2	1.00	2.00	2.00	2.00	12.00	24.00	6000	0.375	10.75	23.24	30.21	23.90	22.45	23.90	22.45
23	2	1.27	2.00	1.46	2.00	12.00	24.00	3000	0.375	10.68	52.86	68.72	49.14	45.55	55.06	50.62
24	2	1.27	2.00	1.46	2.00	12.00	24.00	4000	0.375	10.68	45.78	59.51	44.66	41.40	50.07	46.03
25	2	1.27	2.00	1.46	2.00	12.00	24.00	6000	0.375	10.68	37.38	48.59	38.87	36.04	43.62	40.10
26	2	1.41	2.00	1.18	2.00	12.00	24.00	3000	0.375	10.65	71.07	92.39	62.98	57.80	72.83	66.07
27	2	1.41	2.00	1.18	2.00	12.00	24.00	4000	0.375	10.65	61.55	80.01	57.20	52.49	66.23	60.08
28	2	1.41	2.00	1.18	2.00	12.00	24.00	6000	0.375	10.65	50.25	65.33	49.73	45.64	57.70	52.34
29	4	0.75	2.00	1.33	2.00	18.00	24.00	4000	0.50	10.81	17.08	22.20	19.21	18.12	22.34	20.90
30	6	0.75	2.00	0.50	2.00	18.00	24.00	4000	0.50	10.81	28.55	37.11	27.95	26.34	41.92	38.58
31	2	1.00	2.00	5.00	2.00	18.00	24.00	4000	0.50	10.75	28.46	37.00	24.88	22.49	24.88	22.49
32	4	1.00	2.00	1.00	2.00	18.00	24.00	4000	0.50	10.75	38.01	49.41	35.23	32.71	42.94	39.34
33	2	1.27	2.00	4.46	2.00	18.00	24.00	4000	0.50	10.68	36.14	46.99	37.00	33.10	37.00	33.10
34	4	1.27	2.00	0.64	2.00	18.00	24.00	4000	0.50	10.68	69.57	90.45	57.51	52.49	75.88	67.71
35	2	1.41	2.00	4.18	2.00	18.00	24.00	4000	0.50	10.65	40.93	53.20	43.82	39.02	43.82	39.02

Table B.2a

Data, development lengths, and splice lengths for hypothetical beams with confining reinforcement (continued)*

Beam No.	n	d_b (in.)	c_{so} (in.)	c_{si} (in.)	c_b (in.)	b (in.)	h (in.)	f'_c (psi)	d_s (in.)	s (in.)	ACI '95 l_d (in.)	ACI '95 l_s (in.)	Eq. 22* l_d(Conv.**) (in.)	Eq. 22* l_d(New***) (in.)	Eq. 23** l_d(Conv.**) (in.)	Eq. 23** l_d(New***) (in.)
Group 2																
1	2	0.75	2.00	0.75	2.00	8.50	12.00	4000	0.50	6.00	17.08	22.20	17.26	14.39	21.18	17.13
2	2	0.75	2.00	0.75	2.00	8.50	12.00	4000	0.50	6.00	17.08	22.20	17.26	14.39	21.18	17.13
3	2	1.00	2.00	1.00	2.00	10.00	12.00	4000	0.50	6.00	28.46	37.00	25.42	21.21	29.40	24.00
4	2	1.27	2.00	1.27	2.00	11.62	12.00	4000	0.50	6.00	36.14	46.99	34.59	28.87	38.34	31.49
5	2	1.41	2.00	1.41	2.00	12.46	12.00	4000	0.50	6.00	41.02	53.33	39.44	32.92	42.98	35.40
6	2	0.75	2.00	0.75	2.00	8.50	12.00	4000	0.50	6.00	17.08	22.20	17.26	14.39	21.18	17.13
7	4	0.75	2.00	0.75	2.00	14.50	12.00	4000	0.50	6.00	17.87	23.23	21.41	19.05	27.50	23.85
8	6	0.75	2.00	0.75	2.00	20.50	12.00	4000	0.50	6.00	20.40	26.52	23.27	21.36	30.54	27.43
9	8	0.75	2.00	0.75	2.00	26.50	12.00	4000	0.50	6.00	21.96	28.54	24.33	22.73	32.33	29.65
10	2	1.00	2.00	1.00	2.00	10.00	12.00	4000	0.50	6.00	28.46	37.00	25.42	21.21	29.40	24.00
11	4	1.00	2.00	1.00	2.00	18.00	12.00	4000	0.50	6.00	32.84	42.69	31.50	28.05	37.63	32.89
12	6	1.00	2.00	1.00	2.00	26.00	12.00	4000	0.50	6.00	36.59	47.57	34.23	31.43	41.50	37.53
13	2	1.27	2.00	1.27	2.00	11.62	12.00	4000	0.50	6.00	36.14	46.99	34.59	28.87	38.34	31.49
14	4	1.27	2.00	1.27	2.00	21.78	12.00	4000	0.50	6.00	44.62	58.01	42.85	38.16	48.60	42.72
15	2	1.41	2.00	1.41	2.00	12.46	12.00	4000	0.50	6.00	41.02	53.33	39.44	32.92	42.98	35.40
16	4	1.41	2.00	1.41	2.00	23.74	12.00	4000	0.50	6.00	50.85	66.11	48.84	43.51	54.30	47.82
17	2	0.75	2.00	0.75	2.00	8.50	24.00	3000	0.50	6.00	19.72	25.63	19.04	15.88	23.30	18.84
18	2	0.75	2.00	0.75	2.00	8.50	24.00	4000	0.50	6.00	17.08	22.20	17.26	14.39	21.18	17.13
19	2	0.75	2.00	0.75	2.00	8.50	24.00	6000	0.50	6.00	13.94	18.13	14.96	12.47	18.45	14.93
20	2	1.00	2.00	1.00	2.00	10.00	24.00	3000	0.50	6.00	32.86	42.72	28.01	23.37	32.33	26.39
21	2	1.00	2.00	1.00	2.00	10.00	24.00	4000	0.50	6.00	28.46	37.00	25.42	21.21	29.40	24.00
22	2	1.00	2.00	1.00	2.00	10.00	24.00	6000	0.50	6.00	23.24	30.21	22.08	18.42	25.61	20.91
23	2	1.27	2.00	1.27	2.00	11.62	24.00	3000	0.50	6.00	41.74	54.26	38.08	31.78	42.16	34.63
24	2	1.27	2.00	1.27	2.00	11.62	24.00	4000	0.50	6.00	36.14	46.99	34.59	28.87	38.34	31.49
25	2	1.27	2.00	1.27	2.00	11.62	24.00	6000	0.50	6.00	29.51	38.37	30.09	25.11	33.40	27.44
26	2	1.41	2.00	1.41	2.00	12.46	24.00	3000	0.50	6.00	47.37	61.58	43.40	36.23	47.27	38.93
27	2	1.41	2.00	1.41	2.00	12.46	24.00	4000	0.50	6.00	41.02	53.33	39.44	32.92	42.98	35.40
28	2	1.41	2.00	1.41	2.00	12.46	24.00	6000	0.50	6.00	33.49	43.54	34.32	28.65	37.45	30.84
29	4	0.75	2.00	0.75	2.00	14.50	24.00	4000	0.50	6.00	17.87	23.23	21.41	19.05	27.50	23.85
30	6	0.75	2.00	0.75	2.00	20.50	24.00	4000	0.50	6.00	20.40	26.52	23.27	21.36	30.54	27.43
31	2	1.00	2.00	1.00	2.00	10.00	24.00	4000	0.50	6.00	28.46	37.00	25.42	21.21	29.40	24.00
32	4	1.00	2.00	1.00	2.00	18.00	24.00	4000	0.50	6.00	32.84	42.69	31.50	28.05	37.63	32.89
33	2	1.27	2.00	1.27	2.00	11.62	24.00	4000	0.50	6.00	36.14	46.99	34.59	28.87	38.34	31.49
34	4	1.27	2.00	1.27	2.00	21.78	24.00	4000	0.50	6.00	44.62	58.01	42.85	38.16	48.60	42.72
35	2	1.41	2.00	1.41	2.00	12.46	24.00	4000	0.50	6.00	41.02	53.33	39.44	32.92	42.98	35.40

Table B.2a

Data, development lengths, and splice lengths for hypothetical beams with confining reinforcement (continued)*

Beam No.	n	d_b (in.)	c_{so} (in.)	c_{si} (in.)	c_b (in.)	b (in.)	h (in.)	f'_c (psi)	d_s (in.)	s (in.)	ACI '95 l_d (in.)	ACI '95 l_s (in.)	Eq. 22* l_d(Conv.**) (in.)	Eq. 22* l_d(New***) (in.)	Eq. 23** l_d(Conv.**) (in.)	Eq. 23** l_d(New***) (in.)
Group 3																
1	2	0.75	2.00	0.50	2.00	8.00	12.00	4000	0.50	8.00	17.08	22.20	20.50	17.35	27.69	22.48
2	2	0.75	2.00	0.50	2.00	8.00	12.00	4000	0.50	8.00	17.08	22.20	20.50	17.35	27.69	22.48
3	2	1.00	2.00	0.50	2.00	9.00	12.00	4000	0.50	8.00	35.58	46.25	31.71	26.59	41.81	33.72
4	2	1.27	2.00	0.64	2.00	10.35	12.00	4000	0.50	8.00	50.55	65.72	43.93	36.76	54.62	44.33
5	2	1.41	2.00	0.71	2.00	11.05	12.00	4000	0.50	8.00	58.70	76.30	50.46	42.20	61.28	49.86
6	2	0.75	2.00	0.50	2.00	8.00	12.00	4000	0.50	8.00	17.08	22.20	20.50	17.35	27.69	22.48
7	4	0.75	2.00	0.50	2.00	13.00	12.00	4000	0.50	8.00	23.29	30.27	24.91	22.43	35.74	31.09
8	6	0.75	2.00	0.50	2.00	18.00	12.00	4000	0.50	8.00	26.50	34.45	26.83	24.86	39.58	35.64
9	8	0.75	2.00	0.50	2.00	23.00	12.00	4000	0.50	8.00	28.46	37.00	27.90	26.28	41.82	38.46
10	2	1.00	2.00	0.50	2.00	9.00	12.00	4000	0.50	8.00	35.58	46.25	31.71	26.59	41.81	33.72
11	4	1.00	2.00	0.50	2.00	15.00	12.00	4000	0.50	8.00	47.43	61.66	39.03	34.89	54.54	47.16
12	6	1.00	2.00	0.50	2.00	21.00	12.00	4000	0.50	8.00	53.36	69.37	42.29	38.95	60.69	54.38
13	2	1.27	2.00	0.64	2.00	10.35	12.00	4000	0.50	8.00	50.55	65.72	43.93	36.76	54.62	44.33
14	4	1.27	2.00	0.64	2.00	17.97	12.00	4000	0.50	8.00	64.84	84.29	54.20	48.38	70.54	61.34
15	2	1.41	2.00	0.71	2.00	11.05	12.00	4000	0.50	8.00	58.70	76.30	50.46	42.20	61.28	49.86
16	4	1.41	2.00	0.71	2.00	19.51	12.00	4000	0.50	8.00	74.06	96.28	62.33	55.61	78.85	68.72
17	2	0.75	2.00	0.50	2.00	8.00	24.00	3000	0.50	8.00	19.72	25.63	22.67	19.18	30.45	24.72
18	2	0.75	2.00	0.50	2.00	8.00	24.00	4000	0.50	8.00	17.08	22.20	20.50	17.35	27.69	22.48
19	2	0.75	2.00	0.50	2.00	8.00	24.00	6000	0.50	8.00	13.94	18.13	17.71	14.98	24.12	19.59
20	2	1.00	2.00	0.50	2.00	9.00	24.00	3000	0.50	8.00	41.08	53.40	35.06	29.39	45.98	37.08
21	2	1.00	2.00	0.50	2.00	9.00	24.00	4000	0.50	8.00	35.58	46.25	31.71	26.59	41.81	33.72
22	2	1.00	2.00	0.50	2.00	9.00	24.00	6000	0.50	8.00	29.05	37.76	27.38	22.96	36.42	29.37
23	2	1.27	2.00	0.64	2.00	10.35	24.00	3000	0.50	8.00	58.38	75.89	48.50	40.58	60.06	48.75
24	2	1.27	2.00	0.64	2.00	10.35	24.00	4000	0.50	8.00	50.55	65.72	43.93	36.76	54.62	44.33
25	2	1.27	2.00	0.64	2.00	10.35	24.00	6000	0.50	8.00	41.28	53.66	38.02	31.81	47.58	38.62
26	2	1.41	2.00	0.71	2.00	11.05	24.00	3000	0.50	8.00	67.78	88.11	55.68	46.56	67.39	54.83
27	2	1.41	2.00	0.71	2.00	11.05	24.00	4000	0.50	8.00	58.70	76.30	50.46	42.20	61.28	49.86
28	2	1.41	2.00	0.71	2.00	11.05	24.00	6000	0.50	8.00	47.92	62.30	43.71	36.55	53.39	43.43
29	4	0.75	2.00	0.50	2.00	13.00	24.00	4000	0.50	8.00	23.29	30.27	24.91	22.43	35.74	31.09
30	6	0.75	2.00	0.50	2.00	18.00	24.00	4000	0.50	8.00	26.50	34.45	26.83	24.86	39.58	35.64
31	2	1.00	2.00	0.50	2.00	9.00	24.00	4000	0.50	8.00	35.58	46.25	31.71	26.59	41.81	33.72
32	4	1.00	2.00	0.50	2.00	15.00	24.00	4000	0.50	8.00	47.43	61.66	39.03	34.89	54.54	47.16
33	2	1.27	2.00	0.64	2.00	10.35	24.00	4000	0.50	8.00	50.55	65.72	43.93	36.76	54.62	44.33
34	4	1.27	2.00	0.64	2.00	17.97	24.00	4000	0.50	8.00	64.84	84.29	54.20	48.38	70.54	61.34
35	2	1.41	2.00	0.71	2.00	11.05	24.00	4000	0.50	8.00	58.70	76.30	50.46	42.20	61.28	49.86

Table B.2a

Data, development lengths, and splice lengths for hypothetical beams with confining reinforcement (continued)*

Beam No.	n	d_b (in.)	c_{so} (in.)	c_{si} (in.)	c_b (in.)	b (in.)	h (in.)	f'_c (psi)	d_s (in.)	s (in.)	ACI '95 l_d (in.)	ACI '95 l_s (in.)	Eq. 22' l_d(Conv.**) (in.)	Eq. 22' l_d(New***) (in.)	Eq. 23'' l_d(Conv.**) (in.)	Eq. 23'' l_d(New***) (in.)
Group 4																
1	2	0.75	2.00	0.50	2.00	8.00	12.00	4000	0.50	4.00	17.08	22.20	15.15	13.87	19.09	14.70
2	2	0.75	2.00	0.50	2.00	8.00	12.00	4000	0.50	4.00	17.08	22.20	15.15	13.87	19.09	14.70
3	2	1.00	2.00	0.50	2.00	9.00	12.00	4000	0.50	4.00	28.46	37.00	23.06	18.50	28.51	21.48
4	2	1.27	2.00	0.64	2.00	10.35	12.00	4000	0.50	4.00	36.14	46.99	31.85	24.83	37.63	28.51
5	2	1.41	2.00	0.71	2.00	11.05	12.00	4000	0.50	4.00	41.48	53.93	36.54	28.46	42.39	32.19
6	2	0.75	2.00	0.50	2.00	8.00	12.00	4000	0.50	4.00	17.08	22.20	15.15	13.87	19.09	14.70
7	4	0.75	2.00	0.50	2.00	13.00	12.00	4000	0.50	4.00	17.08	22.20	20.50	17.35	27.69	22.48
8	6	0.75	2.00	0.50	2.00	18.00	12.00	4000	0.50	4.00	20.77	27.00	23.24	20.44	32.59	27.57
9	8	0.75	2.00	0.50	2.00	23.00	12.00	4000	0.50	4.00	23.29	30.27	24.91	22.43	35.74	31.09
10	2	1.00	2.00	0.50	2.00	9.00	12.00	4000	0.50	4.00	28.46	37.00	23.06	18.50	28.51	21.48
11	4	1.00	2.00	0.50	2.00	15.00	12.00	4000	0.50	4.00	35.58	46.25	31.71	26.59	41.81	33.72
12	6	1.00	2.00	0.50	2.00	21.00	12.00	4000	0.50	4.00	42.69	55.50	36.24	31.60	49.51	41.63
13	2	1.27	2.00	0.64	2.00	10.35	12.00	4000	0.50	4.00	36.14	46.99	31.85	24.83	37.63	28.51
14	4	1.27	2.00	0.64	2.00	17.97	12.00	4000	0.50	4.00	50.55	65.72	43.93	36.76	54.62	44.33
15	2	1.41	2.00	0.71	2.00	11.05	12.00	4000	0.50	4.00	41.48	53.93	36.54	28.46	42.39	32.19
16	4	1.41	2.00	0.71	2.00	19.51	12.00	4000	0.50	4.00	58.70	76.30	50.46	42.20	61.28	49.86
17	2	0.75	2.00	0.50	2.00	8.00	24.00	3000	0.50	4.00	19.72	25.63	16.75	15.34	20.99	16.16
18	2	0.75	2.00	0.50	2.00	8.00	24.00	4000	0.50	4.00	17.08	22.20	15.15	13.87	19.09	14.70
19	2	0.75	2.00	0.50	2.00	8.00	24.00	6000	0.50	4.00	13.94	18.13	13.08	11.98	16.63	12.81
20	2	1.00	2.00	0.50	2.00	9.00	24.00	3000	0.50	4.00	32.86	42.72	25.50	20.45	31.35	23.62
21	2	1.00	2.00	0.50	2.00	9.00	24.00	4000	0.50	4.00	28.46	37.00	23.06	18.50	28.51	21.48
22	2	1.00	2.00	0.50	2.00	9.00	24.00	6000	0.50	4.00	23.24	30.21	19.92	15.97	24.83	18.71
23	2	1.27	2.00	0.64	2.00	10.35	24.00	3000	0.50	4.00	41.74	54.26	35.17	27.41	41.38	31.35
24	2	1.27	2.00	0.64	2.00	10.35	24.00	4000	0.50	4.00	36.14	46.99	31.85	24.83	37.63	28.51
25	2	1.27	2.00	0.64	2.00	10.35	24.00	6000	0.50	4.00	29.51	38.37	27.56	21.49	32.78	24.84
26	2	1.41	2.00	0.71	2.00	11.05	24.00	3000	0.50	4.00	47.90	62.27	40.32	31.41	46.62	35.40
27	2	1.41	2.00	0.71	2.00	11.05	24.00	4000	0.50	4.00	41.48	53.93	36.54	28.46	42.39	32.19
28	2	1.41	2.00	0.71	2.00	11.05	24.00	6000	0.50	4.00	33.87	44.03	31.65	24.66	36.93	28.04
29	4	0.75	2.00	0.50	2.00	13.00	24.00	4000	0.50	4.00	17.08	22.20	20.50	17.35	27.69	22.48
30	6	0.75	2.00	0.50	2.00	18.00	24.00	4000	0.50	4.00	20.77	27.00	23.24	20.44	32.59	27.57
31	2	1.00	2.00	0.50	2.00	9.00	24.00	4000	0.50	4.00	28.46	37.00	23.06	18.50	28.51	21.48
32	4	1.00	2.00	0.50	2.00	15.00	24.00	4000	0.50	4.00	35.58	46.25	31.71	26.59	41.81	33.72
33	2	1.27	2.00	0.64	2.00	10.35	24.00	4000	0.50	4.00	36.14	46.99	31.85	24.83	37.63	28.51
34	4	1.27	2.00	0.64	2.00	17.97	24.00	4000	0.50	4.00	50.55	65.72	43.93	36.76	54.62	44.33
35	2	1.41	2.00	0.71	2.00	11.05	24.00	4000	0.50	4.00	41.48	53.93	36.54	28.46	42.39	32.19

Table B.2b

Data, development lengths, and splice lengths for hypothetical beams with confining reinforcement*

Beam No.	New / Conv. Eq. 23''	New / Conv. Eq. 22'	Eq.22' / ACI '95 l_s Conv.**	Eq.23'' / ACI '95 l_s Conv.**	Eq.22' / ACI '95 l_d Conv.**	Eq.23'' / ACI '95 l_d Conv.**	Eq.22' / ACI '95 l_s New***	Eq.23'' / ACI '95 l_s New***	Eq.22' / ACI '95 l_d New***	Eq.23'' / ACI '95 l_d New***
Group I										
1	0.819	0.854	0.909	1.238	1.182	1.610	0.776	1.015	1.009	1.319
2	1.000	1.000	0.662	0.662	0.861	0.861	0.662	0.662	0.861	0.861
3	0.888	0.888	0.640	0.640	0.832	0.832	0.568	0.568	0.739	0.739
4	0.859	0.870	0.760	0.836	0.987	1.087	0.661	0.718	0.859	0.933
5	0.843	0.856	0.719	0.811	0.935	1.055	0.616	0.684	0.801	0.889
6	1.000	1.000	0.662	0.662	0.861	0.861	0.662	0.662	0.861	0.861
7	0.941	0.941	0.735	0.735	0.955	0.955	0.692	0.692	0.899	0.899
8	0.938	0.947	0.915	1.113	1.190	1.447	0.867	1.044	1.127	1.357
9	0.929	0.948	0.773	1.121	1.005	1.457	0.733	1.042	0.953	1.355
10	0.888	0.888	0.640	0.640	0.832	0.832	0.568	0.568	0.739	0.739
11	0.933	0.933	0.729	0.729	0.948	0.948	0.681	0.681	0.885	0.885
12	0.919	0.934	0.674	0.868	0.877	1.129	0.630	0.798	0.819	1.037
13	0.877	0.877	0.744	0.744	0.967	0.967	0.653	0.653	0.849	0.849
14	0.916	0.923	0.766	0.841	0.996	1.093	0.707	0.771	0.919	1.002
15	0.873	0.873	0.791	0.791	1.028	1.028	0.690	0.690	0.897	0.897
16	0.907	0.915	0.742	0.828	0.965	1.076	0.680	0.751	0.884	0.976
17	0.947	0.947	0.709	0.709	0.922	0.922	0.672	0.672	0.873	0.873
18	0.947	0.947	0.745	0.745	0.968	0.968	0.705	0.705	0.917	0.917
19	0.947	0.947	0.795	0.795	1.033	1.033	0.752	0.752	0.978	0.978
20	0.939	0.939	0.706	0.706	0.918	0.918	0.663	0.663	0.862	0.862
21	0.939	0.939	0.741	0.741	0.964	0.964	0.696	0.696	0.905	0.905
22	0.939	0.939	0.791	0.791	1.028	1.028	0.743	0.743	0.966	0.966
23	0.919	0.927	0.715	0.801	0.930	1.042	0.663	0.737	0.862	0.958
24	0.919	0.927	0.750	0.841	0.976	1.094	0.696	0.774	0.904	1.006
25	0.919	0.927	0.800	0.898	1.040	1.167	0.742	0.825	0.964	1.073
26	0.907	0.918	0.682	0.788	0.886	1.025	0.626	0.715	0.813	0.930
27	0.907	0.918	0.715	0.828	0.929	1.076	0.656	0.751	0.853	0.976
28	0.907	0.918	0.761	0.883	0.989	1.148	0.699	0.801	0.908	1.041
29	0.935	0.943	0.865	1.006	1.125	1.308	0.816	0.941	1.061	1.224
30	0.920	0.942	0.753	1.130	0.979	1.469	0.710	1.040	0.923	1.352
31	0.904	0.904	0.672	0.672	0.874	0.874	0.608	0.608	0.790	0.790
32	0.916	0.929	0.713	0.869	0.927	1.130	0.662	0.796	0.861	1.035
33	0.895	0.895	0.787	0.787	1.024	1.024	0.704	0.704	0.916	0.916
34	0.892	0.913	0.636	0.839	0.827	1.091	0.580	0.749	0.754	0.973
35	0.890	0.890	0.824	0.824	1.071	1.071	0.733	0.733	0.953	0.953
Max	1.000	1.000	0.915	1.238	1.190	1.610	0.867	1.044	1.127	1.357
Min	0.819	0.854	0.636	0.640	0.827	0.832	0.568	0.568	0.739	0.739
Avg	0.915	0.922	0.744	0.826	0.967	1.074	0.685	0.754	0.890	0.981

Table B.2b

Data, development lengths, and splice lengths for hypothetical beams with confining reinforcement (continued)*

Beam No.	New / Conv. Eq. 23"	New / Conv. Eq. 22'	Eq.22' / ACI '95 l_s Conv.**	Eq.23" / ACI '95 l_s Conv.**	Eq.22' / ACI '95 l_d Conv.**	Eq.23" / ACI '95 l_d Conv.**	Eq.22' / ACI '95 l_s New***	Eq.23" / ACI '95 l_s New***	Eq.22' / ACI '95 l_d New***	Eq.23" / ACI '95 l_d New***
Group 2										
1	0.809	0.834	0.777	0.954	1.011	1.241	0.648	0.772	0.843	1.003
2	0.809	0.834	0.777	0.954	1.011	1.241	0.648	0.772	0.843	1.003
3	0.816	0.834	0.687	0.795	0.893	1.033	0.573	0.649	0.745	0.843
4	0.822	0.835	0.736	0.816	0.957	1.061	0.614	0.670	0.799	0.871
5	0.824	0.835	0.740	0.806	0.961	1.048	0.617	0.664	0.803	0.863
6	0.809	0.834	0.777	0.954	1.011	1.241	0.648	0.772	0.843	1.003
7	0.867	0.890	0.921	1.184	1.198	1.539	0.820	1.026	1.066	1.334
8	0.898	0.918	0.877	1.152	1.141	1.497	0.805	1.034	1.047	1.344
9	0.917	0.934	0.852	1.133	1.108	1.472	0.796	1.039	1.035	1.351
10	0.816	0.834	0.687	0.795	0.893	1.033	0.573	0.649	0.745	0.843
11	0.874	0.890	0.738	0.881	0.959	1.146	0.657	0.771	0.854	1.002
12	0.904	0.918	0.720	0.872	0.936	1.134	0.661	0.789	0.859	1.026
13	0.822	0.835	0.736	0.816	0.957	1.061	0.614	0.670	0.799	0.871
14	0.879	0.891	0.739	0.838	0.960	1.089	0.658	0.736	0.855	0.957
15	0.824	0.835	0.740	0.806	0.961	1.048	0.617	0.664	0.803	0.863
16	0.881	0.891	0.739	0.821	0.961	1.068	0.658	0.723	0.856	0.940
17	0.809	0.834	0.743	0.909	0.966	1.181	0.619	0.735	0.805	0.956
18	0.809	0.834	0.777	0.954	1.011	1.241	0.648	0.772	0.843	1.003
19	0.809	0.834	0.825	1.018	1.073	1.324	0.688	0.824	0.895	1.071
20	0.816	0.834	0.656	0.757	0.852	0.984	0.547	0.618	0.711	0.803
21	0.816	0.834	0.687	0.795	0.893	1.033	0.573	0.649	0.745	0.843
22	0.816	0.834	0.731	0.848	0.950	1.102	0.610	0.692	0.793	0.900
23	0.822	0.835	0.702	0.777	0.912	1.010	0.586	0.638	0.761	0.830
24	0.822	0.835	0.736	0.816	0.957	1.061	0.614	0.670	0.799	0.871
25	0.822	0.835	0.784	0.870	1.019	1.132	0.655	0.715	0.851	0.930
26	0.824	0.835	0.705	0.768	0.916	0.998	0.588	0.632	0.765	0.822
27	0.824	0.835	0.740	0.806	0.961	1.048	0.617	0.664	0.803	0.863
28	0.824	0.835	0.788	0.860	1.025	1.118	0.658	0.708	0.855	0.921
29	0.867	0.890	0.921	1.184	1.198	1.539	0.820	1.026	1.066	1.334
30	0.898	0.918	0.877	1.152	1.141	1.497	0.805	1.034	1.047	1.344
31	0.816	0.834	0.687	0.795	0.893	1.033	0.573	0.649	0.745	0.843
32	0.874	0.890	0.738	0.881	0.959	1.146	0.657	0.771	0.854	1.002
33	0.822	0.835	0.736	0.816	0.957	1.061	0.614	0.670	0.799	0.871
34	0.879	0.891	0.739	0.838	0.960	1.089	0.658	0.736	0.855	0.957
35	0.824	0.835	0.740	0.806	0.961	1.048	0.617	0.664	0.803	0.863
Max	0.917	0.934	0.921	1.184	1.198	1.539	0.820	1.039	1.066	1.351
Min	0.809	0.834	0.656	0.757	0.852	0.984	0.547	0.618	0.711	0.803
Avg	0.839	0.856	0.759	0.892	0.986	1.160	0.650	0.750	0.845	0.976

Table B.2b

Data, development lengths, and splice lengths for hypothetical beams with confining reinforcement (continued)*

Beam No.	New / Conv. Eq. 23''	New / Conv. Eq. 22'	Eq.22' / ACI '95 l_s Conv.**	Eq.23'' / ACI '95 l_s Conv.**	Eq.22' / ACI '95 l_d Conv.**	Eq.23'' / ACI '95 l_d Conv.**	Eq.22' / ACI '95 l_s New***	Eq.23'' / ACI '95 l_s New***	Eq.22' / ACI '95 l_d New***	Eq.23'' / ACI '95 l_d New***
Group 3										
1	0.812	0.846	0.924	1.247	1.201	1.622	0.782	1.013	1.016	1.317
2	0.812	0.846	0.924	1.247	1.201	1.622	0.782	1.013	1.016	1.317
3	0.806	0.838	0.686	0.904	0.891	1.175	0.575	0.729	0.747	0.948
4	0.812	0.837	0.668	0.831	0.869	1.080	0.559	0.674	0.727	0.877
5	0.814	0.836	0.661	0.803	0.860	1.044	0.553	0.653	0.719	0.849
6	0.812	0.846	0.924	1.247	1.201	1.622	0.782	1.013	1.016	1.317
7	0.870	0.901	0.823	1.181	1.070	1.535	0.741	1.027	0.963	1.335
8	0.901	0.927	0.779	1.149	1.012	1.494	0.722	1.035	0.938	1.345
9	0.920	0.942	0.754	1.130	0.980	1.470	0.710	1.039	0.923	1.351
10	0.806	0.838	0.686	0.904	0.891	1.175	0.575	0.729	0.747	0.948
11	0.865	0.894	0.633	0.884	0.823	1.150	0.566	0.765	0.736	0.994
12	0.896	0.921	0.610	0.875	0.792	1.137	0.561	0.784	0.730	1.019
13	0.812	0.837	0.668	0.831	0.869	1.080	0.559	0.674	0.727	0.877
14	0.870	0.893	0.643	0.837	0.836	1.088	0.574	0.728	0.746	0.946
15	0.814	0.836	0.661	0.803	0.860	1.044	0.553	0.653	0.719	0.849
16	0.872	0.892	0.647	0.819	0.842	1.065	0.578	0.714	0.751	0.928
17	0.812	0.846	0.884	1.188	1.150	1.544	0.748	0.964	0.973	1.254
18	0.812	0.846	0.924	1.247	1.201	1.622	0.782	1.013	1.016	1.317
19	0.812	0.846	0.977	1.331	1.270	1.730	0.827	1.081	1.075	1.405
20	0.806	0.838	0.657	0.861	0.854	1.119	0.550	0.694	0.716	0.903
21	0.806	0.838	0.686	0.904	0.891	1.175	0.575	0.729	0.747	0.948
22	0.806	0.838	0.725	0.965	0.943	1.254	0.608	0.778	0.790	1.011
23	0.812	0.837	0.639	0.791	0.831	1.029	0.535	0.642	0.695	0.835
24	0.812	0.837	0.668	0.831	0.869	1.080	0.559	0.674	0.727	0.877
25	0.812	0.837	0.708	0.887	0.921	1.153	0.593	0.720	0.771	0.936
26	0.814	0.836	0.632	0.765	0.822	0.994	0.528	0.622	0.687	0.809
27	0.814	0.836	0.661	0.803	0.860	1.044	0.553	0.653	0.719	0.849
28	0.814	0.836	0.702	0.857	0.912	1.114	0.587	0.697	0.763	0.906
29	0.870	0.901	0.823	1.181	1.070	1.535	0.741	1.027	0.963	1.335
30	0.901	0.927	0.779	1.149	1.012	1.494	0.722	1.035	0.938	1.345
31	0.806	0.838	0.686	0.904	0.891	1.175	0.575	0.729	0.747	0.948
32	0.865	0.894	0.633	0.884	0.823	1.150	0.566	0.765	0.736	0.994
33	0.812	0.837	0.668	0.831	0.869	1.080	0.559	0.674	0.727	0.877
34	0.870	0.893	0.643	0.837	0.836	1.088	0.574	0.728	0.746	0.946
35	0.814	0.836	0.661	0.803	0.860	1.044	0.553	0.653	0.719	0.849
Max	0.920	0.942	0.977	1.331	1.270	1.730	0.827	1.081	1.075	1.405
Min	0.806	0.836	0.610	0.765	0.792	0.994	0.528	0.622	0.687	0.809
Avg	0.833	0.861	0.727	0.963	0.945	1.252	0.626	0.804	0.814	1.045

Table B.2b

Data, development lengths, and splice lengths for hypothetical beams with confining reinforcement (continued)*

Beam No.	New / Conv. Eq. 23"	New / Conv. Eq. 22'	Eq.22' / ACI '95 l_s Conv.**	Eq.23" / ACI '95 l_s Conv.**	Eq.22' / ACI '95 l_d Conv.**	Eq.23" / ACI '95 l_d Conv.**	Eq.22' / ACI '95 l_s New***	Eq.23" / ACI '95 l_s New***	Eq.22' / ACI '95 l_d New***	Eq.23" / ACI '95 l_d New***
Group 4										
1	0.770	0.916	0.682	0.860	0.887	1.118	0.625	0.662	0.813	0.861
2	0.770	0.916	0.682	0.860	0.887	1.118	0.625	0.662	0.813	0.861
3	0.753	0.802	0.623	0.771	0.810	1.002	0.500	0.581	0.650	0.755
4	0.758	0.780	0.678	0.801	0.881	1.041	0.528	0.607	0.687	0.789
5	0.759	0.779	0.678	0.786	0.881	1.022	0.528	0.597	0.686	0.776
6	0.770	0.916	0.682	0.860	0.887	1.118	0.625	0.662	0.813	0.861
7	0.812	0.846	0.924	1.247	1.201	1.622	0.782	1.013	1.016	1.317
8	0.846	0.879	0.861	1.207	1.119	1.569	0.757	1.021	0.984	1.328
9	0.870	0.901	0.823	1.181	1.070	1.535	0.741	1.027	0.963	1.335
10	0.753	0.802	0.623	0.771	0.810	1.002	0.500	0.581	0.650	0.755
11	0.806	0.838	0.686	0.904	0.891	1.175	0.575	0.729	0.747	0.948
12	0.841	0.872	0.653	0.892	0.849	1.160	0.569	0.750	0.740	0.975
13	0.758	0.780	0.678	0.801	0.881	1.041	0.528	0.607	0.687	0.789
14	0.812	0.837	0.668	0.831	0.869	1.080	0.559	0.674	0.727	0.877
15	0.759	0.779	0.678	0.786	0.881	1.022	0.528	0.597	0.686	0.776
16	0.814	0.836	0.661	0.803	0.860	1.044	0.553	0.653	0.719	0.849
17	0.770	0.916	0.653	0.819	0.849	1.065	0.598	0.631	0.778	0.820
18	0.770	0.916	0.682	0.860	0.887	1.118	0.625	0.662	0.813	0.861
19	0.770	0.916	0.722	0.918	0.938	1.193	0.661	0.706	0.859	0.918
20	0.753	0.802	0.597	0.734	0.776	0.954	0.479	0.553	0.622	0.719
21	0.753	0.802	0.623	0.771	0.810	1.002	0.500	0.581	0.650	0.755
22	0.753	0.802	0.659	0.822	0.857	1.069	0.529	0.619	0.687	0.805
23	0.758	0.780	0.648	0.763	0.843	0.991	0.505	0.578	0.657	0.751
24	0.758	0.780	0.678	0.801	0.881	1.041	0.528	0.607	0.687	0.789
25	0.758	0.780	0.718	0.854	0.934	1.111	0.560	0.647	0.728	0.842
26	0.759	0.779	0.648	0.749	0.842	0.973	0.504	0.568	0.656	0.739
27	0.759	0.779	0.678	0.786	0.881	1.022	0.528	0.597	0.686	0.776
28	0.759	0.779	0.719	0.839	0.935	1.090	0.560	0.637	0.728	0.828
29	0.812	0.846	0.924	1.247	1.201	1.622	0.782	1.013	1.016	1.317
30	0.846	0.879	0.861	1.207	1.119	1.569	0.757	1.021	0.984	1.328
31	0.753	0.802	0.623	0.771	0.810	1.002	0.500	0.581	0.650	0.755
32	0.806	0.838	0.686	0.904	0.891	1.175	0.575	0.729	0.747	0.948
33	0.758	0.780	0.678	0.801	0.881	1.041	0.528	0.607	0.687	0.789
34	0.812	0.837	0.668	0.831	0.869	1.080	0.559	0.674	0.727	0.877
35	0.759	0.779	0.678	0.786	0.881	1.022	0.528	0.597	0.686	0.776
Max	0.870	0.916	0.924	1.247	1.201	1.622	0.782	1.027	1.016	1.335
Min	0.753	0.779	0.597	0.734	0.776	0.954	0.479	0.553	0.622	0.719
Avg	0.781	0.831	0.698	0.875	0.907	1.137	0.581	0.687	0.755	0.893

Table B.2b

Data, development lengths, and splice lengths for hypothetical beams with confining reinforcement (continued)*

Beam No.	New / Conv. Eq. 23''	New / Conv. Eq. 22'	Eq.22' / ACI '95 l_s Conv.**	Eq.23'' / ACI '95 l_s Conv.**	Eq.22' / ACI '95 l_d Conv.**	Eq.23'' / ACI '95 l_d Conv.**	Eq.22' / ACI '95 l_s New***	Eq.23'' / ACI '95 l_s New***	Eq.22' / ACI '95 l_d New***	Eq.23'' / ACI '95 l_d New***
For all 140 beams										
Max	1.000	1.000	0.977	1.331	1.270	1.730	0.867	1.081	1.127	1.405
Min	0.753	0.779	0.597	0.640	0.776	0.832	0.479	0.553	0.622	0.719
Avg	0.842	0.867	0.732	0.889	0.951	1.156	0.635	0.749	0.826	0.973

* Using $\phi = 0.9$ and $f_y = 60$ ksi

** Conventional bars, $R_r = 0.0727$

*** High relative rib area bars, $R_r = 0.1275$

'
$$\text{Eq. } 22 = \frac{l_d}{d_b} = \frac{\dfrac{f_y}{f'_c{}^{1/4}} - 1900\left(0.1\dfrac{c_M}{c_m} + 0.9\right)}{72\left(\dfrac{c + K_{tr}}{d_b}\right)}$$

''
$$\text{Eq. } 23 = \frac{l_d}{d_b} = \frac{\dfrac{f_y}{f'_c{}^{1/4}} - 1900}{72\left(\dfrac{c + K_{tr}}{d_b}\right)}$$

1 in. = 25.4 mm; 1 psi = 6.89 kPa