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



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*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 ( $\phi$ ) 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  $l_d f'_c^{1/2}$  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.  $f'_c^{1/4}$  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). 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

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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 ( $\phi$ ) 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

$$T_b = T_c + T_s \quad (1)$$

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)  $f'_c{}^{1/2}$  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  $T_b$

$$T_s = T_b - T_c \quad (2)$$

$T_s$  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 ( $\phi$ ) 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  $f'_c$  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

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

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.

$c_s$  =  $\min(c_{si} + 0.25 \text{ in.}, c_{so})$ , 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.<sup>2</sup>, and  $f_s, f'_c$ , and  $f'_c$  are in psi.

Eq. (3) is obtained following the procedures of Darwin et al. (1992a, 1992b). A best-fit is obtained between  $T_c/f'_c$  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  $f'_c$  gives a good representation for concrete strengths between 4500 and 7500 psi (31 and 52 MPa). Outside of this range,  $f'_c$  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

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

in which  $f'_c$  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.

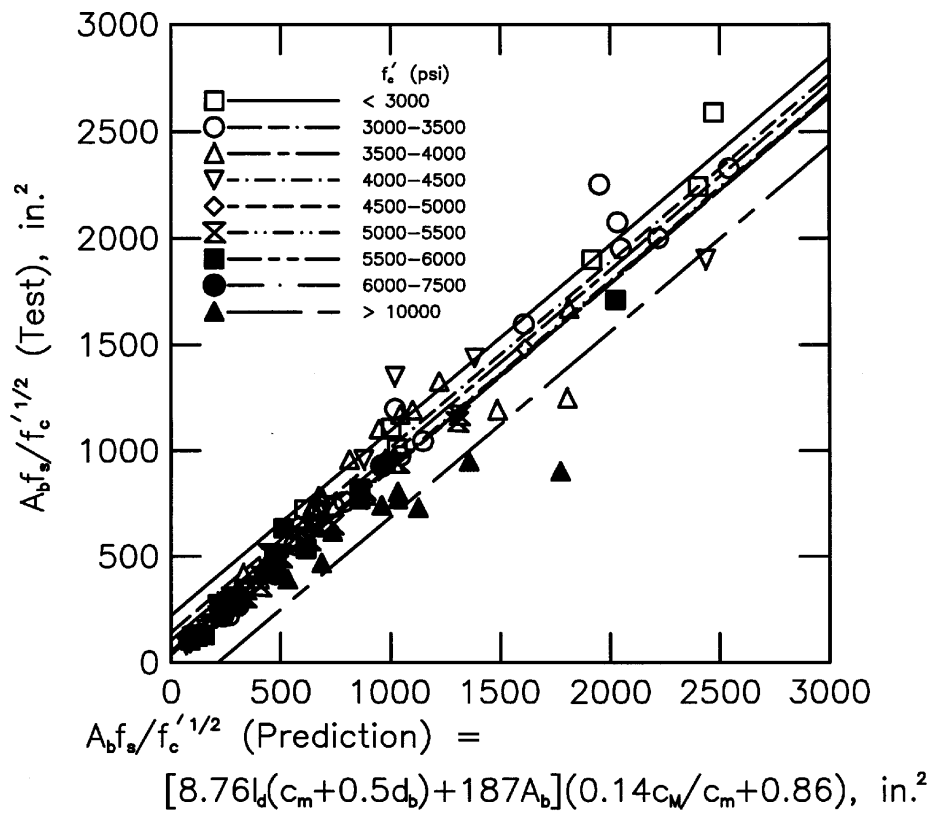


Fig. 1—Experimental bond force  $T_c = A_b f_s$  normalized with respect to  $f_c'^{1/2}$  versus predicted bond force  $A_b f_s / f_c'^{1/2}$ , as a function of concrete compressive strength for bars without confining reinforcement

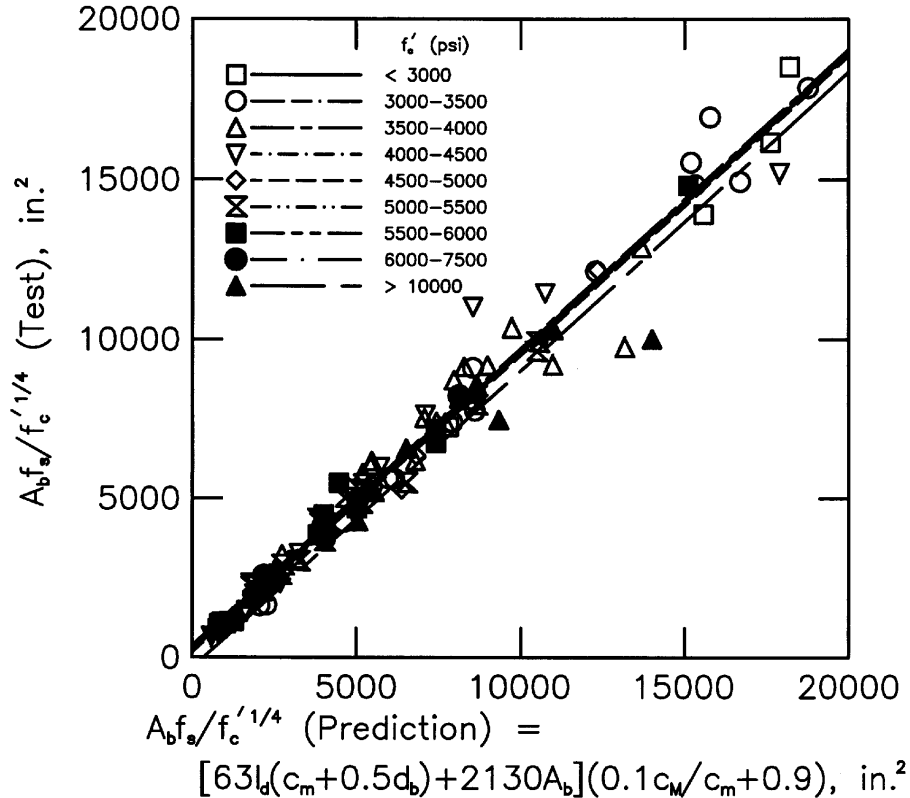


Fig. 2—Experimental bond force  $T_c = A_b f_s$  normalized with respect to  $f_c'^{1/4}$  versus predicted bond force  $A_b f_s / f_c'^{1/4}$  as a function of concrete compressive strength for bars without confining reinforcement

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  $T_s$ .

$$t_r = 9.6R_r + 0.28 \quad (5)$$

$$t_d = 0.72d_b + 0.28 \quad (6)$$

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,  $t_r$  typi-

cally 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)];  $t_d = 0.73, 1.00, \text{ and } 1.295$  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;  $NA_{tr}f_{yt}/n$ ,  $NA_{tr}/n$ ,  $t_r NA_{tr}/n$ , and  $t_d NA_{tr}/n$ . 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 Rezanoff 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, $l_d/d_b \geq 16$	134	$1/4$ [Eq. (17)]	0.664	1.352	0.989	0.135	0.137
With transverse reinforcement, $l_d/d_b \geq 16$ , $(c + K_{tr})/d_b \leq 4^*$	119 <sup>†</sup>	$1/4$ [Eq. (17)]	0.770	1.352	1.010	0.127	0.125
With transverse reinforcement, $f_s > f_y$ , $l_d/d_b \geq 16$ , $(c + K_{tr})/d_b \leq 4^*$	20	$1/4$ [Eq. (17)]	0.931	1.352	1.153	0.154	0.134
With transverse reinforcement, $f_s > f_y$ , $l_d/d_b \geq 16$ , $(c + K_{tr})/d_b \leq 4^*$	99	$1/4$ [Eq. (17)]	0.770	1.261	0.981	0.098	0.100

\*Based on  $K_{tr} = 35.3 t_r A_{tr}/sn$ .

<sup>†</sup>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  $f'_c{}^{1/4}$  are in psi, and  $A_{tr}$  is in in.<sup>2</sup> 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  $T_s/f'_c{}^{1/4} = 0$ , the best-fit expressions for the four combinations are

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

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

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

with  $r^2 = 0.787$ .

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

with  $r^2 = 0.840$ .

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

with  $r^2 = 0.839$ .

The closer the coefficient of determination  $r^2$  is to 1.0, the better the correlation between  $T_s/f'_c{}^{1/4}$  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

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

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

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

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  $T_s/f'_c{}^{1/4} = 0$ , the best-fit expressions for the four combinations are

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

with  $r^2 = 0.758$ .

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

with  $r^2 = 0.783$ .

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

with  $r^2 = 0.853$ .

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

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  $T_b$

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

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

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

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

in which  $c = (c_m + 0.5d_b) \left(0.1 \frac{c_M}{c_m} + 0.9\right)$  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  $(c + K_{tr})/d_b \leq 4.0$ . 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  $l_d/d_b \geq 16$  and  $(c + K_{tr})/d_b \leq 4.0$  (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.

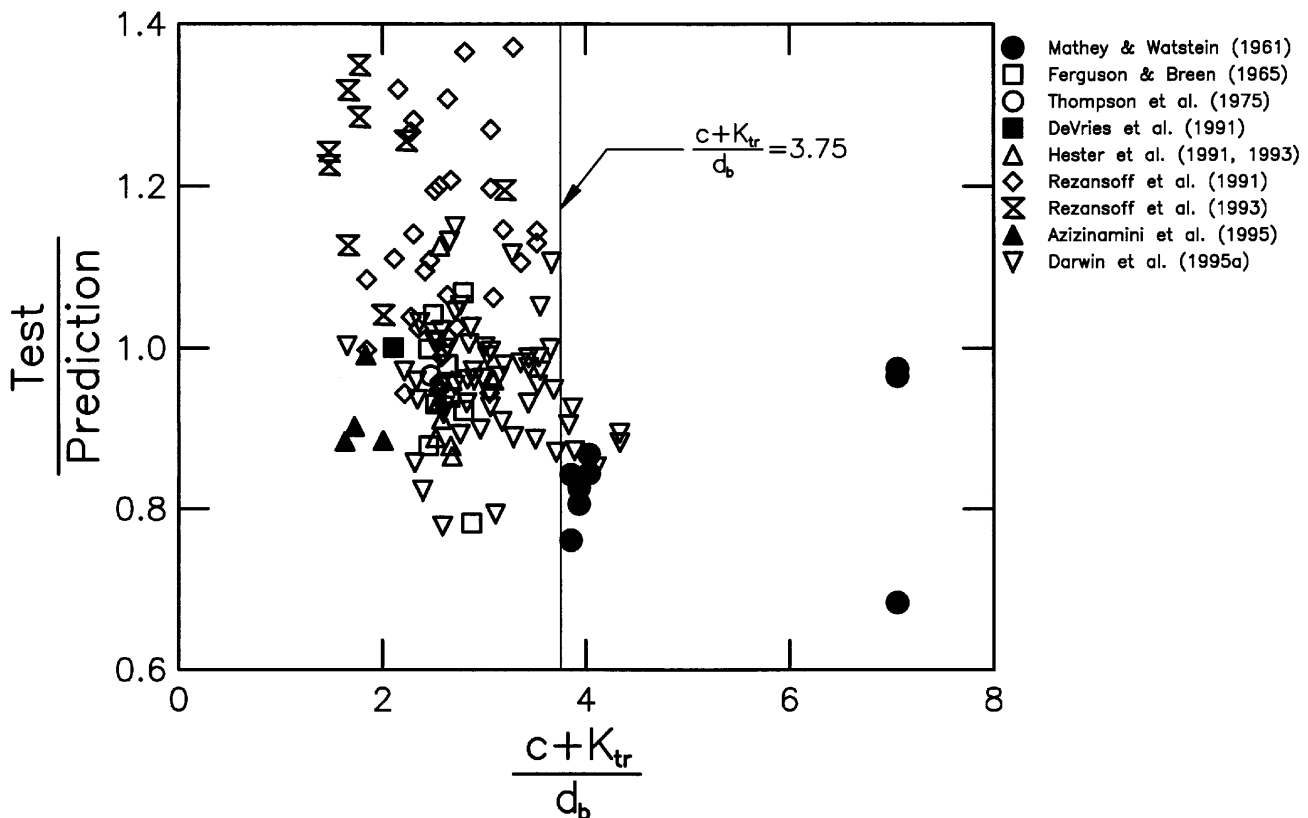


Fig. 3—Test/prediction ratio versus  $(c + K_{tr})/d_b$  for 134 beams with  $l_d/d_b \geq 16$  ( $K_{tr} = 29.6 t_r t_d A_{tr}/sn$ )

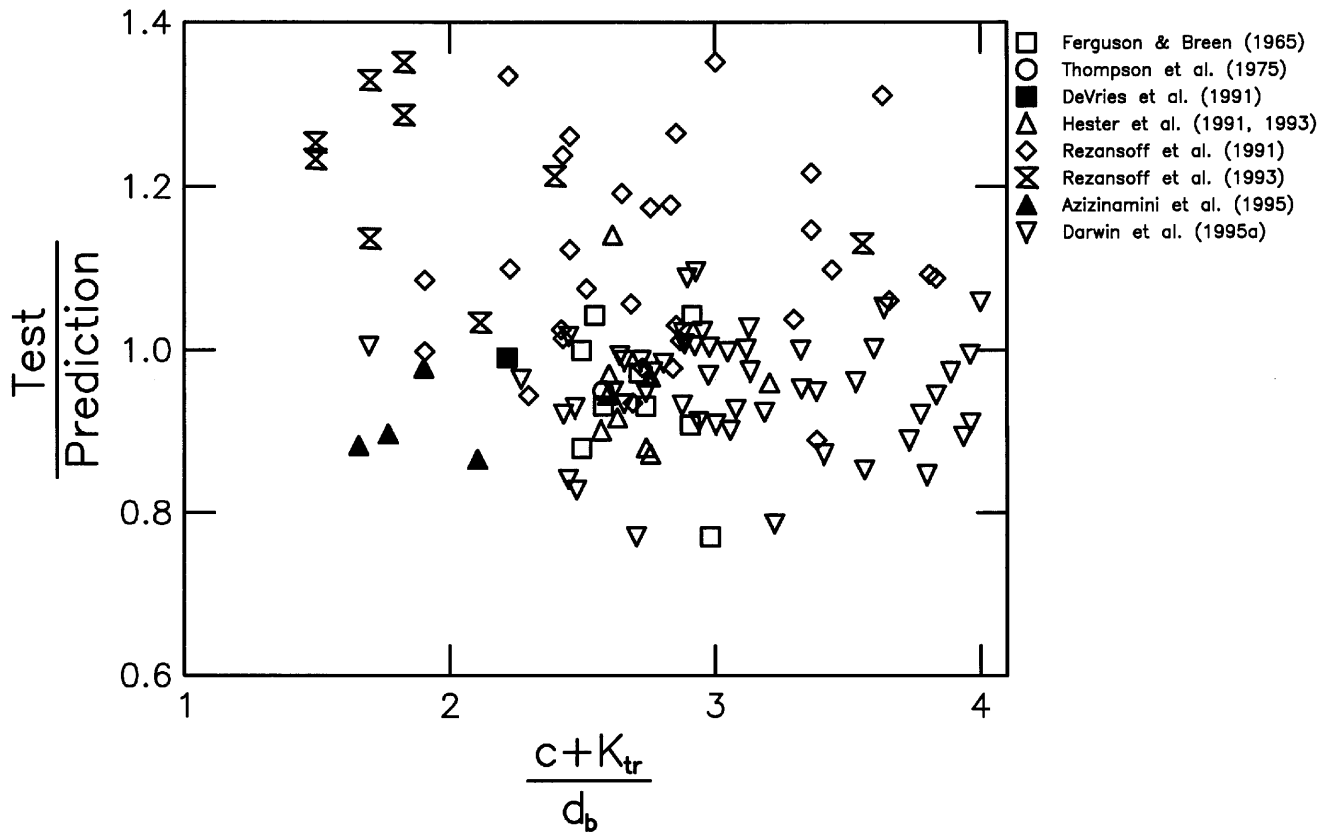


Fig. 4—Test/prediction ratio versus  $(c + K_{tr})/d_b$  for 117 beams with  $l_d/d_b \geq 16$  and  $(c + K_{tr})/d_b \leq 4$  ( $K_{tr} = 35.3 t_r t_d A_{tr}/s_n$ )

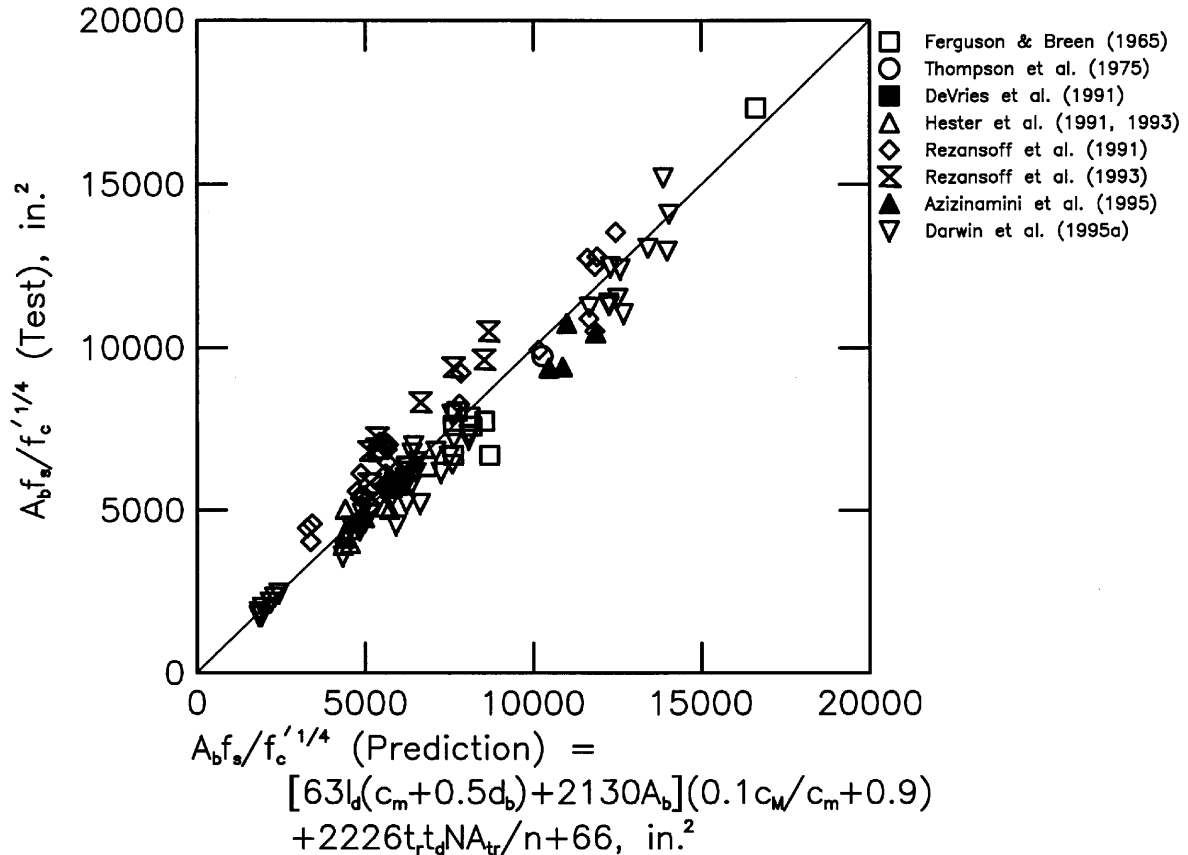


Fig. 5—Experimental bond force  $T_b = A_b f_s$  normalized with respect to  $f_c^{1/4}$  versus predicted bond force  $A_b f_s / f_c^{1/4}$  for bars with confining reinforcement



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 ( $\phi$ ) 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 ( $\phi$ ) 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 ( $\phi$ ) factor of 0.9 for development and splice strength has been obtained using a reliability index  $\beta$  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  $\beta = 3.0$  is normally obtained (Ellingwood et al. 1980).  $\phi = 0.9$  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  $\phi$  (Darwin et al. 1995c, 1996b).

$\phi = 0.9$  for bond is applied in addition to the  $\phi$  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  $\phi$  factor against a primary mode of failure in bond is the product of 0.9 and the  $\phi$  factor for the main load effect.

In addition to allowing the selection of a desired relative probability of failure, using a reliability-based  $\phi$  factor provides another important benefit. Since 87 percent of the tests in the database used to calculate  $\phi$  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),  $\phi = 0.9$  and Eq. (17) through (19) are already calibrated

based on splice strength. Therefore, values of  $l_d$  calculated using  $\phi = 0.9$  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  $\phi$  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

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

### Design expressions

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

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

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).

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

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

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

Incorporating  $\phi = 0.9$  into Eq. (21) and conservatively rounding the coefficients gives

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

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  $c_M/c_m = 1$

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

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 spac-

ing. 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

$$\frac{l_d}{d_b} = \frac{\frac{f_y}{f_c^{1/4}} - 1900}{108} \quad (24)$$

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

$$\frac{l_d}{d_b} = \frac{\frac{f_y}{f_c^{1/4}} - 1900}{135} \quad (25)$$

$l_d$  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  $f_c^{1/4}$  rather than  $f_c^{1/2}$ . 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  $f_c^{1/2}$  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,  $l_d/d_b = f_y/(25 f_c^{1/2})$  for No. 6 and smaller bars and  $f_y/(20 f_c^{1/2})$  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,  $l_d/d_b = 3 f_y/(50 f_c^{1/2})$  for No. 6 and smaller bars and  $3 f_y/(40 f_c^{1/2})$  for No. 7 and larger bars.

Under Section 12.2.3

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

in which  $K_{tr} = A_{tr} f_{yt}/(1500 s_n)$ ,  $(c + K_{tr})/d_b \leq 2.5$ . 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  $\phi$  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 ( $\phi$ ) 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.

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## NOTATION

$A_b$	=	bar area, in. <sup>2</sup>
$A_{tr}$	=	area of each stirrup or tie crossing potential plane of splitting adjacent to reinforcement being developed or spliced, in. <sup>2</sup>
$c$	=	$c_m + 0.5 d_b$
$c_b$	=	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; $f'_c$ <sup>1/2</sup> and $f'_c$ <sup>1/4</sup> , 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 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 $T_s$

$\beta$	=	reliability index
$\phi$	=	reliability-based strength reduction factor

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