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Development/Splice Length of Reinforcing Bars

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This paper presents an equation to calculate the required development/splice length of reinforcing bars. The equation is based on previous studies on bond between normal-strength concrete (NSC) and high-strength concrete (HSC) and reinforcing bars. The previous proposed equation to predict the bond strength has been modified to account for the effect of rib properties of reinforcing bars. Also, a new parameter to account for the effect of transverse reinforcement (TR) on bond strength has been introduced. The comparison between the results of 284 available tests in cases of NSC and HSC shows that the new proposed model correlates very well with the test results. Using the proposed equation for bond strength, an equation to calculate the development/splice length has been derived. The equation requires providing some amounts of TR along the development/splice length. By providing the calculated value of TR, the proposed development/splice length would result in adequate ductility for beams with spliced bars. The proposed procedure correlates well with the test results.

Keywords: bond; concrete; development length; reinforcement; rib; splice; transverse reinforcement.

INTRODUCTION

Recent studies on bond between concrete and reinforcing bars have resulted in a significant improvement to our knowledge on bond behavior. The effect of admixtures of silica fume and high-range water-reducing admixtures on bond strength, bond of lightweight aggregate concrete and high-strength concrete (HSC), and the influence of rib properties of reinforcing bars have been widely investigated. Using the results of these studies, new reinforcing bars with improved rib properties have been manufactured.[1,2] The studies have also resulted in some new semi-analytical and empirical models for predicting bond strength.[1-6] The new reinforcing bars with improved bond strength and the new proposed models to calculate the development/splice length will yield in the reduction of steel bars in structural members, especially in the congested beam-column joints of concrete structures. The congestion of steel bars has created serious problems in the construction of HSC structural members with small dimensions.

The ductility of beams with spliced bars is another problem that has been in focus in recent years. Experimental studies conducted by Azizinamini et al.[7,8] have shown that the requirements of the ACI Code regarding the flexural ductility of beams with spliced bars may not be satisfied because of the brittle behavior of bond failure. It has been shown that some amount of transverse reinforcement (TR) is needed to provide the ductility requirements.[8] The improving effect of TR on bond strength has also been studied.[3,8]

Regarding the effect of admixtures of silica fume and high-range water-reducing admixtures, there are some contradictions in different studies.[9-12] There are also contradictions when bond strength of lightweight concrete is compared with that of normal concrete.[13-16] In a discussion,[12] the first author has explained the reasons for the contradictions. It has been shown that silica fume does not have a negative effect on bond strength. Also, the bond strength of lightweight concrete may not be less than that of normal concrete.[16]

For the case of HSC, it has been shown that most code provisions and proposed equations previously presented for normal-strength concrete (NSC) overestimate the bond strength of HSC. This has led to the conclusion that the bond strength of HSC is smaller than that of NSC.[17] To compare the results of NSC with those of HSC, past researchers used normalized bond strength with respect to the square root of concrete compressive strength, that is, $u/(f_c')^{1/2}$,[17] where u is equal to $A_b f_s/\pi d_b L$ at failure in a test, and f_c' is the concrete compressive strength. A_b is the bar area, f_s is the stress in a reinforcing bar at failure, d_b is the bar diameter, and L is the embedded length of a bar in concrete. In two separate discussions,[12,18] it has been shown that the contradiction between the results of different studies on bond strength is because of the following problems:

1. The concrete compressive strength of specimens has generally been different in each study. This is the reason researchers have used the normalized bond strengths as mentioned previously and compared them in different tests. As previously shown,[19] however, the normalized bond strength may not be independent of the concrete compressive strength;
2. In full-scale beam tests, the bond stress distribution influences the bond strength.[5,6] This effect has not been considered by many researchers; and
3. The scatter in the bond strength test results is naturally significant. Therefore, the number of specimens tested by past researchers has not been adequate to be able to reach an acceptable conclusion. In a semi-analytical study conducted by Esfahani and Rangan,[5,6,19,20] it was shown that, depending on the development/splice length of the reinforcing bar, the value of $u/(f_c')^{1/2}$ for HSC may be either larger or smaller than that for NSC. For short lengths, the normalized value of $u/(f_c')^{1/2}$ of HSC is usually larger than that of NSC.[19] With increasing the development/splice length, the value of $u/(f_c')^{1/2}$ decreases for HSC due to the decrease in uniformity of bond stress distribution over the reinforcing bar embedded in HSC. For a larger length, the value of $u/(f_c')^{1/2}$ may be smaller for the case of HSC.

Recently, Zuo and Darwin[2] proposed a statistically based expression to calculate the bond strength for NSC and HSC. The expression includes the effect of TR and the rib properties of reinforcing bars on bond strength. This expression correlates well with available test results. The effect of TR on bond strength has also been studied by Esfahani and Rangan.[3] Based on their study, they modified their previous equation[5]

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to include the effect of TR on bond strength.[3] Azizinamini et al.[7,8] have shown the importance of TR on the strength and ductility of beams having spliced bars. They depicted that the ACI Code ductility requirements of flexural beams may not be satisfied in the beams with spliced bars unless some TR is provided along the spliced bars.[8] Also, they proposed an equation to calculate the TR along the spliced bars required for the strength and ductility of flexural beams. Esfahani[18] discussed the possible effects of different parameters on the ductility of flexural beams with spliced bars. It was shown that the required amount of TR to insure the appropriate ductility may depend on other bond parameters.[18]

RESEARCH SIGNIFICANCE

This paper discusses the effect of different parameters on the bond strength and ductility of beams. The previous equation[5] to calculate the bond strength of spliced bars and development lengths is modified. The modified equation accounts for the effect of rib properties of reinforcing bars on bond strength. Based on the proposed equation, a simple equation to predict the splice/development length of embedded bars is derived. To prevent a brittle bond failure along the splice/development length, the required amount of TR is calculated. The amount of TR changes with cover thickness, development/splice length, relative rib area of steel bars, concrete compressive strength, and longitudinal bar diameter. The equation can be used for NSC and HSC.

PREVIOUS EQUATONS FOR BOND STRENGTH CALCUATION

Based on studies by Esfahani and Rangan,[5,6,19] an equation to calculate the bond strength between concrete and reinforcing bars in cases of NSC and HSC was presented. The equation is given by

$$u = u_c \frac{1 + 1/M}{1.85 + 0.024\sqrt{M}}\left(0.88 + 0.12\frac{C_{med}}{C}\right) \quad (1)$$

where

$$u_c = 2.7\frac{C/d_b + 0.5}{C/d_b + 3.6}\sqrt{f_c'} \text{ for normal-strength concrete} \quad (2)$$

$$u_c = 4.7\frac{C/d_b + 0.5}{C/d_b + 5.5}\sqrt{f_c'} \text{ for high-strength concrete} \quad (3)$$

$$M = \cosh\left(0.0022L\sqrt[4]{3\frac{f_c'}{d_b}}\right) \quad (4)$$

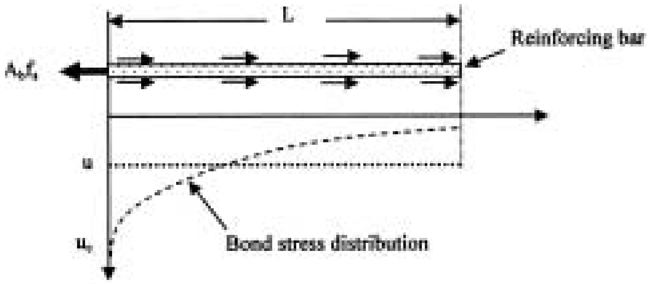

Fig. 1—Bond strength parameters.

where C_{med} is the median of C_x, C_y, and $(C_s + d_b)/2$; and C is the minimum of C_x, C_y, and $(C_s + d_b)/2$. C_x and C_y are the side cover and bottom cover of reinforcing bars in mm, respectively; C_s is the spacing between spliced bars in mm; d_b is the bar diameter in mm; L is the length of the splice in mm; and f_c' is the compressive strength of concrete in MPa.

The parameters u and u_c in Eq. (1) are illustrated in Fig. 1. The bond strength u is the equivalent uniform bond stress along the reinforcing bar at failure. In a test, the value of bond strength u is measured using the equation $u = A_b f_s/(\pi d_b L)$. The local bond strength u_c is the maximum bond stress along the reinforcing bar at failure. In Eq. (1), the expressions $(1 + 1/M)/(1.85 + 0.024\sqrt{M})$ and $(0.88 + 0.12[C_{med}/C])$ account for the bond stress distribution along the reinforcing bar and the effect of different covers on bond strength, respectively.

Equation (1) was later modified[3] to include the influence of TR on bond strength. The modified equation is given by

$$u = u_c \frac{1 + 1/M}{1.85 + 0.024\sqrt{M}}\left(0.88 + 0.12\frac{C_{med}}{C}\right)\left(1 + 0.28\frac{A_t}{S}\right) \quad (5)$$

where A_t is the area of transverse reinforcing bar in mm^2, and S is the spacing between the TR in mm.

Equation (5) can be applied to cases where the splices can be either confined by TR or unconfined (no TR) in both cases of NSC and HSC. Comparisons between the test results and calculated values showed that Eq. (5) correlated very well with the test results.[3]

Equation (1) and (5) were based on Tepfers's partly cracked thick cylinder theory and the displacement theory.[21] The partly cracked theory was used to calculate the maximum bond stress (local bond strength) u_c along the splice length.[5,19] The displacement theory was used to account for the bond stress distribution in splice strength.[5] It was shown that the maximum bond stress u_c and the bond stress distribution over the splice length are different in NSC and HSC.[5,19] As discussed previously and seen in Eq. (1) to (4), the concrete strength has three major effects on bond strength:

1. The increase of concrete tensile strength of an uncracked cylinder around the reinforcing bar increases the local bond strength u_c;

2. The increase of concrete bearing strength in front of the ribs of reinforcing bars decreases the bursting angle α (Fig. 2), and thus increases the local bond strength u_c; and

3. The increase of concrete strength decreases the uniformity of the bond stress distribution over the reinforcing bars, and thus decreases the equivalent uniform bond stress $u = A_b f_s/\pi d_b L$ at failure. That is why the normalized bond strength $u/(f_c')^{1/2}$ in the case of HSC is larger for short lengths and smaller for long anchorage lengths.[5,18,19]

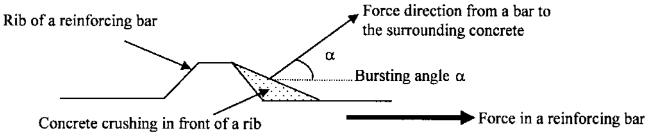

Fig. 2—Bursting angle α.

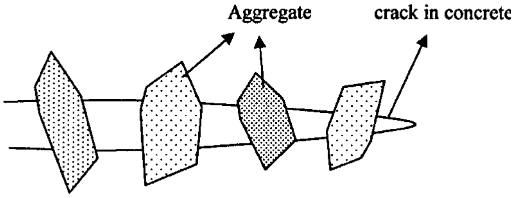

Fig. 3—Toughening mechanism of aggregate bridging.[23]

Although test results have shown that the normalized bond strength $u/(f_c')^{1/2}$ in short lengths increases with the increase of concrete strength,[19] it was also seen that for concrete strengths greater than 70 MPa with the admixtures of silica fume, high-range water-reducing admixtures, and small-size aggregates, $u/(f_c')^{1/2}$ may not increase with the concrete strength.[11,18,22] Previously, it had been reported[10] that the presence of admixtures of silica fume and high-range water-reducing admixtures caused $u/(f_c')^{1/2}$ to decrease in the case of HSC. Recent tests, however, have shown that these admixtures may not be the main contributing factors in decreasing $u/(f_c')^{1/2}$.[9,11] The reduction of $u/(f_c')^{1/2}$ in the case of HSC made of small-size aggregates can be explained by the theory of fracture mechanics in concrete in which concrete is assumed to be a quasi-brittle material.[23] This behavior of concrete prevents a sudden compression or tensile failure and results in a "softening" behavior in the load-deformation response. The softening behavior of concrete is due to some toughening mechanisms such as aggregate bridging in the fracture process zone of concrete (Fig. 3).

The aggregate size affects this behavior. Test results and proposed models of concrete fracture mechanics have shown that with increasing aggregate size, the toughness of concrete increases.[23] Therefore, HSC with small-size aggregate is more brittle than conventional concrete that has been widely used in many experimental studies. The brittleness of HSC with small-size aggregate may be the cause of the reduction of $u/(f_c')^{1/2}$.

Experimental studies for concrete strengths greater than 70 MPa made with small-size aggregates[7] have shown that Eq. (2) is more appropriate for local bond strength.[18] Most of the test results on HSC presented by Azizinamini et al.[7] correlated better with Eq. (1) when u_c was calculated using Eq. (2) rather than Eq. (3).[18] Therefore, it is conservative to use only Eq. (2) to calculate u_c for all cases of NSC and HSC. Later in this paper, Eq. (1) will be modified to include the effects of rib properties of steel bars and TR on bond strength calculations. For all concrete strengths, however, Eq. (2) will be used to calculate u_c.

A new attempt has been made by Zuo and Darwin[2] to obtain an equation to calculate the bond strength and development/splice length. They have proposed a statistically based expression to predict the bond strength and required development/splice length. Their proposed expressions that correlated well with available test results are given by

$$u = \frac{(f_c')^{1/4}}{\pi d_b l_d}\{[59.8 l_d(c_{min} + 0.5d_b) + 2350A_b] \tag{6}$$

$$\left(0.1\frac{c_{max}}{c_{min}} + 0.9\right) + 31.14 t_r t_d \frac{NA_{tr}}{n}(f_c')^{1/2}\}$$

$$l_d = \frac{A_b\left[\frac{f_s}{f_c'^{\,1/4}} - 2350\left(0.1\frac{c_{max}}{c_{min}} + 0.9\right)\right]}{59.8\left[(c_{min} + 0.5d_b)\left(0.1\frac{c_{max}}{c_{min}} + 0.9\right) + 0.52\frac{t_r t_d A_{tr}}{sn} f_c'^{\,1/2}\right]} \tag{7}$$

where

t_r = $9.6R_r + 0.28$;

t_d = $0.78d_b + 0.22$;

A_b = single spliced bar area, in.^{2};

l_d = splice or development length, in.;

c_{min}, c_{max} = minimum or maximum value of c_s or $c_b(c_{max}/c_{min} = 3.5)$, in.;

c_s = min (c_{si} + 0.25 in., c_{s0}), in.;

c_{si} = 1/2 of clear spacing between bars, in.;

c_{s0}, c_b = side or bottom cover of reinforcing bars, in.; and

f_c' = concrete compressive strength, psi; $f_c'^{\,1/4}$, psi.

In the present study, the expressions presented by Zuo and Darwin[2] are used to predict and compare the bond strengths from different test series. These results are compared with those calculated using the proposed equations that will be presented herein.

BOND STRENGTH OF SPLICES AND DEVELOPMENT LENGTHS

In Eq. (5), the expression $(1 + 0.28A_t/S)$ that accounts for the influence of TR on bond strength of development lengths/splices does not depend on the concrete cover thickness and diameter of the longitudinal reinforcing bar. It has been shown,[24,25] however, that the stress in TR depends on the state of cracking of concrete cover. For noncracked cover, the stress in TR is negligible; thus, the presence of TR may not increase the bond strength significantly. After concrete cover cracks, tensile stresses transfer from concrete to TR. For large values of C/d_b, the force transferred is large. In this case, if sufficient A_t/S is not used, TR may not be able to resist the tensile forces transferred from concrete to steel, and it fails immediately after yielding. Therefore, a small value of A_t/S may not increase the bond strength where C/d_b is large, and the expression $1 + 0.28A_t/S$ may no longer be valid. In other words, for a larger value of C/d_b, a larger value of A_t/S is required to be able to increase the bond strength. This reasoning leads to consider the ratio of $(A_t/S)/(C/d_b)$, instead of A_t/S used previously, for evaluation of the effect of TR on bond strength. Another parameter that is appropriate to consider is $(A_t/S)/(C/A_b)$, where A_b is the area of longitudinal bar with a d_b diameter.

Based on previous experimental test data[1,26-30] that contained confined TR at the splice, the bond strength is predicted using Eq. (1) and (2). These results are tabulated and presented in Table 1. The relationship between u_{test}/u_{calc} and $(A_t/S)/(C/d_b)$ as well as (A_tA_b/CS) are shown in Fig. 4 and 5, respectively.

Comparisons between Fig. 4 and 5 show that the parameter (A_tA_b/CS) results in a better correlation between the

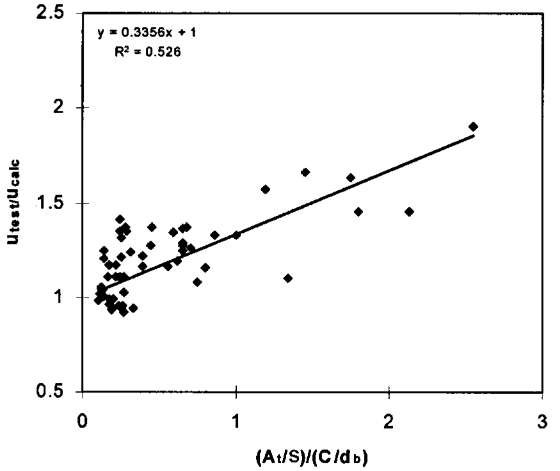

Fig. 4—Relationship between u_{test}/u_{calc} *and* $(A_t/S)/(C/d_b)$.

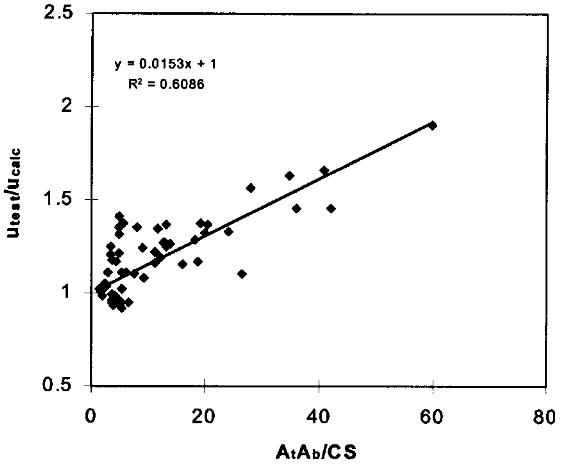

Fig. 5—Relationship between u_{test}/u_{calc} *and* (A_tA_b/CS).

measured and calculated values. The best-fit line for the relationship between u_{test}/u_{calc} and A_tA_b/CS should include the point (0, 1). In this case, for $A_tA_b/CS = 0$, the authors have $u_{test}/u_{calc} = 1$. The line that represents the best fit is shown in Fig. 5 and is given by

$$\frac{u_{test}}{u_{calc}} = 1 + 0.015\frac{A_tA_b}{CS} \tag{8}$$

In Eq. (8), A_t and A_b are in mm^2, and C and S are in mm. Using Eq. (1) and (8), the splice strength is expressed by

$$u = u_c\frac{1 + 1/M}{1.85 + 0.024\sqrt{M}}\left(0.88 + 0.12\frac{C_{med}}{C}\right) \tag{9}$$

$$\left(1 + 0.015\frac{A_tA_b}{CS}\right)$$

As mentioned previously, another parameter that affects the bond strength is the rib properties of reinforcing bars. Equation (9) should be modified to include this effect. Recently, Darwin et al.[1] presented results for tests using reinforcing bars with high relative rib areas R. Accordingly, where TR is used, bars with higher relative rib areas $R \geq 0.11$

Table 1—Test results of splices confined by transverse reinforcement

	Test	d_b, mm	A_t/S, mm	C/d_b	u_t/u_{cal}	A_tA_b/CS, mm^2	$(A_t/S)/(C/d_b)$, mm
Darwin et al.[1]	2.1-8S0	25.4	0.82	1.33	1.19	12.28	0.62
	3.4-8C0	25.4	0.47	2.00	0.96	4.66	0.23
	3.5-8C0	25.4	0.80	1.00	1.16	15.96	0.80
	4.1-8S0	25.4	1.25	1.25	1.33	19.88	1.00
	5.1-8SH0	25.4	0.82	1.25	1.37	13.05	0.65
	5.4-8SH0	25.4	0.82	1.25	1.25	13.05	0.65
	5.5-8SC0	25.4	0.47	1.41	0.95	6.63	0.33
	6.1-8SH0	25.4	1.66	0.92	1.46	35.93	1.80
	6.4-8C0	25.4	0.35	1.34	0.95	5.20	0.26
	8.1-8N0	25.4	1.66	0.95	1.63	34.76	1.74
	9.3-8N0	25.4	0.23	1.82	1.04	2.56	0.13
	10.3-8N0	25.4	0.22	1.80	1.05	2.39	0.12
	10.4-8N0	25.4	1.25	1.92	1.27	12.97	0.65
	11.2-8N0	25.4	1.11	1.88	1.35	11.74	0.59
	12.1-5N0	15.9	1.00	1.33	1.08	9.32	0.75
	12.3-5N0	15.9	0.28	2.07	1.01	1.69	0.14
	13.2-5N0	15.9	0.23	2.10	1.02	1.38	0.11
	14.5-5N0	15.9	0.47	1.94	1.11	3.01	0.24
	15.2-11N0	35.8	1.66	1.14	1.67	40.91	1.46
	15.3-11N0	35.8	0.70	1.08	1.29	18.33	0.65
	16.4-11B0	35.8	0.28	1.31	1.11	6.02	0.21
	17.4-11B0	35.8	0.59	1.32	1.28	12.54	0.45
	17.5-11B0	35.8	1.16	1.35	1.33	24.18	0.86
	18.4-11B0	35.8	0.42	1.33	1.24	8.91	0.32
Rezansoff, Akanni, and Sparling[26]	1a	25.2	0.25	1.02	1.41	4.89	0.25
	3a	25.2	0.25	1.01	1.32	4.98	0.25
	4a	29.9	0.14	0.99	1.25	3.35	0.14
	1b	25.2	0.25	1.02	1.35	4.89	0.25
	3b	25.2	0.25	1.01	1.21	4.98	0.25
	4b	29.9	0.14	0.99	1.21	3.35	0.14
	6	25.2	0.71	1.01	1.26	13.90	0.70
	7	25.2	2.14	1.01	1.46	42.16	2.13
	8	25.2	2.01	1.50	1.10	26.47	1.34
	9	29.9	1.18	0.99	1.57	28.06	1.20
	10	29.9	2.51	0.99	1.90	59.75	2.55
Ferguson and Breen[27]	8F30b	25.4	0.18	1.50	1.05	2.42	0.12
	8F36c	25.4	0.15	1.47	0.99	2.05	0.10
	8F36h	25.4	0.32	1.59	0.99	4.03	0.20
	8F36j	25.4	0.32	1.50	1.17	4.27	0.21
	11R36a	35.0	0.42	1.47	1.35	7.95	0.29
Ferguson, and Krishnaswamy[28]	14S3	42.9	0.79	1.42	1.17	18.72	0.56
	18S2-4 legs	57.2	0.61	1.33	1.37	20.47	0.46
	18S3-4 legs	57.2	0.22	1.33	1.11	7.57	0.17
Hester et al.[29]	B1-8N3-16-2-U	25.4	0.35	1.97	1.17	3.55	0.18
	B2-8C3-16-2-U	25.4	0.35	1.81	0.94	3.86	0.19
	B3-8S3-16-2-U	25.4	0.35	1.97	0.97	3.55	0.18
	B4-8S3-16-2-U	25.4	0.35	1.97	0.96	3.55	0.18
	B4-8S3-16-3-U	25.4	0.53	1.97	1.03	5.33	0.27
	B5-8C3-16-2-U	25.4	0.35	1.97	0.99	3.55	0.18
	B5-8C3-16-3-U	25.4	0.53	1.97	0.92	5.33	0.27
	B6-8C3-223/4-3-U	25.4	0.37	1.97	0.95	3.75	0.19
	B6-8C3-223/4-4-U	25.4	0.49	1.97	0.94	4.99	0.25
	B7-8C3-16-3-U	25.4	0.53	1.97	1.11	5.33	0.27
Thompson et al.[30]	8.15.4/2/2.6/6S5	25.4	0.56	2.00	1.37	5.59	0.28
	11.20.4/2/2.6/6S5	35.8	0.56	1.42	1.16	11.11	0.40
	11.20.4/2/2.6/6S2.9	35.8	0.97	1.42	1.37	19.16	0.68
	11.30.4/2/2.6/6S5	35.8	0.56	1.42	1.22	11.11	0.40

Table 2—Comparison between Eq. (12) and Eq. (6) with different test results

Group	Test series	No. of test	a_1a_2	u_{test}/u_{cal} (Eq. (12)		u_{test}/u_{cal} (Eq. (6)	
			Mean	Standard deviation	Mean	Standard deviation	Mean
Group 1	Chinn, Ferguson, and Thompson[31]	6	0.81	0.071	0.95	0.074	1.02
	Chamberlin[32]	3	0.99	0.036	1.00	0.010	1.03
	Ferguson and Breen[27]	15	0.64	0.061	0.98	0.064	0.95
	Ferguson and Briceno[33]	6	0.58	0.079	1.03	0.071	0.96
	Ferguson and Krishnaswamy[28]	6	0.6	0.083	1.04	0.050	0.95
	Thompson et al.[30]	8	0.65	0.052	1.09	0.084	1.03
	Treece and Jirsa[34]	1	0.56	—	1	—	0.94
	Choi et al.[35]	8	0.722	0.059	0.96	0.119	0.99
	Hester et al.[29]	7	0.66	0.070	0.95	0.075	0.99
	Azizinamini et al.[36]	4	0.57	0.046	0.93	0.066	0.90
	Rezansoff, Akanni, and Sparling[26]	4	0.57	0.025	1.07	0.032	1.10
	Darwin et al.[1]	13	0.63	0.060	1.00	0.059	1.01
Group 1		**81**		**0.077**	**1.00**	**0.085**	**0.99**
Group 2	Darwin et al.[1]	24	0.79	0.073	1.01	0.084	0.95
	Rezansoff, Akanni, and Sparling[26]	12	0.87	0.151	1.10	0.150	1.12
	Ferguson and Breen[27]	5	0.71	0.102	1.04	0.088	0.94
	Ferguson and Krishnaswamy[28]	3	0.74	0.056	0.98	0.023	0.82
	Thompson et al.[30]	4	0.84	0.103	1.09	0.105	0.99
	Hester et al.[29]	10	0.7	0.074	0.94	0.077	0.95
	Darwin et al.[1]	38	0.88	0.082	1.05	0.073	0.96
Groups 1 and 2		**174**		**0.093**	**1.02**	**0.098**	**0.98**
Group 3	Ferguson and Breen[27]	4	0.73	0.052	0.93	0.034	0.86
	Kemp et al.[37,38]	28	0.92	0.142	1.03	0.144	0.99
Group 3		**32**		**0.138**	**1.02**	**0.142**	**0.98**
Groups 1, 2, and 3		**206**		**0.101**	**1.02**	**0.106**	**0.98**
Group 4a	Azizinamini et al.[7]	56	0.53	0.059	0.97	0.055	0.88
	Azizinamini et al.[36]	6	0.51	0.041	0.93	0.094	0.88
Group 4a		**62**		**0.071**	**0.95**	**0.082**	**0.88**
Groups 1, 2, and 3, and 4a		**268**		**0.099**	**1.00**	**0.110**	**0.95**
Group 4b	Hwang, Leu, and Hwang[17]	8	0.97	0.165	1.37	0.149	1.23
	Esfahani and Rangan[5]	8	0.75	0.085	1.32	0.124	1.39
All tests		**284**		**0.128**	**1.02**	**0.139**	**0.97**

result in larger bond strengths. These results are used herein to account for the effect of R in the bond strength equation. Figure 6 shows the relation of u_{test}/u_{calc} using Eq. (1) and tests with $R \geq 0.11$ with the parameter A_tA_b/CS. The best fit for the results presented in Fig. 6 is given by

$$\frac{u_{test}}{u_{calc}} = 1 + 0.024\frac{A_tA_b}{CS} \tag{10}$$

On this basis, Eq. (8) is modified to include the rib effects as follows

$$\frac{u_{test}}{u_{calc}} = 1 + 0.015 f_R \frac{A_tA_b}{CS} \tag{11}$$

in which $f_R = 1$ for $R < 0.11$, and $f_R = 1.6$ for $R \geq 0.11$.

Using Eq. (11), the bond strength is calculated by

$$u = u_c \frac{1 + 1/M}{1.85 + 0.024\sqrt{M}}\left(0.88 + 0.12\frac{C_{med}}{C}\right) \tag{12}$$

$$\left(1 + 0.015\frac{A_tA_b}{CS}\right)$$

Comparisons between Eq. (12) and the results of 284 tests are presented in Table 2. This includes the results of tests on bond in development lengths and splices in NSC and HSC. These tests were selected from the literature using the following limits:

- $C/d_b \geq 1$;
- Beams with two or more development lengths or spliced bars;
- Splices located close to the bottom of the beam;
- Tensile stress in the reinforcing bar at failure was less than the yield stress; and
- Failure was due to bond.

Test results presented in Table 2 are divided into four groups: splices not confined by TR, splices confined by TR, development lengths, and HSC splice tests. For each group, the mean and standard deviation for test/calculated values are given. Also, the mean and standard deviation for test/calculated values of combination of different groups are presented. For splices not confined by TR (Group 1), the mean value is 1.000, with a standard deviation of 0.077. For 174 splice tests in Groups 1 and 2, the mean value is 1.017, with a standard deviation of 0.093. For the tests on development lengths (Group 3), the mean value is 1.017, with a standard deviation of 0.138. It is observed that the bond strength in development lengths is close to that in splices. The mean value of u_{test}/u_{calc} for 206 tests of Groups 1, 2, and 3 is 1.017, with a standard deviation of 0.101. Group 4a includes the test results of splices in HSC beams. For 62 tests conducted by Azizinamini et al.,[7,36] the mean value is 0.952, with a standard deviation of 0.071. For 268 tests of Groups 1 through 4a with NSC and HSC, the mean value is 1.002, with a standard deviation of 0.099. The results of tests (Group 4b) with HSC obtained by Esfahani and Rangan[5] and Hwang, Leu, and Hwang[17] showed higher bond strengths compared with the results given by Azizinamini et al.[7,36] For these two test series, the mean values of u_{test}/u_{calc} are 1.32 and 1.37, respectively. For all 284 results, including tests carried out by Esfahani and Rangan[5] and Hwang, Leu, and Hwang,[17] the mean value of test/calculated bond strengths is 1.02, with a standard deviation of 0.128. Table 2 also presents the mean and standard deviation values for Eq. (6) proposed by Zuo and Darwin.[2] For Eq. (6), the mean value of test/calculated bond strengths is 0.97,with a standard deviation of 0.139. A comparison shows that Eq. (12) predicts the bond strength more accurately than Eq. (6).

Table 2 also includes the results calculated by the expression (Eq. (6)) proposed by Zuo and Darwin.[2] Comparisons between Eq. (12) and (6) for different combinations of test groups are presented in Table 2. For all test groups, Eq. (12) correlates better with the test results as compared with Eq. (6). The values of a_1a_2 in Column 4 of Table 2 are discussed in a following section of this paper.

PROPOSED EQUATION TO PREDICT DEVELOPMENT/SPLICE LENGTH

Equation (12) can be expressed in terms of the maximum tensile force in the reinforcing bar by

$$\frac{T}{\pi d_b L} = u_c \frac{1 + 1/M}{1.85 + 0.024\sqrt{M}}\left(0.88 + 0.12\frac{C_{med}}{C}\right)\left(1 + 0.015 f_R \frac{A_t A_b}{CS}\right) \tag{13}$$

In Eq. (13), the parameter M as given by Eq. (4) depends on the development/splice length L. Therefore, the development/splice length L can only be calculated using Eq. (13) through a trial-and-error process. This may not be an appropriate calculation method in practice. In the following, based on an appropriate assumption, a simple equation to calculate the development/splice length will be derived from Eq. (13).

Equation (13) can be given by

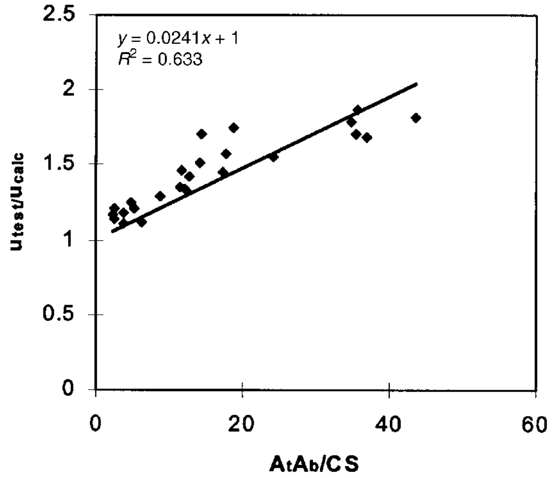

Fig. 6—Relationship between u_{test}/u_{calc} *and* (A_tA_b/CS) *for bars with* $R \geq 0.11$.

$$\frac{T}{\pi d_b L} = u_c a_1 a_2 \tag{14}$$

where

$$a_1 = \frac{1 + 1/M}{1.85 + 0.024\sqrt{M}} \tag{15}$$

$$a_2 = \left(0.88 + 0.12\frac{C_{med}}{C}\right)\left(1 + 0.015 f_R \frac{A_t A_b}{CS}\right) \tag{16}$$

From Eq. (14), the maximum tensile force in the reinforcing bar is calculated by

$$T = \pi d_b L u_c a_1 a_2 \tag{17}$$

For u_c, Eq. (2) is inserted into Eq. (17), then it is rearranged as follows

$$T = \left(\pi d_b \times 2.7\frac{C/d_b + 0.5}{C/d_b + 3.6}\sqrt{f_c'}\,L\right)(a_1 a_2) \tag{18}$$

Equation (18) can be given by

$$T = (a_3\sqrt{f_c'}\,L)(a_1 a_2) \tag{19}$$

where

$$a_3 = 8.5 d_b \frac{C/d_b + 0.5}{C/d_b + 3.6} \tag{20}$$

The development/splice length required to resist the tensile force T can be given by

$$L = \frac{T}{(a_3\sqrt{f_c'})a_1 a_2} \tag{21}$$

The value of a_1a_2 in Eq. (21) depends on the development/splice length and the amount of TR (Eq. (15) and (16)). For design purposes, the amount of TR can be considered as an arbitrary value. For each arbitrary value, a certain value of development/splice length L is required. In the following, it will be shown that this arbitrary value can be determined considering the value of a_1a_2 as a constant. This will lead to a simple equation to calculate the required development/splice length.

In Eq. (14), the parameter a_2 as given by Eq. (16) accounts for the effect of C_{med}/C and TR on bond strength. Previous studies have shown that when adequate TR is used, the uniformity of the bond stress distribution, and thus the bond strength, is increased. There is a limit, however, on the effect of TR on bond strength. Many experimental studies have been carried out to determine the maximum effective value of TR. Because of the interaction of different parameters, however, no appropriate value has yet been suggested.

In Eq. (14), the parameter a_1 accounts for the effect of bond stress distribution over the reinforcing bar on bond strength. As the development/splice length increases, the uniformity of the bond stress distribution, and thus the value of a_1, decreases. On the other hand, TR increases the uniformity of the bond stress distribution and the bond strength. Therefore, the decrease of the value of a_1 and thus the bond strength, in a longer length, can be compensated by increasing the amount of TR. On this basis, it is appropriate to keep the multiple of a_1a_2 constant from a design point of view. This will not only result in a similar bond stress distribution over the reinforcing bars in different cases, but will also lead to a simple equation to calculate the required development/splice length. Also, it is possible to insure an appropriate ductility by applying a constant value for a_1a_2 and a minimum amount of TR. To obtain an appropriate constant value for a_1a_2, the practical ranges from the experimental results are studied.

For all tests with TR given in Table 2, the values of a_1a_2 are calculated as shown. The average value of a_1a_2 is 0.85. Using $a_1a_2 = 0.85$ in Eq. (21) results in the following equation to calculate the bond length

$$L = \frac{T}{a\sqrt{f_c'}} \tag{22}$$

where

$$a = 0.85a_3 = 7.2d_b\frac{C/d_b + 0.5}{C/d_b + 3.6} \tag{23}$$

Equation (22) simply calculates the development/splice length L. The calculated length, however, should satisfy the equation $a_1a_2 = 0.85$ in which a_1 depends on L. Substituting Eq. (15) and (16) for a_1 and a_2 and equating it to 0.85 results in

$$\left(\frac{1 + 1/M}{1.85 + 0.024\sqrt{M}}\right)\left(0.88 + 0.12\frac{C_{med}}{C}\right) \tag{24}$$

$$\left(1 + 0.015f_R\frac{A_tA_b}{CS}\right) = 0.85$$

Test results show that when TR is used, the value of M is much less than 30. According to Esfahani and Rangan,[39] for $M < 30$, the value of a_1 reduces to

$$a_1 = 0.52(1 + 1/M) \tag{25}$$

Using Eq. (25) for $a_1a_2 = 0.85$ results in

$$0.52\left(1 + \frac{1}{M}\right)\left(0.88 + 0.12\frac{C_{med}}{C}\right) \tag{26}$$

$$\left(1 + 0.015f_R\frac{A_tA_b}{CS}\right) = 0.85$$

Equation (26) is simplified to obtain the parameter $f_RA_tA_b/CS$ as follows

$$f_R = \frac{A_tA_b}{CS} = 67\left[\frac{0.85/0.88 + 0.12(C_{med}/C)}{0.52(M + 1)/M}\right] \tag{27}$$

Therefore, A_t/S can be calculated by

$$\frac{A_t}{S} = \frac{67C}{f_RA_b}\left[\frac{1.63M/0.88 + 0.12(C_{med}/C)}{(M + 1)} - 1\right] \tag{28}$$

As a result, the required development/splice length to resist load T can be simply calculated using Eq. (22) when the appropriate TR calculated by Eq. (28) is provided along the development/splice length.

Equation (28) was obtained based on the assumption of the constant value of 0.85 for a_1a_2. As discussed previously, the uniformity of the bond stress distribution over the development/splice length mainly depends on the value of a_1a_2. For a constant value of a_1a_2, the bond stress distribution should be similar in different cases. This may result in a similar behavior of bond and beam ductility. It should be mentioned that it is possible to assume another constant value for a_1a_2. In this case, the coefficient of 1.63 in Eq. (28) would change accordingly. It is clear that a larger value of a_1a_2 results in a smaller splice/development length L and a larger value of TR A_t/S. According to the analysis presented in this paper, any assumption for the constant value of a_1a_2 is acceptable. The value of a_1a_2, however, should be limited to maximum and minimum values. The maximum value is necessary because of the fact that the effect of TR A_t/S on bond strength is limited. The minimum value is needed to provide the minimum ductility requirement for the flexural member. Further experimental studies are required to be able to determine the maximum and minimum values of a_1a_2. The proposed value of 0.85 that is based on previous test data is reasonable and appropriate, however.

CALCULATION OF DEVELOPMENT/SPLICE LENGTH (DESIGN SUMMARY)

The required development/splice length was given by

$$L = \frac{T}{a\sqrt{f_c'}} = \frac{A_bf_s}{a\sqrt{f_c'}} \tag{22}$$

where f_s is the tensile stress in the reinforcing bar at failure. Conservatively, f_s can be replaced by f_y, which also provides a margin of safety. A_b is the area of a longitudinal reinforcing bar, and

$$a = 7.2d_b\frac{C/d_b + 0.5}{C/d_b + 3.6} \tag{23}$$

The development/splice length L calculated by Eq. (22) requires the following value of TR to be used

$$\frac{A_t}{S} = \frac{67C}{f_R A_b}\left[\frac{1.63M/0.88 + 0.12(C_{med}/C)}{(M+1)} - 1\right] \tag{28}$$

where $f_R = 1$ for bars with $R < 0.11$, and $f_R = 1.6$ for bars with $R \geq 0.11$. Other parameters have been defined previously.

Table 3 presents the development/splice lengths calculated using Eq. (22) with the values of TR according to Eq. (28). All values are based on the parameters and measured bond strengths of tests conducted by Darwin et al.[1] The test values of L, a_1a_2, and A_t/S are given in Columns 2 through 4 of Table 3. The values of L and A_t/S in Columns 5 and 7 were calculated from Eq. (22) using the constant value of $a_1a_2 = 0.85$. The value of 0.85 is within the ranges of values in different tests as seen in Column 3. The calculated values of L and A_t/S are comparable with the test data. As an example, the actual values of L, A_t/S, and a_1a_2 in Test 2.1-8S0 are 610 mm, 0.82 mm, and 0.75, respectively. Using the aforementioned procedure to calculate the development/splice length for the proposed constant value of $a_1a_2 = 0.85$, the values of L and A_t/S are 538 and 1.30 mm, respectively. A comparison between the test results and the calculated values of L and A_t/S shows that Eq. (22) and (28) lead to a smaller development/splice length than the test, and with a larger value of TR. The advantage of the proposed procedure is that, in all cases, the values for TR are calculated based on the same value for a_1a_2. As mentioned previously, for the same value of a_1a_2, the bond stress distribution along the reinforcing bar is similar. This may result in a similar ductility for flexural beams having different spliced bars.

Table 3—Development/splice length calculated by Eq. (22) with required values of transverse reinforcement

Tests by Darwin et al.[1]	Test data			Values calculated by Eq. (22)		
	L, mm	a_1a_2	A_t/S, mm	L $a_1a_2 = 0.85$	M $a_1a_2 = 0.85$	A_t/S $a_1a_2 = 0.85$
2.1-8S0	610	0.75	0.82	538	5.93	1.30
3.4-8C0	610	0.63	0.47	405	3.20	1.57
3.5-8C0	711	0.77	0.8	599	5.22	1.00
4.1-8S0	610	0.86	1.25	628	6.37	1.29
5.1-8SH0	610	0.78	0.82	641	6.93	1.37
5.4-8SH0	610	0.78	0.82	584	5.51	1.21
5.5-8C0	610	0.71	0.47	436	3.07	0.78
6.1-8SH0	610	1.06	1.66	717	9.56	0.95
6.4-8C0	406	0.83	0.35	351	2.23	0.25
8.1-8N0	610	1.06	1.66	817	12.28	1.08
9.3-8N0	610	0.64	0.23	460	3.39	1.44
10.3-8N0	660	0.62	0.22	491	3.86	1.63
10.4-8N0	508	0.79	1.25	503	4.04	1.89
11.2-8N0	457	0.81	1.11	499	4.10	1.85
12.1-5N0	254	0.98	1	276	2.18	0.30
12.3-5N0	254	0.82	0.28	242	1.87	0.63
13.2-5N0	305	0.77	0.23	278	2.20	1.08
14.5-5N0	305	0.8	0.47	305	2.54	1.32
15.2-11N0	686	0.98	1.66	819	11.82	1.27
15.3-11N0	1016	0.69	0.7	831	12.36	1.21
16.4-11B0	1016	0.62	0.28	754	9.02	1.12
17.4-11B0	965	0.7	0.59	848	11.13	1.22
17.5-11B0	762	0.86	1.16	747	7.72	1.11
18.4-11B0	1016	0.65	0.42	852	11.27	1.25

CONCLUSIONS

This paper presents an equation to calculate the required development/splice length. The proposed equation is simple, practical, and accurate. Based on the analysis and test results, it is necessary to provide some amounts of TR over the development/splice length. An equation has been presented to calculate the required amount of TR for each development/splice length. The major parameters that affect bond strength have been taken into account in the proposed equations. The effect of rib properties of reinforcing bars on bond strength has been studied and included in these equations. It has been argued that the procedure to provide a value for TR along the development/splice length can rationally yield to an adequate ductility for beams with spliced bars.

Based on the results of this research, the following conclusions are drawn:

1. The proposed bond strength equation can accurately account for the rib properties of the reinforcing bars on bond strength;

2. The proposed bond strength equation that considers the effect of TR improves the prediction of the bond strength significantly. Based on 284 test results, the mean value of measured/calculated ratio of bond strengths is 1.021, with a standard deviation of 0.128. These values show that, for all cases, the equation correlates very well with the test results; and

3. The proposed equation to calculate the development/splice length requires providing a nominal amount of TR along the development/splice length. This procedure may prove to yield adequate ductility for beams with spliced bars. The proposed procedure correlates very well with the test results. Further studies, however, are recommended to check the strength and ductility of beams with spliced bars using the proposed values of L and A_t/S.

NOTATION

A_b = area of longitudinal reinforcing bar
A_t = area of one transverse reinforcing bar
C = minimum of $[C_x, C_y, (C_s + d_b)/2]$
C_{med} = median of $[C_x, C_y, (C_s + d_b)/2]$
C_s = spacing between spliced bars
C_x = side cover
C_y = bottom cover
d_b = bar diameter
f_c' = compressive strength of concrete
f_R = factor to include effect of relative rib area on bond strength
f_y = yield strength of transverse reinforcement
L = development/splice length
R = relative rib area = projected rib area normal to bar axis/(normal bar perimeter × center-to-center rib spacing)
S = spacing of transverse reinforcement
u, u_{calc} = calculated bond strength
u_c = local bond strength
u_{test} = measured bond strength

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