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Comparison of code provisions on lap splices

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Abstract. The code provisions on lap splices are critically assessed in the light of 203 beams without transverse reinforcement and 278 beams with transverse reinforcement. For comparison, the provisions given in the ACI 318, Eurocode 2, and TS 500 Codes are considered. The ACI Committee 408 recommended provision and a new proposal are also taken into account throughout the assessment. The comparison with real beam tests where the splice region was subjected to constant moment indicates that current provisions in the Codes do not agree acceptably with test results. The steel stress prediction graphs calculated by means of the Code provisions show high scatter and remain unsafe especially for test data without transverse reinforcement. Both the recent recommended provision by ACI Committee 408 and a new design expression proposed by the author have much less scatter with fewer unsafe predictions. The simplified design provision proposed by ACI Committee 408 does not yield similar results to that of the advanced design provision proposed by the same committee and therefore it could conveniently be replaced with the simpler equation proposed by the author.

Keywords: lap splice; comparison; code provisions; development length.

1. Introduction

Several reliability assessments of the current code provisions on bond have been carried out as a result of the increase of available test data on beams with lap splices (Lutz *et al.* 1993, Rezansoff *et al.* 1993, Rezansoff and Sparling 1995, Pacholka *et al.* 1999, Azizinamini *et al.* 1999, Zuo and Darwin 2000, Darwin *et al.* 2005). This paper investigates the prediction accuracies of the American Concrete Institute Building Code Requirements for Structural Concrete (ACI 318-05), the European Standard for Design of Concrete Structures (Eurocode 2), and Turkish Standards on Requirements for Design and Construction of Reinforced Concrete Structures (TS 500) when compared with real test results. In addition to the Code provisions, the ACI Committee 408 proposal (Darwin *et al.* 2005) and a new design proposal (Canbay and Frosch 2005) are also considered for the estimation of test results. To show the differences of the five approaches given above, lap splice lengths have been calculated separately for each equation and represented graphically for some practical cases.

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2. Design provisions

In this paper, ACI 318-05, Eurocode 2, and TS 500 design equations are examined in order to evaluate the adequacy of the Code provisions. The provisions will be briefly summarized in this section.

2.1 ACI 318-advanced

The design provisions in ACI 318 for development and splices are based on a bond stress equation developed by Orangun, Jirsa and Breen (1975, 1977). This expression is based on a nonlinear regression analysis of test results of beams with lap splices and reflects the effect of length, cover, spacing, bar diameter, concrete strength, and transverse reinforcement on the strength of anchored bars. The effect of all variables controlling the development length is expressed in ACI Equation 12-1 as provided in ACI 318-05 (Section 12.2.3). This equation is presented here as Eq. (1) and will be termed *ACI Advanced* throughout this paper.

In US customary units:

$$\frac{\ell_d}{d_b} = \frac{3}{40}\frac{f_y}{\sqrt{f'_c}}\frac{\psi_t\psi_e\psi_s\lambda}{\dfrac{c_b + K_{tr}}{d_b}} \tag{1}$$

where K_{tr} = transverse reinforcement index, $K_{tr} = (A_{tr}f_{yt})/(1500sn)$; A_{tr} = total cross-sectional area of all transverse reinforcement that is within the spacing s and that crosses the potential plane of splitting through the reinforcement being developed, in.^{2}; c_b = spacing or cover dimension, in. (Use the smaller of either the distance from the center of the bar or wire to the nearest concrete surface or one-half the center-to-center spacing of the bars or wires being developed); d_b = nominal diameter of reinforcing bars, in.; f'_c = specified compressive strength of concrete, psi; f_y = specified yield strength of reinforcement, psi; f_{yt} = specified yield strength of transverse reinforcement, psi; ℓ_d = development length, in.; n = number of bars being spliced or developed along the plane of splitting; s = spacing of transverse reinforcement, in.; ψ_t = reinforcement location factor; ψ_e = coating factor; ψ_s = reinforcement size factor, ψ_s = 0.8 for No. 6 (19 mm) and smaller bars, ψ_s = 1.0 for No. 7 (22 mm) and larger bars; λ = lightweight aggregate concrete factor.

To limit the probability of a pullout failure, ACI 318-05 requires that the term $(c_b + K_{tr})/d_b$ not be taken greater than 2.5.

Eq. (1) is given for the development of deformed bars in tension. For splices of deformed bars in tension, this equation can be used without any modification if the area of reinforcement provided is at least twice that required by analysis over the entire length of the splice or if one-half or less of the total reinforcement is spliced within the required lap length. In other cases, the calculated development length should be multiplied by 1.3 for lap splices.

2.2 ACI 318-simplified

ACI 318 allows the use of a simplified equation considering minimum cover or transverse reinforcement. This simplification is presented in tabular format in ACI Section 12.2.2 and is presented here in Table 1. The simplified expressions will be termed *ACI Simplified* herein and are based on Eq. (1) using assumed $(c_b + K_{tr})/d_b$ ratios. The first row in the table considers a ratio of 1.5 while the second row (other cases) considers a ratio of 1.0. Because Eq. (1) directly includes the

Table 1 ℓ_d/d_b ratio requirements in ACI 318-05

	≤ No.6 and deformed wires	≥ No.7 bars
clear spacing of bars ≥ d_b, clear cover ≥ d_b, stirrups → code minimum or clear spacing ≥ $2d_b$, clear cover ≥ d_b	$\dfrac{f_y \psi_t \psi_e \lambda}{25\sqrt{f_c'}}$	$\dfrac{f_y \psi_t \psi_e \lambda}{20\sqrt{f_c'}}$
other cases	$\dfrac{3f_y \psi_t \psi_e \lambda}{50\sqrt{f_c'}}$	$\dfrac{3f_y \psi_t \psi_e \lambda}{40\sqrt{f_c'}}$

effect of cover thickness and transverse reinforcement rather than an assumed $(c_b + K_{tr})/d_b$ ratio, significantly shorter development lengths are calculated typically using this expression than are calculated according to Table 1.

2.3 Eurocode 2

The design lap length in Eurocode 2 Part 1.1 is defined in Clause 8.7.3 as follows

In SI units:

$$\ell_0 = \alpha_1 \alpha_2 \alpha_3 \alpha_5 \alpha_6 \ell_{b,rqd} \geq \ell_{0,\min} \tag{2}$$

where α_1 is for the effect of the form of the bars assuming adequate cover, $\alpha_1 = 1.0$ for straight bars in tension; α_2 is for the effect of concrete minimum cover.

$$1.0 \geq \quad \alpha_2 = 1 - 0.15\frac{(c_d - \phi)}{\phi} \geq 0.7 \tag{3}$$

For straight bars $c_d = \min(a/2, c_1, c)$, where a is the clear spacing between longitudinal bars, mm; c_1 and c are the side and face clear covers from outside of the longitudinal bars, respectively, mm; ϕ is the diameter of the lapped bar, mm. α_3 is for the effect of confinement by transverse reinforcement.

$$1.0 \geq \quad \alpha_3 = 1 - K\frac{\sum A_{st} - \sum A_{st,\min}}{A_s} \geq 0.7 \tag{4}$$

where ΣA_{st} is cross-sectional area of the transverse reinforcement along the design lap length ℓ_0, mm^2; $\Sigma A_{st,\min}$ should be taken as $1.0A_s(\sigma_{sd}/f_{yd})$, mm^2; A_s is the area of one lapped bar, mm^2; σ_{sd} is the design stress of the bar, MPa; f_{yd} is the design yield strength of steel, $f_{yd} = f_{yk}/1.15$, MPa; f_{yk} is the characteristic yield strength of steel, MPa; $K = 0.10$ for a bar confined at a corner bend of a stirrup or tie, $K = 0.05$ for a bar confined by a single leg of a stirrup or tie, and $K = 0$ for a bar that is not confined. α_5 is for the effect of the pressure transverse to the plane of splitting along the design anchorage length.

$$1.0 \geq \quad \alpha_5 = 1 - 0.04p \geq 0.7 \tag{5}$$

where p is the transverse pressure at ultimate limit state along ℓ_0, MPa. No specific information is provided in Eurocode 2 for the calculation of the transverse pressure. The pressure p can be exerted externally to the concrete element by bearing such as in the support region. All the splices in the tests are made in the mid-region and consequently, α_5 is taken as unity in this study. α_6 is a multiplier for the percentage of lapped bars in one lapped section.

$$1.5 \geq \alpha_6 = \sqrt{\frac{\rho_1}{25}} \geq 1.0 \tag{6}$$

where ρ_1 is the percentage of reinforcement lapped within $0.65\ell_0$ from the centre of the lap length considered. $\ell_{b,\,rqd}$ is the basic required anchorage length and defined as

$$\ell_{b,rqd} = \frac{\phi \sigma_{sd}}{4 f_{bd}} \tag{7}$$

where f_{bd} is the design value of the ultimate bond stress for deformed bars.

$$f_{bd} = 2.25\, \eta_1\, \eta_2 f_{ctd} \tag{8}$$

where η_1 is a coefficient related to the quality of the bond condition and the position of the bar during concreting. For bottom cast straight bars, it will be taken as 1.0. η_2 is related to the bar diameter

$$\eta_2 = \begin{cases} 1.0 & \text{for } \phi \leq 32 \text{ mm} \\ \dfrac{132 - \phi}{\phi} & \text{for } \phi > 32 \text{ mm} \end{cases} \tag{9}$$

The coefficient f_{ctd} in Eq. (8) is the design value of concrete tensile strength and can be defined as $f_{ctd} = f_{ctk,\,0.05}/1.5$ where $f_{ctk,\,0.05}$ is the characteristic tensile strength of concrete for the 5% fractile. The characteristic tensile strength of concrete is equal to 70% of the mean tensile strength of concrete, $f_{ctk,\,0.05} = 0.7 \times f_{ctm}$. The mean tensile strength of concrete can be related to the characteristic compressive strength of concrete thus

$$f_{ctm} = \begin{cases} 0.30 f_{ck}^{2/3} & \text{for } \leq \text{C50/60} \\ 2.12\, \ln\left(1 + \dfrac{f_{cm}}{10}\right) & \text{for } > \text{C50/60} \end{cases} \tag{10}$$

where the mean strength of concrete can be taken as 8 MPa greater than the characteristic strength of concrete, $f_{cm} = f_{ck} + 8$. According to a report by ACI Committee 408 (ACI 408R-03 2003), the characteristic strength of concrete is related to the specified compressive strength as $f_{ck} = f_c' - 400$ psi $(f_{ck} = f_c' - 2.75 \text{ MPa})$.

2.4 TS 500

Among the equations considered in this study, the Turkish Standards provision (TS 500) yields the simplest equation in which only the two most important parameters are included. According to the Turkish Code for Reinforced Concrete Structures, the development length of deformed reinforcing bars in tension can be calculated as

In SI units:
$$\frac{\ell_b}{\phi} = 0.12\frac{f_{yd}}{f_{ctd}} \geq 20\phi \tag{11}$$

where f_{yd} is the design yield strength of steel, $f_{yd} = f_{yk}/1.15$, MPa; f_{ctd} is the design value of concrete tensile strength, $f_{ctd} = 0.35\sqrt{f_{ck}}/1.5$, MPa; ϕ is the diameter of the developed bar. When the diameter ϕ of the reinforcement is 32 mm < $\phi \leq$ 40 mm, the development length value obtained from Eq. (11) should be increased by multiplying it by 100/(132 − ϕ). The lap splice length ℓ_0 in the case of lap spliced bars should be calculated as

$$\ell_0 = (1 + 0.5r)\ell_b \tag{12}$$

where r is the ratio of spliced reinforcement to total reinforcement at that section.

3. Design proposals

Recently ACI Committee 408 (Darwin *et al*. 2005) has recommended a new provision on development and lap splice lengths for deformed reinforcing bars in tension. The recommended criteria produce designs with improved reliability compared to those in ACI 318. In addition to the ACI 408 proposal, a practical and reliable design proposal by Canbay and Frosch (2006) will be taken into account in this study.

3.1 ACI 408-Advanced

ACI Committee 408 (Darwin *et al*. 2005) recommends splice and development length criteria based on the work of Zuo and Darwin (1998, 2000). This design recommendation applies to both conventional and high relative rib area reinforcement

In US customary units:
$$\frac{\ell_d}{d_b} = \frac{\left(\frac{f_y}{\sqrt[4]{f'_c}} - 2000\omega\right)\psi_t\psi_e\lambda}{62\left(\frac{c_b\omega + K'_{tr}}{d_b}\right)} \tag{13}$$

in which $\left(\frac{c_b\omega + K'_{tr}}{d_b}\right) \leq 4$

$$c_b = c_{\min} + 0.5d_b \tag{14}$$

$$\omega = 0.1\frac{c_{\max}}{c_{\min}} + 0.9 \leq 1.25 \tag{15}$$

$$K'_{tr} = \frac{t_d A_{tr}\sqrt{f'_c}}{2sn} \tag{16}$$

$$t_d = 0.78d_b + 0.22 \tag{17}$$

where $c_{\min}$, $c_{\max}$ = minimum or maximum value of c_s or c_{bb}, *in.;* c_s = min(c_{si} + 0.25, c_{so}); c_{si} = one-half of average clear spacing between bars or lap splices in a single layer, in.; c_{so} = clear cover of

Table 2 ℓ_d/d_b ratio requirements in ACI 408

clear spacing of bars $\geq d_b$, stirrups $\rightarrow K'_{tr}/d_b \geq 0.5$ or clear spacing $\geq 2d_b$, clear cover $\geq d_b$	$\left(\frac{f_y}{93\sqrt[4]{f'_c}} - 21\right)\psi_t\psi_e\lambda$
other cases	$\left(\frac{f_y}{62\sqrt[4]{f'_c}} - 31\right)\psi_t\psi_e\lambda$

reinforcement being developed or lap spliced, measured to the side face of the member, in.; c_{bb} = clear cover of reinforcement being developed or lap spliced, measured to the tension face of member, in.; t_d = term representing the effect of bar size on the steel contribution to the total bond force.

Unlike ACI 318-05, a reinforcement size factor, ψ_s, is not used in the proposed equation. Committee 408 (ACI 408R-03 2003) does not endorse the use of a reinforcement size factor.

Eq. (13) is proposed for the development length of deformed bars in tension. The same expression can be used for splices of bars if the spliced reinforcement is confined with transverse reinforcement at two or more locations with a spacing s not greater than 12 in. (300 mm), providing that K'_{tr}/d_b is at least 1.0 or if no more than one-half of the total reinforcement is spliced within the required lap length. For other cases, the same equation can still be utilized with the use of ω = 1.0 to improve reliability.

3.2 ACI 408-simplified

The ACI Committee 408 proposal for the development and lap splices is given in a similar code format to the current ACI 318-05. Hence, a simplified form of the original design equation is given in tabulated format in Table 2. Since the simplified equations in the ACI 408 proposal do not contain ω, there is no modification even if all the bars are spliced at the same location.

3.3 Canbay & Frosch

With the motivation that almost all the approaches for the calculation of the strength of tension lap splices are based primarily on nonlinear regression analysis of test results, an expression was developed for the calculation of bond strength based on a physical model of tension cracking of concrete in the lap-spliced region (Canbay and Frosch 2005). Bearing in mind that the complexity of design for reinforcement development has progressively increased, a simple and reliable design expression was developed by Canbay and Frosch (2006).

In US customary units:

$$\frac{\ell_d}{d_b} = \frac{0.9 \times 10^{-6} f_y^2 \sqrt{d_b}}{\sqrt{f'_c}} \tag{18}$$

During the development of the equation, concrete strength from 2,500 to 10,000 psi (17 to 69 MPa) and steel stress from 30 to 75 ksi (207 to 517 MPa) was considered. This expression is based on the minimum cover and spacing requirements as required by ACI 318-05 for both beams and slabs. In the case of beams, the inclusion of minimum transverse reinforcement as required by the code was also considered. Bar sizes ranging from No. 3 to 11 (9.5 mm to 35.8 mm) were investigated throughout the derivation of the design expression.

4. Comparison with test results

To investigate the adequacy and reliability of the aforementioned equations, they are compared with the available test results. The database for the comparison is mainly founded on the ACI 408 Database 10-2001. In the comparison, only tests with splice lengths of at least 12 in. (305 mm) and $\ell_d/d_b \geq 16$ are included to ensure that the comparison involves realistic splice lengths. All specimens have uncoated, bottom-cast steel bars containing lap splices located in a constant moment region. In total, 144 tests without transverse reinforcement and 237 tests with transverse reinforcement conform to these limits.

To evaluate the prediction accuracy of the design equations, they are solved for the steel stress and compared with the measured stresses obtained from the test results. All the longitudinal reinforcement in the tests were spliced at the same location and therefore, the multipliers in the Codes for the lap splices which increase the lap splice length have been considered in the calculations. In ACI 318-05, this multiplier is constant and equal to 1.3. In Eurocode 2 and TS 500, the multipliers are defined with Eqs. (6) and (12), respectively. In the ACI 408 proposal, it is stated that strength requirements are fulfilled by the development length equation (Eq. (13)) for splices with a factor of 1.0, even when all bars are spliced at the same location. For improved reliability, however, for some cases ω should be taken as 1.0 even for high cover ratios. The equation proposed by Canbay & Frosch is based on minimum requirements of cover and transverse reinforcement. Therefore, the splice length can be considered the same as the development length.

The distribution of the ratio of the measured to calculated steel stresses is given in Figs. 1 and 2 for tests without transverse reinforcement and with transverse reinforcement, respectively. The line at 1.0 on the graphs indicates a perfect match for steel stresses between the test results and calculated values. The values of the ratio of test to calculated steel stress higher than 1.0 designate

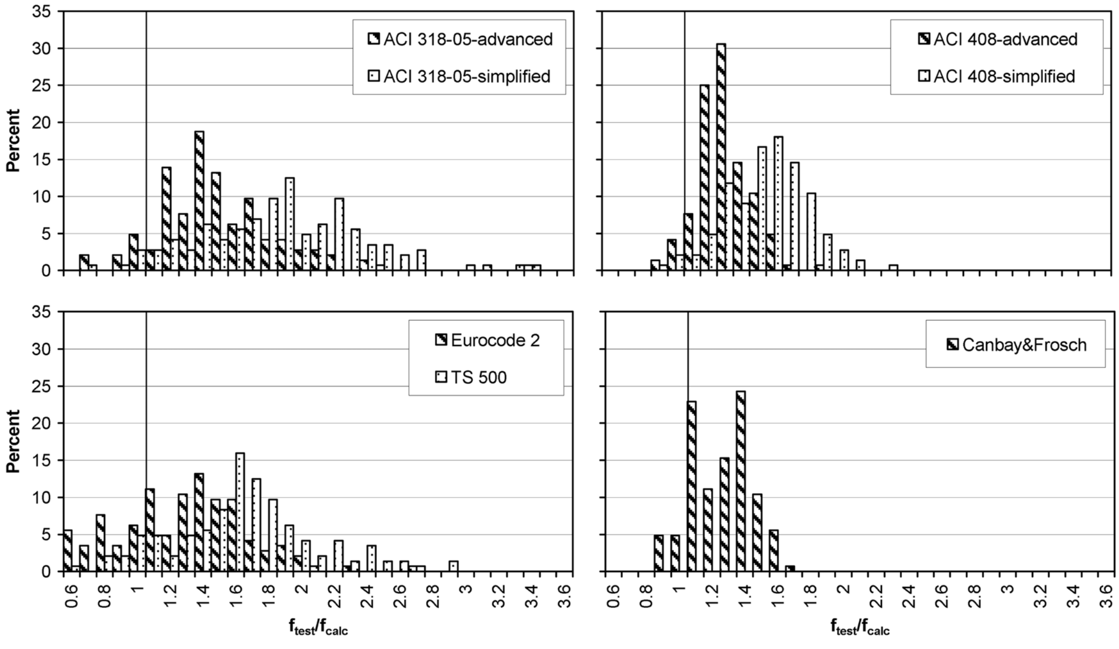

Fig. 1 Comparison of design equations for test data without transverse reinforcement

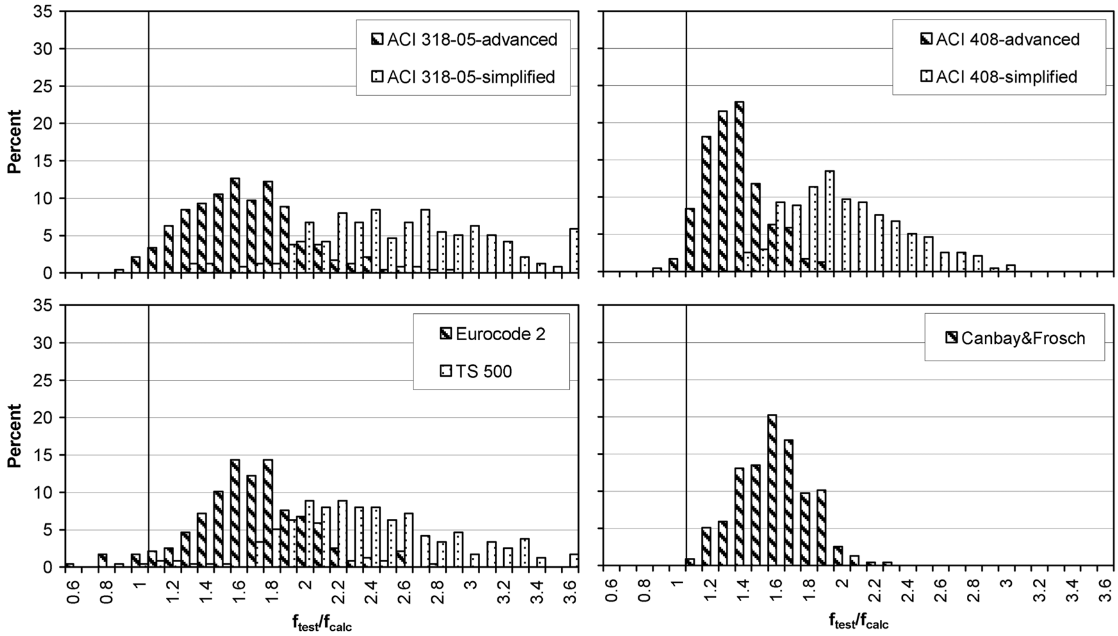

Fig. 2 Comparison of design equations for test data with transverse reinforcement

Table 3 Test prediction ratios of design provisions for test data without transverse reinforcement

	ACI 318-05		ACI 408		TS 500	Eurocode 2	Canbay Frosch
	Advanced	Simplified	Advanced	Simplified			
Maximum	3.316	3.316	1.806	2.290	2.842	2.662	1.613
Minimum	0.660	0.661	0.879	0.885	0.589	0.419	0.822
Average	1.445	1.837	1.251	1.507	1.607	1.239	1.220
Standard deviation	0.375	0.488	0.157	0.243	0.435	0.394	0.182
Coefficient of variation	0.260	0.266	0.126	0.161	0.271	0.318	0.149
Unconservative tests, %	9.0	4.2	5.6	2.8	9.7	26.4	9.7

Table 4 Test prediction ratios of design provisions for test data with transverse reinforcement

	ACI 318-05		ACI 408		TS 500	Eurocode 2	Canbay Frosch
	Advanced	Simplified	Advanced	Simplified			
Maximum	2.813	4.430	1.892	2.957	3.962	2.783	2.251
Minimum	0.833	1.201	0.883	1.322	0.957	0.567	1.008
Average	1.599	2.542	1.314	1.973	2.335	1.649	1.558
Standard deviation	0.358	0.559	0.180	0.348	0.517	0.356	0.215
Coefficient of variation	0.224	0.220	0.137	0.176	0.221	0.216	0.138
Unconservative tests, %	2.5	0.0	2.1	0.0	0.4	4.2	0.0

conservative predictions whereas values below 1.0 indicate unsafe/unconservative predictions. Table 3 and 4 present the statistical data as well as the percentage of unconservative predictions for the test data without transverse reinforcement and with transverse reinforcement, respectively.

As shown in Fig. 1, both the ACI 318-05 advanced and simplified equations give a widespread distribution with 9.0% and 4.2% unsafe predictions, respectively. It should be noted that the 1.3 multiplier for splices lapped in the same location is utilized in the steel stress calculations. The TS 500 equation performs in a similar manner to that of ACI 318-05 provisions. TS 500 calculates 9.7% of the tests unsafely. The Eurocode 2 equation exhibits the worst predictions with 26.4% unconservative tests. The coefficient of variation of the Eurocode 2 equation has the highest value which again indicates a poor distribution. The Canbay & Frosch design proposal shows a narrow distribution with superior statistical values. It gives 9.7% unsafe predictions for test data without transverse reinforcement. It should be also noted that the equation does not contain any parameter for transverse reinforcement and was derived for a minimum amount of transverse reinforcement. The safest predictions are produced by the ACI 408 simplified proposal with only 2.8% data below 1.0. The ACI 408 simplified proposal, however, provides slightly over-conservative results and its statistical values are not better than the Canbay & Frosch proposal. The simplified proposal also consists of two equations which inherently violates its simplicity. As can be seen in Fig. 1, the best graph is obtained by the ACI 408 advanced design proposal. It has a fairly low percentage of unconservative test results (5.6%). As Fig. 1 and Table 3 imply, the difference between the ACI 408 advanced and Canbay & Frosch proposal is rather insignificant especially if the complexity of the ACI 408 advanced proposal is taken into account.

As shown in Fig. 2 for test data with transverse reinforcement, all equations demonstrate higher scatter when compared to the tests results without transverse reinforcement. The ACI 318-05 advanced equation give quite acceptable results both graphically as shown in Fig. 2 and statistically as given in Table 4. Only 2.5% of the predictions by the ACI 318-05 advanced equation fall below 1.0. The ACI 318-05 simplified equation, however, is shifted considerably to the right providing an excessive level of safety. Because of this shift to the right, no tests fall below 1.0. It has the highest standard deviation and coefficient of variation among the equations considered. The Eurocode 2 design provision gives much better results as compared to that of the data without transverse reinforcement with only 4.2% unsafe predictions. The distribution and statistical values are close to the predictions by the ACI 318-05 advanced equation. The TS 500 design equation provides over-conservative results similar to the ACI 318-05 simplified equation with only 0.4% unconservative predictions. The ACI 408 simplified equation again provides the safest prediction with no tests below 1.0. Its standard deviation and coefficient of variation are reasonably adequate. The Canbay & Frosch design proposal yields very good predictions of the test results for test data with transverse reinforcement. As shown in Fig. 2, no unsafe tests are predicted and the distribution of results is narrow. The coefficient of variation is practically the same as that for the ACI 408 advanced equation while providing a much simpler approach. The ACI 408 advanced equation provides, once more, the best distribution and statistical values with only 2.1% unconservative predictions.

5. Relative comparison of the design provisions and proposed expressions

To make a relative comparison between the design provisions and design proposals considered in this study, the required design anchorage length is calculated for some typical cases. The evaluation is based on the tension development length of bars with no transverse reinforcement or no transverse welded bars in order to simplify the comparisons. Different bar sizes ranging from No. 3

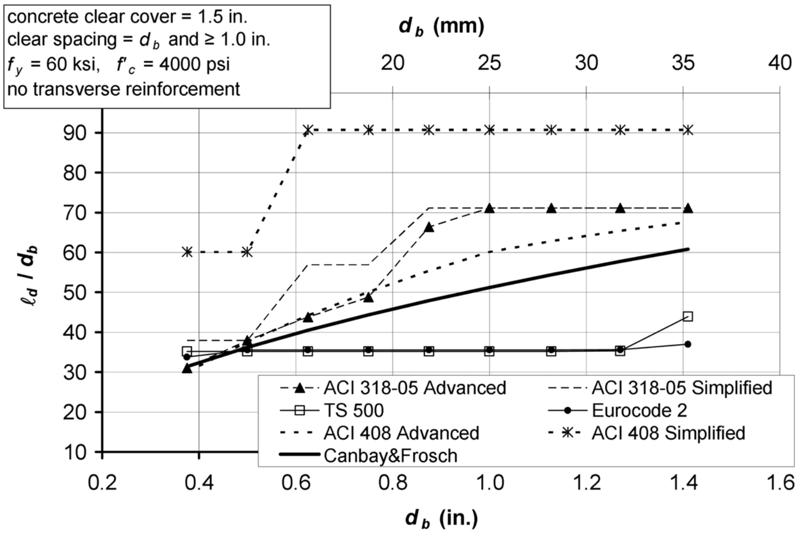

Fig. 3 Comparison of design equations for minimum cover and spacing

to 11 (9.5 to 35.8 mm) were investigated. The steel yield strength and concrete compressive strength were considered as 60,000 psi (413.8 MPa) and 4,000 psi (27.6 MPa), respectively.

In the first case, the concrete cover was taken as the minimum (1.5 in., 38.1 mm) allowed by the building code (Section 7.7.1 of ACI 318-05). The minimum clear spacing between bars was taken as the bar diameter d_b but not less than 1 in. (25.4 mm) (ACI 318-05, Section 7.6.1). Fig. 3 shows the results of this particular case. As shown in the figure, the ACI 408-Advanced proposal displays a similar trend when compared to the Canbay & Frosch proposal, with a slight higher safety. Only these two equations show continuous curves whereas other equations constitute discrete, broken lines. Both the TS 500 and the Eurocode 2 provisions provide the lower bound in the figure. These two lowered curves, however, result in a safety concern especially for larger bar diameters. The ACI 318-05 Advanced equation requires almost the same development length as the ACI 408 Advanced equation up to No. 6 bars. Because of the multiplier in the ACI 318-05 Advanced equation for bars greater than No. 6 bars, the curve deviates from the ACI 408 Advanced proposal and gets closer to the ACI 318-05 Simplified equation. As shown in Fig. 3, the ACI 408 Simplified equation provides the upper bound with questionably high safety. A design based on the ACI 408 Simplified equation surely will produce uneconomical and impractical long development lengths. For example, for No. 5 (15.9 mm) bars, the ACI 408 Simplified equation requires more than twice the ACI 408 Advanced equation values (ℓ_s/d_b = 44 vs. 91).

To examine the beneficial effect of the increased cover condition, another case was studied where the clear spacing between bars was taken as two times the bar diameter d_b but not less than 1 in. (25.4 mm) and the clear cover was taken as 1.5 in. (38.1 mm) but not less than the bar diameter d_b. The results of this case are shown in Fig. 4. Because the TS 500 and the Canbay & Frosch equation do not include cover or spacing dimensions as a parameter, they are completely the same as the former case. Although the lack of the cover parameter in the TS 500 equation is a disadvantage for the precise calculation of the development length, it does provide simplicity. The Canbay & Frosch design proposal does not contain the cover parameter explicitly. The equation, however, have been derived for minimum cover and spacing conditions. Therefore, the advantageous effect of the

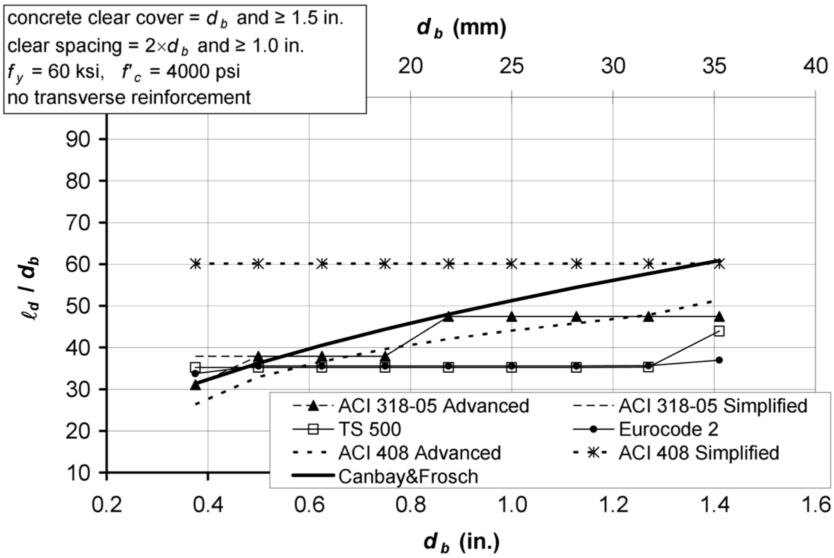

Fig. 4 Comparison of design equations for increased cover and spacing

increased cover cannot be obtained with the Canbay & Frosch equation. As shown in Fig. 4, the Eurocode 2 equation also yields the same development length for the increased cover dimensions as compared to Fig. 3. The equation, in fact, includes a parameter α_2 for cover; however, it is effective if half of the spacing between longitudinal bars or the clear cover is greater than the bar diameter ϕ. The ACI 318-05 Advanced and Simplified equations coincide with each other for increased cover dimensions because the simplified equation was derived for this specific case. The ACI 318-05 equations give similar development lengths as the ACI 408 Advanced equation. The ACI 408 Advanced equation still shows similar trend to the Canbay & Frosch equation remaining, however, below the Canbay & Frosch curve. The ACI 408 Simplified equation, once again, produces the upper bound with over-safety for small diameter bars.

Some other practical cases with different cover and spacing dimensions, and concrete strength have been studied as well. The results of these studies are very similar to the results of the case studies mentioned above and for considerations of brevity will not be presented herein.

A final case will be highlighted in this study to resolve a question on ACI equations. For this case, a typical beam was considered with four longitudinal bars spliced in a staggered manner. Therefore, only one bar (25% of the total longitudinal bars) is taken as lapped at a particular location. Because both the K_{tr} in ACI 318-05 and K'_{tr} in ACI 408 include the number of spliced bars, all the cases should be studied carefully. For a face splitting type of failure, since A_{tr} in the nominator and n in the denominator of the equations change in the same manner, the final value does not change. For the side splitting failure, however, as A_{tr} remains the same, the number of spliced bars n in the denominator reduces to ¼ of the total number of bars. Consequently, K_{tr} and K'_{tr} increase 4 times. This increase in transverse reinforcement index causes a very significant decrease in the required splice length. This trend, obviously, is an artificial decrease and the empirical derivation of the transverse reinforcement index has been based on tests results on beams where all the longitudinal bars were spliced at the same region. Therefore, this doubtful trend needs to be studied and verified experimentally in depth.

6. Conclusions

The provisions on lap splices of bars in tension were analytically assessed in the light of 203 beam tests without transverse reinforcement and 278 beam tests with transverse reinforcement. The provisions considered in this study were the ACI 318-05 advanced and simplified equations, the Eurocode 2 equation, and the TS 500 equation. The ACI Committee 408 advanced and simplified recommended design expressions were also taken into considerations throughout the comparisons. A simple yet accurate design equation proposed by the author (Canbay and Frosch, 2006) was also introduced for purposes of comparison. Based on the comparisons with real beam tests the following conclusions can be drawn:

- The most complex approach among the Codes considered is the Eurocode 2 design method. For test data without transverse reinforcement, however, the Eurocode 2 equation calculates several tests unsafely.
- All design provisions in the codes have poor prediction capabilities for test data without transverse reinforcement and with transverse reinforcement. The poor behavior can be seen either graphically with a wide distribution of the ratio of test to calculated steel stresses or analytically with a high coefficient of variation.
- Among the equations considered in this study, the ACI 408 Advanced equation gives the best results for test data without transverse reinforcement and with transverse reinforcement.
- The simple Canbay & Frosch design expression gives highly acceptable overall results for both without transverse reinforcement and with transverse reinforcement test data.

For some typical cases, the required development length is calculated analytically using the code provisions and proposed expressions. Based on this theoretical study, the following conclusions can be given:

- The ACI 408 Advanced equation and Canbay & Frosch equation give similar results for many practical cases.
- For all practical cases, the Eurocode 2 and TS 500 provisions yield doubtfully low development lengths which create, in fact, safety concerns.
- The ACI 408 Simplified design proposal requires usually extremely high development lengths. Comparing with other expressions and with real test results, it can be stated that the ACI 408 Simplified expression is impractical and uneconomical.

The simplified design provision proposed by ACI Committee 408 is not complex but simple. It does, however, not yield satisfactory results according to the comparisons on real test data and according to the practical case studies. Therefore, instead of the ACI 408 Simplified equation, the simple Canbay & Frosch equation may easily be substituted.

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