Fracture Mechanics of Concrete and Concrete Structures -
High Performance, Fiber Reinforced Concrete, Special Loadings and Structural Applications- B. H. Oh, et al. (eds)
ⓒ 2010 Korea Concrete Institute, ISBN 978-89-5708-182-2

Compression splice length in confined concrete

S.-C. Chun, S.-H. Lee, & B. Oh
Daewoo Institute of Construction Technology, Suwon, Korea

ABSTRACT: A compression lap splice may be calculated to be longer than a tension lap splice in high strength concrete according to current design codes. An experimental study was conducted using compressive concrete strengths of 40 and 60 MPa with and without transverse reinforcement, and the effects of compressive strength of concrete, transverse reinforcement, and splice length were assessed. A design equation was derived for compression lap splices with and without transverse reinforcement through regression analysis. For practical purposes, additional provisions were proposed regarding the strength limits of the materials and the arrangement of transverse reinforcement. In addition, a simplified equation was suggested for a design code provision.

1 INTRODUCTION

The ACI 318 (2008) lap requirements for compression splices have remained the same since the 1963 Code and do not include the effects of compressive strength of concrete and transverse reinforcement. Because of end bearing, the splice length in compression can be shorter than the length in tension to develop the specified yield strength of the reinforcing bars. However, according to ACI 318 (2008), a compression lap splice can be longer than a tension lap splice as the concrete strength becomes higher, as shown in Figure 1. This anomaly arises because the provisions for compression splices do not properly consider the effects of transverse reinforcement and the compressive strength of the concrete. Therefore, new criteria for compression lap splices with transverse reinforcement are required.

This research proposed an equation to predict splice strengths with transverse reinforcement, which was then converted into an equation for splice lengths. The equation was derived through a regression analysis of the test results (Chun et al. 2009a, b) conducted by the authors based on a model (Chun et al. 2009c) of unconfined splices. For practical purposes, additional provisions were proposed regarding the strength limits of the materials and the arrangement of transverse reinforcement. In addition, a more simplified equation for a design code provision was suggested.

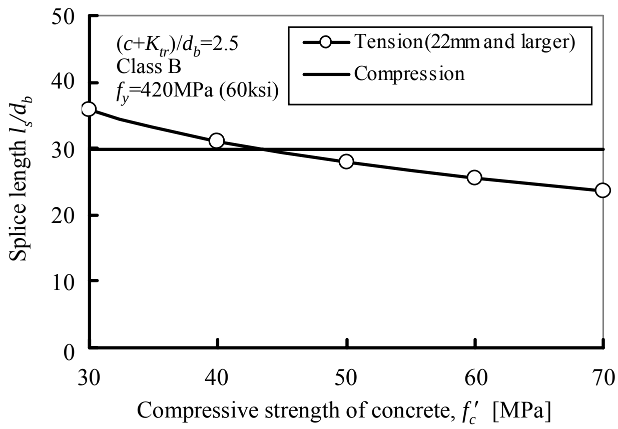

Figure 1. Comparison of calculated splice lengths with varying concrete compressive strengths.

2 EXPERIMENTAL PROGRAM

In order to evaluate the effects of compressive strength of concrete and transverse reinforcement, column specimens with lapped splices were concentrically loaded in a manner similar to that used in previous tests (Cairns & Arthur 1979, Pfister & Mattock 1963).

Two bar diameters, 22 mm and 29 mm, were chosen, and their design yield strength was 420 MPa. The measured yield strength, tensile strength, and modulus of elasticity of the 22 mm bars were 513.5 MPa, 617.6 MPa, and 183.9 GPa, respectively, and those of the 29 mm bars were 471.4 MPa, 601.9 MPa, and 189.4 GPa, respectively. The compressive strengths of the concrete were designed to be 40 MPa and 60 MPa, which were higher than the maximum strength used in the previous tests (Cairns & Arthur 1979, Pfister & Mattock 1963).

Three kinds of clear spacings were used: the minimum clear spacing of $1.5d_b$ required by ACI 318

(2008) for compression members, along with clear spacings of $2.5d_b$ and $3.0d_b$. The splice lengths of all of the specimens were fixed as $10d_b$, because a splice length longer than $10d_b$ was expected to make the bars yield before a splice failure. Each specimen had a duplicate.

Tied columns with a rectangular cross section were selected. The details for a typical test specimen are shown in Figure 2. Splitting cracks were intended to form through the side cover and between the bars, as shown in the horizontal lines of Figure 2(b).

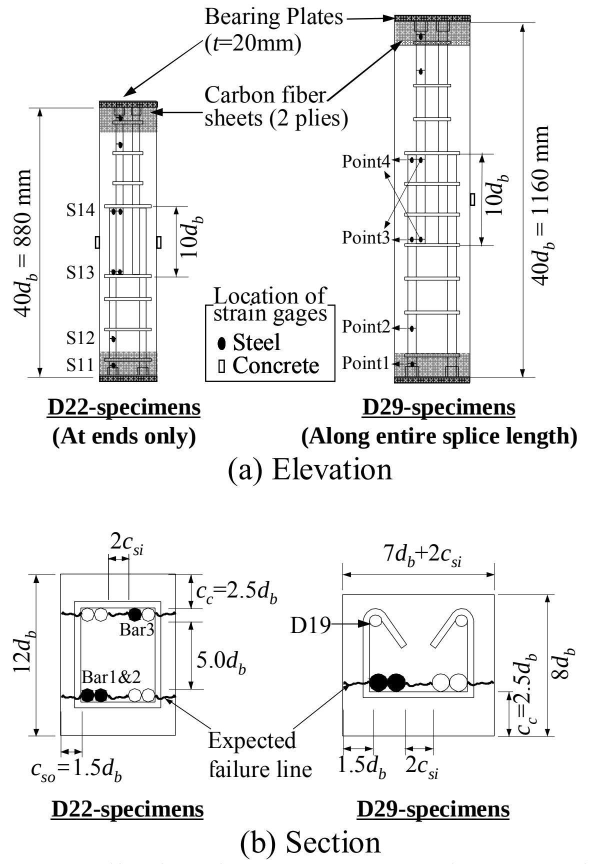

Figure 2. Details of specimens. (Note: S14 refers to a strain at point 4 of bar 1.)

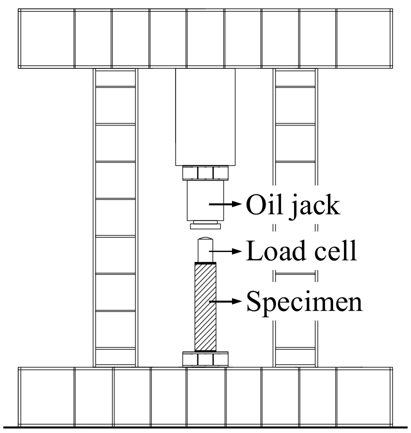

Figure 3. Test setup.

A monotonic axial load was applied to each specimen using a hydraulic jack with a capacity of 5000kN, as shown in Figure 3. To determine the end bearing and bond contributions, electrical resistance strain gages were attached to four points per bar, as shown in Figure 2(a). The gages were mounted at a distance of $1d_b$ from the end of one bar and at the same level for the other spliced bar. Detailed test results were reported in Chun et al. (2009a, b).

3 PROPOSED MODEL OF COMPRESSION SPLICES

A new model for predicting the splice strength with transverse reinforcement was developed on the basis of the experimental results and the model (Chun et al. 2009c) for compression splices without transverse reinforcement. For practical purposes, an equation for the splice length was derived, and additional provisions were proposed regarding the strength limits of materials and arrangement of the transverse reinforcement. In addition, a more simplified equation for a design code provision was suggested.

4 MEAN STRENGTH OF COMPRESSION SPLICES

The compression splice strength with transverse reinforcement can be obtained by adding the contribution of the transverse reinforcement to the splice strength without transverse reinforcement. Since the splice strength consists of the bond and the end bearing capacities, both effects of the transverse reinforcement, on the bond and the end bearing, should be assessed.

The test results showed that only when the transverse reinforcement was placed at the ends, the end bearing strength was enhanced by $1.8\sqrt{f_c'}$ MPa. The bond strength increases proportionally to the amount of transverse reinforcement within $K_{tr}/d_b = 1.76$.

A regression analysis was carried out with 21 specimens that failed in splitting, which provided an equation for predicting the mean strengths of compression splices, $f_{sc,p}$.

$$f_{sc,p} = \left[\left(11.1 + 1.5\frac{K_{tr}}{d_b} \right) \sqrt{\frac{l_s}{d_b}} + 16.4 + 1.8\delta \right] \sqrt{f_c'} \quad (1)$$

where $f_{sc,p}$ = predicted mean strength of compression splice; K_{tr} = transverse reinforcement index of ACI 318-08; d_b = bar diameter; l_s = compression splice length; f_c' = compressive strength of concrete; δ = 1 (one) if transverse reinforcement is placed at the ends or δ is 0 (zero); and K_{tr}/d_b cannot be greater than 1.76.

The splice strengths predicted by Equation (1) were compared to the test values for 51 specimens tested by the authors, including 30 specimens (Chun et al. 2009a) without transverse reinforcement, as seen in Figure 4. Equation (1) could be used to properly evaluate the splice strengths regardless of the existence of transverse reinforcement. The coefficient of variation (COV) for the ratios of test to predicted values was only 9.1% and the average value of the ratios was 1.01.

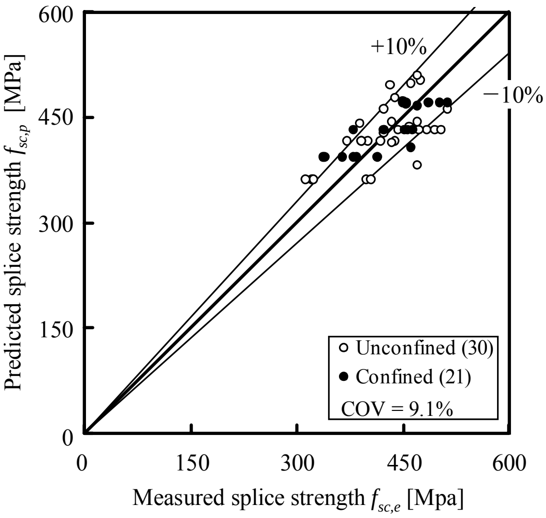

Figure 4. Comparison of test results and predicted values. (Note: ( ) = number of specimens.)

4.1 *Design strength and length of compression splices*

A 5% fractile (Natrella 1966) coefficient, $n_{5\%}$, was introduced to determine the design strength ($f_{sc,d}$) from the mean strength of a compression splice ($f_{sc,p}$). A value of 0.82 was calculated for $n_{5\%}$ using the COV of 9.1% and the specimen number of 51. For design purposes, it is desirable to determine the splice length rather than the splice strength. The current equation of ACI 318-08 can be adopted as the upper limit of the splice length because it has been practically justified for normal strength concrete. Equation (1) can be solved for l_s by incorporating the $n_{5\%}$ of 0.82.

$$\frac{l_s}{d_b} = \left(\frac{\dfrac{f_y}{0.82\sqrt{f_c'}} - 16.4 - 1.8\delta}{11.1 + 1.5\dfrac{K_{tr}}{d_b}} \right)^2 \leq 0.071 f_y \qquad (2)$$

where f_y = specified yield strength of a reinforcing bar; and the upper limits are replaced with $(0.13f_y{-}24)$ if f_y is greater than 420 MPa.

4.2 *Additional provisions for compression splices*

The maximum compressive strength of the concrete of the specimens was 73.7 MPa, used in developing Equation (1). Equation (2) is suggested to be available within a compressive strength of concrete of 70 MPa, which is the upper limit adopted in Chapter 12 of ACI 318-08.

The maximum yield strength used in this study was 513.5 MPa, and therefore, it is possible to splice Grade 520 reinforcing bars in compression using Equation (2). For reinforcing bars conforming to ASTM A 1035 (2007) and bars with a higher yield strength than 520 MPa, lap splices should not be used in compression because the yield strain of the bars is greater than the ultimate strain of the cover concrete (usually 0.003 mm/mm). Mechanical or welded splices are recommended for these reinforcing bars.

Only the transverse reinforcement at the ends of the lap length enhances the end bearing strength. If it is not possible to accurately place transverse reinforcement at the ends, the additional bearing strength of $1.8\sqrt{f_c'}$ MPa should be ignored in Equation (1). Moreover, in a case where the lap length is less than $16d_b$, no transverse reinforcement may be placed along the lap length; therefore, K_{tr}/d_b should be calculated as a precaution. Instead of the 300 mm of Section 12.16.1 of ACI 318-08, $16d_b$ is suggested as a minimum compression lap length with transverse reinforcement, in accordance with a minimum vertical spacing of ties in compression members.

The splice lengths given by Equation (2), with the suggested provisions, are compared with the lengths given by ACI 318-08 in Figure 5. The anomaly that a compression lap splice could be longer than a tension lap splice is settled with the proposed equation and provisions.

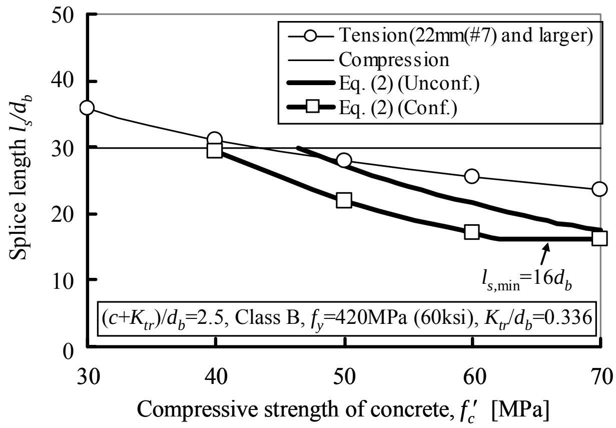

Figure 5. Comparison of splice lengths by ACI 318-08 with those by the proposed equation.

4.3 *Simplified equation for compression splice length*

Compared with the ACI 318-08 equation for a compression splice, Equation (2) is too complicated, even though each term of Equation (2) has a distinct meaning. For practical purposes, the simplified form shown in Equation (3) was suggested from a regression analysis with a coefficient of determination (R^2) of 0.955. The form of Equation (3) was based on the equation (12-1) of ACI 318-08, and the data for the regression analysis were generated using Equation (2) with f_y = 420 MPa and 520 MPa.

$$\left(\frac{l_s}{d_b}\right)_{\text{simplifed}} = 0.0075\frac{\left(f_y\right)^2}{f_c'\left(1+0.134\,K_{tr}/d_b\right)^2} \quad (3)$$

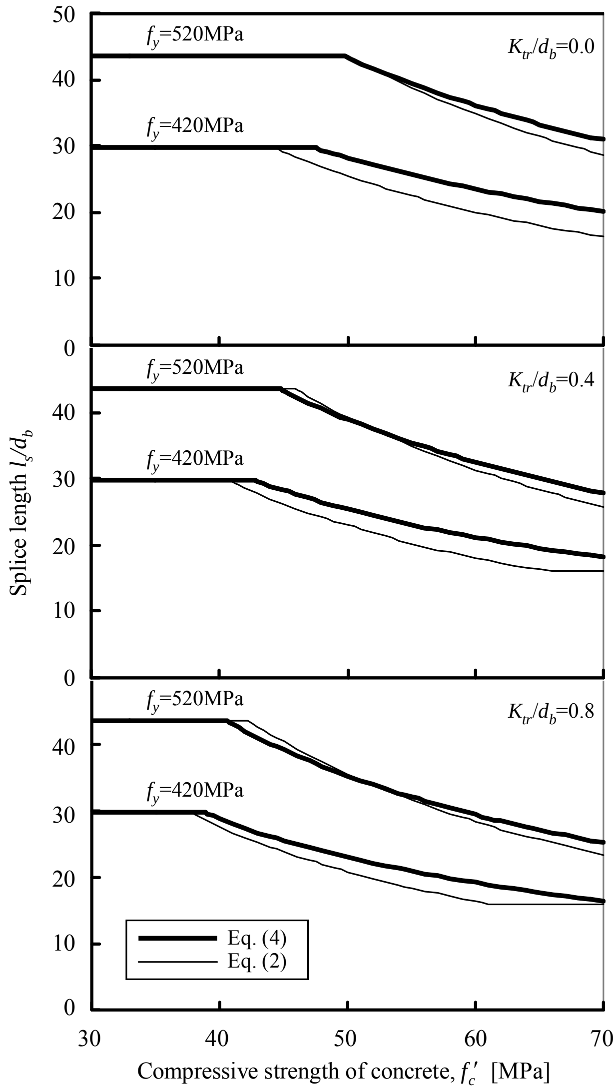

Figure 6. Comparison of splice lengths by Eq. (2) and Eq. (4).

A parametric study showed that Equation (3) gave unconservative results for splices with low strength concrete and higher Ktr. Therefore, the coefficient of 0.0075 needed to increase. The final simplified equation is proposed in Equation (4). The splice lengths given by Equation (4) are compared with the lengths given by Equation (2) in Figure 6, which shows that the simplified equation gives safe splice lengths.

$$\left(\frac{l_s}{d_b}\right)_{\text{final}} = 0.008\frac{\left(f_y\right)^2}{f_c'} \le 0.071 f_y \quad (4)$$

where the splice length (l_s/d_b)final shall be multiplied by the factor $1/(1+0.134K_{tr}/d_b)^2$ if a transverse reinforcement is placed, and the term K_{tr}/d_b shall not be taken greater than 1.76. The upper limits of Equation (4) are replaced with ($0.13f_y$−24) if f_y is greater than 420 MPa.

5 CONCLUSIONS

A compression splice can be longer than a tension splice when using ACI 318-08 with high strength concrete. A design equation for a splice length in compression was developed through a regression analysis for 30 unconfined and 21 confined specimens that failed in splitting. By using the 5% fractile coefficient of 0.82, the splice length calculated by the proposed equation had a reliability equivalent to reinforcing bars. For practical purposes, additional provisions were proposed regarding the strength limits of materials and arrangement of the transverse reinforcement. In addition, a more simplified equation for a design code provision was also suggested.

REFERENCES

ACI Committee 318. 2008. *Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary*. American Concrete Institute. Farmington Hills. Mich.

ASTM A 1035-07. 2007. *Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement*. West Conshohocken, PA.

Cairns, J. & Arthur, P. D. 1979. Strength of Lapped Splices in Reinforced Concrete Columns. *ACI Journal, Proceedings* 76(2): 277-296.

Chun, S.-C., Lee, S.-H., and Oh, B. 2009a. Behavior and Capacity of Compression Lap Splice in Unconfined Concrete with Compressive Strength of 40 and 60 MPa. *Journal of the Korea Concrete Institute* 21(3): 291-302.

Chun, S.-C., Lee, S.-H., and Oh, B. 2009b. Behavior and Capacity of Compression Lap Splice in Confined Concrete with Compressive Strength of 40 and 60 MPa. *Journal of the Korea Concrete Institute* 21(4): 389-400.

Chun, S.-C., Lee, S.-H., and Oh, B. 2009. Compression Lap Splice in Unconfined Concrete of 40 and 60 MPa Compressive Strengths. *ACI Structural Journal*. (Accepted for publication)

Natrella, M. G. 1966. *Experimental Statistics*. National Bureau of Standards Handbook 91. United States Department of Commerce. USA.

Pfister, J. F. & Mattock, A. H. 1963. High Strength Bars as Concrete Reinforcement, Part 5: Lapped Splices in Concentrically Loaded Columns. *Journal, PCA Research and Development Laboratories* 5(2): 27-40.