Title no. 96-S101

Proposed Modifications to ACI 318-95 Tension Development and Lap Splice for High-Strength Concrete

by Atorod Azizinamini, David Darwin, Rolf Eligehausen, Rob Pavel, and S. K. Ghosh

Safety concerns and a lack of test data are responsible for the current upper limit of 100 psi on the square root of the concrete compressive strength for use in calculating tension development and lap splice lengths. Based on recent research on the lap splice strength of reinforcing bars in high-strength concrete, modifications to current design criteria are formulated that will allow removal of the limit on the square root of the compressive strength, ensure adequate ductility and bond, and improve the overall safety of the tension development and lap splice criteria in ACI 318-95 for concrete with strengths above 10,000 psi. The result of the analyses used to develop the new design criteria indicate that increasing lap splice length, without providing transverse reinforcement, does not provide an adequate level of ductility in high-strength concrete members. Adequate ductility can be achieved by using a minimum splice length, as defined by ACI 318-95 for beams without transverse reinforcement, plus a minimum quantity of transverse reinforcement over the tension development/lap splice length with an area equal to 50% of the area of the bars being developed/spliced.

Keywords: bond (concrete to reinforcement); building codes; deformed reinforcement; high-strength concrete; reinforcing steels; splicing; structural engineering.

INTRODUCTION

Due to safety concerns and a lack of test data, the ACI Building Code (ACI 318-95)[1] has an upper limit of 100 psi on $\sqrt{f_c'}$ for use in calculating tension development and splice lengths of reinforcing bars (f_c' is the specified compressive strength of concrete; f_c' and $\sqrt{f_c'}$ are expressed in units of stress). Recent research on high-strength concrete[2,3] has demonstrated that, without confining transverse reinforcement, the limitation on $\sqrt{f_c'}$ is justified. The research has also demonstrated that, even with the limit on the $\sqrt{f_c'}$, bond failure, which is normally nonductile, becomes especially brittle and even explosive as concrete strengths approach 15,000 psi (100 MPa). While other research[4] indicates that the ACI development and splice provisions become progressively less accurate as f_c' increases above 7000 to 10,000 psi (50 to 70 MPa), it is not the goal of this paper to introduce new design expressions, but rather to provide modifications to the current design criteria that will: 1) allow removal of the limit on $\sqrt{f_c'}$; 2) ensure adequate ductility in bond; and 3) improve the overall safety of the development and splice criteria in ACI 318-95 for concretes with strengths above 10,000 psi (70 MPa).

The changes proposed in this paper rest heavily on the work of Azizinamini et al.[2,3] on splice strength in high-strength concrete. A typical test specimen is shown in Fig. 1. One of the principal goals of their study was to determine the combination of splice length and confining transverse reinforcement that would provide not only adequate strength, but a displacement ductility μ that would ensure adequate warning of failure. As illustrated in Fig. 2, displacement ductility is defined as the ratio of the maximum deflection Δ_{max} to the yield deflection Δ_y.

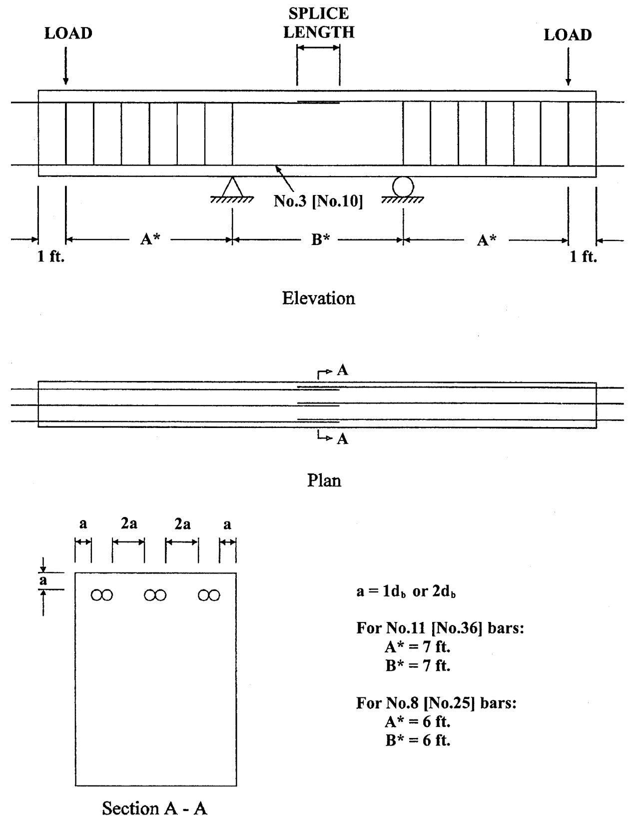

Fig. 1—Test specimen.

In their study, Azizinamini et al.[2,3] evaluated splice strengths of No. 8 and No. 11 (No. 25 and No. 36) bars with concrete covers of 1 bar diameter (d_b) and clear spacings of $2d_b$, and with concrete covers of $2d_b$ and clear spacings of $4d_b$. Of the test specimens, those containing No. 11 bars with a $1d_b$ concrete cover provided the lowest ductility. With the proper combination of splice length and confining transverse reinforcement, however, these specimens were able to attain a displacement ductility of 2.7 at failure without splitting the concrete cover within the splice region and, thus, provide ample warning before failure.

Using this as a starting point, the principal goal of this paper is to establish general criteria and implement code language for development/splice length and transverse reinforcement to ensure both adequate displacement ductility and strength for high-strength concrete members. The resulting criteria represent a

ACI Structural Journal, V. 96, No. 6, November-December 1999.
Received March 23, 1998, and reviewed under Institute publication policies. Pertinent discussion will be published in the September-October 2000 *ACI Structural Journal* if received by May 1, 2000.

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departure from the usual approach to development and splice design.

Full details of the tests are presented by Azizinamini et al.[2,3] and are summarized in Appendix A.*

DEVELOPMENT OF CRITERIA

Displacement ductility

Desirable minimum values of displacement ductility μ can be established for the full range of tests by Azizinamini et al.[2,3] using the value of 2.7 obtained for the specimens with No. 11 (No. 36) bars with $1d_b$ cover. The latter specimens had a reinforcement ratio, $\rho = A_s/bd$, of 0.0164, where A_s is the total area of longitudinal reinforcement outside of the splice region, b = width of the cross section, and d = distance from the centroid of the tension steel to the extreme compression fiber of the concrete. Reducing ρ results in an increase in the curvature at failure and, thus, in the displacement ductility. The target ductilities for the other test specimens in Reference 2 and 3 are established by multiplying μ = 2.7 by the ratio of 0.0164 to the reinforcement ratio for those specimens. The values for the four combinations of bar size and cover/clear spacing are shown in Table 1. They range from 2.7 for specimens containing No. 11 bars with $1d_b$ cover and $2d_b$ clear spacing, to 4.5 for specimens containing No. 8 bars with $2d_b$ cover and $4d_b$ clear spacing.

Behavior of specimens without stirrups

Before establishing minimum requirements for transverse reinforcement, it is worth determining whether adequate ductility can be provided when using high-strength concrete simply by increasing development/splice length without the use of confining stirrups. As demonstrated in Fig. 3(a) and (b) for 15,000 psi (100 MPa) concrete, adequate ductility cannot be provided by increasing splice length alone.[2,3] Figure 3(a) and (b) compare the displacement ductility μ with splice length for No. 11 and No. 8 (No. 36 and No. 25) bars, respectively. In the figures, data points for each combination of bar size and cover/clear spacing are connected by straight lines. The figures also contain horizontal lines representing the target values of μ in Table 1. The figures contain vertical lines corresponding to the splice lengths for each bar size and cover required by ACI 318-95 (without setting a limit on $\sqrt{f_c'}$). Member ductility is adequate if the target value of μ is attained with a splice length that is less than or equal to the splice length required by ACI 318-95. As shown in Fig. 3(a) and (b), this is not accomplished for any of the four combinations of bar size and cover/clear spacing illustrated. This is especially clear for the No. 11 bars with $1d_b$ cover that do not reach the target ductility of 2.7, even at 1.78 times the design splice length.

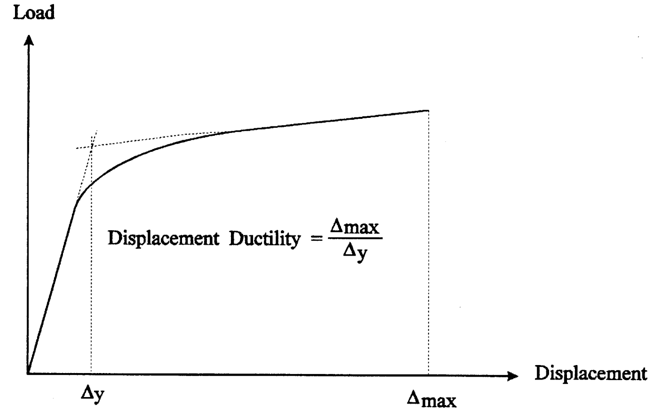

Fig. 2—Definition of displacement ductility.

Table 1—Section properties and target minimum displacement ductilities

Specimen type	Beam* cross section b	d	h	Longitudinal reinforcement ratio ρ	Target displacement ductility μ†
No. 8 (No. 25) bars with 1 d_b cover	9	14.5	16	0.0121	3.6
No. 8 (No. 25) bars with 2 d_b cover	12	13.5	16	0.0098	4.5
No. 11 (No. 36) bars with 1 d_b cover	18	15.9	18	0.0164	2.7
No. 11 (No. 36) bars with 2 d_b cover	18	14.5	18	0.0120	3.7

*b = width; d = effective depth; and h = total depth.
†$\mu = 2.7 \times 0.0164/\rho$.
Note: 1 in. = 25.4 mm.

Behavior of specimens with stirrups

The amount of transverse reinforcement needed to provide adequate ductility depends on the splice length. Figure 4 through 7 compare the displacement ductilities achieved for each combination of bar size and cover/clear spacing with the amount of transverse reinforcement provided for the specimens.[2,3] Transverse reinforcement is expressed as the ratio of the total area of transverse reinforcement provided within the splice length A_{sp} to a quantity of transverse reinforcement equal to 60% of the total area of the bars being spliced, $A_{sr} = 0.6nA_b$, in which n = the number of spliced bars, and A_b = the area of a single spliced bar.†

Each data point in Fig. 4 through 7 corresponds to an individual test.[2,3] In the figure, data points corresponding to specimens with the same splice lengths are connected using straight lines between points. Three splice lengths are used for each combination of cover/clear spacing for No. 11 (No. 36) bars and two

*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.

†A_{sr} approximates the amount of confining transverse steel needed to balance the splitting forces exerted by a longitudinal bar with a 45 degree rib face angle and a zero coefficient of friction between the bar and the surrounding medium. Stresses in the bar and in the transverse reinforcement are assumed to be equal.[4]

Concrete Buildings to Lateral Forces.

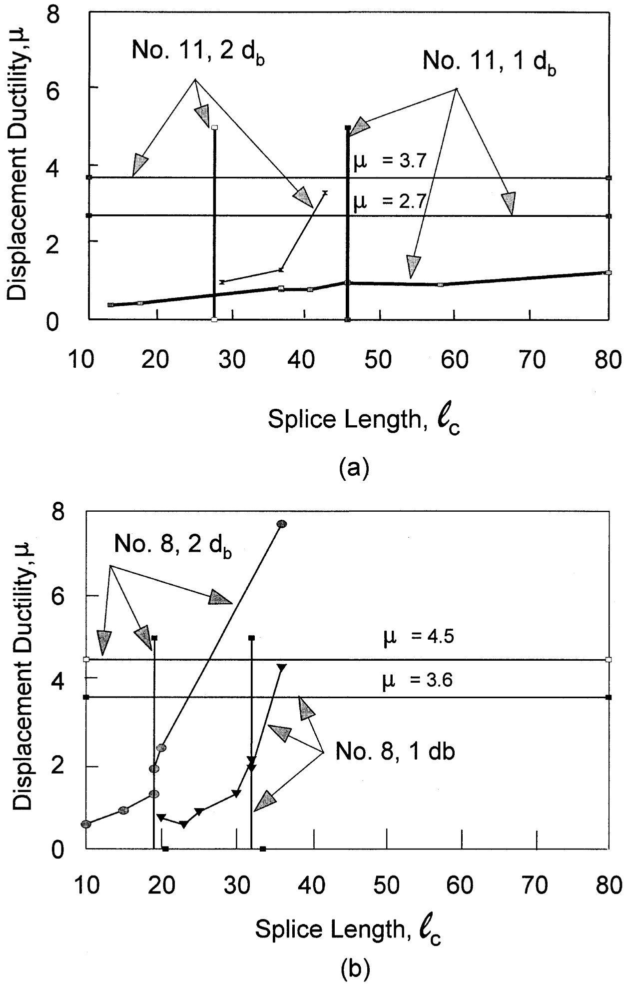

Fig. 3—Displacement ductility versus splice length for: (a) No. 11 (No. 36) bars; and (b) No. 8 (No. 25) bars.

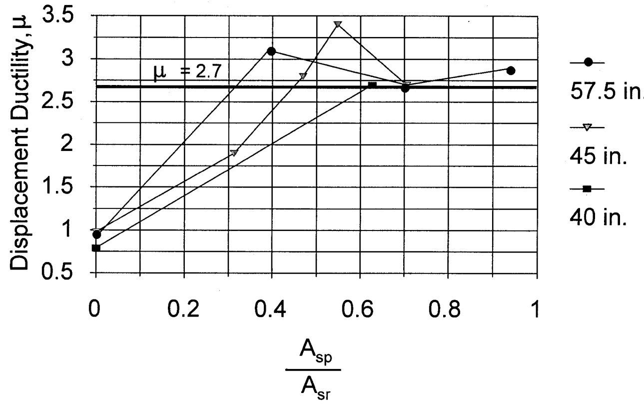

Fig. 4—Displacement ductility versus A_{sp}/A_{sr} *(A_{sp} = total area of transverse reinforcement within splice length; A_{sr} = 60% of total area of bars being spliced) for No. 11 (No. 36) bars with* $1d_b$ *cover and* $2d_b$ *clear spacing.*

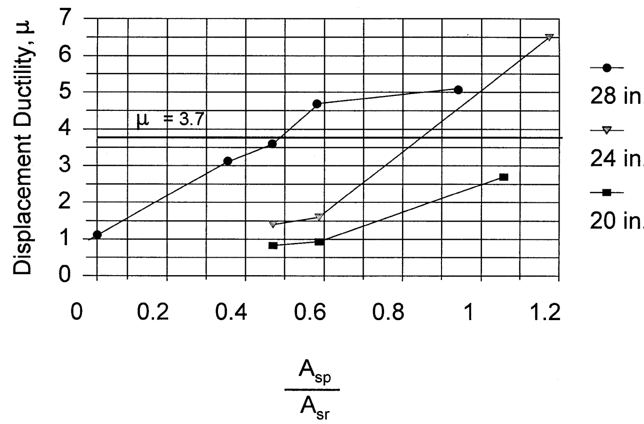

Fig. 5—Displacement ductility versus A_{sp}/A_{sr} *(A_{sp} = total area of transverse reinforcement within splice length; A_{sr} = 60% of total area of bars being spliced) for No. 11 (No. 36) bars with* $2d_b$ *cover and* $4d_b$ *clear spacing.*

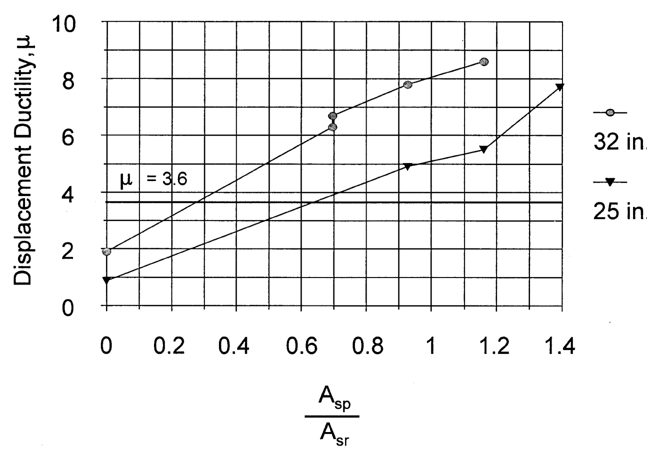

Fig. 6—Displacement ductility versus A_{sp}/A_{sr} *(A_{sp} = total area of transverse reinforcement within splice length; A_{sr} = 60% of total area of bars being spliced) for No. 8 (No. 25) bars with* $1d_b$ *cover and* $2d_b$ *clear spacing.*

splice lengths are used for each combination for No. 8 (No. 25) bars. The three sets of lines in Fig. 4 represent specimens with No. 11 (No. 36) bars with $1d_b$ cover and splice lengths of 40, 45, and 57.5 in. (1020, 1140, and 1460 mm). Because the specimens without stirrups ($A_{sp}/A_{sr} = 0$) failed before exhibiting substantial ductility, their ductility is defined as the ratio of the maximum bar stress at failure to the yield strength of the bars.

The values of A_{sp}/A_{sr} corresponding to the target ductilities are represented by the intersection of the lines connecting the data points with the horizontal lines for the target values for μ. In Fig. 4, the values of A_{sp}/A_{sr} needed to achieve μ = 2.7 are 0.627, 0.453, and 0.320 for splice lengths of 40, 45, and 57.5 in. (1020, 1140, and 1460 mm), respectively. Similar results are presented for the other combinations of bar size and cover/clear spacing in Fig. 5 through 7. For No. 11 (No. 36) bars with $2d_b$ cover, the values of A_{sp}/A_{sr} needed to achieve μ = 3.7 are 1.325, 0.839, and 0.481 for splice lengths of 20, 24, and 28 in. (510, 610, and 710 mm), respectively. For No. 8 (No. 25) bars with $1d_b$ cover, the values of A_{sp}/A_{sr} for μ = 3.6 are 0.629 and 0.269 for splice lengths of 25 and 32 in. (640 and 810 mm), respectively, and for No. 8 (No. 25) bars with $2d_b$ cover, the values of A_{sp}/A_{sr} for μ = 4.5 are 1.328 and 0.76 for splice lengths of 15 and 19 in. (380 and 480 mm), respectively.

These values of A_{sp}/A_{sr} can now be used to determine the amount of transverse reinforcement needed to achieve the target ductilities (Table 1) as a function of splice length. To do this, the values of A_{sp}/A_{sr} are plotted in Fig. 8 versus the corresponding values of l_{sp}/l_{sr}, where l_{sp} is the actual splice length (the splice length provided), and l_{sr} is the splice length required by ACI 318-95 without transverse reinforcement and neglecting limitations on $\sqrt{f_c'}$. (l_{sp} is calculated using Eq. (12-1) in ACI 318-95.[1]) Figure 8 contains four curves, each representing one of the four combinations of bar size and cover/clear spacing.

Using $l_{sp}/l_{sr} = 1.0$ as the basis, the values of A_{sp}/A_{sr} required to achieve the target displacement ductilities range from 0.34 to 0.81, as shown in Fig. 8. As shown in Table 2, these values, in

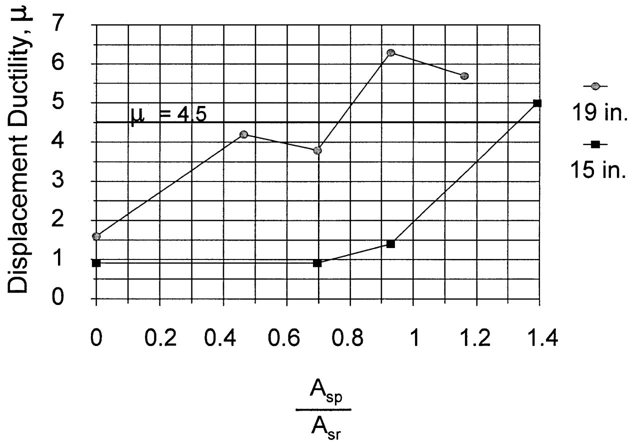

Fig. 7—Displacement ductility versus A_{sp}/A_{sr} *(*A_{sp} *= total area of transverse reinforcement with splice length;* A_{sr} *= 60% of total area of bars being spliced) for No. 8 (No. 25) bars with* $2d_b$ *cover and* $4d_b$ *clear spacing.*

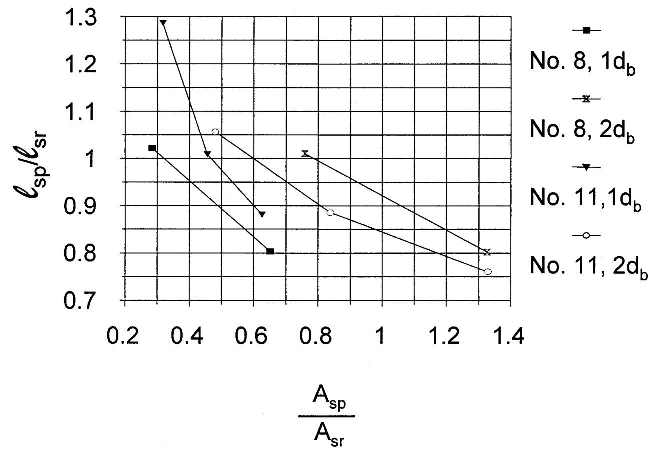

Fig. 8—Ratio of development provided l_{sp} *to development length required by ACI 318-95 without transverse reinforcement and within no limit on* $\sqrt{f_c'}$ *,* l_{sr} *versus* A_{sp}/A_{sr}.

Table 2—Required total area of stirrups for ductile failure

Specimen type	A_{sp}/A_{sr} required to achieve target displacement ductility	A_{sp} required to achieve target displacement ductility
No. 8 (No. 25) bars with $1d_b$ cover	0.34	$0.20nA_b$
No. 8 (No. 25) bars with $2d_b$ cover	0.81	$0.48nA_b$
No. 11 (No. 36) bars with $1d_b$ cover	0.54	$0.32nA_b$
No. 11 (No. 36) bars with $2d_b$ cover	0.59	$0.35nA_b$

Note: A_{sp} = total area of transverse reinforcement within splice length; $A_{sr} = 0.60nA_b$; nA_b = total area of spliced bars.

turn, convert to total stirrup areas, A_{sp} between $0.20nA_b$ to $0.48nA_b$.

Based on these results, it appears prudent, for 15,000 psi (104 MPa) concrete, to require a total cross-sectional area of transverse reinforcement

$$A_{sp} = 0.5nA_b \qquad (1)$$

over a splice region.

Earlier research[5] indicates that adding A_{sp} is equivalent to increasing the stress in a developed/spliced bar by a fixed value Δf_s. For conventional reinforcement

$$\Delta f_s = \left(2177t_d\frac{A_{sp}}{n} + 66\right)\frac{f_c'^{\,1/4}}{A_b} \qquad (2)$$

where $t_d = 0.72\ d_b + 0.28$.

Based on Eq. (2), the amount of transverse reinforcement shown in Eq. (1) will increase the stress in a No. 8 (No. 25) bar by about 13,000 psi (90 MPa) when f_c' = 15,000 psi (104 MPa). This additional strength matches the increases in strength observed in Reference 2 and 3.

The minimum amount of stirrups required by Eq. (1) is based on the test data obtained from testing specimens with concrete compressive strengths of approximately 15,000 psi (104 MPa). Therefore, use of this equation for cases with concrete compressive strength of less than 15,000 psi (104 MPa) will be conservative. Further, the test data and the failure hypothesis presented indicate that, as concrete compressive strength decreases, the severity of the problem with the use of higher strength concrete decreases. As a result, it is suggested that the amount of minimum stirrups required decrease in a linear manner, as the concrete strength decreases. The following equation could be used to reflect this philosophy

$$A_{sp} = 0.5nA_b(f_c'/15{,}000) \qquad (3)$$

where f_c' has a psi unit.

The maximum spacing of stirrups used in the experimental program described in Reference 2 and 3 was 12 in. (300 mm) for specimens containing No. 11 (No. 36) bars, and 15 in. (380 mm) for specimens containing No. 8 (No. 25) bars. Using the more restrictive of the two spacings, it is recommended that stirrups used to provide A_{sp} have a spacing not greater than 12 in. (300 mm). Because the confinement provided by transverse reinforcement is based on a confining force, which can be mobilized by shear or torsion as well as bond splitting, stirrups used as shear and/or torsion reinforcement can also be used to satisfy the area of steel required in Eq. (1). The transverse reinforcement should not be smaller than a No. 3 (No. 10) bar, the smallest size used by Azizinamini et al.[2,3]

RECOMMENDATIONS

Based on the information provided in this paper, the following specific changes are recommended for future editions of ACI 318.

Existing Section 12.1.2 of ACI 318-95

"The values of $\sqrt{f_c'}$ used in this chapter shall not exceed 100 psi."

Change Section 12.1.2 of the ACI 318-95 as follows:

"When the value of $\sqrt{f_c'}$ exceeds 100 psi, the requirements of Sec. 12.2.6 must be satisfied in calculating tension development or lap splice length. For other cases, the values of $\sqrt{f_c'}$ used in this chapter shall not exceed 100 psi."

Add a new section (Section 12.2.6) as follows:

"When the value of $\sqrt{f_c'}$ exceeds 100 psi, l_d shall be calculated from either 12.2.2 or 12.2.3 with $K_{tr} = 0$, and transverse reinforcement with total cross-sectional area A_{sp} crossing the potential plane of splitting through the reinforcement being developed shall be provided over the tension development or tension splice length.

$$A_{sp} = 0.5nA_b(f_c'/15{,}000) \qquad (12\text{-}2)$$

"The maximum spacing of stirrups in the longitudinal direction shall not exceed 12 in., where d_b is the bar diameter. A minimum of three stirrups shall be used, and the minimum stirrup bar size shall be No. 3."

Add new commentary (Section R12.2.6)

"Research results show that when $\sqrt{f_c'}$ exceeds 100 psi, a minimum tension development or splice length equal to the value calculated without confining transverse reinforcement and without a limit on $\sqrt{f_c'}$ must be combined with a minimum amount of transverse reinforcement to assure adequate strength and ductility. As a minimum, No. 3 reinforcing bars must be used as stirrups. Test results indicate that use of smaller bar sizes may result in fracturing the stirrups."[2,3]

CONCLUSIONS

Based on the analysis presented in this paper, it can be concluded that for high-strength concrete:

1. Increasing tension lap splice length without providing transverse reinforcement will not provide an adequate level of ductility in high-strength concrete members.

2. Adequate ductility can be achieved by using a minimum lap splice length, as defined by ACI 318-95 for beams without transverse reinforcement, plus a minimum amount of transverse reinforcement over the tension development/lap splice length with an area equal to 50% of the area of the bars being developed/spliced.

ACKNOWLEDGMENTS

The work reported in this paper is based on research performed at the University of Nebraska-Lincoln and the University of Kansas. Work at the University of Nebraska was supported by the National Science Foundation under NSF Grant No. CMS-9402311, the Portland Cement Association, and the Center for Infrastructure Research at the University of Nebraska-Lincoln. Research at the University of Kansas was supported by the National Science Foundation under NSF Grants No. MSS-9021066 and CMS-9402563, the Civil Engineering Research Foundation under CERF Contract No. 91-N6002, ABC Coating, Inc., AmeriSteel, Birmingham Steel Corp., Chapparal Steel Co., Fletcher Coating Co., Florida Steel Corp., North Star Steel Co., 3M Corp., Iron Mountain Trap Rock Co., Geiger Ready Mix, and Richmond Screw Anchor Co.

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