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Conventional and High-Strength Hooked Bars—Part 2: Data Analysis

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Empirical equations are developed to characterize the anchorage strength of hooked bars. The equations are based on tests of 245 simulated beam-column joint specimens with two hooked bars: 146 with confining reinforcement and 99 without. Bar stresses at failure for specimens used in the analysis ranged from 30,800 to 144,100 psi (212 to 994 MPa), and concrete compressive strengths ranged from 2570 to 16,200 psi (17.7 to 112 MPa). For the specimens analyzed, hooked bar anchorage strength was proportional to concrete compressive strength raised to the 0.29 power. For confining reinforcement parallel to and located within eight or 10 bar diameters of the straight portion of the hooked bar, the contribution to anchorage strength was proportional to the area of confining reinforcement; for confining reinforcement perpendicular to the straight portion of the bar, more legs of the confining reinforcement contributed to anchor strength, but each leg made a smaller contribution.

Keywords: anchorage; beam-column joints; bond and development; high-strength concrete; high-strength steel; hooks; reinforcement.

INTRODUCTION

Since the early 1900s, many studies have investigated the development and splice strength of straight deformed bars for a wide range of material properties (Abrams [1913]; Lutz and Gergely [1967]; Azizinamini et al. [1993]; Darwin and Graham [1993]; Darwin et al. [1996]; Zuo and Darwin [2000], among others). The large number of physical tests performed in these studies provided a solid basis for developing equations that accurately characterize bond strength for reinforcing steel with yield strengths up to 120,000 psi (827 MPa) and concrete compressive strengths up to 16,000 psi (110 MPa) (Darwin et al. 1996; Zuo and Darwin 2000; ACI Committee 408 2003; Darwin et al. 2005; Seliem et al. 2009). Similar equations, however, have not been formulated for hooked bars. Therefore, when describing the strength or behavior of hooked bars, researchers typically compare test results with strengths calculated using the provisions for hooked bar development length ℓ_{dh} in the ACI 318 Building Code (ACI Committee 318 2014). The main drawback of these provisions is that they were developed based on a very small data set that does not include high-strength steel or high-strength concrete (Minor and Jirsa 1975; Marques and Jirsa 1975; and Pinc et al. 1977). Furthermore, the ACI 318 hooked bar development length equation is not meant to characterize the behavior of hooked bars, but rather to provide a safe estimate of development length for design. Thus, the anchorage strength of hooked bars, particularly in structural elements with high-strength materials, cannot be accurately calculated using the development length equation of ACI 318-14, as demonstrated by Sperry et al. (2015a,b; 2017). The goal of this study is to develop an expression that characterizes the anchorage strength of hooked bars and is applicable to the entire range of concrete and steel strengths currently available in construction practice.

The equation for hooked bar development length in tension ℓ_{dh} in ACI 318-14 is

$$\ell_{dh} = \left(\frac{f_y \psi_e \psi_c \psi_r}{50\lambda\sqrt{f_c'}}\right) d_b \text{ (in.-lb)} \tag{1a}$$

$$\ell_{dh} = \left(\frac{0.24 f_y \psi_e \psi_c \psi_r}{\lambda\sqrt{f_c'}}\right) d_b \text{ (SI)} \tag{1b}$$

where ℓ_{dh} is measured from the outside end of the hook at the point of tangency, toward the critical section (in. or mm); f_y is the yield strength of the hooked bar (psi or MPa); d_b is the nominal diameter of the hooked bar (in. or mm); λ is the modification factor that reflects the reduced mechanical properties of lightweight concrete compared to normalweight concrete with the same compressive strength; and f_c' is the specified concrete compressive strength (psi or MPa). Equation (1) also includes three modification factors ψ that account for bar coating ψ_e, concrete cover ψ_c, and confining reinforcement in the hook region ψ_r.

The stress corresponding to the anchorage capacity of an uncoated hooked bar cast in normalweight concrete, designated $f_{s,ACI}$, can be obtained from Eq. (1) by substituting $f_{s,ACI}$ for f_y, the measured embedment length ℓ_{eh} for ℓ_{dh}, the measured concrete compressive strength f_{cm} for f_c', and setting ψ_e and λ equal to 1.0.

$$f_{s,ACI} = \frac{50\ell_{eh}\sqrt{f_{cm}}}{\psi_c \psi_r d_b} \text{ (in.-lb)} \tag{2a}$$

$$f_{s,ACI} = \frac{\ell_{eh}\sqrt{f_{cm}}}{0.24\psi_c \psi_r d_b} \text{ (SI)} \tag{2b}$$

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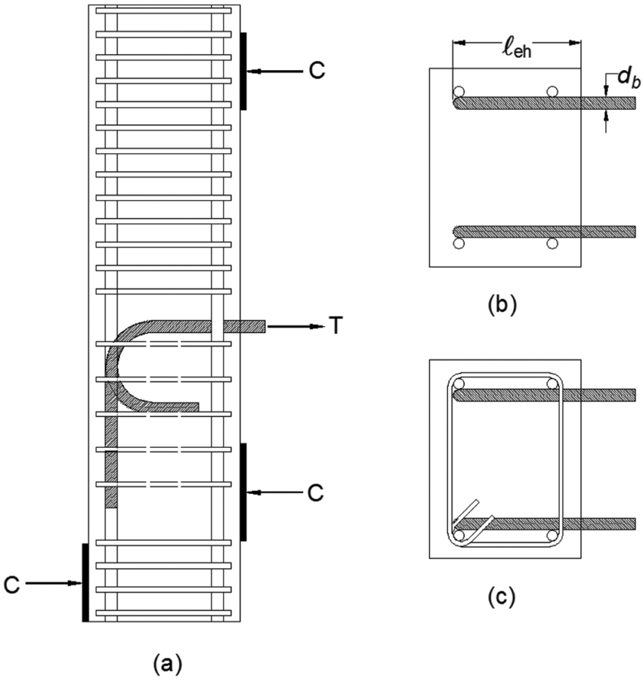

Fig. 1—Beam-column specimens: (a) side view; (b) cross section without confining reinforcement; and (c) cross section of specimen with confining reinforcement parallel to straight portion of hooked bar.

ℓ_{eh} is shown in Fig. 1 for the specimens used in this study.

Two modification factors, ψ_c and ψ_r, remain in Eq. (2). As defined in Section 25.4.3.2 of ACI 318-14, the cover factor ψ_c is 0.7 for No. 11 and smaller hooked bars with side cover of at least 2.5 in. (65 mm) and for 90-degree hooks with at least 2 in. (50 mm) of clear cover to the tail of the hook; otherwise, ψ_c is 1.0. The factor ψ_r is 0.8 for No. 11 and smaller hooked bars with confining reinforcement parallel (90-degree hooks only) or perpendicular (90- and 180-degree hooks) to the straight portion of the hooked bar and spaced no further than $3d_b$ apart; otherwise, ψ_r is 1.0.

Equations (1) and (2) imply that the stress in a hooked bar at failure is proportional to the square root of the concrete compressive strength and inversely proportional to the bar diameter. It was shown by Sperry et al. (2015a,b; 2017), however, that as the concrete compressive strength increases, the development length calculated using Eq. (1) becomes less conservative. This trend implies that using the square root of the concrete compressive strength as a design parameter overstates the effect of compressive strength on anchorage strength. This is consistent with findings for straight bars, where studies have shown that the stress developed in a bar is proportional to the concrete compressive strength raised to the quarter power (Darwin et al. 1996; Zuo and Darwin 2000; Darwin et al. 2005). Sperry et al. (2015a,b; 2017) also showed that anchorage strengths calculated with Eq. (2) underestimate measured strengths in small hooked bars (No. 5 [No. 16]) and overestimate strengths for larger bars (No. 11 [No. 36]). This trend indicates that the inversely proportional relationship between anchorage strength and bar diameter in Eq. (2) is not accurate. Sperry et al. (2015a,b; 2017) observed that when modification factors for cover and confining reinforcement in Section 25.4.3.2 of ACI 318-14 (equal to 0.7 and 0.8, respectively) were used; calculated anchorage strengths were unconservative, particularly for higher-strength concretes and larger diameter bars.

In light of the inconsistencies that arise when extrapolating the provisions of ACI 318-14 well beyond the range of material strengths and bars sizes for which they were originally calibrated, a new set of equations were developed to accurately characterize the effects of concrete compressive strength, bar diameter, and confining reinforcement on the anchorage strength of hooked bars. The effects of other parameters, such as hook bend angle, clear concrete side cover to the hooked bar, hooked bar placement inside or outside the column core, and spacing between hooked bars are described by Sperry et al. (2015a).

RESEARCH SIGNIFICANCE

Although equations characterizing the development length of straight deformed bars are available in the literature for a wide range of material strengths and bar sizes, the same cannot be said for hooked bars. The research presented in this paper is aimed at developing anchorage strength equations for hooked bars that apply to the full range of concrete compressive strengths and reinforcing steel yield strengths currently used in practice. These equations are derived based on the results from a large-scale experimental study investigating key parameters affecting hooked bar anchorage strength.

HOOKED BAR DATABASE

Test data from 245 simulated exterior beam-column joint specimen tests were used in the analysis. The data represent specimens containing two hooked bars, 214 from the recent study by Sperry et al. (2015a,b; 2017) and 31 from previous research (Marques and Jirsa 1975; Pinc et al. 1977; Hamad et al. 1993; Ramirez and Russell 2008; Lee and Park 2010). Details of the specimens used in the analysis are presented in Appendix A.*

The majority of the tests in the database, those by Sperry et al. (2015a,b, 2017), were used to study the effects on hooked bar anchorage strength of embedment length, side cover, amount of confining reinforcement, concrete compressive strength, hooked bar size, and hook bend angle. No. 5, 8, and 11 (No. 16, 25, and 36) hooked bars were tested in normalweight concrete with compressive strengths ranging from 4300 to 16,200 psi (30 to 112 MPa). Figure 1 shows the geometry and loading configuration of the simulated beam-column joints tested by Sperry et al. (2015a,b; 2017). The straight portions of two hooked bars, representing longitudinal beam reinforcement, protruded from the face of the column. The compression zone of the beam was simulated using a bearing member on the testing frame (Sperry et al. 2015a,b; 2017). For specimens with confining reinforcement, the majority of that reinforcement was oriented

*The Appendix is available at **www.concrete.org/publications** in PDF format, appended to the online version of the published paper. It is also available in hard copy from ACI headquarters for a fee equal to the cost of reproduction plus handling at the time of the request.

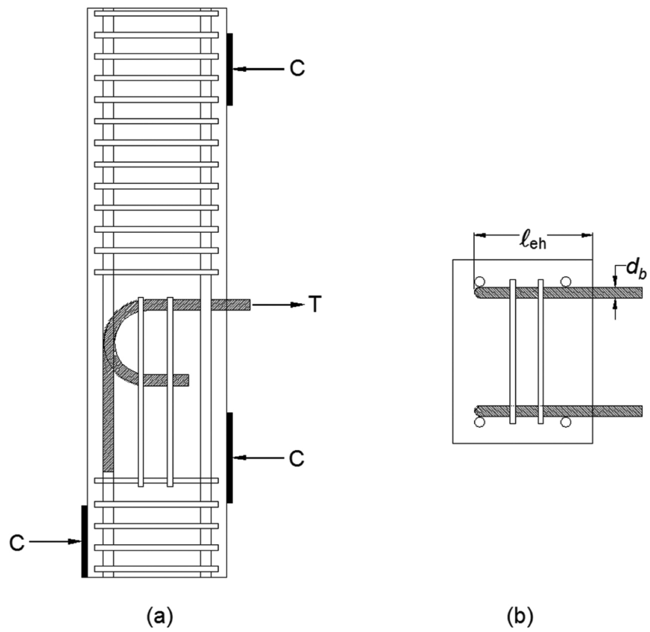

Fig. 2—Beam-column specimen with confining reinforcement perpendicular to straight portion of hooked bar: (a) side view; and (b) cross section.

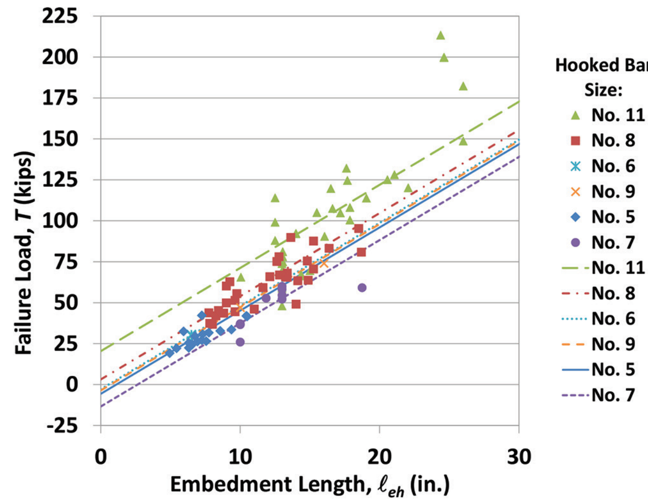

Fig. 3—Bar force at failure T versus embedment length ℓ_{eh} for hooked bars without confining reinforcement. (Note: 1 kip = 4.448 kN; 1 in. = 25.4 mm.)

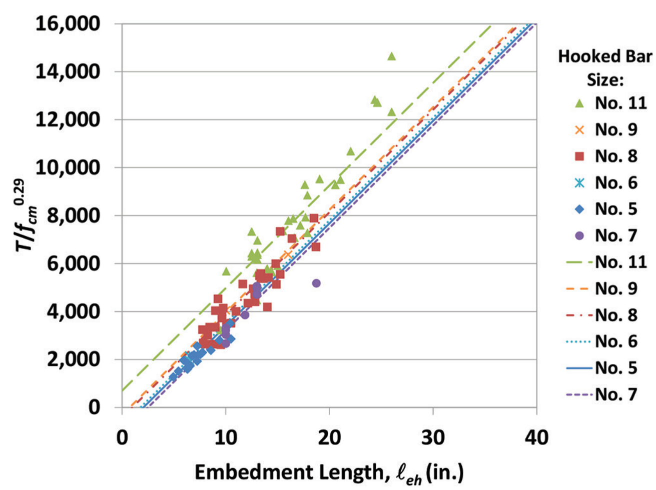

Fig. 4—Bar force at failure T normalized to $f_{cm}^{0.29}$ versus embedment length ℓ_{eh} for hooked bars without confining reinforcement. T in lb and f_{cm} in psi. (Note: 1 lb = 4.448 N; 1 psi = 0.006895 MPa; 1 in. = 25.4 mm.)

parallel to the straight portion of hooked bars (Fig. 1). A limited number of specimens had confining reinforcement oriented perpendicular to the straight portion of the hooked bars, as shown in Fig. 2. Nominal clear cover from the side of the hooked bar to the side of the column (side cover) ranged from 2.5 to 3.5 in. (65 to 90 mm). Hooked bar center-to-center spacing was $11d_b$. Hooked bar stresses at failure ranged from 33,000 to 144,100 psi (228 to 994 MPa). The 31 specimens from previous studies (Marques and Jirsa 1975; Pinc et al. 1977; Hamad et al. 1993; Ramirez and Russell 2008; Lee and Park 2010) included tests of No. 7, 9, and 11 (No. 22, 29, and 36) hooked bars in normalweight concrete with compressive strengths ranging from 2570 to 12,850 psi (17.7 to 88.6 MPa). Hooked bar stresses at failure ranged from 30,800 to 143,900 psi (212 to 992 MPa). Overall, the database used in this analysis included 99 specimens without confining reinforcement and 146 with confining reinforcement.

ANALYSIS OF TEST RESULTS

Iterative statistical analyses were conducted to determine the effects of key parameters (embedment length, concrete compressive strength, hooked bar diameter, and quantity of confining reinforcement) on hooked bar anchorage strength using the test results included in the database.

Three different cases were addressed: hooked bars without confining reinforcement (Fig. 1(b)), hooked bars with differing quantities of confining reinforcement oriented parallel to the straight portion of the hooked bar (Fig. 1(c)), and hooked bars with differing quantities of confining reinforcement oriented perpendicular to the straight portion of the hooked bar (Fig. 2). The average bar force at failure T is defined as the peak load on the specimen divided by the number (two) of hooked bars, and the embedment length ℓ_{eh} refers to the average of the measured embedded lengths of the two bars in a specimen.

Descriptive equation for hooked bars without confining reinforcement

A least-squares regression technique including dummy variables (Draper and Smith 1981) was used to evaluate the influence of various design parameters on anchorage strength. This analysis technique consists of calculating linear regression equations with the same slope and different intercepts for data subsets that include one or more dummy variables. Linear regression equations derived in this manner produce a series of parallel lines, as shown in Fig. 3 and 4. The legends in these figures identify the data subsets in the order, top to bottom, in which they appear. The difference between the intercepts of these "dummy variable lines" shows the relative effect of the dummy variable on the dependent variable—for example, the effect of bar size on failure force T (lb [N]) in Fig. 3. A small spread in the intercepts of the dummy variable lines with respect to the total range in the data indicates that the relationship between the variables could be represented satisfactorily by a single best-fit line, which is the ultimate goal of the optimization process. In this analysis, emphasis was placed on finding the best-fit equation for the data set, leaving simplifications and rounding of coefficients for the implementation of design provisions.

Figure 3 shows the measured average bar force at failure T as a function of embedment length ℓ_{eh} for the 99 beam-column joint specimens without confining reinforcement. The values of T ranged from 19 to 213 kip (84.5 to 947 kN). Bar stresses ranged from 30,800 to 136,700 psi (212 to 943 MPa), embedment lengths ℓ_{eh} ranged from 4.9 to 26.0 in. (124 to 660 mm), and concrete compressive strengths ranged from 2570 to 16,200 psi (17.7 to 112 MPa). The general trend shows that anchorage strength increases with increased embedment length.

The analysis shown in Fig. 3 did not include the influence of concrete compressive strength. As the next step, dummy variables analysis was used to determine the appropriate power of concrete compressive strength p_1 for use in an expression to characterize anchorage capacity. The optimal value of the exponent p_1 was determined by minimizing the spread in the intercepts when $T/f_{cm}^{p_1}$ was plotted versus ℓ_{eh}. The magnitude of the spread was evaluated using the relative intercept, defined as the difference between the maximum and minimum intercepts of the dummy variable lines normalized with respect to the difference between the maximum and minimum values of $T/f_{cm}^{p_1}$. Using this method, the value of p_1 was found to be 0.29. The results are shown in Fig. 4.

The value of p_1 = 0.29 found in the analysis is significantly less than 1/2 (used in the design provisions of the ACI Code [ACI Committee 318 2014]), and is consistent with test results for straight bars that show that bond strength is proportional to concrete compressive strength raised to a power of 1/4 (Darwin et al. 1996; Zuo and Darwin 2000; Darwin et al. 2005). Similar to the bond strength of straight reinforcement, anchorage strength of hooked bars is governed by the combined effects of concrete tensile strength, which controls initial crack formation, and fracture energy, which controls crack propagation. Research shows that while the tensile strength of concrete increases with the compressive strength to a power between 1/2 and 2/3 (Ahmad and Shah 1985), the fracture energy of concrete is nearly independent of compressive strength (Darwin et al. 2001). It is hypothesized that the combined effects of tensile strength and fracture energy cause anchorage strength to be proportional to concrete compressive strength to a power well below 1/2.

In Fig. 4, trend lines for specimens with larger hooked bars have higher intercepts than those for specimens with smaller hooked bars, indicating that for the same embedment length, larger hooked bars provide greater anchorage strength. The relationship between the parameter $T/f_{cm}^{0.29}$ and embedment length times the bar diameter raised to a power

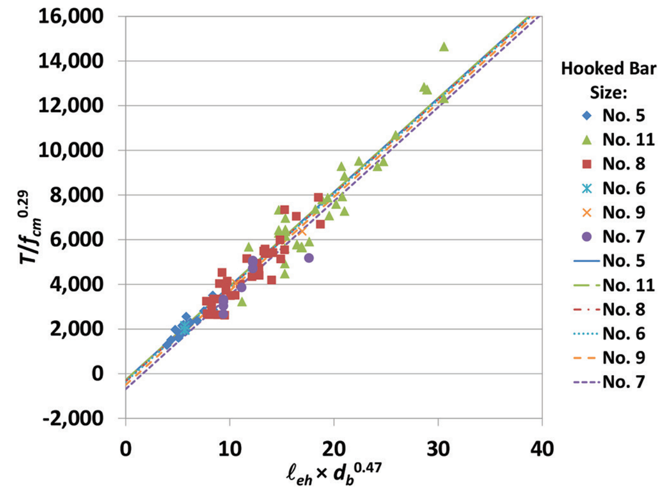

Fig. 5—Bar force at failure T *normalized to* $f_{cm}^{0.29}$ *versus product of embedment length* ℓ_{eh} *and bar diameter* d_b *to the 0.47 power for hooked bars without confining reinforcement.* T *in lb and* f_{cm} *in psi. (Note: 1 lb = 4.448 N; 1 psi = 0.006895 MPa; 1 in. = 25.4 mm.)*

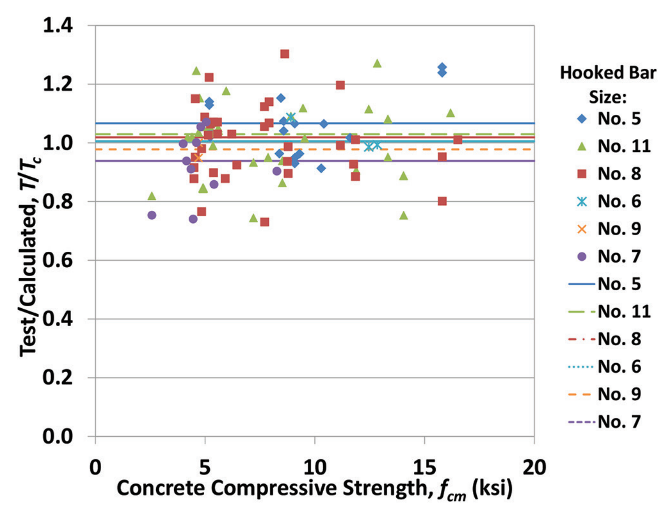

Fig. 6—Ratio of bar force at failure T *to calculated bar force based on Eq. (3)* T_c *versus concrete compressive strength for hooked bars without confining reinforcement. (Note: 1 ksi = 6.895 MPa.)*

p_2 was evaluated to establish the effect of bar diameter on anchorage strength for hooked bars without confining reinforcement (Fig. 5). Statistical analyses showed that p_2 = 0.47 minimized the spread in the intercepts of the dummy variable lines. Using the slope and average intercept of the lines in Fig. 5, the strength of hooked bars without confining reinforcement can be represented as

$$\frac{T_c}{f_{cm}^{0.29}} = 422\ell_{eh}d_b^{0.47} - 417 \text{ (in.-lb)} \qquad (3a)$$

$$\frac{T_c}{f_{cm}^{0.29}} = 68.4\ell_{eh}d_b^{0.47} - 7855 \text{ (SI)} \qquad (3b)$$

Ratios of bar force at failure to bar force calculated using Eq. (3), T/T_c, are plotted with respect to f_{cm} in Fig. 6. The

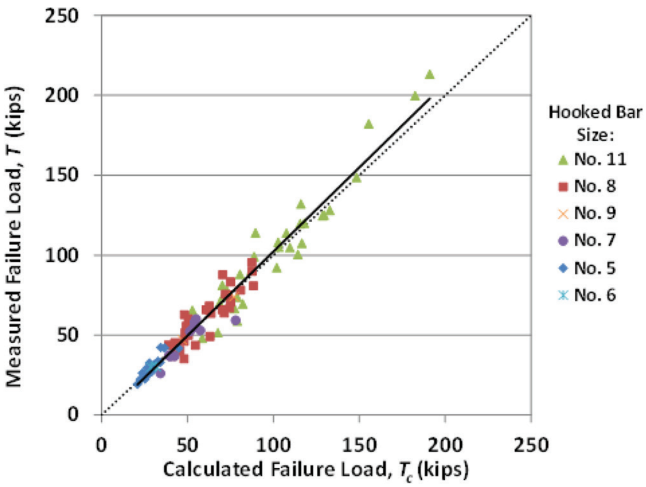

Fig. 7—Bar force at failure T *for hooked bars without confining reinforcement versus calculated bar force based on Eq. (4)* T_c. *(Note: 1 kip = 4.448 kN.)*

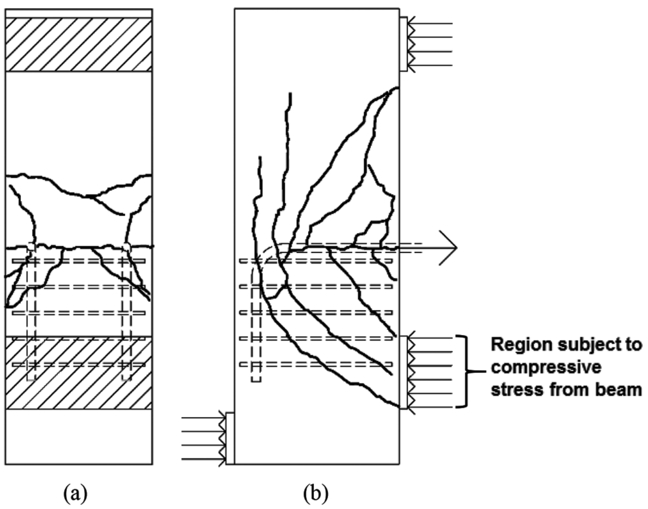

Fig. 8—Crack pattern at failure in beam-column specimen with respect to reinforcement in joint region and region subjected to compressive stress from the beam: (a) front view; and (b) side view.

resulting dummy variable lines are nearly horizontal, indicating that Eq. (3) adequately represents the effect of concrete compressive strength on anchorage strength. The intercepts of the individual trend lines are relatively close, ranging from 0.94 to 1.07, with no order based on bar size, indicating that Eq. (3) adequately captures the effect of bar size. The mean value of the ratio T/T_c is 1.0, with a coefficient of variation of 0.12, and a range between 0.73 and 1.30.

In the analyses described thus far, it was assumed that the relationship between the anchorage force at failure T and embedment length ℓ_{eh} is linear. To further improve accuracy, the data were reanalyzed using a power regression model to characterize the relationship between T and embedment length ℓ_{eh}. The powers of ℓ_{eh} and d_b were chosen to minimize the sum of the squared differences $(1 - T/T_c)^2$. The resulting equation is

$$T_c = 332 f_{cm}^{0.29} \ell_{eh}^{1.06} d_b^{0.54} \text{ (in.-lb)} \quad (4a)$$

$$T_c = 35.4 f_{cm}^{0.29} \ell_{eh}^{1.06} d_b^{0.54} \text{ (SI)} \quad (4b)$$

This nonlinear relationship, which has a power of ℓ_{eh} slightly greater than 1.0, is plausible considering that both the front and side failures described by Sperry et al. (2015a,b, 2017) involve a failure surface that becomes progressively larger as embedment length increases. Figure 7 shows a comparison between the bar forces at failure and the calculated bar forces T_c based on Eq. (4). The dashed line in Fig. 7 represents equality between the measured and calculated anchorage strengths and the solid line is the best fit line for the data set. The fact that the two lines are very close further indicates that Eq. (4) provides a good estimate of anchorage strength for the entire range of test results. The average test-to-calculated ratio using Eq. (4) is equal to 1.0 with a coefficient of variation of 0.12 and ratios of T/T_c ranging from 0.73 to 1.30. These values are identical (to two significant figures) to those calculated using Eq. (3). These results show that a power of 1.06 on ℓ_{eh} produces similar results to a power of 1.0, with the most significant difference being for large bars with deep embedment lengths. Thus, for design, it would be justified to use the power of 1.0 for the embedment length.

Descriptive equations for hooked bars with confining reinforcement

The contribution of the confining reinforcement T_s to the anchorage strength was found by subtracting T_c (the bar force calculated using Eq. (4)) from the measured bar force at failure T for hooked bars with confining reinforcement. On average, the value of T_c represents 82% of the total anchorage strength of a hooked bar with confining reinforcement. Due to the relatively small number of specimens (12) containing standard hooks with confining reinforcement tested prior to this study (Marques and Jirsa 1975; Hamad et al. 1993; Ramirez and Russell 2008; and Lee and Park 2010) and the inherent variability in the contribution of the confining steel to the strength of the hooked bars, only specimens that were tested in this study were used to develop the expression for T_s, eliminating the potential variability introduced by a small number of specimens with a narrow range of input parameters and different methods of testing.

Based on the cracking patterns (Fig. 8) and the observed failure modes described by Sperry et al. (2015a,b; 2017), which were similar for specimens with and without confining reinforcement, confining reinforcement resists widening of cracks in the plane of the hook and inclined cracks within the joint. The nature of the failure modes suggests that confining reinforcement oriented parallel to the straight portion of a hooked bar serves as an anchor for the concrete failure cone pulled out by the hooked bars. According to this model, the increase in anchorage strength attributable to confining reinforcement should be proportional to the quantity of confining reinforcement in the direction of the bar being developed.

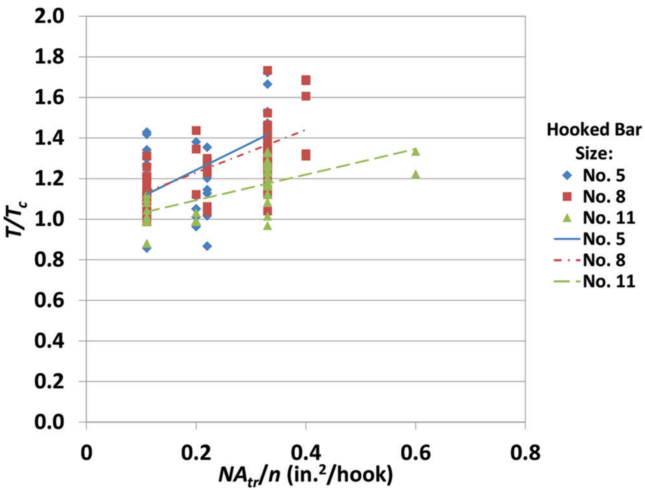

Fig. 9—Ratio of bar force at failure T *for hooked bars confined by reinforcement parallel to straight portion of hooked bar to calculated anchorage strength provided by concrete based on Eq. (4)* T_c. *(Note: 1 in. = 25.4 mm.)*

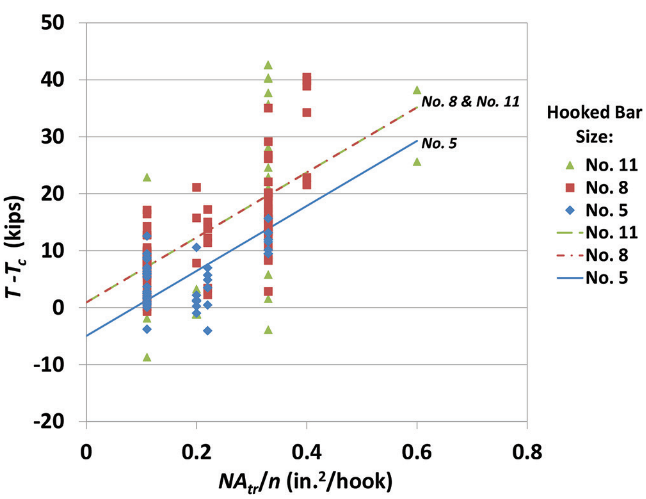

Fig. 10—Bar force at failure in excess of calculated concrete contribution based on Eq. (4) T_c *versus amount of confining reinforcement parallel to straight portion of hooked bar. (Note: 1 kip = 4.448 kN; 1 in. = 25.4 mm.)*

Figures 9 and 10, respectively, show the ratio T/T_c and $T\text{-}T_c$ plotted as functions of NA_{tr}/n, an index representing the effective amount of confining reinforcement within the hook region. The term N is the number of legs of confining reinforcement parallel to the straight portion of a hooked bar within a dimension equal to the outside diameter of a hooked bar bent in accordance with Table 25.3.1 of ACI 318-14 (that is, within $8d_b$ from the top of the hooked bar for No. 3 through No. 8 [No. 10 through No. 25] hooked bars or $10d_b$ from the top of the bar for No. 9 through No. 11 [No. 29 through No. 36] hooked bars), as shown in Fig. 11(a); or the number of legs perpendicular to the hooked bar over the length being developed, as shown in Fig. 11(b). The term A_{tr} is the area of a single leg of confining reinforcement, and n is the number of hooked bars. For example, a configuration with two hooked bars confined by No. 3 (No. 10) ties spaced at $3d_b$ and oriented parallel to

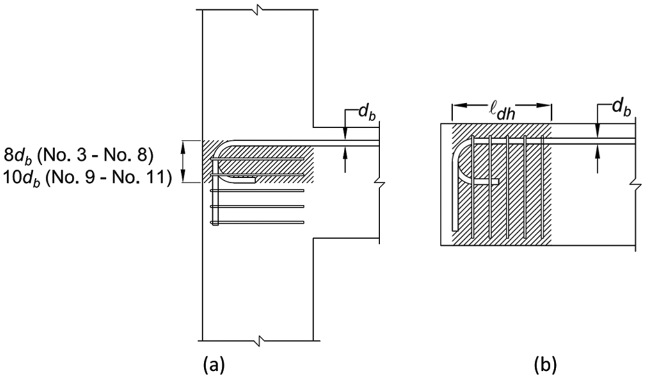

Fig. 11—Locations of effective confining reinforcement: (a) confining reinforcement parallel; or (b) perpendicular to straight portion of hooked bar.

the straight portion of the bar leads to three No. 3 [No. 10] ties for a total of six legs, resulting in $NA_{tr}/n = (6 \times 0.11)/2 = 0.33$ in.^{2}/hook (213 mm^2/hook). For the test specimens used in this analysis, NA_{tr}/n ranged from 0.11 to 0.60 in.^{2}/hook (71 to 387 mm^2/hook), with maximum values of N equal to 6 and 10, respectively, for confining reinforcement oriented parallel and perpendicular to the straight portion of the bar.

In the current formulation, the definition of N for confining reinforcement parallel to the straight portion of a hooked bar is applicable to both 90- or 180-degree standard hooks (in contrast to ACI 318-14, which credits reinforcement parallel to the straight portion of the hooked bar as strengthening only 90-degree hooks) and is based on the observation that not all ties confining a hooked bar will contribute to the tensile capacity of the hook. For example, ties located within the region subjected to compressive stress from the beam, as shown in Fig. 8, are unlikely to carry significant tensile stress. Based on this observation, several definitions of N were systematically evaluated in the analysis of the test results. Using a dimension equal to the minimum outside bend diameter prescribed by ACI 318-14 for a hooked bar to define the region where ties are effective in resisting the pullout force of the hook resulted in the least scatter when compared with test results. This definition of N is also supported by visual observations of specimens after failure, which showed that the majority of the cracks at failure were confined by the ties closest to the straight portion of the hook (that is, those within 8 to $10d_b$ of the straight portion of the hooked bar). Some cracks on the side faces of the specimens extended past ties in the compression region, but the concrete failure cone on the front face of the specimen did not extend below the compression region. This crack pattern suggests that the majority of the tensile force resisted by the confining reinforcement is carried by those bars closest to the hooked bar—that is, outside the compression zone of the beam.

The effect on anchorage strength was also investigated for cases of confining reinforcement placed perpendicular to the straight portion of a hooked bar. The provisions of ACI 318-14 allow the use of a development length modification factor of 0.8 for 180- and 90-degree hooked bars where confining reinforcement is oriented perpendicular to the straight portion of the bar and spaced at $3d_b$ or less. The modification factor is also applicable to 90-degree hooked bars where confining reinforcement meeting the same spacing requirement is placed parallel to the straight portion of the bar. Although adding confining reinforcement perpendicular to the straight portion of a hooked bar was found to increase anchorage strength, the test results indicate that its effect on anchorage strength was different than if it was parallel to the straight portion of the bar. The observed modes of failure (Sperry et al. 2015b) indicate that confining reinforcement oriented parallel to the straight portion of the bar acts as anchor reinforcement, restraining the concrete from being pulled out the front of the column. In contrast, confining reinforcement oriented perpendicular to the straight portion of the bar restrains the propagation of cracks within the joint similar to the manner in which confining reinforcement restrains the propagation of splitting cracks for straight bars, but it does not act as anchor reinforcement and is pulled through the front of the column with the cone of concrete at failure (Sperry et al. 2015b). Thus, the two cases (confining reinforcement parallel versus perpendicular) were analyzed separately.

Confining reinforcement parallel to straight portion of hooked bar—Figure 9 shows the ratio of measured anchorage strength to the calculated anchorage strength provided by concrete (Eq. (4)) T/T_c versus the parameter NA_{tr}/n for hooked bars with confining reinforcement oriented parallel to the straight portion of the bar. The strength in excess of the concrete contribution $T_s = T - T_c$, is plotted versus the parameter NA_{tr}/n in Fig. 10. The figures include results from 140 specimens with values of NA_{tr}/n ranging from 0.11 to 0.60 in.^{2}/hook (71 to 387 mm^2/hook). The average bar force at failure ranged from 19 to 210 kip (84.5 to 934 kN), with the stress ranging from 41,000 to 144,100 psi (283 to 994 MPa). The average embedment lengths ranged from 3.75 to 23.5 in. (95.3 to 597 mm), and concrete compressive strengths ranged from 4300 to 16,200 psi (29.6 to 112 MPa). In the figures, a value of NA_{tr}/n of 0.33 in.^{2}/hook (213 mm^2/hook) corresponds to No. 3 (No. 10) ties spaced at $3d_b$ (which satisfies the requirement for use of the development length modification factor ψ_r = 0.8). Values of NA_{tr}/n of 0.40 in.^{2}/hook (258 mm^2/hook) for No. 8 (No. 25) bars and 0.60 in.^{2}/hook (387 mm^2/hook) for No. 11 (No. 36) bars correspond to the higher quantities of confining reinforcement required by Section 21.7.3 of ACI 318-11 (ACI Committee 318 2011) for joints in special moment frames. The trend lines for each bar size in Fig. 9 and Fig. 10 are, respectively, the best-fit lines and the lines resulting from a dummy variables analysis. Figure 9 shows that T/T_c increased with an increase in NA_{tr}/n, with smaller bars exhibiting a greater relative increase in T/T_c than the larger bars. This comparison shows that the increase in hooked bar anchorage strength provided by confining reinforcement cannot be expressed as a percentage of T_c for all bar sizes. This is contrary to the implication of Section 25.4.3.2 of ACI 318-14, which permits the use of the modification factor ψ_r

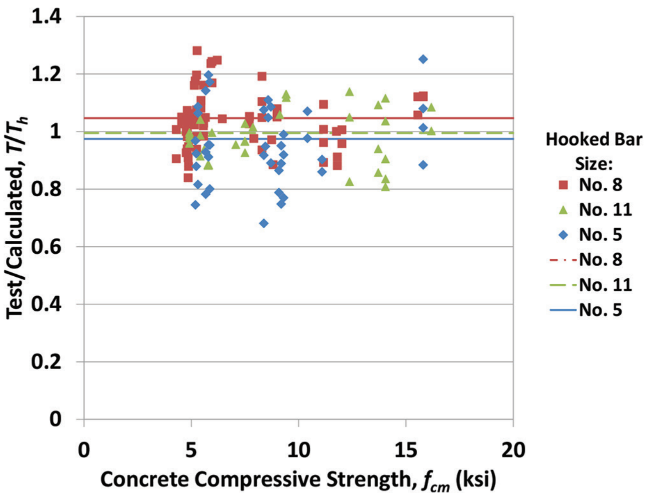

Fig. 12—Ratio of bar force at failure T *to calculated bar force based on Eq. (6)* T_h *versus concrete compressive strength* f_{cm} *for hooked bars with confining reinforcement parallel to straight portion of hooked bar. (Note: 1 ksi = 6.895 MPa.)*

= 0.8 for hooked bar development lengths when confining ties are provided at a spacing not exceeding $3d_b$.

Figure 10 shows $T - T_c$ versus the parameter NA_{tr}/n. The scatter in $T - T_c$ was expected because there was scatter in T, and $T - T_c$ is a small portion (on average 18%) of T. The figure shows that, on average, $T - T_c$ increases proportionally to the parameter NA_{tr}/n. The relationship between $T - T_c$ and the parameter NA_{tr}/n is similar for No. 8 and No. 11 (No. 25 and No. 36) hooked bars. The dummy variable analysis shows that the effect of confining reinforcement is greater for the larger hooked bars (No. 8 and No. 11, No. 25 and No. 36) than for the No. 5 (No. 16) bars.

Using statistical analysis procedures similar to those used for hooked bars without confining reinforcement, the following expression for T_s was obtained

$$T_s = 54{,}250\left(\frac{NA_{tr}}{n}\right)^{1.06} d_b^{\,0.59} \text{ (in.-lb)} \tag{5a}$$

$$T_s = 37.6\left(\frac{NA_{tr}}{n}\right)^{1.06} d_b^{\,0.59} \text{ (SI)} \tag{5b}$$

Similar to the nonlinear relationship between T_c and ℓ_{eh} for hooked bars without confining reinforcement, the power of 1.06 on the parameter NA_{tr}/n is close to 1.0, so a linear relationship between T_s and NA_{tr}/n is acceptable for design.

The anchorage strength of hooked bars with confining reinforcement oriented parallel to the straight portion of the bar in beam-column joints can be expressed as the sum of components corresponding to the contributions of concrete and the confining reinforcement using Eq. (4) and (5).

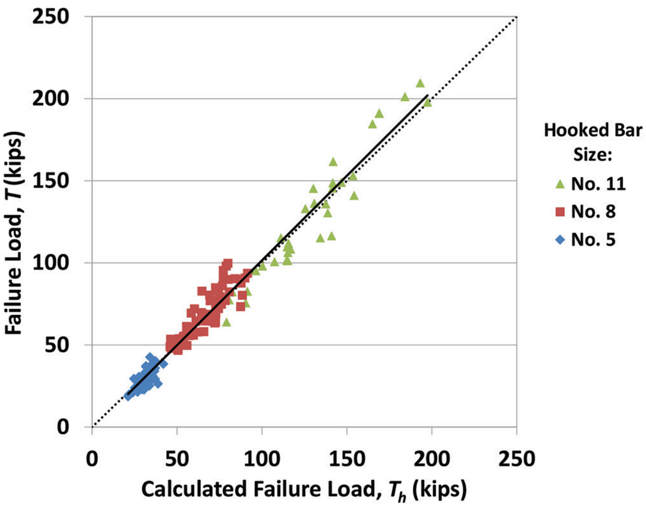

Fig. 13—Bar force at failure T *for hooked bars with confining reinforcement parallel to straight portion of hooked bar* T *versus calculated bar force based on Eq. (6) Th. (Note: 1 kip = 4.448 kN.)*

$$T_h = 332 f_{cm}^{0.29} \ell_{eh}{}^{1.06} d_b{}^{0.54} + 54{,}250\left(\frac{NA_{tr}}{n}\right)^{1.06} d_b{}^{0.59} \quad \text{(in.-lb) (6a)}$$

$$T_h = 35.4 f_{cm}^{0.29} \ell_{eh}{}^{1.06} d_b{}^{0.54} + 37.6\left(\frac{NA_{tr}}{n}\right)^{1.06} d_b{}^{0.59} \quad \text{(SI)(6b)}$$

Figure 12 shows T/T_h as a function of measured concrete compressive strength f_{cm}, where anchorage strength T_h is calculated using Eq. (6) for the specimens with confining reinforcement. The trend lines from the dummy variable analyses are nearly horizontal, showing that the effect of concrete compressive strength is adequately represented by Eq. (6). The intercepts of the trend lines corresponding to specimens with No. 5, 8, and 11 (No. 16, 25, and 36) bars are 0.97, 1.05, and 1.00, respectively.

Figure 13 shows a comparison of anchorage forces measured in the tests with those calculated using Eq. (6). The dotted line represents cases in which the measured and calculated strengths are equal, while the solid line represents the best fit line for the data set. The two lines nearly match, indicating that Eq. (6) provides an accurate estimate of anchorage strength over the entire range of test data. The average test-to-calculated ratio using Eq. (6) is equal to 1.0 with a coefficient of variation of 0.11 and ratios to T/T_h ranging from 0.68 to 1.28.

Confining reinforcement perpendicular to straight portion of hooked bar—Six specimens with confining reinforcement oriented perpendicular to the straight portion of the hooked bar (Fig. 2) were tested by Sperry et al. (2015a,b; 2017) to investigate whether this reinforcement configuration is equally effective to reinforcement parallel to the straight portion of the bar (Fig. 1). For these six specimens, anchorage strengths calculated using Eq. (6), with N equal to the number of legs perpendicular to the hooked bar over the length being developed, overestimated the component T_s by a factor of three or more. In light of the large differences in the calculated values of T_s, experimental results for the six specimens with vertical ties were re-evaluated. The resulting relationship is given by

$$T_{sp} = 14{,}950\left(\frac{NA_{tr}}{n}\right)^{1.06} d_b^{0.59} \text{ (in.-lb)} \quad (7a)$$

$$T_{sp} = 10.4\left(\frac{NA_{tr}}{n}\right)^{1.06} d_b^{0.59} \text{ (SI)} \quad (7b)$$

Because of the small dataset, the powers of NA_{tr}/n and d_b from Eq. (6) were retained in Eq. (7).

When combining T_c from Eq. (4) with T_{sp} from Eq. (7) to calculate T_h for the six specimens with confining reinforcement oriented parallel to the straight portion of the bar, the average test-to-calculated ratio T/T_h was set 0.94, rather than 1.0, to match the average T/T_h ratio of the companion specimens with confining reinforcement oriented parallel to the straight portion of the bar in this group. A comparison of Eq. (7) with Eq. (5) indicates that, on average, each leg of confining reinforcement perpendicular to the straight portion of a hooked bar provided 28% of the contribution of a leg of confining reinforcement parallel to the straight portion of a hooked bar. The calculations indicate that all the legs of reinforcement perpendicular to the straight portion of the bar contributed to T_h, while only those legs that were within 8 or $10d_b$ of the top of the bar contributed for the configuration parallel to the straight portion of the hooked bar. Because this study was limited in scope and no other research addressing confining reinforcement perpendicular to the straight portion of a hooked bar is available for comparison with Eq. (7), additional research is needed to confidently establish the effect of orientation of confining reinforcement over the full range of material properties and bar sizes.

Equations (4) through (7) were developed to characterize the test results for specimens containing two hooked bars with and without confining reinforcement. Design provisions that are relatively easy to apply and that recognize other aspects not addressed by the equations developed in this paper, such as hooked bar spacing, hooked bar placement, additional hooked bars at a cross section, and structural reliability, are the subject of continuing research.

SUMMARY AND CONCLUSIONS

Equations were developed to characterize the anchorage strength of hooked bars with and without confining reinforcement. The equations are based on test results of 245 simulated beam-column joint specimens containing two hooked bars: 99 without confining reinforcement and 146 with confining reinforcement. The data set developed in this study was complemented with test results reported by Marques and Jirsa (1975), Pinc et al. (1977), Hamad et al. (1993), Ramirez and Russell (2008), and Lee and Park (2010). Bar stresses at failure ranged from 30,800 to 144,100 psi (212 to 994 MPa), and concrete compressive strengths ranged from 2570 to 16,200 psi (17.7 to 112 MPa).

The following conclusions are based on the analysis presented in this paper:

1. The effect of concrete compressive strength on the anchorage strength of hooked bars was proportional to the compressive strength raised to the 0.29 power.

2. The contribution to hooked bar anchorage strength of confining reinforcement oriented parallel to and located within eight or 10 bar diameters of the straight portion of the bar was proportional to the area of confining reinforcement.

3. For a given embedment length, the anchorage strength of hooked bars with and without confining reinforcement increased as the diameter of the hooked bar increased.

4. The behavior and contribution to hooked bar anchorage strength of confining reinforcement oriented perpendicular to the straight portion of the hooked bar differed from that of reinforcement oriented parallel to the bar, with more legs of the confining reinforcement contributing but with each leg making a smaller contribution.

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NOTATION

d_b = nominal diameter of hooked bar
f_c' = specified concrete compressive strength
f_{cm} = measured average concrete compressive strength
$f_{s,ACI}$ = stress in hook as calculated by Section 25.4.3 of ACI 318-14
f_y = yield strength of hooked bar
ℓ_{dh} = development length in tension of deformed bar with standard hook, measured from outside end of hook, point of tangency, toward critical section
ℓ_{eh} = embedment length measured from outside end of hook, point of tangency, to front face of column
N = number of legs of confining reinforcement parallel to straight portion of hooked bar within $8d_b$ from top of hooked bar for No. 3 through No. 8 (No. 10 through No. 25) hooked bars or $10d_b$ from top of hooked bar for No. 9 through No. 11 (No. 29 through No. 36) hooked bars; or number of legs perpendicular to hooked bar over length being developed
n = number of hooked bars confined by N legs
T = average bar force at failure on hooked bars in a specimen (failure load)
T_c = contribution of concrete to hooked bar anchorage strength
T_h = hooked bar anchorage strength
T_s = contribution of confining reinforcement oriented parallel to straight portion of hooked bar to anchorage strength
T_{sp} = contribution of confining reinforcement oriented perpendicular to straight portion of hooked bar to anchorage strength
λ = modification factor to reflect reduced mechanical properties of lightweight concrete relative to normalweight concrete of same compressive strength
ψ_c = factor used to modify development length based on cover as defined in ACI 318-14, Section 25.4.3.2
ψ_e = factor used to modify development length based on reinforcement coating as defined in ACI 318-14, Section 25.4.3.2
ψ_r = factor used to modify development length based on confining reinforcement in hook region as defined in ACI 318-14, Section 25.4.3.2

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APPENDIX A:

NOTATION AND DATA TABLES

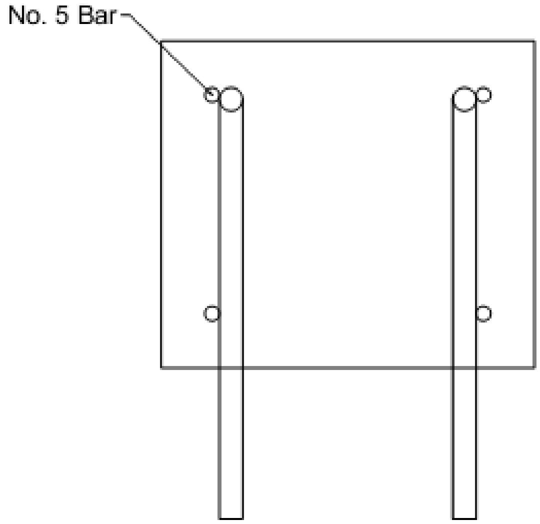
A_h	Area of hooked bar
A_{tr}	Total area of transverse steel inside hook region
A_s	Area of longitudinal steel in the column
A_{cti}	Total area of cross-ties inside the hook region
b	Column width
c_b	Clear cover measured from the center of the hook to the side of the column
c_h	Clear spacing between hooked bars, inside-to-inside spacing
c_{so}	Clear cover measured from the side of the hook to the side of the column
$c_{so,avg}$	Average clear cover of the hooked bars
c_{th}	Clear cover measured from the tail of the hook to the back of the column
d_b	Nominal bar diameter of the hooked bar
d_{cto}	Nominal bar diameter of cross-ties outside the hook region
d_{tr}	Nominal bar diameter of transverse reinforcement inside the hook region
d_s	Nominal bar diameter of transverse reinforcing steel outside the hook region
f'_c	Specified concrete compressive strength
f_{cm}	Measured average concrete compressive strength
$f_{s,\mathrm{ACI}}$	Stress in hook as calculated by Section 25.4.3.1 of ACI 318-14
$f_{su,\mathrm{ind}}$	Stress in hook at failure
f_{su}	Average peak stress in hooked bars at failure
f_{yt}	Nominal yield strength of transverse reinforcement
f_{ys}	Nominal yield strength of longitudinal reinforcing steel in the column
h_c	Width of bearing member flange
h_{cl}	Height measured from the center of the hook to the top of the bearing member flange
h_{cu}	Height measured from the center of the hook to the bottom of the upper compression member
ℓ_{dh}	Development length in tension of deformed bar standard hook, measured from outside end of hook, point of tangency, toward critical section
ℓ_{eh}	Embedment length measured from the outside end of hook, point of tangency, to front face of the column
$\ell_{eh,avg}$	Average embedment length of hooked bars
n	Number of hooked bars confined by N legs
N	Number of legs of confining reinforcement in joint region
N_{cti}	Total number of cross-ties used as supplemental reinforcement inside the hook region
N_{cto}	Number of cross-ties used per layer as supplemental reinforcement outside the hook region and spaced at s_s
N_h	Number of hooked bars loaded simultaneously
N_{tr}	Number of stirrups/ties crossing the hook
T	Average load on hooked bars at failure
T_c	Contribution of concrete to hooked bar anchorage strength
T_{ind}	Load on individual hooked bar at failure
T_{max}	Maximum load on individual hooked bar
T_{total}	Sum of loads on hooked bar at failure
T_h	Hooked bar anchorage strength
T_s	Contribution of confining steel in joint region to hooked bar anchorage strength
R_r	Relative rib area

s_{cti} Center-to-center spacing of cross-ties in the hook region
s_{tr} Center-to-center spacing of transverse reinforcement in the hook region
s_s Center-to-center spacing of stirrups/ties outside the hook region
α Student's t-test significance
ψ_e Epoxy coating factor as defined in ACI 318-14 Section 25.4.3.2
ψ_c Factor for cover as defined in ACI 318-14 Section 25.4.3.2
ψ_r Factor for transverse reinforcement in the hook region
ψ_o Factor for hooked bar location
ψ_m Hooked bar spacing factor

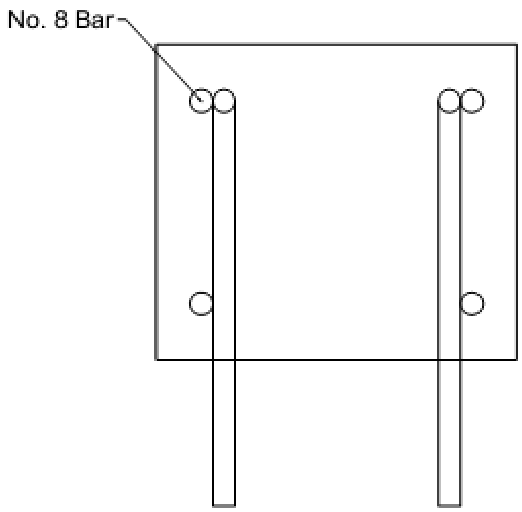
Failure types
FP Front Pullout
FB Front Blowout
SS Side Splitting
SB Side Blowout
TK Tail Kickout
FL Flexural Failure of column
BY Yield of hooked bars

Specimen identification
(A@B) C-D-E-F#G-H-I-J-Kx(L)
A Number of hooks in the specimen
B Clear spacing between hooks in terms of bar diameter
(A@B = blank, indicates standard 2-hook specimen)
C ASTM in.-lb bar size
D Nominal compressive strength of concrete
E Angle of bend
F Number of bars used as transverse reinforcement within the hook region
G ASTM in.-lb bar size of transverse reinforcement
(if D#E = 0 = no transverse reinforcement)
H Hooked bars placed inside (i) or outside (o) of longitudinal reinforcement
I Nominal value of c_{so}
J Nominal value of c_{th}
K Nominal value of ℓ_{eh}
x Replication in a series, blank (or a), b, c, etc.
L Replication not in a series

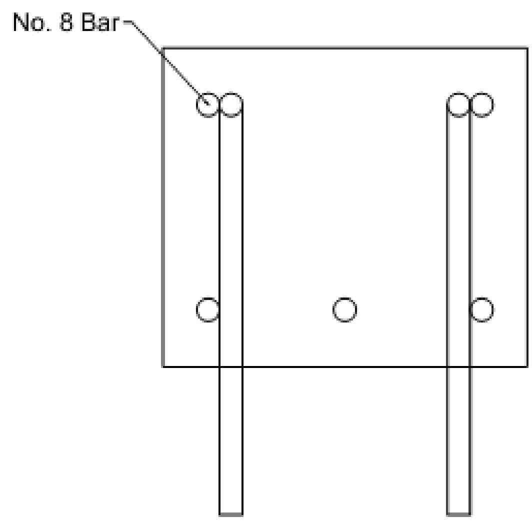
LONGITUDINAL COLUMN STEEL LAYOUTS



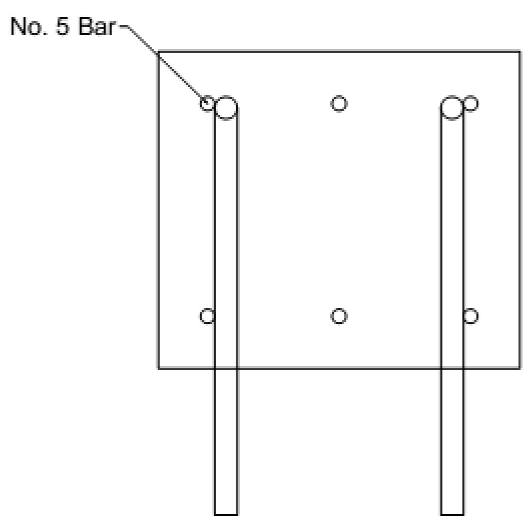
Layout A1: Longitudinal column reinforcement-4 No. 5 bars. Transverse reinforcement not shown.



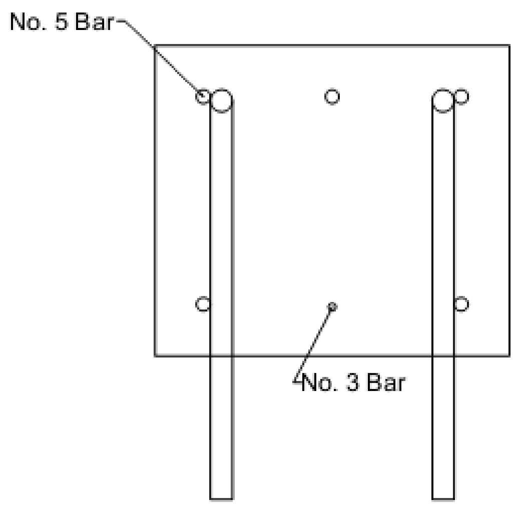
Layout A2: Longitudinal column reinforcement-4 No. 8 bars. Transverse reinforcement not shown.



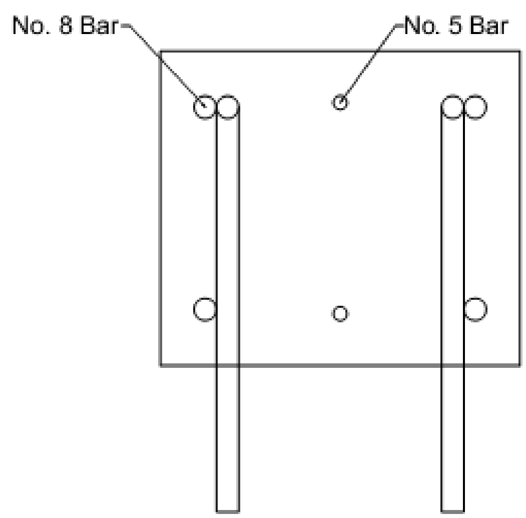
Layout A3: Longitudinal column reinforcement-5 No. 8 bars. Transverse reinforcement not shown.



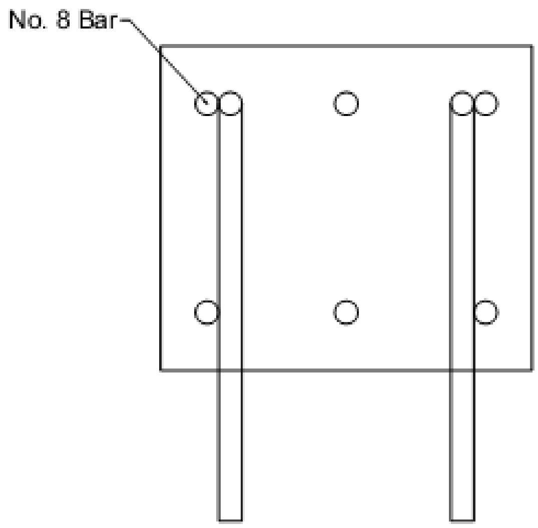
Layout A4: Longitudinal column reinforcement-6 No. 5 bars. Transverse reinforcement not shown.



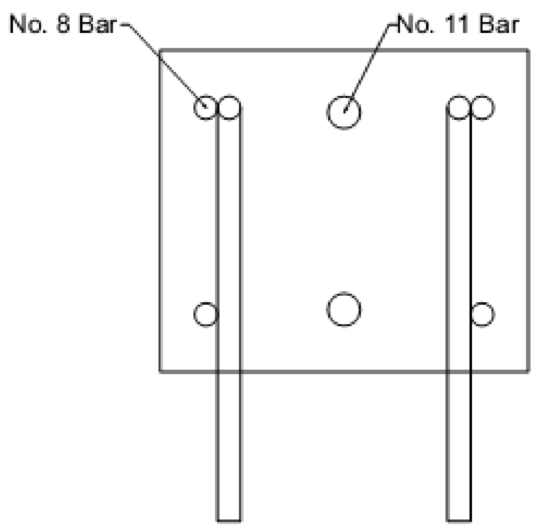
Layout A5: Longitudinal column reinforcement-5 No. 5 bars + 1 No. 3 bar. Transverse reinforcement not shown.



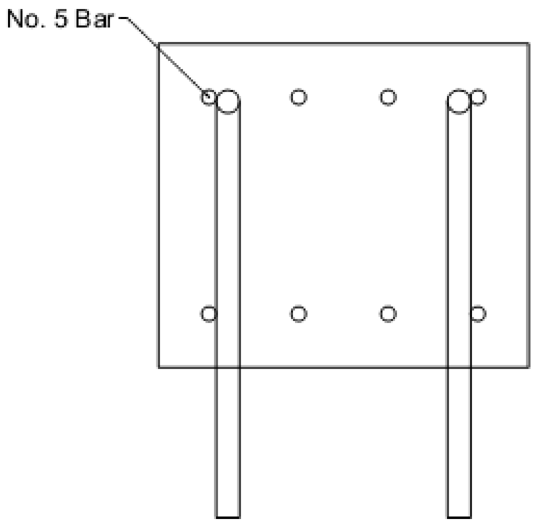
Layout A6: Longitudinal column reinforcement-4 No. 8 bars + 2 No. 5 bars. Transverse reinforcement not shown.



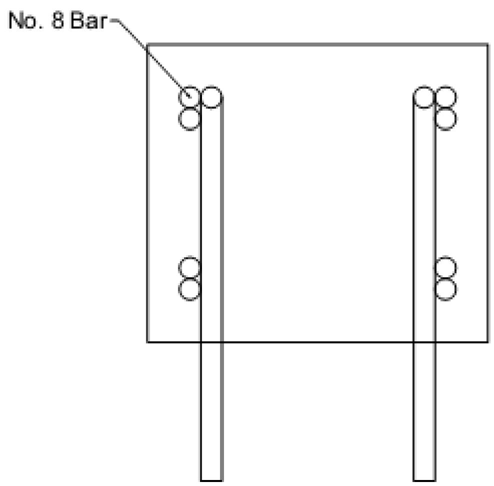
Layout A7: Longitudinal column reinforcement-6 No. 8 bars. Transverse reinforcement not shown.



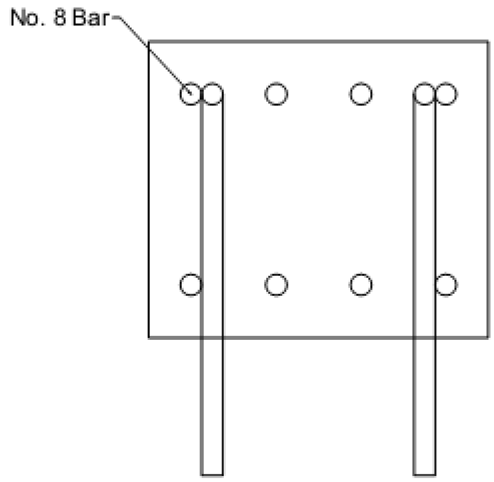
Layout A8: Longitudinal column reinforcement-4 No. 8 bars + 2 No. 11 bars. Transverse reinforcement not shown.



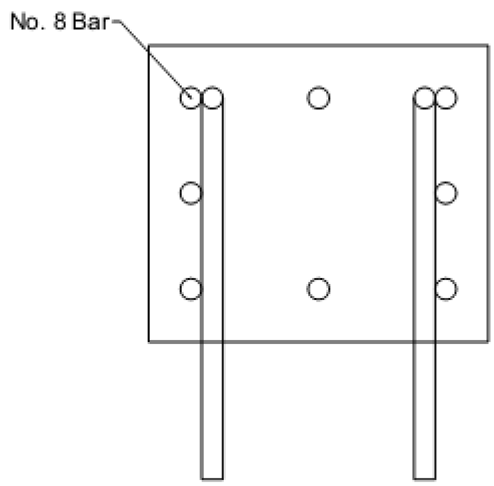
Layout A9: Longitudinal column reinforcement-8 No. 5 bars. Transverse reinforcement not shown.



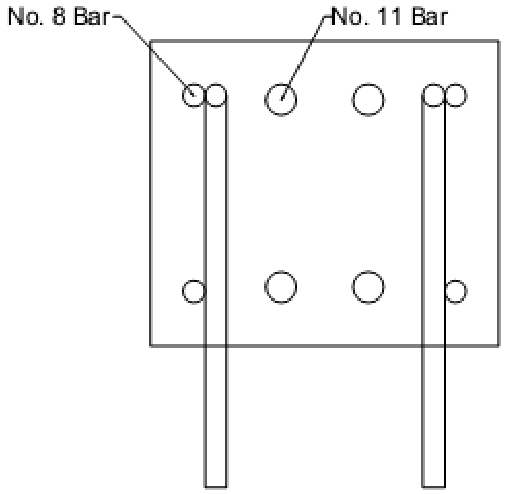
Layout A10: Longitudinal column reinforcement-8 No. 8 bars (four bundles of two bars each). Transverse reinforcement not shown.



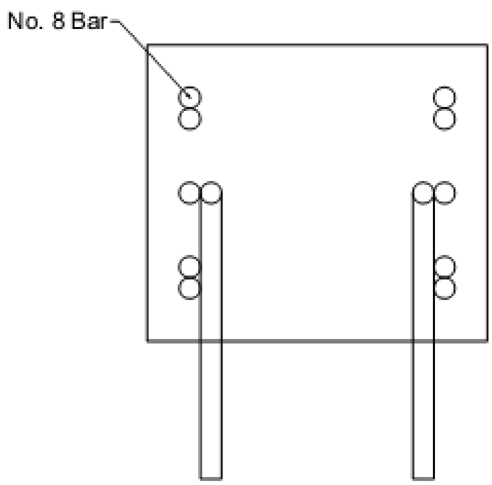
Layout A11: Longitudinal column reinforcement-8 No. 8 bars (distributed across two column faces). Transverse reinforcement not shown.



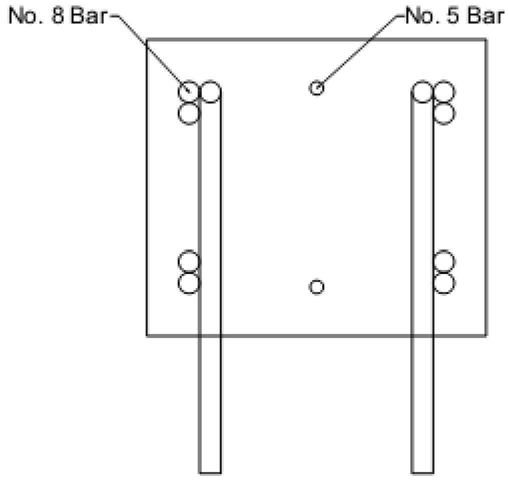
Layout A12: Longitudinal column reinforcement-8 No. 8 bars (distributed across four column faces). Transverse reinforcement not shown.



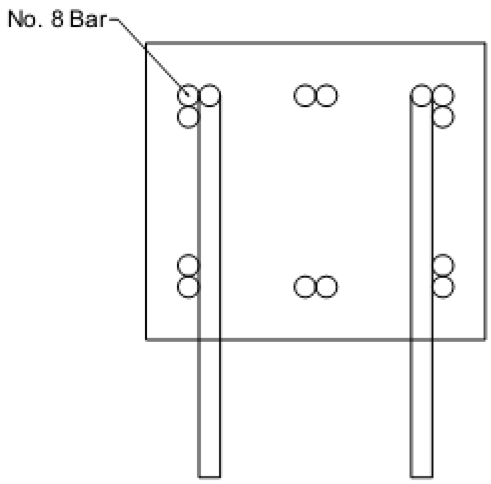
Layout A13: Longitudinal column reinforcement-4 No. 8 bars + 4 No. 11 bars. Transverse reinforcement not shown.



Layout A14: Longitudinal column reinforcement-10 No. 8 bars. Transverse reinforcement not shown.



Layout A15: Longitudinal column reinforcement-8 No. 8 bars + 2 No. 5 bars. Transverse reinforcement not shown.



Layout A16: Longitudinal column reinforcement-12 No. 8 bars. Transverse reinforcement not shown.

Note: In that tables that follow, *1 lb = 4.448 N*, *1 psi = 0.006895 MPa*, *1 in. = 25.4 mm*

Table A.1 Comprehensive test results and data used in analysis for specimens without confining reinforcement

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.	R_r	b in.	h in.	h_{cl} in.	h_c in.
1	5-5-90-0-i-2.5-2-10	A B	90°	-	A1035	9.4 9.4	9.4	5230	6	0.6	0.073	13.1	12.3	5.25	8.375
2	5-5-90-0-i-2.5-2-7	A B	90°	-	A1035	6.9 7.0	6.9	5190	7	0.6	0.073	13.0	9.6	5.25	8.375
3	5-8-90-0-i-2.5-2-6	A B	90°	-	A615	6.8 6.8	6.8	8450	14	0.6	0.073	13.0	8.0	5.25	8.375
4	5-8-90-0-i-2.5-2-6(1)	A B	90°	-	A1035	6.1 6.5	6.3	9080	11	0.6	0.073	13.3	8.8	5.25	8.375
5	5-8-90-0-i-2.5-2-8	A B	90°	-	A1035	8.0 7.5	7.8	8580	15	0.6	0.073	13.1	10.0	5.25	8.375
6	5-12-90-0-i-2.5-2-10	A B	90°	-	A1035	10.0 11.0	10.5	10290	14	0.6	0.073	12.8	12.5	5.25	8.375
7	5-12-90-0-i-2.5-2-5	A B	90°	-	A1035	5.1 4.8	4.9	11600	84	0.6	0.073	13.0	7.3	5.25	8.375
8	5-15-90-0-i-2.5-2-5.5	A B	90°	-	A1035	6.1 5.8	5.9	15800	62	0.6	0.073	12.6	7.7	5.25	8.375
9	5-15-90-0-i-2.5-2-7.5	A B	90°	-	A1035	7.3 7.3	7.3	15800	62	0.6	0.073	12.9	9.8	5.25	8.375
10	5-5-90-0-i-3.5-2-10	A B	90°	-	A1035	10.5 10.4	10.4	5190	7	0.6	0.073	14.8	12.3	5.25	8.375
11	5-5-90-0-i-3.5-2-7	A B	90°	-	A1035	7.5 7.6	7.6	5190	7	0.6	0.073	15.1	8.8	5.25	8.375
12	5-8-90-0-i-3.5-2-6	A B	90°	-	A615	6.3 6.4	6.3	8580	15	0.6	0.073	15.0	8.0	5.38	8.375
13	5-8-90-0-i-3.5-2-6(1)	A B	90°	-	A1035	6.5 6.6	6.6	9300	13	0.6	0.073	15.6	8.6	5.25	8.375
14	5-8-90-0-i-3.5-2-8[†]	A B	90°	-	A1035	8.6 8.5	8.6	8380	13	0.6	0.060	15.5	10.0	5.25	8.375
15	5-12-90-0-i-3.5-2-5	A B	90°	-	A1035	5.5 5.4	5.4	10410	15	0.6	0.073	15.5	7.2	5.25	8.375
16	5-12-90-0-i-3.5-2-10	A B	90°	-	A1035	10.1 10.0	10.1	11600	84	0.6	0.073	15.0	12.1	5.25	8.375
17	5-8-180-0-i-2.5-2-7	A B	180°	-	A1035	7.4 7.1	7.3	9080	11	0.6	0.073	12.6	9.5	5.25	8.375
18	5-8-180-0-i-3.5-2-7	A B	180°	-	A1035	7.4 7.3	7.3	9080	11	0.6	0.073	15.4	9.3	5.25	8.375
19	8-5-90-0-i-2.5-2-16	A B	90°	-	A1035[b]	16.0 16.8	16.4	4980	7	1	0.078	17.0	17.9	10.5	8.375
20	8-5-90-0-i-2.5-2-9.5	A B	90°	-	A615	9.0 10.3	9.6	5140	8	1	0.078	16.8	12.0	10.5	8.375
21	8-5-90-0-i-2.5-2-12.5	A B	90°	-	A615	13.3 13.3	13.3	5240	9	1	0.078	17.3	14.5	10.5	8.375
22	8-5-90-0-i-2.5-2-18	A B	90°	-	A1035[b]	19.5 17.9	18.7	5380	11	1	0.078	17.5	20.3	10.5	8.375
23	8-5-90-0-i-2.5-2-13	A B	90°	-	A1035[b]	13.3 13.5	13.4	5560	11	1	0.078	16.8	15.3	10.5	8.375
24	8-5-90-0-i-2.5-2-15(1)	A B	90°	-	A1035[b]	14.5 15.3	14.9	5910	14	1	0.073	16.7	17.3	10.5	8.375
25	8-5-90-0-i-2.5-2-15	A B	90°	-	A1035[b]	15.3 14.4	14.8	6210	8	1	0.073	16.6	17.3	10.5	8.375

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens without confining reinforcement

	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	T_h lb	$f_{su,max}$ psi	f_{su} psi
1	A B	2.8 2.6	2.7	2.9 2.9	6.4	2	30	A4	37404 32864	34303 32864	67166	33583	33080	120656 106012	108333
2	A B	2.5 2.5	2.5	2.8 2.6	6.8	2	30	A1	26607 26095	26607 25922	52529	26265	23988	85831 84176	84724
3	A B	2.8 2.6	2.7	1.3 1.3	6.4	2	80	A1	27578 32135	27102 32038	59140	29570	26839	88961 103663	95387
4	A B	2.5 2.5	2.5	2.6 2.3	7.0	2	30	A1	21741 24995	21741 23109	44849	22425	25525	70131 80630	72338
5	A B	2.5 2.8	2.6	2.0 2.5	6.6	2	80	A1	31878 35934	31469 31878	63347	31673	31209	102831 115915	102172
6	A B	2.4 2.5	2.4	2.5 1.5	6.6	2	30	A4	40823 42491	40823 42491	83314	41657	45391	131688 137066	134377
7	A B	2.6 2.6	2.6	2.1 2.5	6.5	2	30	A1	19389 23171	19389 19051	38441	19220	21121	62546 74745	62001
8	A B	2.4 2.4	2.4	1.6 1.9	6.6	2	30	A1	36163 32373	32648 32373	65021	32511	28089	116656 104430	104873
9	A B	2.5 2.5	2.5	2.6 2.6	6.6	2	30	A2	42470 41977	42464 41977	84441	42221	34712	137001 135410	136196
10	A B	3.5 3.5	3.5	1.8 1.9	6.5	2	30	A4	43228 41140	43228 40626	83855	41927	36985	139446 132710	135250
11	A B	3.4 3.5	3.4	1.3 1.1	7.0	2	30	A1	27197 25884	27197 25836	53033	26516	26284	87732 83498	85537
12	A B	3.6 3.5	3.6	1.8 1.6	6.6	2	80	A1	25129 29054	25129 25822	50950	25475	25110	81060 93723	82178
13	A B	3.8 3.8	3.8	2.1 1.9	6.9	2	30	A1	24440 27541	24440 24643	49083	24541	26783	78838 88842	79166
14	A B	3.6 3.5	3.6	1.4 1.5	7.1	2	80	A1	39109 34311	31179 34311	65490	32745	34452	126159 110679	105629
15	A B	3.6 3.6	3.6	1.7 1.8	7.0	2	30	A1	22045 23158	22040 22201	44241	22121	22672	71114 74702	71357
16	A B	3.5 3.5	3.5	2.5 1.5	6.8	2	30	A4	46085 46076	46016 44849	90864	45432	44924	148661 148631	146556
17	A B	2.5 2.6	2.6	2.1 2.4	6.3	2	30	A1	26722 35215	26722 27495	54217	27108	29561	86199 113596	87446
18	A B	3.6 3.4	3.5	1.9 2.0	7.1	2	30	A1	34057 31441	30094 31414	61508	30754	29831	109860 101422	99206
19	A B	2.8 2.8	2.8	1.8 1.4	9.5	2	80	A2	83310 86063	83310 83169	166479	83239	75922	105455 108940	105366
20	A B	2.8 2.5	2.6	3.0 1.8	9.5	2	80	A2	44627 65800	44627 44344	88971	44485	43624	56489 83291	56311
21	A B	2.8 2.8	2.8	1.3 1.3	9.8	2	80	A2	65254 69872	65254 66385	131639	65819	61559	82600 88446	83316
22	A B	2.5 2.5	2.5	0.8 2.4	10.5	2	30	A6	100169 79805	82023 79740	161763	80881	89312	126796 101018	102381
23	A B	2.5 2.5	2.5	2.0 1.8	9.8	2	30	A2	73143 65197	65881 65197	131078	65539	63253	92586 82527	82960
24	A B	2.5 2.6	2.5	2.8 2.0	9.6	2	30	A2	64532 87275	64532 63002	127534	63767	72061	81686 110475	80718
25	A B	2.5 2.6	2.6	2.0 2.9	9.5	2	30	A2	76256 80724	76162 74793	150955	75478	72778	96527 102182	95541

° Longitudinal column configurations shown in Appendix A, Layouts A1 – A16

Table A.3 Cont. Comprehensive test results and data used in analysis for specimens without confining reinforcement

	Hook	Slip at Failure in.	Failure Type	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
1	A B	- -	FP/SS FP/SS	60	-	-	-	-	0.33	3	3.0	0.375	3.00	-	-	1.89	60
2	A B	- 0.192	FP/SS FP/SS	60	-	-	-	-	0.80	4	2.5	0.500	3.50	-	-	1.27	60
3	A B	- -	FB/SB SB/FB	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
4	A B	0.296 .330(.030)	FP FP	60	-	-	-	-	0.66	6	3.0	0.500	3.00	-	-	1.27	60
5	A B	- -	SS/FP SS/FP	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
6	A B	0.191 -	SB FB/SB/TK	60	-	-	-	-	0.11	1	7.0	0.375	5.00	-	-	1.89	60
7	A B	- -	FP/SS FP	60	-	-	-	-	0.66	6	2.5	0.500	3.00	-	-	1.27	60
8	A B	- -	FP FB	60	-	-	-	-	-	-	-	0.375	2.50	-	-	1.27	60
9	A B	- -	FB *	60	-	-	-	-	-	-	-	0.375	3.50	-	-	3.16	60
10	A B	- -	SB/FP SB/FP	60	-	-	-	-	0.33	3	3.0	0.375	3.00	-	-	1.89	60
11	A B	- -	SS FP/SS	60	-	-	-	-	0.80	4	2.5	0.375	3.50	-	-	1.27	60
12	A B	- -	FP/SS FP/SS	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
13	A B	0.152 .178(.150)	FP/SS FP/SS	60	-	-	-	-	0.66	6	3.0	0.500	3.00	-	-	1.27	60
14	A B	- -	FB/SS SS	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
15	A B	- -	FP FP	60	-	-	-	-	0.66	6	2.5	0.500	3.00	-	-	1.27	60
16	A B	- -	BY BY	60	-	-	-	-	0.11	1	7.0	0.375	5.00	-	-	1.89	60
17	A B	0.194 .146(.016)	FP/SS SB/FP	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60
18	A B	0.251 .237(.021)	SS/FP FP/SS	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60
19	A B	- -	FP/SB FB/TK	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60
20	A B	- -	FP SS	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60
21	A B	- -	SS/B SS	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60
22	A B	- 0.153	FB/SS/TK FB/SS/TK	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	1	3.78	60
23	A B	- -	SS FP/SS	60	-	-	-	-	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60
24	A B	- -	FB/SB SB	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60
25	A B		SS/FP SB/FP	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60

*No failure of hook; equipment malfunction

Table A.1 Cont. Comprehensive test results and data used in analysis for specimens without confining reinforcement

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.	R_r	b in.	h in.	h_{cl} in.	h_c in.
26	(2@3) 8-5-90-0-i-2.5-2-10‡	A B	90°	-	A615	10.4 10.6	10.5	4490	10	1	0.073	9.0	12.0	10.5	8.375
27	(2@5) 8-5-90-0-i-2.5-2-10‡	A B	90°	-	A615	10.1 10.1	10.1	4490	10	1	0.073	10.9	12.0	10.5	8.375
28	8-8-90-0-i-2.5-2-8	A B	90°	-	A1035[b]	8.9 8.0	8.4	7910	15	1	0.078	16.3	10.0	10.5	8.375
29	8-8-90-0-i-2.5-2-10	A B	90°	-	A1035[b]	9.8 9.5	9.6	7700	14	1	0.078	16.6	12.0	10.5	8.375
30	8-8-90-0-i-2.5-2-8(1)	A B	90°	-	A1035[b]	8.0 8.0	8.0	8780	13	1	0.078	17.0	10.8	10.5	8.375
31	8-8-90-0-i-2.5sc-2tc-9‡	A B	90°	-	A615	9.5 9.5	9.5	7710	25	1	0.073	17.3	11.0	10.5	8.375
32	8-12-90-0-i-2.5-2-9	A B	90°	-	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	17.0	11.4	10.5	8.375
33	8-12-90-0-i-2.5-2-12.5	A B	90°	-	A1035[c]	12.9 12.8	12.8	11850	39	1	0.073	17.4	14.6	10.5	8.375
34	8-12-90-0-i-2.5-2-12	A B	90°	-	A1035[c]	12.1 12.1	12.1	11760	34	1	0.073	16.8	14.0	10.5	8.375
35	8-15-90-0-i-2.5-2-8.5	A B	90°	-	A1035[c]	8.8 8.9	8.8	15800	61	1	0.073	17.0	10.8	10.5	8.375
36	8-15-90-0-i-2.5-2-13	A B	90°	-	A1035[c]	12.8 12.8	12.8	15800	61	1	0.073	16.8	14.8	10.5	8.375
37	8-5-90-0-i-3.5-2-18	A B	90°	-	A1035[b]	19.0 18.0	18.5	5380	11	1	0.078	18.5	20.4	10.5	8.375
38	8-5-90-0-i-3.5-2-13	A B	90°	-	A1035[b]	13.4 13.4	13.4	5560	11	1	0.078	18.4	15.3	10.5	8.375
39	8-5-90-0-i-3.5-2-15(2)	A B	90°	-	A1035[c]	15.6 14.9	15.3	5180	8	1	0.073	18.5	17.3	10.5	8.375
40	8-5-90-0-i-3.5-2-15(1)	A B	90°	-	A1035[c]	15.4 15.1	15.3	6440	9	1	0.073	18.8	17.1	10.5	8.375
41	8-8-90-0-i-3.5-2-8(1)	A B	90°	-	A1035[b]	7.8 7.8	7.8	7910	15	1	0.078	18.3	10.0	10.5	8.375
42	8-8-90-0-i-3.5-2-10	A B	90°	-	A1035[b]	8.8 10.8	9.8	7700	14	1	0.078	18.5	12.0	10.5	8.375
43	8-8-90-0-i-3.5-2-8(2)	A B	90°	-	A1035[b]	8.5 8.0	8.3	8780	13	1	0.078	19.4	10.6	10.5	8.375
44	8-12-90-0-i-3.5-2-9	A B	90°	-	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	19.0	11.3	10.5	8.375
45	8-8-90-0-i-4-2-8	A B	90°	-	A1035[b]	7.6 8.0	7.8	8740	12	1	0.078	19.9	10.5	10.5	8.375
46	8-5-180-0-i-2.5-2-11	A B	180°	-	A615	11.0 11.0	11.0	4550	7	1	0.078	17.5	13.0	10.5	8.375
47	8-5-180-0-i-2.5-2-14	A B	180°	-	A1035[b]	14.0 14.0	14.0	4840	8	1	0.078	17.1	16.0	10.5	8.375
48	8-8-180-0-i-2.5-2-11.5	A B	180°	-	A1035[b]	9.3 9.3	9.3	8630	11	1	0.078	17.5	13.8	10.5	8.375
49	8-12-180-0-i-2.5-2-12.5	A B	180°	-	A1035[c]	12.8 12.5	12.6	11850	39	1	0.073	17.1	14.9	10.5	8.375
50	8-5-180-0-i-3.5-2-11	A B	180°	-	A615	11.6 11.6	11.6	4550	7	1	0.078	19.5	13.0	10.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

Table A.1 Cont. Comprehensive test results and data used in analysis for specimens without confining reinforcement

	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	T_h lb	$f_{su,max}$ psi	f_{su} psi
26	A B	2.5 2.5	2.5	1.6 1.4	2.0	2	30	A2	38900 41700	38908 41718	80626	40313	45999	49241 52785	51029
27	A B	2.5 2.3	2.4	1.9 1.9	4.1	2	30	A2	41853 38251	41853 38251	80104	40052	43959	52979 48419	50699
28	A B	2.8 2.9	2.8	1.1 2.0	8.6	2	30	A2	54674 45169	45317 45169	90486	45243	42993	69208 57176	57269
29	A B	2.8 2.9	2.8	2.3 2.5	9.0	2	30	A2	50000 52926	49985 52926	102911	51455	49048	63291 66995	65134
30	A B	2.8 2.8	2.8	2.8 2.8	9.5	2	30	A2	38047 37660	35988 37654	73642	36821	41882	48161 47671	46609
31	A B	2.5 2.8	2.6	1.5 1.5	10.0	2	30	A2	35543 34656	35543 34656	70199	35100	48392	44991 43868	44430
32	A B	2.8 2.6	2.7	2.4 2.4	9.6	2	30	A2	50809 54796	50677 49168	99845	49923	50870	64315 69362	63193
33	A B	2.6 2.6	2.6	1.7 1.8	10.1	2	30	A2	66009 77378	65995 67878	133873	66937	75268	83555 97947	84730
34	A B	2.5 2.4	2.5	1.9 1.9	9.8	2	30	A2	70689 65778	65980 65778	131758	65879	70837	89479 83263	83391
35	A B	2.5 2.5	2.5	2.0 1.9	10.0	2	30	A6	43063 44087	43063 44087	87150	43575	55024	54510 55807	55158
36	A B	2.4 2.5	2.4	2.1 2.0	9.9	2	30	A7	77232 79007	77232 79007	156239	78120	81605	97762 100009	98885
37	A B	3.8 3.4	3.6	1.4 2.4	9.4	2	30	A6	96026 105140	96026 94717	190743	95372	88362	121552 133089	120724
38	A B	3.6 3.4	3.5	1.9 1.9	9.4	2	30	A2	69449 68307	67892 68307	136199	68099	63253	87910 86464	86202
39	A B	3.5 3.5	3.5	1.6 2.4	9.5	2	30	A2	106184 85459	89959 85459	175417	87709	71213	134410 108176	111024
40	A B	3.3 3.4	3.3	1.8 2.0	10.1	2	30	A2	71216 79405	70412 70890	141302	70651	75854	90146 100512	89432
41	A B	3.5 3.8	3.6	2.3 2.3	9.0	2	30	A2	43697 43993	43697 43993	87690	43845	39289	55313 55687	55500
42	A B	3.8 3.8	3.8	3.3 1.3	9.0	2	30	A2	55230 71880	55088 56046	111134	55567	49724	69911 90987	70338
43	A B	3.6 3.8	3.7	2.1 2.6	10.0	2	30	A2	41170 42930	41170 42899	84069	42034	43271	52114 54341	53208
44	A B	3.5 3.8	3.6	2.4 2.1	9.8	2	30	A2	61380 68385	61380 59097	120477	60238	50870	77696 86563	76251
45	A B	4.5 3.9	4.2	2.9 2.5	9.5	2	30	A2	37554 48708	37554 37309	74863	37431	40788	47537 61656	47381
46	A B	3.0 2.8	2.9	2.0 2.0	9.8	2	80	A2	45587 50511	45587 46699	92286	46143	48511	57705 63938	58409
47	A B	2.8 2.6	2.7	2.0 2.0	9.8	2	80	A2	49439 69415	49439 48866	98305	49152	63773	62581 87867	62218
48	A B	3.0 3.0	3.0	4.5 4.5	9.5	2	30	A2	62777 80190	62777 80190	142967	71484	48606	79465 101506	90485
49	A B	3.0 2.5	2.8	2.1 2.4	9.6	2	30	A2	74782 92250	74782 75635	150417	75208	74101	94661 116772	95201
50	A B	3.8 3.8	3.8	1.4 1.4	10.0	2	80	A2	58575 60519	58145 60439	118584	59292	51437	74145 76606	75053

° Longitudinal column configurations shown in Appendix A, Layouts A1 – A16

Table A.1 Cont. Comprehensive test results and data used in analysis for specimens without confining reinforcement

	Hook	Slip at Failure in.	Failure Type	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
26	A B	0.2 -	FP FP	60	-	-	-	-	-	-	-	0.38	5.00	-	-	3.16	120
27	A B	0.33 0	FP FB/SS	60	-	-	-	-	-	-	-	0.38	5.00	-	-	3.16	120
28	A B	- -	FP/TK FP/SS	60	-	-	-	-	1.60	8	4.0	0.50	1.75	-	-	3.16	60
29	A B	0.195 0.185	FP FP	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60
30	A B	0.387 0.229	FP/SS FP/SS	60	-	-	-	-	1.60	8	4.0	0.50	1.50	-	-	3.16	60
31	A B	0.104 0	FB FB	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.16	60
32	A B	0.219	FP/SS SS/FP	60	-	-	-	-	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60
33	A B	0.295 0.266	FB/SB FB/SB	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60
34	A B	- 0.0119	SB/FP FB/SS	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.16	60
35	A B	- -	FP FP	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.78	60
36	A B	- -	FB/SB FB	60	-	-	-	-	-	-	-	0.38	5.00	-	-	4.74	60
37	A B	0.181 -	FP/SS/TK FB/SS	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	1	3.78	60
38	A B	- -	FP/SS SS/FP	60	-	-	-	-	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60
39	A B	- -	SS SS/FP	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60
40	A B		SS/FP SB	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60
41	A B	0.144 0.156	SS/FP SS/FP	60	-	-	-	-	1.60	8	4.0	0.50	1.75	-	-	3.16	60
42	A B	0.195 0.242	FP/SS SS/FP	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60
43	A B	0.133 0.201	FP FP	60	-	-	-	-	1.60	8	4.0	0.50	1.50	-	-	3.16	60
44	A B	 0.434	FP FP/SS	60	-	-	-	-	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60
45	A B	- -	FP/SS FP	60	-	-	-	-	1.60	8	4.0	0.50	1.75	-	-	3.16	60
46	A B	0.275 -	SS/FP SS	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
47	A B	0.088 0.096	SS SS	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
48	A B	- -	FP/SB FP/SS	60	-	-	-	-	0.44	4	3.0	0.50	3.00	-	-	3.16	60
49	A B	0.193 0.242	FB/SB FP	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60
50	A B	0.372 0.239	FP/SS SS	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60

Table A.1 Cont. Comprehensive test results and data used in analysis for specimens without confining reinforcement

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.	R_r	b in.	h in.	h_{cl} in.	h_c in.
51	8-5-180-0-i-3.5-2-14	A B	180°	-	A1035[b]	14.4 13.9	14.1	4840	8	1	0.078	19.4	16.0	10.5	8.375
52	11-5-90-0-i-2.5-2-14	A B	90°	-	A615	13.5 15.3	14.4	4910	13	1.4	0.069	21.6	16.0	19.5	8.375
53	11-5-90-0-i-2.5-2-26	A B	90°	-	A1035	26.0 26.0	26.0	5360	6	1.4	0.085	21.5	28.1	19.5	8.375
54	11-8-90-0-i-2.5-2-17	A B	90°	-	A1035	17.3 18.0	17.6	9460	9	1.4	0.085	21.2	19.3	19.5	8.375
55	11-8-90-0-i-2.5-2-21	A B	90°	-	A1035	20.0 21.1	20.6	7870	6	1.4	0.085	21.1	23.4	19.5	8.375
56	11-8-90-0-i-2.5-2-17	A B	90°	-	A1035	16.3 18.1	17.2	8520	7	1.4	0.085	21.3	19.3	19.5	8.375
57	11-12-90-0-i-2.5-2-17	A B	90°	-	A1035	16.1 16.9	16.5	11880	35	1.4	0.085	21.2	19.3	19.5	8.375
58	11-12-90-0-i-2.5-2-17.5	A B	90°	-	A1035	17.6 17.8	17.7	13330	31	1.4	0.085	22.8	19.8	19.5	8.375
59	11-12-90-0-i-2.5-2-25	A B	90°	-	A1035	24.9 24.4	24.6	13330	34	1.4	0.085	20.9	27.3	19.5	8.375
60	11-15-90-0-i-2.5-2-24	A B	90°	-	A1035	24.0 24.8	24.4	16180	62	1.4	0.085	21.3	26.0	19.5	8.375
61	11-15-90-0-i-2.5-2-10‡	A B	90°	-	A615	9.5 9.5	9.5	14050	76	1.4	0.085	21.9	12.0	19.5	8.375
62	11-15-90-0-i-2.5-2-15‡	A B	90°	-	A1035	14.0 14.0	14.0	14050	77	1.4	0.085	21.4	17.0	19.5	8.375
63	11-5-90-0-i-3.5-2-17	A B	90°	-	A1035	18.1 17.6	17.9	5600	24	1.4	0.085	23.8	20.0	19.5	8.375
64	11-5-90-0-i-3.5-2-14	A B	90°	-	A615	14.8 15.3	15.0	4910	13	1.4	0.069	23.7	16.3	19.5	8.375
65	11-5-90-0-i-3.5-2-26	A B	90°	-	A1035	26.3 25.8	26.0	5960	8	1.4	0.085	23.8	28.4	19.5	8.375
66	11-8-180-0-i-2.5-2-21	A B	180°	-	A1035	21.3 20.9	21.1	7870	6	1.4	0.085	21.1	23.1	19.5	8.375
67	11-8-180-0-i-2.5-2-17	A B	180°	-	A1035	17.8 18.0	17.9	8520	7	1.4	0.085	21.4	19.1	19.5	8.375
68	11-12-180-0-i-2.5-2-17	A B	180°	-	A1035	16.6 16.6	16.6	11880	35	1.4	0.085	21.6	19.2	19.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

Table A.1 Cont. Comprehensive test results and data used in analysis for specimens without confining reinforcement

	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	T_h lb	$f_{su,max}$ psi	f_{su} psi
51	A B	3.9 3.8	3.8	1.6 2.1	9.8	2	80	A2	63745 78050	63689 63320	127009	63504	64377	80690 98797	80385
52	A B	2.8 2.8	2.8	2.5 0.8	13.3	2	97	A7	67249 81430	67249 65931	133180	66590	79286	43108 52199	42686
53	A B	2.5 2.9	2.7	2.1 2.1	13.3	2	169	A12	165682 146801	150653 146801	297454	148727	152421	106206 94103	95338
54	A B	2.5 2.5	2.5	2.0 1.3	13.4	2	114	A16	131998 141233	131969 132141	264111	132055	119020	84614 90534	84651
55	A B	2.5 2.8	2.6	3.4 2.3	13.0	2	138	A13	127061 147904	127061 123191	250252	125126	132865	81449 94810	80209
56	A B	2.5 2.5	2.5	3.0 1.1	13.5	2	115	A8	105626 115172	105537 104020	209557	104779	112427	67709 73828	67166
57	A B	2.5 2.6	2.6	3.1 2.4	13.3	2	114	A13	148361 120380	148361 120380	268741	134371	118562	95103 77167	86135
58	A B	3.8 2.5	3.1	2.1 2.0	13.8	2	126	A7	125648 123622	125648 123597	249245	124622	131960	80544 79245	79886
59	A B	2.5 2.5	2.5	2.4 2.9	13.1	2	160	A12	205050 198110	201395 198091	399486	199743	187403	131443 126994	128040
60	A B	2.5 2.5	2.5	2.0 1.3	13.5	2	155	A11	212601 231323	212601 213928	426530	213265	196102	136283 148284	136708
61	A B	2.8 2.7	2.7	2.5 2.5	13.6	2	74	A15	52097 50882	52097 50866	102962	51481	69331	33395 32617	33001
62	A B	2.8 2.8	2.8	3.0 3.0	13.0	2	102	A15	93327 91008	93327 91008	184335	92168	104578	59825 58339	59082
63	A B	4.0 3.9	3.9	1.8 2.5	13.1	2	133	A7	105772 117570	105772 110472	216244	108122	103770	67803 75366	69309
64	A B	3.8 3.9	3.8	1.5 1.0	13.3	2	108	A7	82601 68982	70046 68982	139027	69514	82944	52949 44219	44560
65	A B	3.8 3.8	3.8	2.1 2.6	13.5	2	189	A12	198346 181661	183026 181481	364508	182254	157184	127145 116449	116829
66	A B	2.9 2.4	2.7	1.8 2.2	13.0	2	137	A13	137773 126839	129406 126839	256246	128123	136292	88316 81307	82130
67	A B	2.4 2.5	2.4	1.4 1.1	13.8	2	115	A8	101710 121269	101710 99197	200907	100453	117199	65199 77737	64393
68	A B	3.0 2.5	2.8	2.5 2.5	13.3	2	116	A13	106726 108195	106726 108195	214921	107461	119514	68414 69356	68885

° Longitudinal column configurations shown in Appendix A, Layouts A1 – A16

Table A.1 Cont. Comprehensive test results and data used in analysis for specimens without confining reinforcement

	Hook	Slip at Failure in.	Failure Type	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
51	A B	- -	SS FB/SS	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
52	A B	0.139 -	FP/SS SS	60	-	-	-	-	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
53	A B	- -	FB/SS FB/SS/TK	60	-	-	-	-	1.86	6	4.0	0.50	4.0	0.375	1	6.32	60
54	A B	- -	FP/TK FB/TK	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.48	60
55	A B	- -	FP/TK FB	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
56	A B	- -	SS FP	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60
57	A B	- -	SB SB/FP	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
58	A B	- 0.25	SS/TK SS	60	-	-	-	-	2.4	12	4.0	0.50	4.0	-	-	4.74	60
59	A B	- -	SB SB	60	-	-	-	-	3.6	18	4.0	0.50	4.0	0.5	1	6.32	60
60	A B	- -	SB/TK SB/TK	60	-	-	-	-	-	-	-	0.50	3.5	-	-	6.32	60
61	A B	- -	FP FP	60	-	-	-	-	-	-	-	0.50	4.5	-	-	6.94	120
62	A B	- -	SB SB	60	-	-	-	-	-	-	-	0.50	4.5	-	-	6.94	120
63	A B	0.187 -	SS/TK SS	60	-	-	-	-	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
64	A B	- -	FP/SS FP/SS/TK	60	-	-	-	-	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
65	A B	- -	SB/FB FB/SB	60	-	-	-	-	1.86	6	4.0	0.50	4.0	0.375	1	6.32	60
66	A B	- -	FB FB/SB	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
67	A B	- -	FP FB	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60
68	A B	0.156 -	SB/FP SS	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60

Table A.2 Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.	R_r	b in.	h in.	h_{cl} in.	h_c in.
69	5-5-90-1#3-i-2.5-2-8	A B	90°	Para	A1035	8.0 7.6	7.8	5310	6	0.6	0.073	13.1	10.4	5.25	8.375
70	5-5-90-1#3-i-2.5-2-6	A B	90°	Para	A615	4.8 5.5	5.1	5800	9	0.6	0.060	13.1	8.0	5.25	8.375
71	5-8-90-1#3-i-2.5-2-6	A B	90°	Para	A615	6.0 6.3	6.1	8450	14	0.6	0.060	12.9	8.0	5.25	8.375
72	5-8-90-1#3-i-2.5-2-6(1)	A B	90°	Para	A1035	6.1 5.6	5.9	9300	13	0.6	0.073	13.1	8.3	5.25	8.375
73	5-8-90-1#3-i-3.5-2-6	A B	90°	Para	A1035	6.0 6.0	6.0	8710	16	0.6	0.060	15.3	8.0	5.25	8.375
74	5-8-90-1#3-i-3.5-2-6(1)	A B	90°	Para	A1035	6.3 6.3	6.3	9190	12	0.6	0.073	15.3	8.6	5.25	8.375
75	5-5-180-1#3-i-2.5-2-8	A B	180°	Para	A1035	8.0 7.8	7.9	5670	7	0.6	0.073	13.0	10.3	5.25	8.375
76	5-5-180-1#3-i-2.5-2-6	A B	180°	Para	A615	6.0 6.0	6.0	5800	9	0.6	0.060	13.1	8.0	5.25	8.375
77	5-8-180-1#3-i-2.5-2-7	A B	180°	Para	A1035	7.1 7.3	7.2	9300	13	0.6	0.073	12.8	9.5	5.25	8.375
78	5-8-180-1#3-i-3.5-2-7	A B	180°	Para	A1035	7.1 6.8	6.9	9190	12	0.6	0.073	15.3	9.3	5.25	8.375
79	5-5-90-1#4-i-2.5-2-8	A B	90°	Para	A1035	7.4 7.8	7.6	5310	6	0.6	0.073	13.1	10.1	9.25	8.375
80	5-5-90-1#4-i-2.5-2-6	A B	90°	Para	A615	5.3 5.8	5.5	5860	8	0.6	0.060	12.9	8.0	5.25	8.375
81	5-8-90-1#4-i-2.5-2-6	A B	90°	Para	A1035	5.9 6.0	6.0	9300	13	0.6	0.073	12.9	8.8	5.25	8.375
82	5-8-90-1#4-i-3.5-2-6	A B	90°	Para	A1035	6.0 7.0	6.5	9190	12	0.6	0.073	15.1	9.0	5.25	8.375
83	5-5-180-1#4-i-2.5-2-8	A B	180°	Para	A1035	8.0 8.0	8.0	5310	6	0.6	0.073	12.9	10.0	5.25	8.375
84	5-5-180-1#4-i-2.5-2-6	A B	180°	Para	A615	6.5 6.0	6.3	5670	7	0.6	0.060	13.0	8.5	5.25	8.375
85	5-5-90-2#3-i-2.5-2-8	A B	90°	Para	A1035	8.0 7.5	7.8	5860	8	0.6	0.073	12.9	10.0	5.38	8.375
86	5-5-90-2#3-i-2.5-2-6	A B	90°	Para	A615	6.0 5.8	5.9	5800	9	0.6	0.060	13.1	8.5	5.25	8.375
87	5-8-90-2#3-i-2.5-2-6	A B	90°	Para	A1035	6.0 6.0	6.0	8580	15	0.6	0.073	13.0	8.0	5.25	8.375
88	5-8-90-2#3-i-2.5-2-8	A B	90°	Para	A1035	8.3 8.5	8.4	8380	13	0.6	0.073	12.9	10.0	5.25	8.375
89	5-12-90-2#3-i-2.5-2-5	A B	90°	Para	A1035	5.8 5.8	5.8	11090	83	0.6	0.073	13.0	8.8	5.25	8.375
90	5-15-90-2#3-i-2.5-2-6	A B	90°	Para	A1035	6.3 6.5	6.4	15800	61	0.6	0.073	12.6	8.2	5.25	8.375
91	5-15-90-2#3-i-2.5-2-4	A B	90°	Para	A1035	3.5 4.0	3.8	15800	61	0.6	0.073	13.0	6.1	5.25	8.375
92	5-5-90-2#3-i-3.5-2-6	A B	90°	Para	A1035	6.0 5.8	5.9	5230	6	0.6	0.073	14.5	8.3	5.25	8.375
93	5-5-90-2#3-i-3.5-2-8	A B	90°	Para	A1035	7.9 7.5	7.7	5190	7	0.6	0.073	14.9	10.3	5.25	8.375

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	T_h lb	$f_{su,max}$ psi	f_{su} psi
69	A B	2.5 2.5	2.5	2.4 2.8	6.9	2	80	A1	32860 37440	32628 33645	66273	33136	31349	106001 120776	106892
70	A B	2.5 2.5	2.5	3.3 2.5	6.9	2	80	A1	20038 29285	19968 19863	39830	19915	21933	64639 94469	64242
71	A B	2.5 2.5	2.5	2.0 1.8	6.6	2	80	A1	26203 27858	26172 26974	53146	26573	28174	84524 89865	85719
72	A B	2.6 2.8	2.7	2.1 2.6	6.5	2	30	A1	29328 25430	29328 25430	54758	27379	27780	94606 82032	88319
73	A B	3.6 3.6	3.6	2.0 2.0	6.8	2	80	A1	41369 31173	28996 31173	60169	30084	27859	133448 100558	97046
74	A B	3.8 3.5	3.6	2.4 2.4	6.8	2	30	A1	28967 26270	25617 26194	51811	25905	29307	93441 84741	83565
75	A B	2.6 2.5	2.6	2.3 2.5	6.6	2	80	A1	36570 39949	36332 36565	72896	36448	32111	117967 128867	117575
76	A B	2.6 2.6	2.6	2.0 2.0	6.6	2	80	A1	29091 24285	23661 24171	47832	23916	25201	93843 78338	77148
77	A B	2.5 2.5	2.5	2.4 2.3	6.5	2	30	A1	34198 35367	34198 31621	65819	32909	33456	110316 114087	106159
78	A B	3.5 3.5	3.5	2.1 2.5	7.0	2	30	A1	35824 28925	35733 25266	60999	30500	32272	115563 93305	98386
79	A B	2.5 2.5	2.5	2.8 2.4	6.9	2	80	A1	35739 27537	27537 27537	55074	27537	33925	115288 88829	88829
80	A B	2.5 2.5	2.5	2.8 2.3	6.6	2	80	A1	21633 26769	21535 21379	42914	21457	26892	69782 86352	69217
81	A B	2.5 2.8	2.6	2.8 2.8	6.4	2	30	A1	23854 27932	23854 24731	48585	24292	31688	76947 90103	78363
82	A B	3.6 3.5	3.6	3.0 2.0	6.8	2	30	A1	25266 25221	25261 25221	50482	25241	33887	81504 81359	81423
83	A B	2.5 2.5	2.5	2.0 2.0	6.6	2	80	A1	43142 38421	38421 38421	76842	38421	35550	139167 123938	123938
84	A B	2.5 2.6	2.6	2.0 2.5	6.6	2	80	A1	25321 22912	23275 22679	45954	22977	29499	81681 73909	74119
85	A B	2.5 2.5	2.5	2.0 2.5	6.6	2	80	A1	37932 38949	37807 36500	74307	37154	31904	122360 125642	119850
86	A B	2.6 2.6	2.6	2.5 2.8	6.6	2	80	A1	31846 29191	29697 29191	58888	29444	24732	102730 94164	94980
87	A B	2.8 2.9	2.8	2.0 2.0	6.1	2	80	A1	33454 30874	30402 30874	61277	30638	27755	107916 99595	98833
88	A B	2.6 2.5	2.6	1.8 1.5	6.5	2	80	A5	39822 40545	39791 40545	80336	40168	37614	128457 130789	129574
89	A B	2.5 2.8	2.6	3.0 3.0	6.5	2	30	A1	25201 29393	25120 23576	48696	24348	28463	81295 94816	78542
90	A B	2.4 2.4	2.4	1.9 1.7	6.6	2	30	A2	42381 42895	42381 42895	85276	42638	34250	136714 138371	137542
91	A B	2.5 2.5	2.5	2.6 2.1	6.8	2	30	A9	18652 21256	18652 18683	37334	18667	21220	60167 68569	60217
92	A B	3.4 3.4	3.4	2.3 2.5	6.5	2	30	A1	21341 21262	21146 21040	42186	21093	24118	68842 68586	68042
93	A B	3.4 3.5	3.4	2.3 2.8	6.8	2	30	A1	43675 45654	43675 45654	89329	44665	30822	140887 147271	144079

° Longitudinal column configurations shown in Appendix A, Layouts A1 – A16

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Hook	Slip at Failure in.	Failure Type	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
69	A B	- -	FP SB/FB	60	0.38	0.11	1	5.00	0.44	4	6.0	0.375	4.00	-	-	1.27	60
70	A B	- -	SS SS/FP	60	0.38	0.11	1	5.00	0.44	4	6.0	0.375	4.00	-	-	1.27	60
71	A B	- -	FP SS	60	0.38	0.11	1	5.00	0.80	4	6.0	0.500	4.00	-	-	1.27	60
72	A B	- -	FP/SS FP/SS	60	0.38	0.11	1	6.00	0.66	6	3.0	0.500	3.00	-	-	1.27	60
73	A B	- -	FP/SS FP/SS	60	0.38	0.11	1	5.00	0.80	4	6.0	0.500	4.00	-	-	1.27	60
74	A B	0.239 0.158	FP/SS FP/SS	60	0.38	0.11	1	6.00	0.66	6	3.0	0.500	3.00	-	-	1.27	60
75	A B	- -	SS SS/FP	60	0.38	0.11	1	4.00	-	-	-	0.375	4.00	-	-	1.27	60
76	A B	- -	SS/FP FP/SS	60	0.38	0.11	1	4.00	-	-	-	0.375	4.00	-	-	1.27	60
77	A B	0.373 .261(.035)	FP/SS FP/SS	60	0.38	0.11	1	3.00	-	-	-	0.375	3.00	-	-	1.27	60
78	A B	0.205 0.238	FP FP	60	0.38	0.11	1	3.00	-	-	-	0.375	3.00	-	-	1.27	60
79	A B	- -	FP/SS SB	60	0.5	0.20	1	5.00	0.44	4	6.0	0.375	4.00	-	-	1.27	60
80	A B	- -	SS SS	60	0.5	0.20	1	5.00	0.44	4	6.0	0.375	4.00	-	-	1.27	60
81	A B	0.25 0.22	FP FP/SS	60	0.5	0.20	1	6.00	0.44	4	6.0	0.500	3.00	-	-	1.27	60
82	A B	- -	FP/SS FP/SS	60	0.5	0.20	1	6.00	0.44	4	6.0	0.500	3.00	-	-	1.27	60
83	A B	- -	FP/SS FP	60	0.5	0.20	1	4.00	-	-	-	0.375	4.00	-	-	1.27	60
84	A B	- -	FP/SS FP	60	0.5	0.20	1	4.00	-	-	-	0.375	4.00	-	-	1.27	60
85	A B	- -	SS/FP SS/FP	60	0.38	0.11	2	4.00	-	-	-	0.375	4.00	-	-	1.27	60
86	A B	- -	FP/SS FP/SS	60	0.38	0.11	2	4.00	-	-	-	0.375	4.00	-	-	1.27	60
87	A B	- -	FP/SS FP/SS	60	0.38	0.11	2	4.00	-	-	-	0.500	4.00	-	-	1.27	60
88	A B	- -	FP/SS FP/SS	60	0.38	0.11	2	4.00	-	-	-	0.500	4.00	-	-	1.67	60
89	A B	- -	FP/SS FP	60	0.38	0.11	2	3.30	0.33	3	3.3	0.500	3.00	-	-	1.27	60
90	A B	- -	FP FB	60	0.38	0.11	2	3.00	-	-	-	0.375	2.75	-	-	3.16	60
91	A B	- -	FB FP	60	0.38	0.11	2	3.00	-	-	-	0.375	1.75	-	-	2.51	60
92	A B	0.183 -	SS/FP SS/FP	60	0.38	0.11	2	3.50	0.11	1	3.5	0.375	3.50	-	-	1.27	60
93	A B	- -	FP FP	60	0.38	0.11	2	3.50	-	-	-	0.375	4.00	-	-	1.27	60

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.	R_r	b in.	h in.	h_{cl} in.	h_c in.
94	5-8-90-2#3-i-3.5-2-6	A B	90°	Para	A1035	6.5 6.0	6.3	8580	15	0.6	0.073	14.9	8.0	5.25	8.375
95	5-8-90-2#3-i-3.5-2-8	A B	90°	Para	A1035	7.1 7.0	7.1	8710	16	0.6	0.060	14.9	10.0	5.25	8.375
96	5-12-90-2#3-i-3.5-2-5	A B	90°	Para	A1035	5.6 5.3	5.4	10410	15	0.6	0.073	15.1	7.4	5.25	8.375
97	5-5-180-2#3-i-2.5-2-8	A B	180°	Para	A1035	8.0 8.0	8.0	5670	7	0.6	0.073	13.1	10.0	5.25	8.375
98	5-5-180-2#3-i-2.5-2-6	A B	180°	Para	A615	5.8 5.5	5.6	5860	8	0.6	0.060	13.1	7.8	5.25	8.375
99	5-8-180-2#3-i-2.5-2-7	A B	180°	Para	A1035	7.0 7.3	7.1	9080	11	0.6	0.073	12.6	9.3	5.25	8.375
100	5-8-180-2#3-i-3.5-2-7	A B	180°	Para	A1035	6.8 6.9	6.8	9080	11	0.6	0.073	15.1	9.2	5.25	8.375
101	5-8-90-4#3-i-2.5-2-8	A B	90°	Para	A1035	7.9 7.5	7.7	8380	13	0.6	0.060	12.6	10.0	5.25	8.375
102	5-8-90-4#3-i-3.5-2-8	A B	90°	Para	A1035	8.6 8.3	8.4	8380	13	0.6	0.060	15.1	10.0	5.25	8.375
103	5-5-90-5#3-i-2.5-2-7	A B	90°	Para	A1035	5.6 7.0	6.3	5230	6	0.6	0.073	13.3	9.3	5.25	8.375
104	5-12-90-5#3-i-2.5-2-5	A B	90°	Para	A1035	5.1 5.8	5.4	10410	15	0.6	0.073	13.0	7.3	5.25	8.375
105	5-15-90-5#3-i-2.5-2-4	A B	90°	Para	A1035	3.8 4.1	4.0	15800	62	0.6	0.073	12.8	6.0	5.25	8.375
106	5-15-90-5#3-i-2.5-2-5	A B	90°	Para	A1035	5.0 5.1	5.1	15800	62	0.6	0.073	12.8	7.1	5.25	8.375
107	5-5-90-5#3-i-3.5-2-7	A B	90°	Para	A1035	7.5 6.8	7.1	5190	7	0.6	0.073	15.1	9.5	5.25	8.375
108	5-12-90-5#3-i-3.5-2-5	A B	90°	Para	A1035	5.3 4.8	5.0	11090	83	0.6	0.073	14.4	7.0	5.25	8.375
109	8-5-90-1#3-i-2.5-2-16	A B	90°	Para	A1035[b]	15.6 15.6	15.6	4810	6	1	0.078	17.3	17.9	10.5	8.375
110	8-5-90-1#3-i-2.5-2-12.5	A B	90°	Para	A1035[b]	12.5 12.5	12.5	5140	8	1	0.078	17.1	14.6	10.5	8.375
111	8-5-90-1#3-i-2.5-2-9.5	A B	90°	Para	A615	9.0 9.0	9.0	5240	9	1	0.078	17.1	11.5	10.5	8.375
112	8-5-180-1#3-i-2.5-2-11	A B	180°	Para	A615	11.5 11.5	11.5	4300	6	1	0.078	17.0	13.0	10.5	8.375
113	8-5-180-1#3-i-2.5-2-14	A B	180°	Para	A1035[b]	14.8 15.0	14.9	4870	9	1	0.078	17.5	16.0	10.5	8.375
114	8-5-180-1#3-i-3.5-2-11	A B	180°	Para	A615	11.6 10.6	11.1	4550	7	1	0.078	19.3	13.0	10.5	8.375
115	8-5-180-1#3-i-3.5-2-14	A B	180°	Para	A1035[b]	15.6 14.5	15.1	4840	8	1	0.078	19.3	16.5	10.5	8.375
116	8-8-180-1#4-i-2.5-2-11.5	A B	180°	Para	A1035[b]	12.0 12.3	12.1	8740	12	1	0.078	17.1	14.0	10.5	8.375
117	8-5-90-2#3-i-2.5-2-16	A B	90°	Para	A1035[b]	15.0 15.8	15.4	4810	6	1	0.078	17.1	17.9	10.5	8.375
118	8-5-90-2#3-i-2.5-2-9.5	A B	90°	Para	A615	9.0 9.3	9.1	5140	8	1	0.078	17.0	11.6	10.5	8.375

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	T_h lb	$f_{su,max}$ psi	f_{su} psi
94	A B	3.5 3.8	3.6	1.5 2.0	6.4	2	80	A1	29930 30139	29930 30139	60069	30035	28807	96549 97223	96886
95	A B	3.5 3.5	3.5	2.9 3.0	6.6	2	80	A5	38022 28596	28716 28596	57312	28656	32368	122652 92246	92439
96	A B	3.8 3.5	3.6	1.8 2.2	6.6	2	30	A1	27860 28869	27860 28869	56728	28364	26634	89871 93124	91497
97	A B	2.5 2.5	2.5	2.0 2.0	6.9	2	80	A1	34036 34483	33674 34483	68157	34078	36883	109795 111236	109930
98	A B	2.6 2.6	2.6	2.0 2.3	6.6	2	80	A1	26852 26912	26782 26674	53456	26728	28154	86620 86814	86220
99	A B	2.5 2.5	2.5	2.3 2.1	6.4	2	30	A1	34580 28697	29762 28697	58459	29230	37280	111548 92572	94289
100	A B	3.4 3.5	3.4	2.4 2.3	7.0	2	30	A1	29310 32577	29285 32577	61862	30931	35933	94550 105086	99777
101	A B	2.5 2.5	2.5	2.1 2.5	6.4	2	80	A5	33367 27016	25867 26955	52823	26411	38991	107636 87150	85198
102	A B	3.5 3.5	3.5	1.4 1.8	6.9	2	80	A5	42471 39278	37810 39150	76960	38480	42178	137003 126704	124130
103	A B	2.8 2.8	2.8	3.6 2.3	6.5	2	30	A1	32080 31340	32080 31313	63393	31696	34446	103484 101095	102246
104	A B	2.6 2.6	2.6	2.1 1.5	6.5	2	30	A1	33923 34916	33923 34916	68839	34420	35366	109428 112634	111031
105	A B	2.4 2.5	2.4	2.2 1.9	6.6	2	30	A9	31312 31325	31312 31325	62637	31318	31021	101006 101048	101027
106	A B	2.4 2.3	2.4	2.1 1.9	6.8	2	30	A2	38574 46165	38574 39737	78312	39156	36416	124434 148921	126309
107	A B	3.4 3.5	3.4	2.0 2.8	7.0	2	30	A1	44301 35206	36844 35206	72050	36025	37369	142906 113568	116210
108	A B	3.3 3.3	3.3	2.5 1.5	6.6	2	30	A1	31472 31302	31396 29485	60882	30441	33822	101522 100973	98196
109	A B	2.8 3.0	2.9	2.3 2.3	9.5	2	80	A2	94588 73936	75682 73936	149617	74809	76769	119731 93589	94694
110	A B	2.6 2.8	2.7	2.1 2.1	9.8	2	80	A2	73919 64783	64891 64783	129674	64837	62777	93569 82004	82072
111	A B	2.6 2.8	2.7	2.5 2.5	9.8	2	80	A2	62525 65289	59716 64750	124467	62233	46082	79145 82645	78776
112	A B	2.5 2.5	2.5	1.5 1.5	10.0	2	80	A2	57294 68950	48342 51122	99464	49732	55252	72524 87278	62952
113	A B	2.8 2.9	2.8	1.3 1.0	9.9	2	80	A2	67269 70909	67183 70860	138043	69021	73355	85150 89758	87369
114	A B	3.8 3.5	3.6	1.4 2.4	10.0	2	80	A2	62945 56154	54681 56100	110781	55390	54323	79678 71082	70114
115	A B	3.6 3.6	3.6	0.9 2.0	10.0	2	80	A2	78657 76919	75069 76919	151988	75994	74142	99565 97366	96195
116	A B	2.9 2.8	2.8	2.0 1.8	9.5	2	30	A2	72047 72506	71987 72475	144462	72231	74846	91199 91780	91432
117	A B	2.8 2.9	2.8	2.9 2.1	9.5	2	80	A2	80014 92780	79629 79629	159258	79629	75532	101284 117443	100796
118	A B	2.5 2.5	2.5	2.6 2.3	10.0	2	80	A2	54916 53621	53621 53621	107242	53621	46453	69513 67874	67874

° Longitudinal column configurations shown in Appendix A, Layouts A1 – A16

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Hook	**Slip at Failure in.**	**Failure Type**	f_{yt} **ksi**	d_{tr} **in.**	$A_{tr,l}$ **in.**^{2}	N_{tr}	s_{tr} **in.**	A_{cti} **in.**^{2}	N_{cti}	s_{cti} **in.**	d_s **in.**	s_s **in.**	d_{cto} **in.**	N_{cto}	A_s **in.**^{2}	f_{ys} **ksi**
94	A B	- -	FP FP/SS	60	0.38	0.11	2	4.00	-	-	-	0.500	4.00	-	-	1.27	60
95	A B	- -	FP FP	60	0.38	0.11	2	4.00	-	-	-	0.500	4.00	-	-	1.67	60
96	A B	- 0.349	FP FP	60	0.38	0.11	2	3.33	0.33	3	3.3	0.500	3.00	-	-	1.27	60
97	A B	- -	FP/SS FP/SS	60	0.38	0.11	2	2.50	-	-	-	0.375	4.00	-	-	1.27	60
98	A B	- -	FP/SS FP	60	0.38	0.11	2	2.50	-	-	-	0.375	4.00	-	-	1.27	60
99	A B	- .369(.081)	FP/SS FP/SS	60	0.38	0.11	2	2.00	-	-	-	0.375	3.00	-	-	1.27	60
100	A B	- .329(.028)	FP/SS FP	60	0.38	0.11	2	2.00	-	-	-	0.375	3.00	-	-	1.27	60
101	A B	- -	FP/SS FP/SS	60	0.38	0.11	4	2.00	-	-	-	0.500	4.00	-	-	1.67	60
102	A B	- -	FP SS/FP	60	0.38	0.11	4	2.00	-	-	-	0.500	4.00	-	-	1.67	60
103	A B	- -	FP FP/SS	60	0.38	0.11	5	1.75	-	-	-	0.500	3.50	-	-	1.27	60
104	A B	0.292 0.295	FP/SS SS/FP	60	0.38	0.11	5	1.67	-	-	-	0.500	3.00	-	-	1.27	60
105	A B	0.603 0.378	FP FP	60	0.38	0.11	5	1.75	-	-	-	0.375	1.75	-	-	2.51	60
106	A B	- -	FP BY	60	0.38	0.11	5	1.75	-	-	-	0.375	2.25	-	-	3.16	60
107	A B	- -	FP FP	60	0.38	0.11	5	1.75	-	-	-	0.500	3.50	-	-	1.27	60
108	A B	- -	FP FP	60	0.38	0.11	5	1.70	-	-	-	0.500	3.00	-	-	1.27	60
109	A B	- -	FP/SS FP/SS	60	0.38	0.11	1	9.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
110	A B	- -	FP/SS SS/FP	60	0.38	0.11	1	9.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
111	A B	- -	SB FP/SS	60	0.38	0.11	1	9.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
112	A B	0.088 0.341	SS/FP SS/FP	60	0.38	0.11	1	3.50	0.44	4	4.5	0.50	3.50	-	-	3.16	60
113	A B	- 0.123	SS/FP FP/SS	60	0.38	0.11	1	3.50	0.44	4	4.5	0.50	3.50	-	-	3.16	60
114	A B	0.434 0.216	SS SS	60	0.38	0.11	1	3.50	0.44	4	4.5	0.50	3.50	-	-	3.16	60
115	A B	0.232 0.227	SS/FP SS/FP	60	0.38	0.11	1	3.50	0.44	4	4.5	0.50	3.50	-	-	3.16	60
116	A B	- .(0.013)	FP/SS FP/SS	60	0.5	0.20	1	3.00	0.44	4	3.0	0.50	3.00	-	-	3.16	60
117	A B	- -	SS/FP FP	60	0.38	0.11	2	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
118	A B	- -	FP FP	60	0.38	0.11	2	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.	R_r	b in.	h in.	h_{cl} in.	h_c in.
119	8-5-90-2#3-i-2.5-2-12.5	A B	90°	Para	A615	12.0 12.0	12.0	5240	9	1	0.078	17.0	14.6	10.5	8.375
120	8-5-90-2#3-i-2.5-2-8.5	A B	90°	Para	A1035[c]	8.9 9.6	9.3	5240	6	1	0.073	17.1	10.7	10.5	8.375
121	8-5-90-2#3-i-2.5-2-14	A B	90°	Para	A1035[c]	13.5 14.0	13.8	5450	7	1	0.073	17.0	16.1	10.5	8.375
122	(2@3) 8-5-90-2#3-i-2.5-2-10‡	A B	90°	Para	A615	10.0 10.5	10.3	4760	11	1	0.073	9.3	12.0	10.5	8.375
123	(2@5) 8-5-90-2#3-i-2.5-2-10‡	A B	90°	Para	A615	9.6 10.0	9.8	4760	11	1	0.073	10.9	12.0	10.5	8.375
124	8-8-90-2#3-i-2.5-2-8	A B	90°	Para	A1035[b]	8.0 8.5	8.3	7700	14	1	0.078	16.9	10.0	10.5	8.375
125	8-8-90-2#3-i-2.5-2-10	A B	90°	Para	A1035[b]	9.9 9.5	9.7	8990	17	1	0.078	16.0	12.0	10.5	8.375
126	8-12-90-2#3-i-2.5-2-9	A B	90°	Para	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	17.0	11.3	10.5	8.375
127	8-12-90-2#3-i-2.5-2-11	A B	90°	Para	A1035[c]	10.5 11.3	10.9	12010	42	1	0.073	17.0	12.9	10.5	8.375
128	8-12-90-2#3vr-i-2.5-2-11	A B	90°	Perp	A1035[c]	10.9 10.4	10.6	12010	42	1	0.073	16.5	13.0	10.5	8.375
129	8-15-90-2#3-i-2.5-2-11	A B	90°	Para	A1035[c]	11.3 10.8	11.0	15800	61	1	0.073	17.0	13.1	10.5	8.375
130	8-5-90-2#3-i-3.5-2-17	A B	90°	Para	A1035[b]	17.5 17.0	17.3	5570	12	1	0.078	18.9	19.3	10.5	8.375
131	8-5-90-2#3-i-3.5-2-13	A B	90°	Para	A1035[b]	13.8 13.5	13.6	5560	11	1	0.078	19.0	15.3	10.5	8.375
132	8-8-90-2#3-i-3.5-2-8	A B	90°	Para	A1035[b]	8.0 8.1	8.1	8290	16	1	0.078	17.9	10.0	10.5	8.375
133	8-8-90-2#3-i-3.5-2-10	A B	90°	Para	A1035[b]	8.8 8.8	8.8	8990	17	1	0.078	17.9	12.0	10.5	8.375
134	8-12-90-2#3-i-3.5-2-9	A B	90°	Para	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	19.3	11.3	10.5	8.375
135	8-5-180-2#3-i-2.5-2-11	A B	180°	Para	A615	10.8 10.5	10.6	4550	7	1	0.078	16.8	13.0	10.5	8.375
136	8-5-180-2#3-i-2.5-2-14	A B	180°	Para	A1035[b]	13.5 14.0	13.8	4870	9	1	0.078	17.3	16.0	10.5	8.375
137	8-8-180-2#3-i-2.5-2-11.5	A B	180°	Para	A1035[b]	10.5 10.3	10.4	8810	14	1	0.078	17.5	12.8	10.5	8.375
138	8-12-180-2#3-i-2.5-2-11	A B	180°	Para	A1035[c]	11.1 10.4	10.8	12010	42	1	0.073	16.8	13.2	10.5	8.375
139	8-12-180-2#3vr-i-2.5-2-11	A B	180°	Perp	A1035[b]	10.9 10.9	10.9	12010	42	1	0.073	17.1	13.3	10.5	8.375
140	8-5-180-2#3-i-3.5-2-11	A B	180°	Para	A1035[b]	10.1 10.6	10.4	4300	6	1	0.078	18.6	13.0	10.5	8.375
141	8-5-180-2#3-i-3.5-2-14	A B	180°	Para	A1035[b]	13.5 13.6	13.6	4870	9	1	0.078	19.1	16.0	10.5	8.375
142	8-15-180-2#3-i-2.5-2-11	A B	180°	Para	A1035[b]	11.1 11.1	11.1	15550	87	1	0.073	17.3	13.1	10.5	8.375
143	8-8-90-2#4-i-2.5-2-10	A B	90°	Para	A1035[b]	8.5 9.3	8.9	8290	16	1	0.078	17.3	12.0	10.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	T_h lb	$f_{su,max}$ psi	f_{su} psi
119	A B	2.8 2.8	2.8	2.6 2.6	9.5	2	80	A2	74108 76334	67801 76334	144135	72067	60649	93808 96625	91225
120	A B	3.0 3.0	3.0	1.8 1.1	9.1	2	30	A2	52863 48439	52862 48260	101122	50561	47286	66915 61315	64001
121	A B	2.8 3.0	2.9	2.6 2.1	9.3	2	30	A2	76959 77540	76388 77540	153927	76964	69985	97416 98151	97422
122	A B	2.5 2.5	2.5	2.0 1.5	2.3	2	30	A2	58584 47051	58435 35184	93619	46810	50832	74157 59558	59253
123	A B	2.5 2.5	2.5	2.4 2.0	3.9	2	30	A2	48430 48617	48412 48617	97029	48515	48772	61303 61541	61411
124	A B	3.0 2.9	2.9	2.0 1.5	9.0	2	30	A2	46211 55377	46211 49540	95751	47876	46882	58495 70098	60602
125	A B	2.8 2.8	2.8	2.1 2.5	8.5	2	30	A2	60670 67001	60670 61378	122047	61024	56882	76797 84812	77245
126	A B	2.9 2.6	2.8	2.3 2.3	9.5	2	30	A2	61813 60251	61813 60213	122026	61013	56097	78244 76267	77232
127	A B	2.8 2.8	2.8	2.4 1.6	9.5	2	30	A2	68128 79794	68101 69264	137365	68683	68734	86237 101004	86940
128	A B	2.5 2.3	2.4	2.1 2.6	9.8	2	30	A2	50709 66830	50709 54637	105346	52673	64971	64188 84595	66674
129	A B	2.5 2.5	2.5	1.9 2.4	10.0	2	30	A11	99011 83603	83072 83567	166640	83320	74830	125330 105827	105468
130	A B	3.3 3.5	3.4	1.8 2.3	10.1	2	30	A2	102613 88572	91402 88426	179829	89914	88104	129889 112117	113816
131	A B	3.1 3.6	3.4	1.5 1.8	10.3	2	30	A2	81199 86858	81199 79522	160720	80360	69734	102783 109946	101722
132	A B	3.6 3.8	3.7	2.0 1.9	8.5	2	30	A2	48324 49258	48324 49222	97545	48773	46759	61169 62352	61738
133	A B	3.6 3.8	3.7	3.3 3.3	8.5	2	30	A2	53960 53810	53960 53810	107770	53885	51599	68304 68113	68209
134	A B	3.6 4.0	3.8	2.3 2.4	9.6	2	30	A2	50266 49289	50266 49289	99555	49777	56097	63628 62391	63009
135	A B	2.8 2.5	2.6	2.3 2.5	9.5	2	80	A2	64232 61892	58650 61819	120469	60235	57658	81306 78345	76246
136	A B	2.8 2.8	2.8	2.5 2.0	9.8	2	80	A2	87080 76851	75744 76814	152558	76279	73578	110228 97279	96556
137	A B	2.8 2.8	2.8	2.3 2.5	10.0	2	30	A2	70102 59494	56934 59408	116343	58171	66123	88737 75309	73635
138	A B	2.5 2.6	2.6	2.1 2.8	9.6	2	30	A2	73700 66170	63140 66170	129310	64655	67961	93291 83759	81842
139	A B	2.8 2.6	2.7	2.4 2.4	9.8	2	30	A2	67136 87053	67136 64423	131559	65780	66517	84983 110194	83265
140	A B	3.4 3.5	3.4	2.9 2.4	9.8	2	80	A2	57158 54943	56965 54772	111737	55869	55752	72352 69548	70720
141	A B	3.6 3.8	3.7	2.5 2.4	9.8	2	80	A2	68293 90408	68293 58642	126934	63467	72672	86446 114441	80338
142	A B	2.8 2.8	2.8	2.1 2.0	9.8	2	30	A7	79626 78291	79553 78291	157845	78922	75135	100792 99103	99902
143	A B	3.0 3.0	3.0	3.5 2.8	9.3	2	30	A2	61367 71322	61286 61434	122721	61360	55832	77680 90281	77671

° Longitudinal column configurations shown in Appendix A, Layouts A1 – A16

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Hook	Slip at Failure in.	Failure Type	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
119	A B	- -	FP FP/SS	60	0.38	0.11	2	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
120	A B		FP/SS SS	60	0.38	0.11	2	7.50	2.00	10	2.5	0.50	3.25	0.5	1	3.16	60
121	A B		SS/FP FP/SS	60	0.38	0.11	2	6.00	0.88	8	3.0	0.50	3.50	0.5	1	3.16	60
122	A B	0.21 -	FP FP	60	0.38	0.11	2	3.00	-	-	-	0.38	4.00	-	-	3.16	120
123	A B	0.23 0.108	FB FB	60	0.38	0.11	2	3.00	-	-	-	0.38	5.00	-	-	3.16	120
124	A B	- -	FP/SS FP/SS	60	0.38	0.11	2	7.13	1.20	6	4.0	0.50	1.50	-	-	3.16	60
125	A B	0.186 0.152	FP FB	60	0.38	0.11	2	7.13	1.20	6	4.0	0.63	3.50	-	-	3.16	60
126	A B	0.345 0.361	FP/SS SS/FP	60	0.38	0.11	2	8.00	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60
127	A B	0.181 0.165	FP FP	60	0.38	0.11	2	8.00	-	-	-	0.50	2.00	-	-	3.16	60
128	A B	- 0.13	FP/SS FP	60	0.38	0.11	2	2.67	-	-	-	0.50	2.00	-	-	3.16	60
129	A B	- 0.123	FB FB	60	0.38	0.11	2	5.50	-	-	-	0.38	4.00	-	-	6.32	60
130	A B	- -	SS SS/FP	60	0.38	0.11	2	8.00	0.80	4	4.0	0.50	4.00	0.375	1	3.16	60
131	A B	- -	SS/FP SS/FP	60	0.38	0.11	2	8.00	0.44	4	4.0	0.50	3.00	-	-	3.16	60
132	A B	0.31 .340(.147)	FP FP	60	0.38	0.11	2	7.13	1.20	6	4.0	0.50	1.50	-	-	3.16	60
133	A B	- -	SS FP	60	0.38	0.11	2	7.13	1.20	6	4.0	0.63	3.50	-	-	3.16	60
134	A B	0.15	FP/SS FP/SS	60	0.38	0.11	2	8.00	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60
135	A B	0.26 0.087	SS/FP SS/FP	60	0.38	0.11	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60
136	A B	0.774 0.199	FP FP/SS	60	0.38	0.11	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60
137	A B	0.261 .25(.027)	FB/SS FP/SS	60	0.38	0.11	2	3.00	-	-	-	0.50	3.00	-	-	3.16	60
138	A B	- -	FP FB	60	0.38	0.11	2	8.00	-	-	-	0.50	2.00	-	-	3.16	60
139	A B	- 0.369	SS/FP FB/SB	60	0.38	0.11	2	2.67	-	-	-	0.50	2.00	-	-	3.16	60
140	A B	0.167 0.212	SS/FP SS/FP	60	0.38	0.11	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60
141	A B	- -	FP/SS FP/SS	60	0.38	0.11	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60
142	A B	- -	FB/SS FP	60	0.38	0.11	2	5.00	-	-	-	0.50	4.00	-	-	4.74	60
143	A B	0.171 .285(.129)	FP/SS FP/SS	60	0.5	0.20	2	7.13	1.20	6	4.0	0.50	2.00	-	-	3.16	60

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.	R_r	b in.	h in.	h_{cl} in.	h_c in.
144	8-8-90-2#4-i-3.5-2-10	A B	90°	Para	A1035[b]	9.0 9.8	9.4	8290	16	1	0.078	18.8	12.0	10.5	8.375
145	8-5-90-4#3-i-2.5-2-16	B A	90°	Para	A1035[b]	16.0 16.3	16.1	4810	6	1	0.078	17.3	17.9	10.5	8.375
146	8-5-90-4#3-i-2.5-2-12.5	A B	90°	Para	A1035[b]	11.9 11.9	11.9	4980	7	1	0.078	17.0	13.9	10.5	8.375
147	8-5-90-4#3-i-2.5-2-9.5	A B	90°	Para	A615	9.5 9.5	9.5	5140	8	1	0.078	17.1	11.5	10.5	8.375
148	8-5-90-5#3-i-2.5-2-10b	A B	90°	Para	A1035[a]	10.3 10.5	10.4	5440	8	1	0.084	17.3	12.3	10.5	8.375
149	8-5-90-5#3-i-2.5-2-10c	A B	90°	Para	A1035[a]	10.5 10.5	10.5	5650	9	1	0.084	17.0	12.5	10.5	8.375
150	8-5-90-5#3-i-2.5-2-15	A B	90°	Para	A1035[b]	15.3 15.8	15.5	4850	7	1	0.078	17.1	17.2	10.5	8.375
151	8-5-90-5#3-i-2.5-2-13	A B	90°	Para	A1035[b]	13.8 13.5	13.6	5560	11	1	0.078	17.1	15.3	10.5	8.375
152	8-5-90-5#3-i-2.5-2-12(1)	A B	90°	Para	A1035[c]	11.5 11.1	11.3	5090	7	1	0.073	16.8	14.1	10.5	8.375
153	8-5-90-5#3-i-2.5-2-12	A B	90°	Para	A1035[c]	11.3 12.3	11.8	5960	7	1	0.073	16.6	14.3	10.5	8.375
154	8-5-90-5#3-i-2.5-2-12(2)	A B	90°	Para	A1035[c]	12.4 12.0	12.2	5240	6	1	0.073	16.1	14.1	10.5	8.375
155	8-5-90-5#3-i-2.5-2-8	A B	90°	Para	A1035[c]	7.8 7.4	7.6	5240	6	1	0.073	16.6	10.3	10.5	8.375
156	8-5-90-5#3-i-2.5-2-10a	B	90°	Para	A1035[a]	10.5	10.5	5270	7	1	0.08	17	12.3	10.5	8.375
157	(2@3) 8-5-90-5#3-i-2.5-2-10‡	A B	90°	Para	A615	10.0 10.5	10.3	4805	12	1	0.073	9.2	12.0	10.5	8.375
158	(2@5) 8-5-90-5#3-i-2.5-2-10‡	A B	90°	Para	A615	9.9 9.5	9.7	4805	12	1	0.073	10.9	12.0	10.5	8.375
159	8-8-90-5#3-i-2.5-2-8	A B	90°	Para	A1035[b]	7.3 7.3	7.3	8290	16	1	0.078	16.1	10.0	10.5	8.375
160	8-8-90-5#3-i-2.5-2-9‡	A B	90°	Para	A615	8.6 9.0	8.8	7710	25	1	0.073	17.8	11.0	10.5	8.375
161	8-12-90-5#3-i-2.5-2-9	A B	90°	Para	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	16.6	11.5	10.5	8.375
162	8-12-90-5#3-i-2.5-2-10	A B	90°	Para	A1035[c]	9.0 9.9	9.4	11800	38	1	0.073	16.8	12.2	10.5	8.375
163	8-12-90-5#3-i-2.5-2-12‡	A B	90°	Para	A1035[c]	12.2 12.3	12.2	11760	34	1	0.073	16.9	14.2	10.5	8.375
164	8-12-90-5#3vr-i-2.5-2-10	A B	90°	Perp	A1035[c]	10.3 10.2	10.2	11800	38	1	0.073	16.6	11.9	10.5	8.375
165	8-12-90-4#3vr-i-2.5-2-10	A B	90°	Perp	A1035[c]	10.6 10.3	10.4	11850	39	1	0.073	16.0	12.4	10.5	8.375
166	8-15-90-5#3-i-2.5-2-10	A B	90°	Para	A1035[c]	10.6 9.7	10.1	15800	60	1	0.073	16.7	12.1	10.5	8.375
167	8-5-90-5#3-i-3.5-2-15	A B	90°	Para	A1035[b]	15.8 15.8	15.8	4850	7	1	0.078	19.3	17.0	10.5	8.375
168	8-5-90-5#3-i-3.5-2-13	A B	90°	Para	A1035[b]	13.3 13.0	13.1	5570	12	1	0.078	19.3	15.4	10.5	8.375
169	8-5-90-5#3-i-3.5-2-12(1)	A B	90°	Para	A1035[c]	12.8 12.3	12.5	5090	7	1	0.073	18.7	14.3	10.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout[o]	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	T_h lb	$f_{su,max}$ psi	f_{su} psi
144	A B	3.8 3.9	3.8	3.0 2.3	9.1	2	30	A2	69451 69474	69451 69474	138925	69463	58583	87913 87942	87927
145	B A	2.8 3.0	2.9	1.9 1.6	9.5	2	80	A2	91801 97200	91801 89056	180857	90429	84844	116204 123038	114467
146	A B	2.5 2.5	2.5	2.0 2.0	10.0	2	80	A2	83079 68634	68532 68634	137165	68583	64929	105164 86878	86814
147	A B	2.8 2.9	2.8	2.0 2.0	9.5	2	80	A2	63275 54846	55094 54733	109827	54914	53922	80094 69425	69511
148	A B	2.8 2.6	2.7	2.0 1.8	9.9	2	80	A2	78824 66728	75418 64012	139430	69715	64769	99777 84466	88247
149	A B	2.5 2.5	2.5	2.0 2.0	10.0	2	80	A2	68947 69633	68071 69604	137674	68837	65920	87275 88143	87136
150	A B	2.8 2.5	2.6	1.9 1.4	9.9	2	30	A2	77125 72603	74150 72603	146753	73377	87983	97627 91903	92882
151	A B	2.5 2.4	2.4	1.5 1.8	10.3	2	30	A2	93116 81340	83412 81340	164752	82376	81257	117868 102962	104273
152	A B	2.5 2.5	2.5	2.6 3.0	9.8	2	30	A2	66726 75878	66726 66001	132727	66363	68375	84463 96048	84004
153	A B	2.5 2.4	2.4	3.0 2.0	9.8	2	30	A2	84900 72000	* 72000	72000	72000	73010	107468 91139	91139
154	A B	2.5 2.6	2.6	1.8 2.1	9.0	2	30	A2	72359 77425	72321 70619	142939	71470	73090	91593 98006	90468
155	A B	2.8 2.9	2.8	2.6 2.9	9.0	2	30	A2	48024 47008	47948 47008	94956	47478	50723	60790 59503	60099
156	B	2.5	2.5	1.8	9.8	2	80	A2	82800	82800	82800	82800	64937	104800	104800
157	A B	2.4 2.8	2.6	2.0 1.5	2.0	2	30	A2	61451 58224	57620 58224	115845	57922	62480	77787 73702	73319
158	A B	2.3 2.4	2.3	2.1 2.5	4.3	2	30	A2	59715 52232	59715 52205	111921	55960	59824	75589 66116	70836
159	A B	2.9 2.8	2.8	2.8 2.8	8.5	2	30	A2	56006 51206	49326 51206	100532	50266	53859	70893 64818	63628
160	A B	2.8 3.3	3.0	2.4 2.0	9.8	2	30	A2	64834 64027	64834 63961	128795	64397	61438	82068 81047	81516
161	A B	2.5 2.6	2.6	2.5 2.5	9.5	2	30	A2	66512 63119	66512 62994	129507	64753	67620	84193 79897	81966
162	A B	2.6 2.3	2.4	3.2 2.3	9.9	2	30	A2	66000 64599	64479 64582	129061	64530	71117	83544 81771	81684
163	A B	2.4 2.5	2.4	2.0 1.9	10.0	2	30	A2	90544 86469	88954 86469	175422	87711	88168	114613 109454	111027
164	A B	2.5 2.4	2.4	1.7 1.7	9.8	2	30	A2	59428 64145	59428 61011	120439	60219	67059	75225 81196	76227
165	A B	2.5 2.5	2.5	1.8 2.1	9.0	2	30	A2	80288 59267	59214 59267	118481	59241	66818	101630 75021	74988
166	A B	2.4 2.4	2.4	1.6 2.4	9.9	2	30	A11	111610 90223	89783 90223	180007	90003	80498	141278 114207	113928
167	A B	3.6 3.5	3.5	1.3 1.3	10.3	2	30	A2	81187 87144	81187 79494	160681	80341	89047	102768 110309	101697
168	A B	3.4 3.5	3.4	2.1 2.4	10.4	2	30	A2	89620 75971	78290 75847	154137	77069	78783	113443 96166	97555
169	A B	3.5 3.4	3.5	1.6 2.1	9.8	2	30	A2	78862 75869	78813 74050	152863	76431	74137	99825 96037	96749

[o] Longitudinal column configurations shown in Appendix A, Layouts A1 – A16

*Data not available

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Hook	Slip at Failure in.	Failure Type	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
144	A B	0.26 .181(.104)	SS/FP FP/SS	60	0.5	0.20	2	7.13	1.20	6	4.0	0.50	2.00	-	-	3.16	60
145	B A	- -	FP/SS FP/SS	60	0.38	0.11	4	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
146	A B	- -	FP FP	60	0.38	0.11	4	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
147	A B	- -	FP FP/SS	60	0.38	0.11	4	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
148	A B	0.129 -	FP/SS FP	60	0.38	0.11	5	3.00	1.10	10	3.0	0.63	5.00	-	-	3.16	60
149	A B	- -	FP/SS FP/SS	60	0.38	0.11	5	3.00	1.10	10	3.0	0.63	5.00	-	-	3.16	60
150	A B	0.196 -	FP/SS FP/SS	60	0.38	0.11	5	3.00	0.55	5	3.0	0.38	3.50	0.375	2	3.16	60
151	A B	- -	SS/FP FP/SS	60	0.38	0.11	5	3.00	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60
152	A B	- -	SS/FP SS/FP	60	0.38	0.11	5	3.00	0.55	5	3.0	0.38	3.50	0.5	2	3.16	60
153	A B		SS SS	60	0.38	0.11	5	3.00	0.55	5	3.0	0.38	3.50	0.5	2	3.16	60
154	A B		FP/SS FP/SS	60	0.38	0.11	5	3.00	0.55	5	3.0	0.38	3.50	0.375	1	3.16	60
155	A B	 0.321	FP FP	60	0.38	0.11	5	3.00	1.55	5	3.0	0.50	3.00	0.5	1	3.16	60
156	B	0.164	FP/SS	60	0.375	0.11	5	3.0	1.10	10	3.0	0.63	3.50	-	-	3.16	60
157	A B	0.05 0.37	FB/SS FB/SS	60	0.38	0.11	5	3.00	-	-	-	0.38	4.00	-	-	3.16	120
158	A B	0.12 0.29	FB FB	60	0.38	0.11	5	3.00	-	-	-	0.38	4.00	-	-	3.16	120
159	A B	0.3 .375 (.092)	FP FP	60	0.38	0.11	5	3.00	1.20	6	3.0	0.50	1.50	-	-	3.16	60
160	A B	0.047 0	FB FB	60	0.38	0.11	5	3.00	-	-	-	0.38	4.00	-	-	3.16	120
161	A B	0.224 0.252	FP/SS FP/SS	60	0.38	0.11	5	3.00	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60
162	A B	0.44 0.547	FB/SS SS/FP	60	0.38	0.11	5	3.00	-	-	-	0.50	1.75	-	-	3.16	60
163	A B	- -	FB/SS SS/FP	60	0.38	0.11	5	3.00	-	-	-	0.38	4.00	-	-	3.16	120
164	A B	0.236 0.246	FP FP	60	0.38	0.11	5	1.75	-	-	-	0.50	1.75	-	-	3.16	60
165	A B	0.123 0.101	FP/SS FP	60	0.38	0.11	4	2.25	-	-	-	0.50	1.75	-	-	3.16	60
166	A B	- 0.407	FB/SS FB/SS	60	0.38	0.11	5	3.00	-	-	-	0.38	3.00	-	-	6.32	60
167	A B	.214(.026) -	SS/FP SS/FP	60	0.38	0.11	5	3.00	0.55	5	3.0	0.38	3.50	0.375	2	3.16	60
168	A B	- -	SS SS/FP	60	0.38	0.11	5	3.00	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60
169	A B	- -	SS/FP SS	60	0.38	0.11	5	3.00	0.55	5	3.0	0.38	3.50	0.5	2	3.16	60

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.	R_r	b in.	h in.	h_{cl} in.	h_c in.
170	8-5-90-5#3-i-3.5-2-12	A B	90°	Para	A1035[c]	12.5 11.8	12.1	6440	9	1	0.073	18.6	14.2	10.5	8.375
171	8-8-90-5#3-i-3.5-2-8	A B	90°	Para	A1035[b]	8.0 8.0	8.0	7910	15	1	0.078	18.0	10.0	10.5	8.375
172	8-12-90-5#3-i-3.5-2-9	A B	90°	Para	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	18.1	11.5	10.5	8.375
173	8-12-180-5#3-i-2.5-2-10	A B	180°	Para	A1035[c]	9.9 9.6	9.8	11800	38	1	0.073	16.9	12.2	10.5	8.375
174	8-12-180-5#3vr-i-2.5-2-10	A B	180°	Perp	A1035[c]	11.1 10.5	10.8	11800	38	1	0.073	16.8	12.4	10.5	8.375
175	8-12-180-4#3vr-i-2.5-2-10	A B	180°	Perp	A1035[c]	10.5 10.0	10.3	11850	39	1	0.073	17.0	12.3	10.5	8.375
176	8-15-180-5#3-i-2.5-2-9.5	A B	180°	Para	A1035[c]	9.6 9.8	9.7	15550	87	1	0.073	17.3	11.7	10.5	8.375
177	8-5-90-4#4s-i-2.5-2-15	A B	90°	Para	A1035[b]	15.6 15.6	15.6	4810	6	1	0.078	17.0	17.3	10.5	8.375
178	8-5-90-4#4s-i-2.5-2-12(1)	A B	90°	Para	A1035[c]	12.3 12.5	12.4	5180	8	1	0.073	17.1	14.4	10.5	8.375
179	8-5-90-4#4s-i-2.5-2-12	A B	90°	Para	A1035[c]	12.0 12.6	12.3	6210	8	1	0.073	16.6	14.3	10.5	8.375
180	8-5-90-4#4s-i-3.5-2-15	A B	90°	Para	A1035[b]	15.5 15.1	15.3	4810	6	1	0.078	19.6	17.3	10.5	8.375
181	8-5-90-4#4s-i-3.5-2-12(1)	A B	90°	Para	A1035[c]	12.0 11.9	11.9	5910	14	1	0.073	19.0	14.3	10.5	8.375
182	8-5-90-4#4s-i-3.5-2-12	A B	90°	Para	A1035[c]	12.0 12.5	12.3	5960	7	1	0.073	18.3	14.4	10.5	8.375
183	11-5-90-1#4-i-2.5-2-17	A B	90°	Para	A1035	17.8 17.6	17.7	5790	25	1.4	0.085	21.4	19.6	19.5	8.375
184	11-5-90-1#4-i-3.5-2-17	A B	90°	Para	A1035	17.8 17.8	17.8	5790	25	1.4	0.085	23.6	19.5	19.5	8.375
185	11-5-90-2#3-i-2.5-2-17	A B	90°	Para	A1035	17.4 17.8	17.6	5600	24	1.4	0.085	21.3	19.6	19.5	8.375
186	11-5-90-2#3-i-2.5-2-14	A B	90°	Para	A615	13.5 13.8	13.6	4910	13	1.4	0.069	21.7	16.0	19.5	8.375
187	11-12-90-2#3-i-2.5-2-17.5	A B	90°	Para	A1035	18.0 17.5	17.8	13710	30	1.4	0.085	21.1	19.5	19.5	8.375
188	11-15-90-2#3-i-2.5-2-23	A B	90°	Para	A1035	23.5 23.5	23.5	16180	62	1.4	0.085	21.3	25.0	19.5	8.375
189	11-15-90-2#3-i-2.5-2-10‡	A B	90°	Para	A615	10.0 10.0	10.0	14045	76	1.4	0.085	22.0	12.0	19.5	8.375
190	11-15-90-2#3-i-2.5-2-15‡	A B	90°	Para	A1035	14.0 14.3	14.1	14045	80	1.4	0.085	21.5	17.0	19.5	8.375
191	11-5-90-2#3-i-3.5-2-17	A B	90°	Para	A1035	17.5 17.8	17.6	7070	28	1.4	0.085	23.4	19.7	19.5	8.375
192	11-5-90-2#3-i-3.5-2-14	A B	90°	Para	A615	14.5 13.4	13.9	4910	12	1.4	0.069	23.7	16.1	19.5	8.375
193	11-5-90-5#3-i-2.5-2-14	A B	90°	Para	A615	14.3 13.5	13.9	4910	12	1.4	0.069	21.8	16.0	19.5	8.375
194	11-5-90-5#3-i-3.5-2-14	A B	90°	Para	A615	14.6 14.5	14.6	4910	14	1.4	0.069	23.7	16.0	19.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	T_h lb	$f_{su,max}$ psi	f_{su} psi
170	A B	3.4 3.5	3.4	1.7 2.4	9.8	2	30	A2	79156 79258	79156 79145	158301	79150	76237	100198 100327	100190
171	A B	3.5 3.6	3.6	2.0 2.0	8.9	2	30	A2	55391 56240	55391 56228	111619	55810	57384	70116 71190	70645
172	A B	3.3 3.4	3.3	2.5 2.5	9.5	2	30	A2	68822 82227	68822 66841	135663	67831	67620	87116 104084	85863
173	A B	2.3 2.8	2.5	2.3 2.6	9.9	2	30	A2	63041 81419	63041 65173	128214	64107	73027	79798 103062	81148
174	A B	2.5 2.5	2.5	1.3 1.9	9.8	2	30	A2	67538 68023	67538 68023	135560	67780	70708	85491 86105	85798
175	A B	2.8 2.5	2.6	1.8 2.3	9.8	2	30	A2	69654 68753	69654 68723	138377	69188	65665	88170 87030	87580
176	A B	2.5 2.8	2.6	2.1 1.9	10.0	2	30	A10	85951 85951	85951 85951	171901	85951	77095	108798 108798	108798
177	A B	3.0 2.9	2.9	1.6 1.6	9.1	2	30	A2	93337 107709	93337 93969	187306	93653	92056	118148 136340	118548
178	A B	2.5 2.6	2.6	2.1 1.9	10.0	2	30	A2	100177 90092	91540 90092	181632	90816	77607	126806 114041	114957
179	A B	2.6 2.5	2.6	2.3 1.6	9.5	2	30	A2	116352 99672	99838 99672	199509	99755	80367	147281 126167	126272
180	A B	4.1 4.0	4.1	1.8 2.1	9.5	2	30	A2	105974 90156	91613 90118	181730	90865	90541	134144 114121	115019
181	A B	3.8 3.5	3.6	2.3 2.4	9.8	2	30	A2	115165 92876	113609 77301	190910	95455	77612	145779 117565	120829
182	A B	3.8 3.5	3.6	2.4 1.9	9.0	2	30	A2	103861 96919	99392 96919	196312	98156	79340	131470 122683	124248
183	A B	2.8 2.8	2.8	1.8 2.0	13.1	2	117	A7	99443 119681	99403 103592	202995	101498	115679	63746 76718	65063
184	A B	3.8 3.9	3.8	1.8 1.8	13.1	2	129	A7	105692 108846	103693 108846	212540	106270	116068	67751 69773	68122
185	A B	2.5 2.6	2.6	2.3 1.8	13.4	2	117	A7	108406 103234	98172 103218	201390	100695	108250	69491 66176	64548
186	A B	2.8 2.9	2.8	2.5 2.3	13.3	2	97	A7	77718 77214	77718 77127	154845	77422	81310	49819 49496	49630
187	A B	2.5 2.5	2.5	1.5 2.0	13.3	2	115	A7	133178 129868	132555 128223	260779	130389	139941	85371 83249	83583
188	A B	2.8 2.8	2.8	1.5 1.5	13.0	2	149	A11	232100 206900	212550 206600	419150	209575	195050	148782 132628	134343
189	A B	2.8 3.0	2.9	2.0 2.0	13.4	2	74	A15	64250 63631	64250 63631	127881	63940	79600	41186 40789	40987
190	A B	2.6 2.6	2.6	3.0 2.8	13.6	2	102	A15	115577 114801	115577 114801	230377	115189	111959	74088 73590	73839
191	A B	3.6 3.6	3.6	2.1 2.0	13.4	2	129	A7	107807 111480	107807 111480	219287	109644	115784	69107 71462	70284
192	A B	3.8 3.9	3.8	1.6 2.8	13.3	2	107	A7	92719 81848	82732 81817	164549	82275	83132	59435 52467	52740
193	A B	2.8 2.9	2.8	1.8 2.5	13.4	2	98	A7	105597 94115	96267 94072	190339	95170	96880	67690 60330	61006
194	A B	3.9 3.9	3.9	1.4 1.5	13.1	2	106	A7	101315 94663	101315 94663	195979	97989	100897	64946 60682	62814

° Longitudinal column configurations shown in Appendix A, Layouts A1 – A16

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Hook	**Slip at Failure** **in.**	**Failure Type**	f_{yt} **ksi**	d_{tr} **in.**	$A_{tr,l}$ **in.^{2}**	N_{tr}	s_{tr} **in.**	A_{cti} **in.^{2}**	N_{cti}	s_{cti} **in.**	d_s **in.**	s_s **in.**	d_{cto} **in.**	N_{cto}	A_s **in.^{2}**	f_{ys} **ksi**
170	A B	 0.162	FP FP/SS	60	0.38	0.11	5	3.00	0.55	5	3.0	0.38	3.50	0.5	2	3.16	60
171	A B	- -	FP FP	60	0.38	0.11	5	3.00	1.20	6	3.0	0.50	1.50	-	-	3.16	60
172	A B	 0.415	FP/SS FP/SS	60	0.38	0.11	5	3.00	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60
173	A B	- 0.339	FP/SS FP	60	0.38	0.11	5	3.00	-	-	-	0.50	1.75	-	-	3.16	60
174	A B	- 0.321	FP FB	60	0.38	0.11	5	1.75	-	-	-	0.50	1.75	-	-	3.16	60
175	A B	- -	FP FP	60	0.38	0.11	4	2.25	-	-	-	0.50	1.75	-	-	3.16	60
176	A B	- -	SS FP/SS	60	0.38	0.11	5	3.00	-	-	-	0.50	4.00	-	-	6.32	60
177	A B	0.21 -	SS/FP FP/SS	60	0.5	0.20	4	4.00	0.88	8	4.0	0.38	3.50	0.375	2	3.16	60
178	A B	- -	FP/SS FP/SS	60	0.5	0.20	4	4.00	1.60	8	4.0	0.50	3.50	0.5	1	3.16	60
179	A B		FP/SS SS/FP	60	0.5	0.20	4	4.00	1.60	8	4.0	0.50	3.50	0.5	1	3.16	60
180	A B	- -	FP/SS SS/FP	60	0.5	0.20	4	4.00	0.88	8	4.0	0.38	3.50	0.375	2	3.16	60
181	A B	- -	SS FP/SS	60	0.5	0.20	4	4.00	1.60	8	4.0	0.50	3.50	0.5	1	3.16	60
182	A B		SS/FP FP/SS	60	0.5	0.20	4	4.00	1.60	8	4.0	0.50	3.50	0.5	1	3.16	60
183	A B	- -	SS/FP FP/SS	60	0.5	0.20	1	8.75	2.2	11	4.0	0.50	4.0	0.375	2	4.74	60
184	A B	- -	SS SS/FP/TK	60	0.5	0.20	1	8.75	2.2	11	4.0	0.50	4.0	0.375	2	4.74	60
185	A B	- -	SS/FP SS/FP	60	0.38	0.11	2	8.00	2	10	4.0	0.50	4.0	0.375	2	4.74	60
186	A B	0.206 -	FP/SS SS	60	0.38	0.11	2	8.00	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
187	A B	- -	SS SS	60	0.38	0.11	2	12.0	2.4	12	4.0	0.50	4.0	-	-	4.74	60
188	A B	- -	SB SB/FB	60	0.38	0.11	2	8.00	-	-	-	0.50	3.0	-	-	6.32	60
189	A B	- 	FP FP	60	0.38	0.11	2	8.00	-	-	-	0.50	4.5	-	-	6.94	120
190	A B	- -	FP/SB FP/SB	60	0.38	0.11	2	8.00	-	-	-	0.50	4.5	-	-	6.94	120
191	A B	- -	SS/FP/TK SS	60	0.38	0.11	2	8.00	2	10	4.0	0.50	4.0	0.375	2	4.74	60
192	A B	- -	FP/SS SS/FP/TK	60	0.38	0.11	2	8.00	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
193	A B	0.397 0.375	SS/FP SS/FP	60	0.38	0.11	5	4.38	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
194	A B	- -	FP/SS SS/FP	60	0.38	0.11	5	4.38	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.	R_r	b in.	h in.	h_{cl} in.	h_c in.
195	11-5-90-6#3-i-2.5-2-20	A B	90°	Para	A1035	19.5 19.0	19.3	5420	7	1.4	0.085	20.9	22.3	19.5	8.375
196	11-8-90-6#3-i-2.5-2-16	A B	90°	Para	A1035	15.5 16.4	15.9	9120	7	1.4	0.085	21.2	18.3	19.5	8.375
197	11-8-90-6#3-i-2.5-2-22	A B	90°	Para	A1035	21.3 21.5	21.4	9420	8	1.4	0.085	21.4	24.1	19.5	8.375
198	11-8-90-6#3-i-2.5-2-22	A B	90°	Para	A1035	21.9 22.0	21.9	9420	8	1.4	0.085	21.7	24.2	19.5	8.375
199	11-8-90-6#3-i-2.5-2-15	A B	90°	Para	A1035	15.8 15.3	15.5	7500	5	1.4	0.085	21.6	17.3	19.5	8.375
200	11-8-90-6#3-i-2.5-2-19	A B	90°	Para	A1035	19.1 19.4	19.2	7500	5	1.4	0.085	21.4	21.0	19.5	8.375
201	11-12-90-6#3-i-2.5-2-17	A B	90°	Para	A1035	17.1 16.5	16.8	12370	37	1.4	0.085	21.4	19.1	19.5	8.375
202	11-12-90-6#3-i-2.5-2-16	A B	90°	Para	A1035	14.8 16.0	15.4	13710	31	1.4	0.085	20.8	18.0	19.5	8.375
203	11-12-90-6#3-i-2.5-2-22	A B	90°	Para	A1035	21.9 21.5	21.7	13710	31	1.4	0.085	22.1	24.3	19.5	8.375
204	11-15-90-6#3-i-2.5-2-22	A B	90°	Para	A1035	22.3 22.4	22.3	16180	62	1.4	0.085	21.8	24.0	19.5	8.375
205	11-15-90-6#3-i-2.5-2-10a‡	A B	90°	Para	A615	9.5 10.0	9.8	14045	76	1.4	0.085	21.5	12.0	19.5	8.375
206	11-15-90-6#3-i-2.5-2-10b‡	A B	90°	Para	A615	9.5 9.8	9.6	14050	77	1.4	0.085	21.4	12.0	19.5	8.375
207	11-15-90-6#3-i-2.5-2-15‡	A B	90°	Para	A1035	14.5 15.0	14.8	14045	80	1.4	0.085	21.5	17.0	19.5	8.375
208	11-5-90-6#3-i-3.5-2-20	A B	90°	Para	A1035	20.5 20.3	20.4	5420	7	1.4	0.085	23.6	22.3	19.5	8.375
209	11-8-180-6#3-i-2.5-2-15	A B	180°	Para	A1035	15.1 15.5	15.3	7500	5	1.4	0.085	21.8	17.1	19.5	8.375
210	11-8-180-6#3-i-2.5-2-19	A B	180°	Para	A1035	19.6 19.9	19.8	7870	6	1.4	0.085	21.8	21.2	19.5	8.375
211	11-12-180-6#3-i-2.5-2-17	A B	180°	Para	A1035	16.9 16.5	16.7	12370	37	1.4	0.085	21.7	19.8	19.5	8.375
212	11-12-180-6#3-i-2.5-2-17	A B	180°	Para	A1035	16.8 16.8	16.8	12370	37	1.4	0.085	21.4	19.4	19.5	8.375
213	11-5-90-5#4s-i-2.5-2-20	A B	90°	Para	A1035	20.0 20.3	20.1	5420	7	1.4	0.085	21.4	22.3	19.5	8.375
214	11-5-90-5#4s-i-3.5-2-20	A B	90°	Para	A1035	19.8 19.3	19.5	5960	8	1.4	0.085	23.4	22.0	19.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout[o]	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	T_h lb	$f_{su,max}$ psi	f_{su} psi
195	A B	2.6 2.6	2.6	2.8 3.3	12.9	2	130	A7	153119 134977	137617 134927	272543	136272	131706	98153 86524	87354
196	A B	2.5 2.5	2.5	2.8 1.9	13.4	2	108	A16	147508 129692	136385 129586	265971	132986	126362	94556 83136	85247
197	A B	2.5 2.6	2.6	2.8 2.6	13.5	2	145	A11	204260 183175	186246 182892	369138	184569	166360	130936 117420	118314
198	A B	2.6 2.9	2.8	2.3 2.2	13.4	2	147	A16	197739 191344	190740 191344	382084	191042	170431	126756 122656	122463
199	A B	2.8 2.5	2.6	1.5 2.0	13.5	2	104	A13	142278 108021	108602 108021	216623	108312	117618	91204 69245	69431
200	A B	2.5 2.6	2.6	2.0 1.7	13.5	2	126	A13	182735 146093	144766 146093	290860	145430	142479	117138 93650	93224
201	A B	2.6 3.0	2.8	1.9 2.6	13.0	2	114	A13	179693 162285	161019 162277	323295	161648	142884	115188 104029	103620
202	A B	2.5 2.5	2.5	3.3 2.0	13.0	2	105	A7	115139 127542	115089 115306	230394	115197	135193	73807 81758	73844
203	A B	2.9 3.1	3.0	2.4 2.8	13.3	2	150	A12	206283 199234	203983 198395	402379	201189	185650	132233 127714	128967
204	A B	3.0 2.5	2.8	1.8 1.6	13.5	2	147	A10	204557 195710	200084 195534	395618	197809	199073	131126 125455	126801
205	A B	2.6 2.8	2.7	2.5 2.0	13.4	2	72	A15	83558 81804	83558 81804	165362	82681	91774	53563 52438	53001
206	A B	2.8 2.8	2.8	2.5 2.3	13.0	2	72	A10	76605 74596	76605 74553	151158	75579	90813	49106 47818	48448
207	A B	2.6 2.6	2.6	2.5 2.0	13.6	2	102	A15	145670 144870	145664 144870	290534	145267	131029	93378 92866	93120
208	A B	3.8 3.9	3.8	1.8 2.0	13.1	2	147	A7	150216 135259	136607 135036	271643	135821	138606	96293 86704	87065
209	A B	2.9 3.1	3.0	2.0 1.6	13.0	2	104	A13	112423 110981	112423 110933	223356	111678	116374	72066 71142	71588
210	A B	2.9 2.9	2.9	1.5 1.3	13.3	2	129	A13	170000 149000	149000 149000	298000	149000	147821	108974 95513	95513
211	A B	2.6 2.8	2.7	2.9 3.3	13.5	2	120	A7	123150 117638	115105 117638	232743	116371	141920	78942 75409	74597
212	A B	2.5 2.8	2.6	2.7 2.6	13.4	2	117	A13	148872 173034	148872 148484	297356	148678	142643	95431 110919	95306
213	A B	2.5 2.8	2.6	2.3 2.0	13.4	2	134	A7	141399 161640	141399 140691	282090	141045	155218	90640 103615	90414
214	A B	3.8 3.8	3.8	2.3 2.8	13.1	2	144	A7	186703 153546	152402 153532	305934	152967	154532	119681 98427	98056

[o] Longitudinal column configurations shown in Appendix A, Layouts A1 – A16

Table A.2 Cont. Comprehensive test results and data used in analysis for specimens with confining reinforcement

	Hook	Slip at Failure in.	Failure Type	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
195	A B	0.274 -	FP/SS FP/SS	60	0.38	0.11	6	4.00	1.2	6	4.0	0.50	4.0	0.375	2	4.74	60
196	A B	- -	FP/SS FP/SS	60	0.38	0.11	6	4.00	-	-	-	0.50	6.0	-	-	9.48	60
197	A B	- -	* SS	60	0.38	0.11	6	4.00	-	-	-	0.50	2.5	-	-	6.32	60
198	A B	- -	* SB/FB	60	0.38	0.11	6	4.00	-	-	-	0.50	6.0	-	-	9.48	60
199	A B	- -	SS SS/FP	60	0.38	0.11	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60
200	A B	- -	FB/SS FB/SS	60	0.38	0.11	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60
201	A B	0.334 -	FB/SB SP/SS	60	0.38	0.11	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60
202	A B	- 0.952	SS/FP SB/FB	60	0.38	0.11	6	4.00	2.4	12	4.0	0.50	4.0	0.375	1	4.74	60
203	A B	- -	SS/FB FB	60	0.38	0.11	6	4.00	3.06	12	4.0	0.50	4.0	0.375	2	6.32	60
204	A B	- -	FB/SS SB/FB	60	0.38	0.11	6	4.00	-	-	-	0.50	3.0	-	-	6.32	60
205	A B	- -	FP FP	60	0.38	0.11	6	4.00	-	-	-	0.50	4.5	-	-	6.94	120
206	A B	 -	FP FP	60	0.38	0.11	6	4.00	-	-	-	0.50	4.5	-	-	6.32	120
207	A B	- -	FP FP	60	0.38	0.11	6	4.00	-	-	-	0.50	4.5	-	-	6.94	120
208	A B	- -	SS/FP SS	60	0.38	0.11	6	4.00	1.2	6	4.0	0.50	4.0	0.375	2	4.74	60
209	A B	- -	SS SS	60	0.38	0.11	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60
210	A B	- -	FB/SS FB/SS	60	0.38	0.11	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60
211	A B	- 0.379	FP FP/SB	60	0.38	0.11	6	4.00	-	-	-	0.50	3.0	-	-	4.74	60
212	A B	- -	FP/SS SB/FB	60	0.38	0.11	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60
213	A B	- -	FP/SS FP/SS	60	0.5	0.20	5	5.00	4	10	5.0	0.50	5.0	0.375	2	4.74	60
214	A B	- -	SS/FP FP/SS	60	0.5	0.20	5	5.00	4	10	5.0	0.50	5.0	0.375	2	4.74	60

*Test terminated prior to failure of second hooked bar

Table A.3 Test results for specimens from other researchers referenced in this study used in analysis for specimens without confining reinforcement

	Specimen	Bend Angle	ℓ_{eh}	f_{cm}	f_y	d_b	b	h_{cl}	h_c	c_{so}	c_{th}	c_h	N_h	A_h	d_{tr}	A_{tr}[†]	N_{tr}	s_{tr}	T
			in.	psi	psi	in.	in.	in.	in.	in.	in.	in.		in.^{2}	in.	in.^{2}		in.	lb
Marques and Jirsa (1975)	J7-180-12-1H	180°	10.0	4350	64000	0.88	12	11.5	6	2.88	2.0	4.5	2	0.60	-	-	-	-	36600
	J7-180-15-1 H	180°	13.0	4000	64000	0.88	12	11.5	6	2.88	2.0	4.5	2	0.60	-	-	-	-	52200
	J7-90-12-1H	90°	10.0	4150	64000	0.88	12	11.5	6	2.88	2.0	4.5	2	0.60	-	-	-	-	37200
	J7-90-15-1-H	90°	13.0	4600	64000	0.88	12	11.5	6	2.88	2.0	4.5	2	0.60	-	-	-	-	54600
	J7-90-15-1- L	90°	13.0	4800	64000	0.88	12	11.5	6	2.88	2.0	4.5	2	0.60	-	-	-	-	58200
	J7-90-15-1M	90°	13.0	5050	64000	0.88	12	11.5	6	2.88	2.0	4.5	2	0.60	-	-	-	-	60000
	J11-180-15-1H	180°	13.1	4400	68000	1.41	12	11.3	6	2.88	1.5	3.4	2	1.56	-	-	-	-	70200
	J11-90-12-1H	90°	10.1	4600	68000	1.41	12	11.3	6	2.88	1.5	3.4	2	1.56	-	-	-	-	65520
	J11-90-15-1H	90°	13.1	4900	68000	1.41	12	11.3	6	2.88	1.5	3.4	2	1.56	-	-	-	-	74880
	J11-90-15-1L	90°	13.1	4750	68000	1.41	12	11.3	6	2.88	1.5	3.4	2	1.56	-	-	-	-	81120
Pinc et al. (1977)	9-12	90°	10.0	4700	65000	1.13	12	*	*	2.88	2	4	2	1.0	-	-	-		47000
	9-18	90°	16.0	4700	65000	1.13	12	*	*	2.88	2	4	2	1.0	-	-	-		74000
	11-24	90°	22.1	4200	60000	1.41	12	*	*	2.88	2	3.4	2	1.56	-	-	-		120120
	11-15	90°	13.1	5400	60000	1.41	12	*	*	2.88	2	3.4	2	1.56	-	-	-		78000
	11-18	90°	16.1	4700	60000	1.41	12	*	*	2.88	2	3.4	2	1.56	-	-	-		90480
	11-21	90°	19.1	5200	60000	1.41	12	*	*	2.88	2	3.4	2	1.56	-	-	-		113880
Hamad et al. (1993)	7-90-U	90°	10.0	2570	60000[a]	0.88	12	11	6	3	2	4.25	2	0.60	-	-	-	-	25998
	7-90-U'	90°	10.0	5400	60000[a]	0.88	12	11	6	3	2	4.25	2	0.60	-	-	-	-	36732
	11-90-U	90°	13.0	2570	60000[a]	1.41	12	11	6	3	2	3.18	2	1.56	-	-	-	-	48048
	11-90-U'	90°	13.0	5400	60000[a]	1.41	12	11	6	3	2	3.18	2	1.56	-	-	-	-	75005
	11-180-U-HS	180°	13.0	7200	60000[a]	1.41	12	11	6	3	2	3.18	2	1.56	-	-	-	-	58843
	11-90-U-HS	90°	13.0	7200	60000[a]	1.41	12	11	6	3	2	3.18	2	1.56	-	-	-	-	73788
Ramirez & Russel (2008)	I-1	90°	6.5	8910	81900	0.75	15	12	6	2.5	2.5	8.5	2	0.44	-	-	-	-	30000
	I-3	90°	6.5	12460	81900	0.75	15	12	6	2.5	2.5	8.5	2	0.44	-	-	-	-	30000
	I-5	90°	6.5	12850	81900	0.75	15	12	6	2.5	2.5	8.5	2	0.44	-	-	-	-	30500
	I-2	90°	12.5	8910	63100	1.41	15	12	6	2.5	2.5	7.18	2	1.56	-	-	-	-	88000
	I-2'	90°	15.5	9540	63100	1.41	15	12	6	2.5	2.5	7.18	2	1.56	-	-	-	-	105000
	I-4	90°	12.5	12460	63100	1.41	15	12	6	2.5	2.5	7.18	2	1.56	-	-	-	-	99100
	I-6	90°	12.5	12850	63100	1.41	15	12	6	2.5	2.5	7.18	2	1.56	-	-	-	-	114000
Lee & Park (2010)	H1	90°	18.7	4450	87000	0.88	14.6	*	*	3	2	7	2	0.6	-	-	-	-	86345
	H2	90°	11.9	8270	87000	0.88	14.6	*	*	3	2	7	2	0.6	-	-	-	-	76992

[†]60,000 psi nominal yield strength for all transverse reinforcement
*Information not provided
[a] Nominal value