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Conventional and High-Strength Steel Hooked Bars: Detailing Effects

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Findings from a study on the effect of hook bend angle, concrete clear cover, and orientation of confining reinforcement on hook anchorage strength are presented. The range of test parameters was much broader than in previous studies. Bar stress at anchorage failure ranged from 33,000 to 137,400 psi (228 to 947 MPa) and concrete compressive strengths ranged from 4300 to 16,500 psi (30 to 114 MPa). Anchorage strength of hooked bars was insensitive to bend angle (90 or 180 degrees) and side cover (between 2.5 and 3.5 in. [65 and 90 mm]). Confining reinforcement was found to increase anchorage strength for 180-degree hooked bars regardless of orientation (parallel or perpendicular to the embedment length). For 90-degree hooked bars, reinforcement oriented parallel to the embedment length had a greater effect on anchorage strength than reinforcement oriented perpendicular to the embedment length.

Keywords: anchorage; beam-column joints; bond; development length; high-strength concrete; high-strength steel; hook bend angle; reinforced concrete; side cover.

INTRODUCTION

Current design provisions for anchorage of hooked bars in reinforced concrete (ACI Committee 318 2014; ACI Committee 349 2006; AASHTO 2012) are based on several assumptions about their behavior: among others, hooked bars with 90- and 180-degree bend angles are assumed to have similar strengths, hooked bars with side covers of 2.5 in. (65 mm) or greater have similar strengths, and confining reinforcement oriented parallel or perpendicular to the straight portion of a 90-degree hooked bar ("straight portion of the hooked bar" refers to the straight portion of the bar in the direction of the embedment or development length) is assumed to be equally effective in providing confinement, but only confining reinforcement oriented perpendicular to the straight portion of a 180-degree hooked bar is assumed to be effective.

The design provisions are based on 38 tests by Marques and Jirsa (1975) and Pinc et al. (1977) of beam-column joint specimens containing Grade 60 (420) No. 7, No. 9, or No. 11 (No. 22, No. 29, or No. 36) bars with standard hooks (ACI Committee 318 2014), and concrete with compressive strengths ranging from 3600 to 5400 psi (25 to 37 MPa). Marques and Jirsa (1975) observed that the thickness of the concrete cover had a significant effect on the slip and stress at failure but indicated no advantage for covers greater than 2.5 in. (65 mm). None of the test specimens in these earlier studies contained confining reinforcement perpendicular to the straight portion of the hooked bars.

To validate the applicability of the earlier findings, tests were performed in this study to evaluate the effects of hook bend angle, concrete clear cover, and orientation of confining reinforcement on hook anchorage strength for a broader range of steel and concrete strengths than used in the earlier studies. Additional results and analyses are presented by Sperry et al. (2015a,b; 2017a,b).

RESEARCH SIGNIFICANCE

The use of high-strength steel and concrete as a means of reducing reinforcement congestion, member dimensions, and material use has increased. The analysis reported herein is the first to evaluate whether previous findings showing that bars with 90- and 180-degree hooks have equivalent anchorage strengths are valid for high-strength materials and the first to establish the effect of increasing concrete clear cover from 2.5 to 3.5 in. (65 to 90 mm). The effectiveness of confining reinforcement oriented either parallel or perpendicular to the straight portion of hooked bars is also evaluated to confirm whether current ACI 318 provisions are appropriate.

EXPERIMENTAL INVESTIGATION

Tests of 166 simulated beam-column joint specimens containing two hooked bars, included as part of a larger research program (Sperry et al. 2015a,b; 2017a,b), were used to investigate the effect of bend angle, side cover, and orientation of confining reinforcement on anchorage strength. No. 5, 8, and 11 (No. 16, 25, and 36) hooked bars were tested in normalweight concrete with compressive strengths ranging from 4300 to 16,500 psi (30 to 114 MPa). Nominal clear cover from the hooked bars to the outside of the column (side cover) ranged from 2.5 to 3.5 in. (65 to 90 mm). Bar stresses at anchorage failure ranged from 33,000 to 137,400 psi (228 to 947 MPa). The results of these tests are reported and used in conjunction with the results of previous studies (Marques and Jirsa 1975; Pinc et al. 1977; Hamad et al. 1993; Ramirez and Russell 2008; Lee and Park 2010) to determine the effect on hooked bar anchorage strength of bend angle, concrete side cover, and confining reinforcement orientation. The details of the experimental investigation are provided by Sperry et al. (2015a,b).

Test specimens

Figure 1 shows side and plan views of a typical specimen. Specimens were designed to represent exterior beam-column

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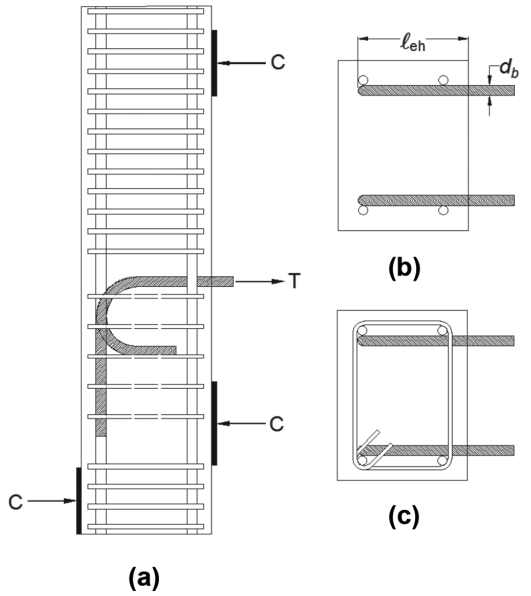

Fig. 1—Simulated beam-column specimens: (a) side view; (b) cross section without confining reinforcement; and (c) cross section of specimen with confining reinforcement parallel to straight portion of hooked bar (Sperry et al. 2017a).

joints and were cast without the beam. They were similar to the specimens used in the studies by Marques and Jirsa (1975) and Pinc et al. (1977). The specimens analyzed in this paper contained two hooked bars cast inside the column longitudinal reinforcement. The out-to-out spacing of the hooked bars was the same for each bar size—8, 12, and 16.5 in. (203, 305, and 419 mm) for specimens with No. 5, No. 8, and No. 11 (No. 16, 25, and 36) hooked bars, respectively. Total column widths are given in Appendix A.* In this paper, embedment length ℓ_{eh} refers to the distance from the front of the column face to the back of the tail of the hook. This is in contrast to the development length ℓ_{dh}, which refers to the minimum length of anchorage required in Section 25.4.3 of ACI 318-14 (ACI Committee 318 2014) to ensure that a bar can develop its yield strength. Column reinforcement was proportioned to resist the maximum expected shear and moment assuming that both hooked bars reached their expected strength simultaneously.

The specimens contained one of three quantities of confining reinforcement, in all but six cases oriented parallel to the straight portion of the hooked bar: 1) no confining reinforcement; 2) two No. 3 (No. 10) hoops spaced along the length of the tail of the hook; or 3) No. 3 (No. 10) hoops spaced at three bar diameters ($3d_b$) along the tail and the bend of the hook, where d_b is the diameter of the hooked bar. No. 3 (No. 10) hoops spaced at $3d_b$ represents the amount of confining reinforcement required in Section 25.4.3 of ACI 318-14 to allow the use of the confining reinforcement modification factor $\psi_r = 0.8$ in the calculation of the development length of hooked bars. At this spacing, five

*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.

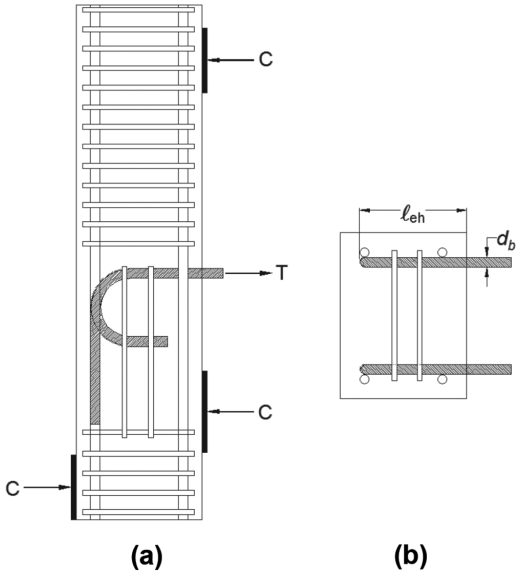

Fig. 2—Specimen with confining reinforcement perpendicular to straight portion of hooked bar: (a) side view; and (b) cross section (Sperry et al. 2017a).

No. 3 (No. 10) hoops were used to confine No. 5 (No. 16) and No. 8 (No. 25) standard hooks and six No. 3 (No. 10) hoops were used to confine No. 11 (No. 36) standard hooks. For case (3), the first hoop was centered $2d_b$ from the top of the hooked bar ($1.5d_b$ from the longitudinal axis of the straight portion of the hooked bar). For case (2), in specimens with No. 5 or No. 8 hooked bars, the first hoop was spaced 3 in. (76.2 mm) from the center of the straight portion of the hooked bars; the second hoop was spaced 3 and 8 in. (76.2 and 203.2 mm), respectively, from the first hoop. For case (2) in specimens with No. 11 hooked bars, the first and second hoops were spaced at 8 in. (203.2 mm) intervals from the center of the straight portion of the hooked bars.

To evaluate the effect of reinforcement orientation, six specimens were tested with confining reinforcement oriented perpendicular to the straight portion of the hooked bar, as shown in Fig. 2. Of the six, two contained two No. 3 (No. 10) hoops, two contained four No. 3 (No. 10) hoops, and two contained five No. 3 (No. 10) hoops. The latter two cases meet the requirement to allow the use of $\psi_r = 0.8$.

Specimen heights were chosen so that the support reactions from the test frame had minimal effect on the hook region during testing, as shown in Fig. 3. The column height was 52-3/4 in. (1340 mm) for the specimens with No. 5 (No. 16) or No. 8 (No. 25) hooked bars and 96 in. (2438 mm) for the specimens with No. 11 (No. 36) hooked bars. The distances from the longitudinal axis of the straight portion of the hooked bar to the upper compression member h_{cu} were 18.5, 18.5, and 48.5 in. (470, 470, and 1232 mm) for No. 5, No. 8, and No. 11 (No. 16, No. 25, and No. 36) hooked bars, respectively, and the distances from the center of the hooked bar to the bearing member, simulating the compression region of the concrete beam framing into the column h_{cl} were 5.25, 10, and 19.2 in. (133, 254, and 488 mm) for No. 5, No. 8, and No. 11 (No. 16, No. 25, and No. 36) hooked bars, respectively.

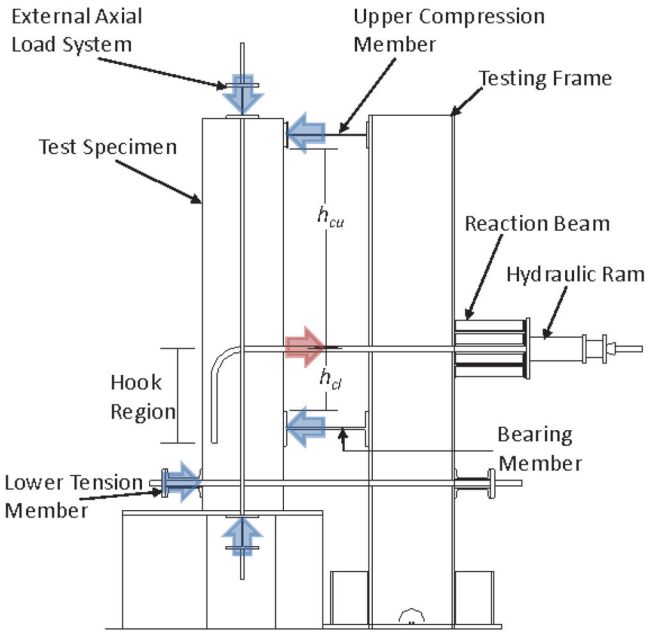

Fig. 3—Testing frame and forces applied to specimens during testing (Sperry et al. 2017b).

Material properties

Specimens were cast using non-air-entrained ready mixed concrete with nominal compressive strengths of 5000, 8000, 12,000, and 15,000 psi (34, 55, 83, and 103 MPa). Measured strengths obtained using 6 x 12 in. (150 x 300 mm) cylinders cured in the same manner as the test specimen and tested on the same day as the anchorage tests ranged from 4300 to 16,500 psi (30 to 114 MPa). The concrete contained Type I/II portland cement, crushed limestone, or granite with a maximum size of 0.75 in. (19 mm), Kansas river sand, and a high-range water-reducing admixture. Pea gravel was incorporated as a portion of the aggregate in the 12,000 psi (83 MPa) concrete to improve the workability of the mixture. Silica fume and Class C fly ash were used as supplementary cementitious materials for the 15,000 psi (103 MPa) concrete. Polycarboxylate-based high-range water-reducing admixtures were used in the mixtures. Mixture proportions are presented in Appendix A and by Sperry et al. (2015a,b, 2017a).

Hooked bars were fabricated using ASTM A615 Grade 80 (550 MPa) and A1035 Grade 120 (830 MPa) reinforcement. For most specimens, the ancillary steel for column and confining reinforcement consisted of ASTM A615 Grade 60 (420 MPa) reinforcing bars. ASTM A1035 Grade 120 (830 MPa) bars were used as the column longitudinal steel for specimens that had a greater flexural demand (based on the expected strength of the hooked bars) than could be satisfied using ASTM A615 Grade 60 (420 MPa) reinforcing bars. Yield strength, nominal diameter, deformation spacing and height, gap width, and relative rib area for the deformed steel bars used as hooked bars are presented in Appendix A and in Sperry et al. (2017b). Appendix A also includes representative stress-strain curves for the hooked bars.

Test procedure

Specimens were tested using a self-reacting system configured to simulate the boundary conditions of a beam-column joint (Fig. 3). The test frame was a modified version of the apparatus used by Marques and Jirsa (1975). The flange width of the upper compression member and the bearing member were 6-5/8 and 8-3/8 in. (168 and 213 mm), respectively.

For specimens with No. 5 and No. 8 (No. 16 and No. 25) hooked bars, a constant column axial load of 30,000 lb (133 kN) was applied to most of the specimens, corresponding to a range in axial stress of 90 to 460 psi (0.6 to 3.2 MPa). For early tests, a constant force of 80,000 lb (356 kN) was used, corresponding to an axial stress range of 505 to 1930 psi (3.5 to 13.3 MPa) based on column size. Specimens with No. 11 hooked bars had a constant axial stress of 280 psi (1.9 MPa) applied. These axial stresses were chosen based on the capacity of the axial load application system. Marques and Jirsa (1975) found that changes in axial stress up to 3000 psi (21 MPa) resulted in negligible changes in the anchorage strength of the hooked bars; the effect of varying axial stress was therefore not examined.

The load was applied monotonically to the hooked bars using hydraulic jacks to simulate tensile forces in the beam reinforcement at the face of a beam-column joint. Specimens were loaded to approximately 80% of the expected failure load in, for most cases, four increments. Between increments, cracks were marked and photographs were taken. Above 80% of the expected failure load, the specimens were loaded continually to failure. Tests lasted 15 to 25 minutes. Detailed descriptions of the test frame and testing procedure are provided by Peckover and Darwin (2013).

RESULTS AND ANALYSIS

Results from 166 tests of beam-column joint specimens with No. 5, No. 8, and No. 11 (No. 16, No. 25, and No. 36) hooked bars were selected from the data presented by Sperry et al. (2015a,b, 2017b) to evaluate the effect of hook bend angle, concrete side cover, and confining reinforcement orientation on anchorage strength. These results were combined with selected test results from Marques and Jirsa (1975), Pinc et al. (1977), Hamad et al. (1993), Ramirez and Russell (2008), and Lee and Park (2010). The forces applied to the hooked bars at failure for the specimens included in the analysis are presented in Appendix A. As described by Sperry et al. (2017b), the average bar force at the peak load, equal to the maximum total force applied to a specimen divided by the number of hooked bars under load, is treated as the failure load per hooked bar and used to calculate the average bar stress at failure.

To limit the effect of concrete compressive strength on anchorage strength and simplify the comparisons, the average bar forces at failure were normalized with respect to a concrete compressive strength of 5000 psi (34.5 MPa) by multiplying the average bar forces at failure T by $\left(5000/f_{cm}\right)^{p_1}$ ($\left[34.5/f_{cm}\right]^{p_1}$). The result is reported as the normalized average failure load T_N. A value of $p_1 = 0.25$ was selected based on the observation by Sperry et al. (2015a,b; 2017a,b) that the power of 0.5, currently used in the provisions of ACI 318-14 (ACI Committee 318 2014), greatly

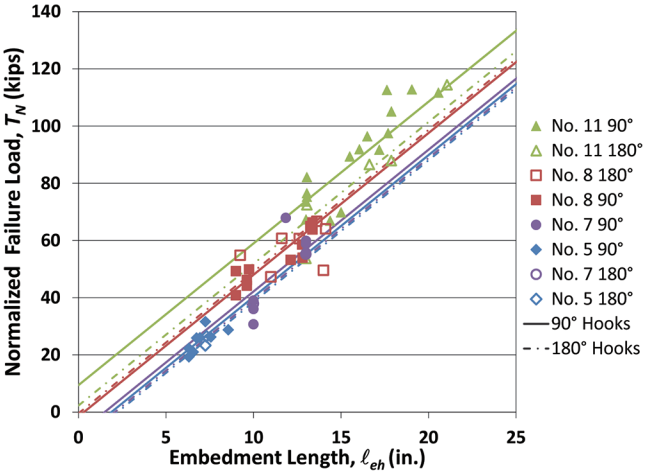

Fig. 4—Bar force at failure normalized to concrete compressive strength of 5000 psi (34.5 MPa) versus embedment length for No. 5, 7, 8, and 11 (No. 16, 22, 25, and 36) hooked bars without confining reinforcement. (Note: 1 kip = 4.448 kN; 1 in. = 25.4 mm.)

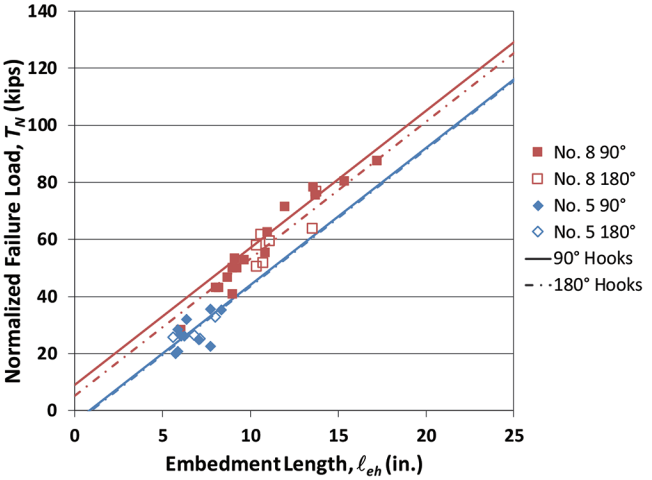

Fig. 5—Bar force at failure normalized to concrete compressive strength of 5000 psi (34.5 MPa) versus embedment length for No. 5 and 8 (No. 16 and 25) hooked bars confined by two No. 3 (No. 10) hoops oriented parallel to straight portion of hooked bar. (Note: 1 kip = 4.448 kN; 1 in. = 25.4 mm.)

overestimates the effect of concrete compressive strength on anchorage strength, and that values of p_1 in the range of 0.25 to 0.29 provide a realistic representation of the effect of concrete compressive strength on the anchorage strength of hooked bars. This observation is further supported by test results for straight bar lap splices (Darwin et al. 1995, 1996; Zuo and Darwin 1998, 2000; Joint ACI-ASCE Committee 408 2003) and headed bars (Shao et al. 2016), which indicate that a value of $p_1 = 0.25$ characterizes the effect of concrete compressive strength on both straight bar bond and headed bar anchorage strength.

In the comparisons that follow, a regression analysis technique based on dummy variables (Draper and Smith 1981) is used to identify trends in the data. Dummy variables analysis is a least-squares regression analysis method that allows differences in populations to be taken into account when formulating relationships between principal variables. For example, the effect of embedment length ℓ_{eh} on bar force at failure T can be found for different bar sizes based on the assumption that the effect of changes in ℓ_{eh} on changes in T is the same for the bar sizes considered, but that the absolute value of T for a given ℓ_{eh} will differ for each bar size.

Effect of bend angle

Figure 4 shows the normalized average failure loads T_N as a function of embedment length for a subset of 58 beam-column specimens, of which 39 are from the current study. These specimens contained No. 5, No. 7, No. 8, and No. 11 (No. 16, No. 22, No. 25, and No. 36) hooked bars without confining reinforcement in the joint region, with bend angles of 90 or 180 degrees. The results for the nine No. 7 (No. 22) hooked bar tests and 11 of the No. 11 (No. 36) hooked bar tests were taken from studies by Marques and Jirsa (1975), Pinc et al. (1977), Hamad et al. (1993), Ramirez and Russell (2008), and Lee and Park (2010). The solid lines and data points represent the results for 90-degree hooked bars, while the broken lines and open data points represent the results for 180-degree hooked bars. Both trend lines and data points are identified based on bar size. In this figure and those that follow, the order of the results in the legend coincides with the order of the lines in the figure. For each bar size, the range of embedment lengths was similar for 90- and 180-degree hooked bars. The embedment lengths ℓ_{eh} ranged from 6.3 to 21.1 in. (160 to 536 mm), the bar stresses at failure ranged from 42,700 to 136,100 psi (294 to 938 MPa), and the normalized average bar forces at failure ranged from 19,300 to 114,400 lb (86 to 509 kN). The concrete compressive strengths ranged from 2570 to 16,500 psi (17.7 to 114 MPa).

As shown in Fig. 4, an increase in embedment length is associated with an increase in the normalized average bar force at failure. The results in Fig. 4 show no clear correlation between anchorage strength and bend angle. For No. 5, 7, and 11 (No. 16, 22, and 36) hooked bars, the trend line corresponding to a 90-degree bend angle is higher than the trend line corresponding to a 180-degree bend angle. The opposite trend is observed for No. 8 (No. 25) hooked bars. The difference between intercepts of the trend lines corresponding to 90- and 180-degree bend angles is greater for the No. 11 (No. 36) bars than for the smaller bars. The results were evaluated using Student's t-test by comparing the intercepts obtained by extending a line with the same slope as the trend lines from each data point to the T_N axis. That evaluation shows that the differences in anchorage strength for bars with bend angles of 90 and 180 degrees are not statistically significant at the 95% confidence level (5% or lower risk of concluding that a difference exists when there is no actual difference) regardless of bar size. In the cases shown in Fig. 4, the variable p ranges between 0.13 and 0.80, where p less than 0.05 would indicate that the differences in anchorage strength based on bend angle are significant (Wonnacott and Wonnacott 1985).

The relationship between normalized failure load and embedment length for 26 beam-column specimens (all from the current study) containing No. 5 or No. 8 (No. 16 and 25) hooked bars with 90- or 180-degree hooks and with two No. 3 (No. 10) hoops in the joint region is shown in Fig. 5.

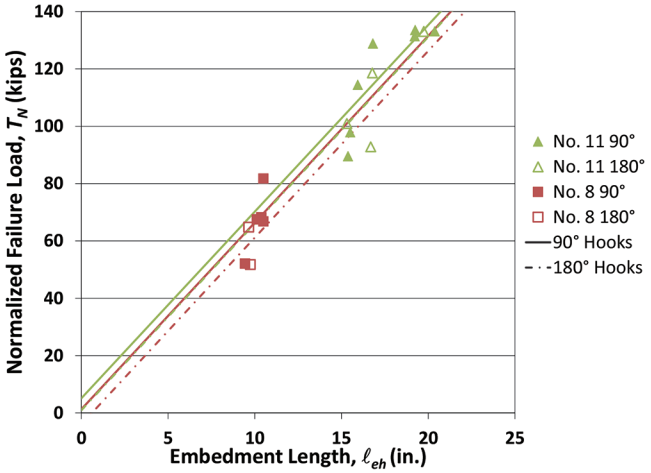

Fig. 6—Bar force at failure normalized to concrete compressive strength of 5000 psi (34.5 MPa) versus embedment length for No. 8 and 11 (No. 25 and 36) hooked bars with confining reinforcement conforming to Section 25.4.3.2 of ACI 318-14 and oriented parallel to straight portion of hooked bar. (Note: 1 kip = 4.448 kN; 1 in. = 25.4 mm.)

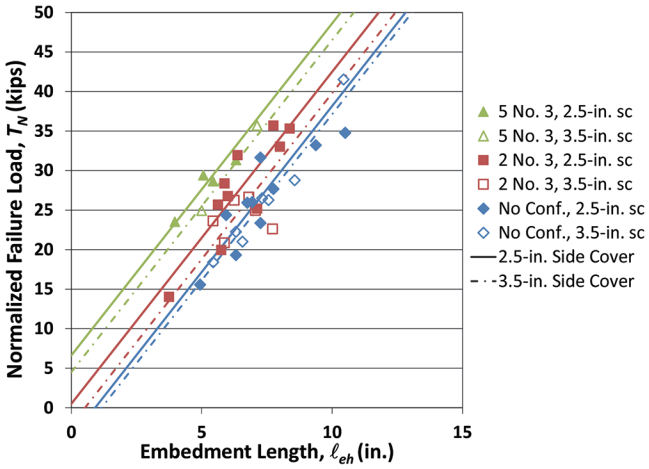

Fig. 7—Bar force at failure normalized to concrete compressive strength of 5000 psi (34.5 MPa) versus embedment length for No. 5 (No. 16) hooked bars with different amounts of No. 3 (No. 10) bar confining reinforcement oriented parallel to straight portion of hooked bar and side cover (sc). (Note: 1 kip = 4.448 kN; 1 in. = 25.4 mm.)

The two hoops were oriented parallel to the straight portion of the hooked bars. Two hoops are insufficient to satisfy ACI Code (ACI 318-14) requirements for the use of a development length modification factor $\psi_r = 0.8$ for hooked bars, and hoops oriented parallel to the straight portion of the hooked bar, regardless of number or spacing, are not considered by the Code to increase the anchorage strength of bars with 180-degree hooks. Contrary to the Code, however, Sperry et al. (2015a,b; 2017a,b) have shown that hoops placed parallel to the straight portion of hooked bars provide similar increases in anchorage strength for both 90- and 180-degree hooked bars. The embedment lengths ℓ_{eh} ranged from 5.6 to 17.3 in. (142 to 439 mm), the normalized average bar forces at failure T_N ranged from 20,000 to 87,500 lb (89 to 389 kN), the bar stresses at failure ranged from 68,000 to 137,400 psi (469 to 947 MPa), and the concrete compressive strengths ranged from 4300 to 15,800 psi (30 to 109 MPa).

The trend lines for anchorage strength nearly coincide for the 90- and 180-degree No. 5 (No. 16) hooked bars, while the 180-degree No. 8 (No. 25) hooked bars had a lower strength than the 90-degree No. 8 (No. 25) hooked bars. The results of Student's t-test show that the differences in anchorage strength for No. 5 and 8 (No. 16 and 25) bars with 90- or 180-degree hooks are not statistically significant at the 95% confidence level, with $p = 0.81$ and 0.12, respectively.

Figure 6 compares the anchorage strengths of No. 8 and No. 11 (No. 25 and 36) bars with 90- and 180-degree hooks confined by No. 3 (No. 10) hoops oriented parallel to the straight portion of the hooked bar and spaced at $3d_b$, which satisfies the requirements for use of the development length modification factor $\psi_r = 0.8$ for 90-degree hooks in ACI 318-14, Section 25.4.3.2. The data in Fig. 6 represent 18 specimens, all tested as part of this study, containing No. 8 or No. 11 (No. 25 or No. 36) hooked bars with 90- and 180-degree bend angles. The embedment lengths ℓ_{eh} ranged from 9.4 to 20.4 in. (239 to 518 mm), the normalized average bar forces at failure T_N ranged from 51,700 to 133,600 lb (230 to 594 kN), the bar stresses at failure ranged from 69,400 to 113,900 psi (478 to 785 MPa), and the concrete compressive strengths ranged from 5420 to 15,800 psi (37.4 to 109 MPa). For both the No. 8 and No. 11 (No. 25 and No. 36) hooked bars, the anchorage strength of the hooked bars with a bend angle of 180 degrees was slightly lower than the strength of the hooked bars with a 90-degree bend angle, although the results of Student's t-test show that the differences are not statistically significant ($p = 0.54$ and 0.50, respectively).

Because differences between the anchorage strengths of hooked bars with 90- and 180-degree bend angles were found to be small and not statistically significant, hooked bars with either bend angle, and with all other parameters the same, should be treated as having the same anchorage strength, as reflected in the design provisions of ACI 318-14. Further, confining reinforcement parallel to the straight portion of hooks is shown to provide the same contribution to the anchorage strength for both 90- and 180-degree standard hooks.

Effect of side cover

Based on the observations that bend angle has no measurable effect on anchorage strength, the comparisons in this section include specimens with both 90- and 180-degree bend angles. The relationship between normalized anchorage strength T_N and embedment length ℓ_{eh} for 39 beam-column joint specimens containing No. 5 (No. 16) hooked bars is shown in Fig. 7. The specimens in Fig. 7 were tested as part of this study and had nominal side covers of 2.5 in. (65 mm) (solid lines) or 3.5 in. (90 mm) (broken lines). Three different quantities of confining reinforcement (parallel to the straight portion of the hooked bar) were investigated: no confining reinforcement; two No. 3 (No. 10) hoops within the joint region; and No. 3 (No. 10) hoops spaced at $3d_b$ (satisfying the requirements for $\psi_r = 0.8$). The embedment lengths ℓ_{eh} ranged from 3.75 in. to 10.5 in. (95 to 267 mm). The normalized failure load T_N ranged from 14,000 to 41,500 lb (62 to

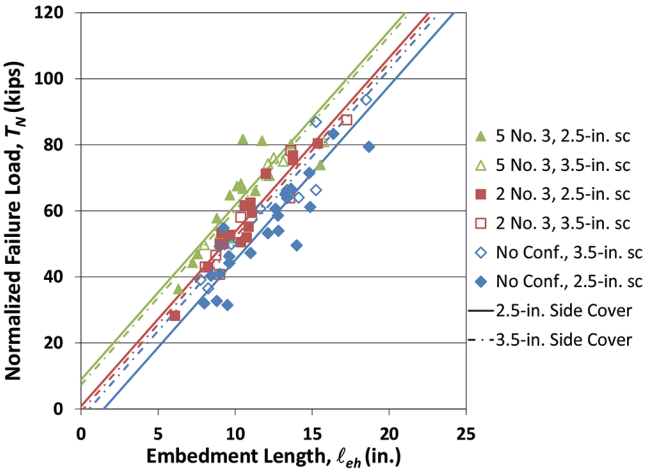

Fig. 8—Bar force at failure normalized to concrete compressive strength of 5000 psi (34.5 MPa) versus embedment length for No. 8 (No. 25) hooked bars with different amounts of No. 3 (No. 10) bar confining reinforcement oriented parallel to straight portion of hooked bar and side cover (sc). (Note: 1 kip = 4.448 kN; 1 in. = 25.4 mm.)

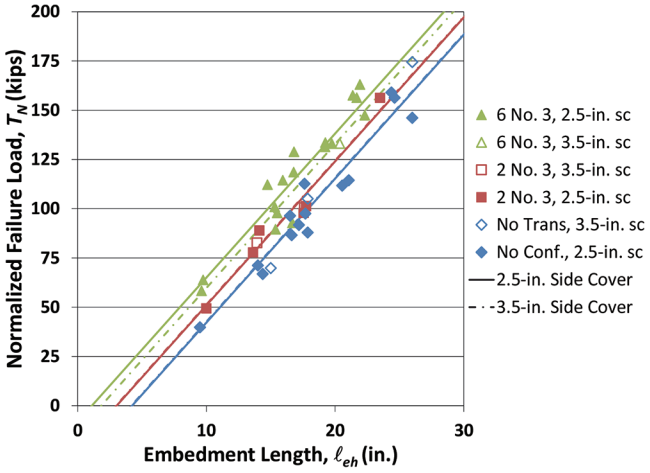

Fig. 9—Bar force at failure normalized to concrete compressive strength of 5000 psi (34.5 MPa) versus embedment length for No. 11 (No. 36) hooked bars with different amounts of No. 3 (No. 10) bar confining reinforcement oriented parallel to straight portion of hooked bar and side cover (sc). (Note: 1 kip = 4.448 kN; 1 in. = 25.4 mm.)

185 kN), the bar stresses at failure ranged from 60,300 to 136,100 psi (416 to 938 MPa), and the concrete compressive strengths ranged from 5190 to 15,800 psi (36 to 109 MPa). The trend lines in Fig. 7 show that anchorage strength increased with increasing embedment length and amount of confining reinforcement. Regardless of the amount of confining reinforcement, the results shown in Fig. 7 indicate that there was a decrease in strength as the side cover increased from 2.5 to 3.5 in. (65 to 90 mm), although the results from Student's t-test show that this decrease was not statistically significant at the 95% confidence level, with p = 0.72, 0.08, and 0.30 for specimens without confining reinforcement, specimens with two No. 3 (No. 10) hoops, and specimens with No. 3 (No. 10) hoops spaced at $3d_b$, respectively.

The relationship between normalized failure load T_N and embedment length ℓ_{eh} for beam-column joint specimens with No. 8 (No. 25) hooked bars with nominal side covers of 2.5 or 3.5 in. (65 or 90 mm) is shown in Fig. 8. The data represent 78 specimens tested as part of this study. The embedment lengths ℓ_{eh} ranged from 6.1 to 18.7 in. (155 to 475 mm), the concrete compressive strengths ranged from 4300 to 16,500 psi (30 to 114 MPa), the bar stresses at failure ranged from 44,430 to 120,700 psi (306 to 832 MPa), and the normalized failure load T_N ranged from 28,200 to 93,600 lb (125 to 416 kN). The trend lines in Fig. 8 show that the normalized failure load increased with increasing embedment length and amount of confining reinforcement. For specimens without confining reinforcement, increasing the side cover from 2.5 to 3.5 in. (65 to 90 mm) led to increases in anchorage strength. Specimens with confining reinforcement included configurations with two No. 3 (No. 10) hoops and with five No. 3 (No. 10) hoops spaced at $3d_b$ in the joint region. For both of these configurations, specimens with 3.5 in. (90 mm) side cover had normalized failure loads slightly lower than those of specimens with 2.5 in. (65 mm) side cover. The results of Student's t-test show that the differences in anchorage strength associated with changes in cover for specimens with two No. 3 (No. 10) hoops and No. 3 (No. 10) hoops spaced at $3d_b$ are not statistically significant at the 95% confidence level, with p equal to 0.32 and 0.47, respectively. For specimens without confining reinforcement, the difference in anchorage strength between hooked bars with 2.5 or 3.5 in. (65 or 90 mm) side cover is statistically significant (p = 0.03).

The relationship between normalized bar force at failure T_N and embedment length ℓ_{eh} is shown in Fig. 9 for 49 beam-column joint specimens with No. 11 (No. 36) hooked bars with nominal side covers of 2.5 or 3.5 in. (65 or 90 mm) tested as part of this study. The embedment lengths ℓ_{eh} ranged from 9.5 to 26.0 in. (241 to 660 mm), the concrete compressive strengths ranged from 4910 to 16,180 psi (34 to 112 MPa), the bar stresses at failure ranged from 33,000 to 136,700 psi (228 to 943 MPa), and the normalized average bar forces at failure T_N ranged from 39,800 to 174,400 lb (177 to 776 kN). Similar to the test results for the smaller hooked bars, anchorage strength increased with embedment length and the amount of confining reinforcement. For specimens without confining reinforcement and specimens with two No. 3 (No. 10) hoops, the change in the normalized failure load was negligible as side cover increased from 2.5 to 3.5 in. (65 to 90 mm). For specimens with six No. 3 (No. 10) hoops spaced at $3d_b$, the trend lines show that there was a small decrease in normalized failure load as side cover increased from 2.5 to 3.5 in. (65 to 90 mm). Because there was only one specimen with 3.5 in. (90 mm) side cover, the most meaningful conclusion that can be drawn from the data is that the normalized failure load was comparable for the two configurations. The results of Student's t-test indicate that the differences in anchorage strength associated with changes in side cover for specimens without confining reinforcement and specimens with two No. 3 (No. 10) hoops are not statistically significant at the 95% confidence level (p = 0.56 and 0.82, respectively). Student's t-test cannot be performed for the specimens with No. 3 (No. 10) hoops

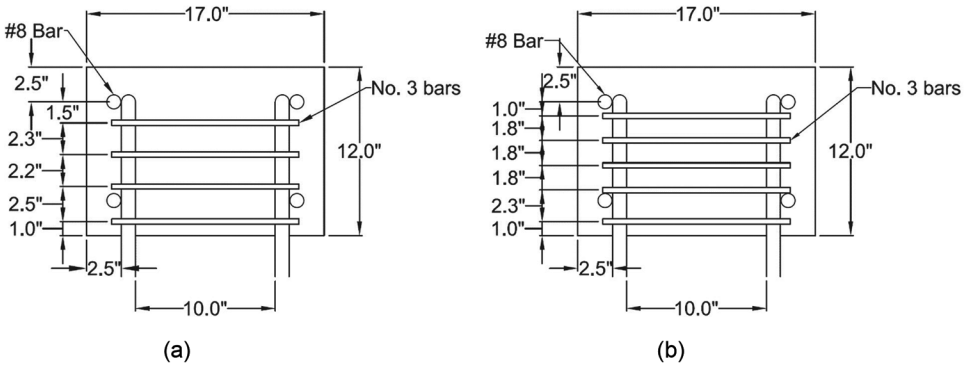

Fig. 10—Plan view of hooked bars with confining reinforcement oriented perpendicular to bar being developed satisfying maximum spacing requirement in ACI 318-14, Section 25.4.3.2: (a) four No. 3 (No. 10) hoops; and (b) five No. 3 (No. 10) hoops. (Note: 1 in. = 25.4 mm.)

spaced at $3d_b$ because there was only one specimen with 3.5 in. (90 mm) side cover.

Of all the Student's t-tests performed, in only one instance, No. 8 (No. 25) hooked bars without confining reinforcement was the value of p less than 0.05, indicative of a statistically significant difference between the anchorage strength of hooked bars with 2.5 in. (65 mm) side cover and hooked bars with 3.5 in. (90 mm) side cover. Overall, the results indicate that anchorage strength was not affected by differences in side cover in the range of 2.5 to 3.5 in. (65 to 90 mm).

Effect of orientation of confining reinforcement

To take advantage of the modification factor $\psi_r = 0.8$ for development length of hooked bars with a 90-degree bend angle, ACI 318-14, Section 25.4.3.2, requires confining reinforcement spaced at $\leq 3d_b$ and placed perpendicular or parallel to the straight portion of the bar being developed. For hooked bars with a 180-degree bend angle, $\psi_r = 0.8$ can only be applied for confining reinforcement oriented perpendicular to the straight portion of the bar. The equivalence of the contribution of confining reinforcement oriented parallel to the straight portion of a hooked bar to the anchorage strength of bars with 90- and 180-degree hooks has already been demonstrated in this paper. Prior to this study, no tests had been performed to evaluate the contribution to anchorage strength of confining reinforcement oriented perpendicular to the straight portion of a hooked bar.

To address this question, a test series was planned with 12 similar beam-column joint specimens cast with the same batch of concrete. This set of specimens contained No. 8 (No. 25) hooked bars with bend angles of 90 or 180 degrees. The specimens had embedment lengths ℓ_{eh} with nominal values of 10, 11, and 12.5 in. (254, 279, and 318 mm). The corresponding column cross-sectional dimensions were 17 x 12 in., 17 x 13 in., and 17 x 14.5 in. (432 x 305 mm, 432 x 330 mm, and 432 x 368 mm). Compressive strengths on the day of the tests were similar, ranging from 11,800 to 12,000 psi (81 to 83 MPa). Average measured embedment lengths ranged from 9.4 to 12.8 in. (234 to 325 mm), bar stresses at failure ranged from 66,600 to 95,200 psi (459 to 656 MPa), and average failure loads ranged from 60,200 to 75,200 lb (268 to 335 kN). Of the 12 specimens, six contained hooked bars with a 90-degree bend angle and six contained hooked bars with a 180-degree bend angle. For both sets of six, one specimen was cast without confining reinforcement, one contained two hoops oriented parallel to the bars being developed (parallel hoops), one contained two hoops oriented perpendicular to the bars being developed (perpendicular hoops), one contained parallel hoops spaced at $3d_b$, and two contained perpendicular hoops spaced at less than $3d_b$.

In the specimens with parallel hoops placed along the tail of the hook, a minimum of five hoops were needed to meet the $3d_b$ spacing requirement. In the specimens with perpendicular hoops, the specimen dimensions and the depth of the joint were such that only four hoops were needed to meet the $3d_b$ spacing requirement specified in the code provisions (ACI 318-14, Section 25.4.3.2). To evaluate the effect of hoop orientation on anchorage strength without favoring the parallel orientation, two different reinforcement configurations were used in specimens with perpendicular hoops satisfying the $3d_b$ maximum spacing requirement—one with the minimum of four hoops needed to achieve the $3d_b$ spacing and one with five hoops to match the area of confining reinforcement used in the specimens with parallel hoops spaced at $3d_b$. The two configurations are shown in Fig. 10. For specimens with a 180-degree bend angle, parallel hoops were placed throughout the region defined by the bend and tail of a 90-degree hooked bar, as shown in Fig. 1.

Because all of the specimens in this batch had different embedment lengths ℓ_{eh} and slightly different concrete compressive strengths f_{cm}, the average bar forces at failure T were normalized with respect to an embedment length of 10 in. (254 mm) and a concrete compressive strength of 12,000 psi (83 MPa) by multiplying the average bar forces at failure T by $(10/\ell_{eh})(12{,}000/f_{cm})^{0.25}$ $\left[(254/\ell_{eh})(83/f_{cm})^{0.25}\right]$ to obtain the normalized average failure load T_N.

The values of T_N for the specimens with two No. 3 (No. 10) hoops and the specimens with No. 3 (No. 10) hoops spaced at $\leq 3d_b$ are shown in the bar graph in Fig. 11. The first set of four bars in the graph shows T_N for the 90- and 180-degree hooked bars confined by two hoops oriented parallel or perpendicular to the straight portion of the bar. As shown for these four specimens, the value of T_N for the specimen containing 90-degree hooked bars confined by parallel hoops was 1.27 times the value of T_N for the spec-

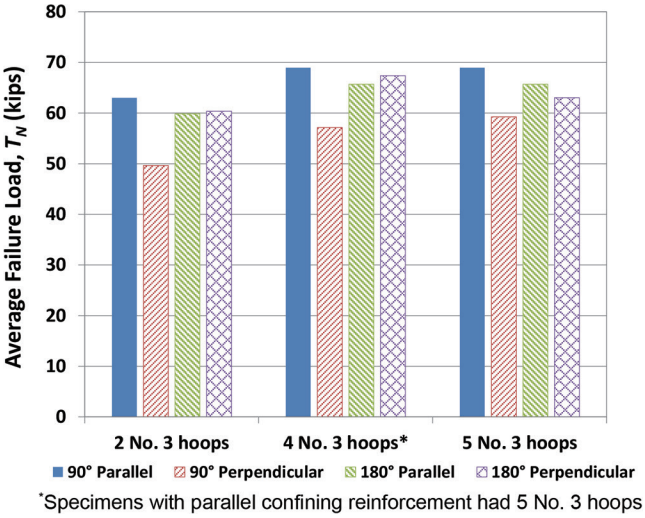

Fig. 11—Bar force at failure normalized to embedment length of 10 in. (254 mm) and concrete compressive strength of 12,000 psi (83 MPa) for specimens containing No. 8 (No. 25) hooked bars with No. 3 (No. 10) confining reinforcement oriented parallel or perpendicular to straight portion of hooked bar and 90- or 180-degree bend angles. (Note: 1 kip = 4.448 kN.)

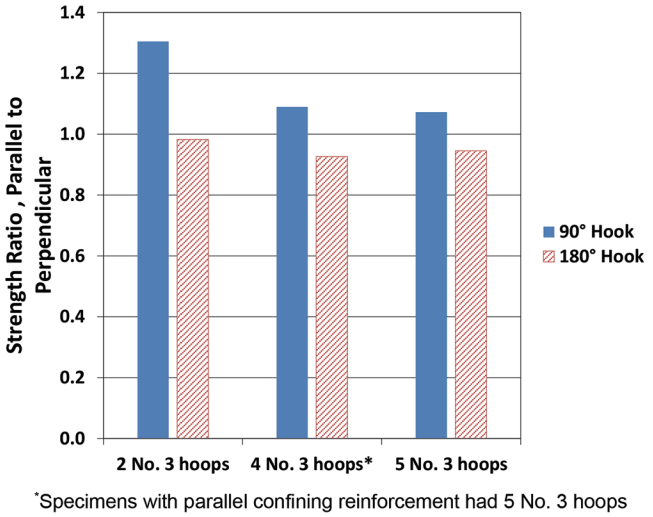

Fig. 12—Ratio of anchorage strength of No. 8 (No. 25) hooked bars with confining reinforcement oriented parallel to straight portion of bar to anchorage strength of No. 8 (No. 25) hooked bars with confining reinforcement oriented perpendicular to straight portion of bar. Strengths normalized to embedment length of 10 in. (254 mm) and concrete compressive strength of 12,000 psi (83 MPa).

imen containing 90-degree hooked bars confined by perpendicular hoops. For the specimens containing 180-degree hooked bars, T_N for the specimens with the two orientations of confining reinforcement had similar strengths—T_N for the specimen with perpendicular hoops was 1.01 times T_N for the specimen with parallel hoops.

The second and third sets of four bars in Fig. 11 show the results for specimens with hoops spaced $\leq 3d_b$. In each of these sets, two specimens were cast with hoops oriented in the parallel direction, one with 90-degree hooked bars and the other with 180-degree hooked bars, both having five hoops spaced $\leq 3d_b$. Because there were no specimens with four hoops with a parallel orientation, specimens with five hoops are shown in the first and third columns of the second set for reference. The trends for the specimens with hoops spaced $\leq 3d_b$ are similar to those observed for specimens with two hoops. The value of T_N for the specimen with 90-degree hooked bars confined by parallel hoops is higher than T_N for the specimens containing 90-degree hooked bars confined by perpendicular hoops, although the difference is smaller than observed for the specimens with two hoops. T_N for the 90-degree hooked bar specimen with five parallel hoops was, respectively, 1.21 and 1.16 times T_N for the 90-degree hooked bar specimens with four and five perpendicular hoops. For the 180-degree hooked bar specimens, the specimen with four perpendicular hoops had the highest strength, while the specimen with five perpendicular hoops had the lowest. T_N for the 180-degree hooked bar specimen with five parallel hoops was, respectively, 0.97 and 1.05 times the failure loads of the companion specimens with four and five perpendicular hoops. T_N for the 180-degree hooked bar specimen with five parallel hoops was equal to 0.95 of T_N for the 90-degree hooked bar specimen with parallel hoops and 1.15 and 1.11 times T_N for the 90-degree hooked bar specimens with, respectively, four and five perpendicular hoops. In this limited test series, increasing from four to five perpendicular hoops had little effect on the strength of hooked bars with bend angles of either 90 or 180 degrees.

Figure 12 shows the ratio of the anchorage strength of the hooked bars confined by parallel hoops to the anchorage strength of hooked bars confined by perpendicular hoops. The figure indicates that for 90-degree hooked bars, all of which had ratios greater than unity, parallel hoops provided a greater increase in anchorage strength than perpendicular hoops. In contrast, for 180-degree hooked bars, all had ratios below unity, indicating that perpendicular hoops provided the greater increase in strength. The greater contribution of parallel hoops for 90-degree hooked bars may result because the hoops serve as anchor reinforcement that resists a breakout failure. In this configuration, hoop orientation is optimal for carrying a direct tensile force, which helps keep the joint region adjacent to the 90-degree hooked bar intact. In contrast, perpendicular hoops do not develop a direct tensile force to counteract the tensile force in the hooked bars, causing the hoops to be less efficient than hoops with a parallel orientation in preventing a breakout failure of the joint region. Confining reinforcement oriented perpendicular to the straight portion of the hooked bar, however, may be more efficient in limiting splitting of the concrete caused by slip of the hooked bars—splitting that may be greater for 180-degree hooked bars than for 90-degree hooked bars. Greater slip was observed for 180-degree hooked bars by Marques and Jirsa (1975) and Hamad et al. (1993). Splitting due to slip is also key in developing straight bar reinforcement, where the resistance to the wedging action of the bar due to slip is a function of the amount of confining reinforcement oriented perpendicular to the bar and the concrete compressive strength. This suggests that the confinement

provided by perpendicular hoops may be similar to that of the confinement provided by reinforcement perpendicular to straight bars (Darwin et al. 1995, 1996; Zuo and Darwin 1998, 2000, Joint ACI-ASCE Committee 408 2003).

Figure 13 shows the ratio of the anchorage strength of 90-degree hooked bars to that of 180-degree hooked bars for specimens with both hoop orientations. The ratio for specimens with parallel hoops ranged from 1.01 to 1.06, while the ratio for specimens with perpendicular hoops ranged from 0.80 to 0.89. For specimens with parallel hoops, anchorage strength ratios were very close to 1.0, which indicates that regardless of the number of hoops in the specimens, placing the confining reinforcement parallel to the straight portion of the hooked bar resulted in a similar increase in strength for hooked bars with 90- and 180-degree bend angles. For specimens with perpendicular hoops, the average anchorage strength ratio was approximately 0.85, which shows that placing confining reinforcement perpendicular to the straight portion of the hooked bar resulted in lower increases in anchorage strength for 90-degree hooked bars than for 180-degree hooked bars.

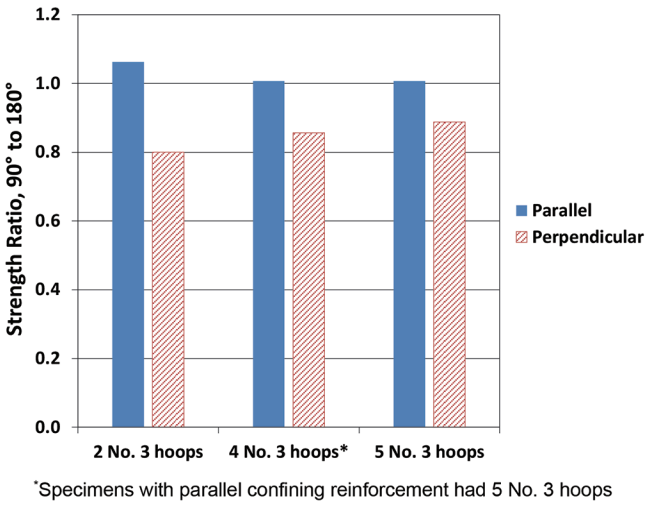

Fig. 13—Ratio of anchorage strength of No. 8 (No. 25) hooked bars with 90-degree bend angle to anchorage strength of No. 8 (No. 25) hooked bars with 180-degree bend angle for hooks confined by No. 3 (No. 10) hoops oriented parallel or perpendicular to straight portion of bar. Strengths normalized to embedment length of 10 in. (254 mm) and concrete compressive strength of 12,000 psi (83 MPa).

The observed failure modes (Fig. 14(a) and (b)) support the theory that confining reinforcement oriented parallel to the straight portion of a hooked bar is more effective in keeping the concrete in the joint region together by acting as anchor reinforcement, limiting the potential for a concrete breakout failure at the front of the column. As observed by Searle et al. (2014) and Sperry et al. (2015a,b; 2017a), the tensile force in the hooked bars pulls out a triangular-shaped block of concrete (with its base at the front of the column), as shown in Fig. 14(a), with the tensile force in the hoops directly opposing that breakout force and pinning the triangular-shaped block to the compression zone at the back of the column. When reinforcement oriented perpendicular to the straight portion of the bar is used to confine hooked bars with 90-degree bend angles, it does help to keep the concrete in the joint together, although it is less effective because it no longer acts as anchor reinforcement. Failure occurs as a block of confined concrete is pulled toward the front of the column with the hoops, as shown in Fig. 14(b).

Based on these results, it is concluded that the anchorage strength of 180-degree hooked bars with either orientation of confining reinforcement is similar to that of 90-degree hooked bars with confining reinforcement oriented parallel to the straight portion of the hooked bar. Confining reinforcement oriented perpendicular to the straight portion of the bar is less effective for 90-degree hooked bars. Considering the limited amount of test data in this study to address the effect on anchorage strength of confining reinforcement perpendicular to the straight portion of a hooked bar, more research on the effect of confining reinforcement with this orientation is needed.

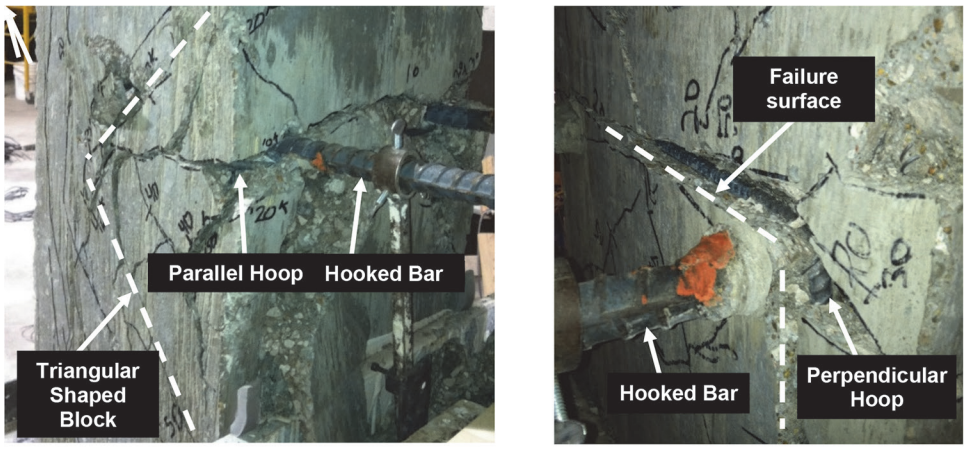

Fig. 14—Failure modes of specimens with 90-degree hooked bars with different orientations of confining reinforcement: (a) hoops parallel to straight portion of hooked bars pinning triangular-shaped block to compression zone; and (b) hoops perpendicular to straight portion of hooked bar with concrete block being pulled toward front of column.

SUMMARY AND CONCLUSIONS

Test results for 166 simulated exterior beam-column joints with two hooked bars were used to investigate the effects of bend angle, concrete side cover, and confining reinforcement orientation on the anchorage strength of hooked bars. The simulated beam-column joint specimens contained No. 5, No. 8, and No. 11 (No. 16, No. 25, and No. 36) hooked bars with 90- or 180-degree bend angles. The clear concrete side cover ranged from 2.5 to 3.5 in. (65 to 90 mm). The specimens were cast using normalweight concrete with compressive strengths ranging from 4300 to 16,500 psi (30 to 114 MPa). Bar stresses at failure ranged from 33,000 to 137,400 psi (228 to 947 MPa). A set of specimens was cast with confining reinforcement oriented either parallel or perpendicular to the straight portion of the hooked bar in the joint region, with all other parameters held constant to study the effect of confining reinforcement orientation on anchorage strength. Data from prior studies were included in the analysis where applicable.

The following conclusions are based on the data and analysis presented herein:

1. Hooked bars with 90- and 180-degree bend angles have similar anchorage strengths and can be used interchangeably. This includes hooked bars with a 180-degree bend angle confined by parallel reinforcement following Section 25.4.3.2 of ACI 318-14 to allow use of the 0.8 modification factor for calculating the development length of hooked bars.

2. For hooked bars with a 90-degree bend angle, confining reinforcement placed perpendicular to the straight portion of the bars results in a lower anchorage strength than confining reinforcement with a similar spacing placed parallel to the straight portion of the bars.

3. Increasing concrete side cover from 2.5 to 3.5 in. (65 to 90 mm) does not increase the anchorage strength of hooked bars.

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Appendix A:

Table A.1—Concrete mixture proportions

Material	Quantity (SSD)			
Design Compressive Strength	**5,000 psi**	**8,000 psi**	**12,000 psi**	**15,000 psi**
Type I/II Cement, lb/yd^3	600	700	750	760
Class C Fly Ash, lb/yd^3	-	-	-	160
Silica Fume, lb/yd^3	-	-	-	100
Water, lb/yd^3	263	225	217	233
Kansas River Sand[a], lb/yd^3	1396	1375	1050	1138
Pea Gravel[b], lb/yd^3	-	-	316	-
Crushed Limestone[c], lb/yd^3	1734	1683	1796	-
Granite[d], lb/yd^3	-	-	-	1693
Estimated Air Content, %	1	1	1	1
High-Range Water-Reducer[e], oz (US)	30	171	104	205
w/cm ratio	0.44	0.32	0.29	0.24

BSG (SSD): [a]2.63, [b]2.60, [c]2.59, [d]2.61; Maximum size of Limestone and Granite = ¾ in. (19 mm)
[e]Polycarboxylate-based, 1 psi = 0.00689 MPa, 1 lb/yd^3 = 0.593 kg/m^3, 1 oz = 29.6 mL

Table A.2—Hooked bar properties

Bar Size	ASTM Designation	Yield Strength (ksi)[1]	Nominal Diameter (in.)	Average Rib Spacing (in.)	Average Rib Height		Gap Width		Relative Rib Area[3]
					A[2] (in.)	B[3] (in.)	Side 1 (in.)	Side 2 (in.)	
5	A615	88	0.625	0.417	0.031	0.029	0.179	0.169	0.060
5	A1035*	122	0.625	0.391	0.038	0.034	0.200	0.175	0.073
8	A615*	88	1	0.666	0.059	0.056	0.146	0.155	0.073
8	A1035[a]	120	1	0.686	0.068	0.065	0.186	0.181	0.084
8	A1035[b]	122	1	0.574	0.057	0.052	0.16	0.157	0.078
8	A1035[c]*	122	1	0.666	0.056	0.059	0.146	0.155	0.073
11	A615*	84	1.41	0.894	0.080	0.074	0.204	0.196	0.069
11	A1035*	123	1.41	0.830	0.098	0.088	0.248	0.220	0.085

[1] From mill test report [2] Per ASTM A615, A706. [3] Per ACI 408R-3 [a] Heat 1, [b] Heat 2, [c] Heat 3, 1 in. = 25.4 mm, 1 ksi = 6.89 MPa
*Stress-strain curves on following pages

Stress-Strain Curves

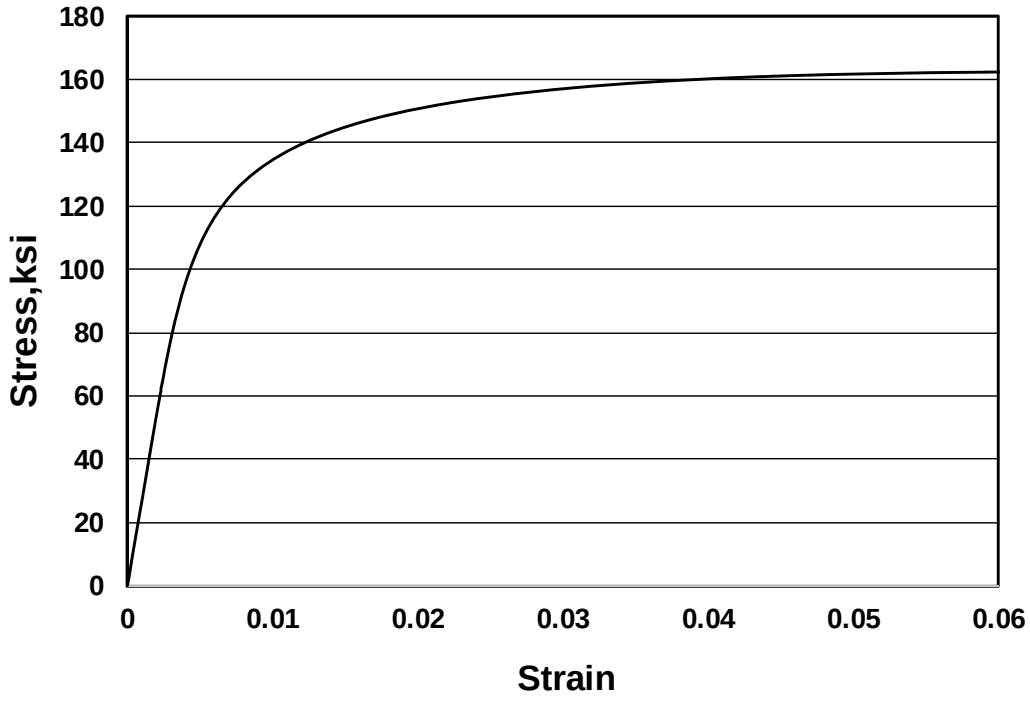


Figure A.1 Stress-strain curve for No. 5 (No. 16) (A1035 steel)

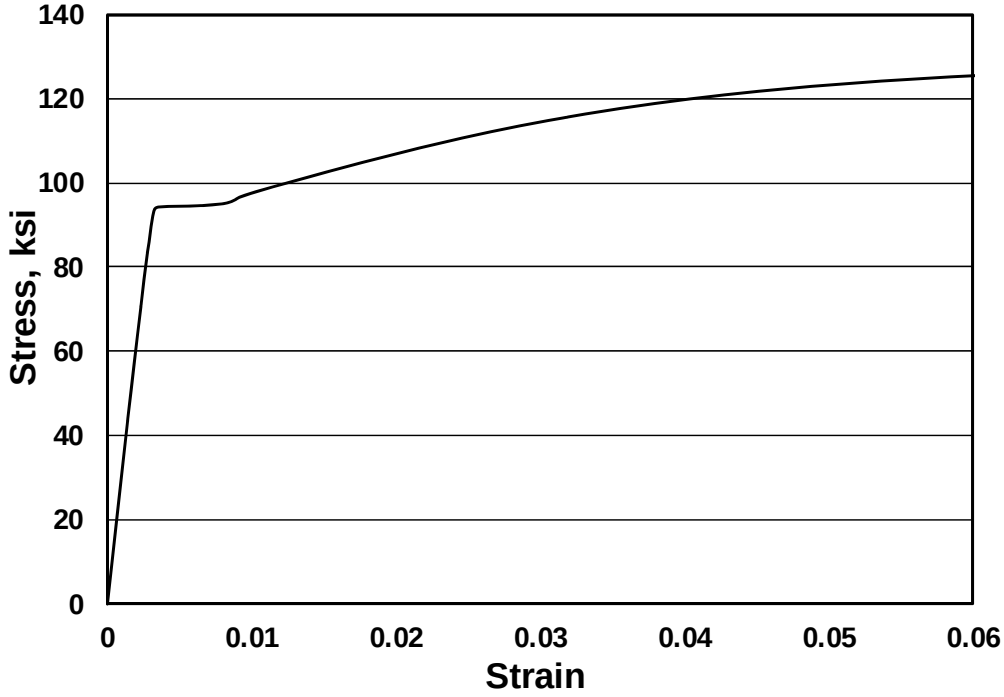


Figure A.2 Stress-strain curve for No. 8 (No. 25) (A615 steel)

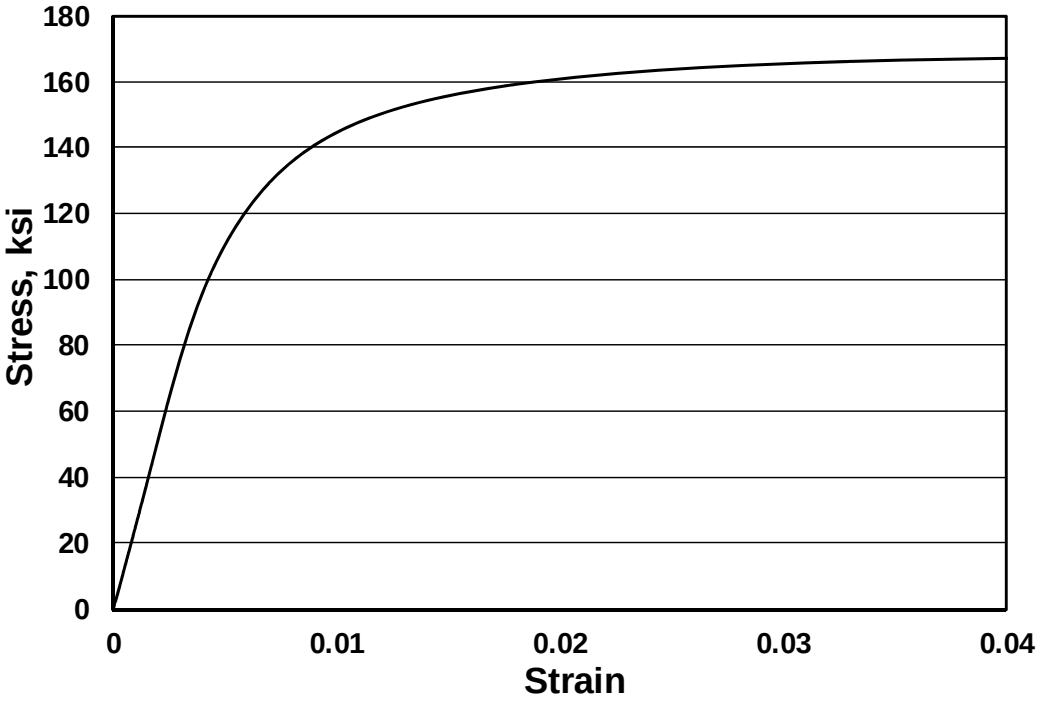


Figure A.3 Stress-strain curve for No. 8 (No. 25) (A1035 steel) Heat 3

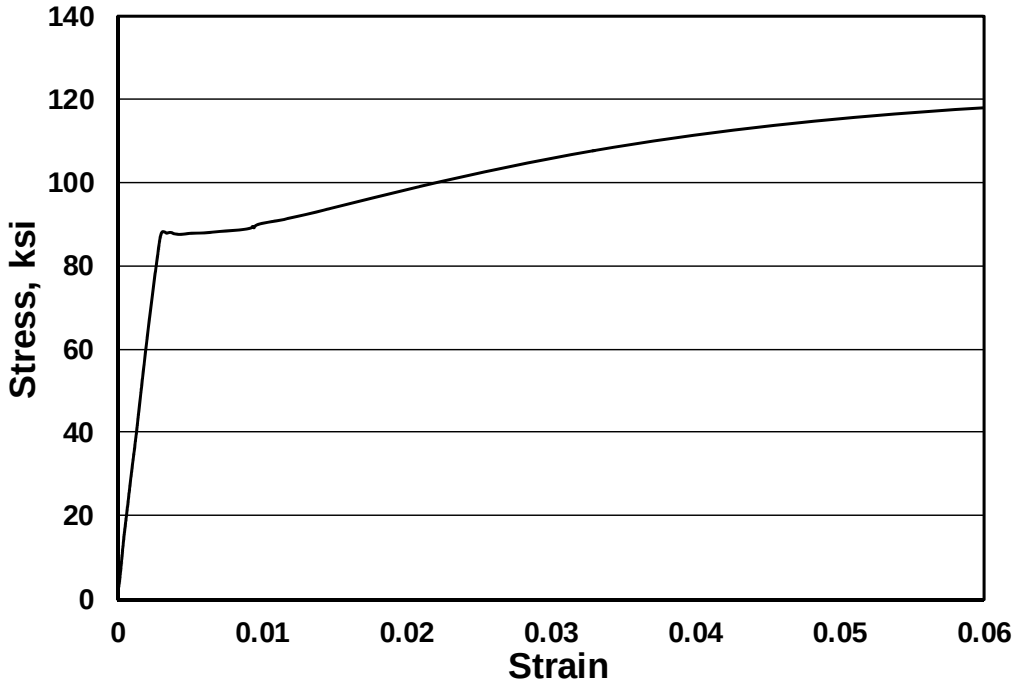


Figure A.4 Stress-strain curve for No. 11 (No. 36) (A615 steel)

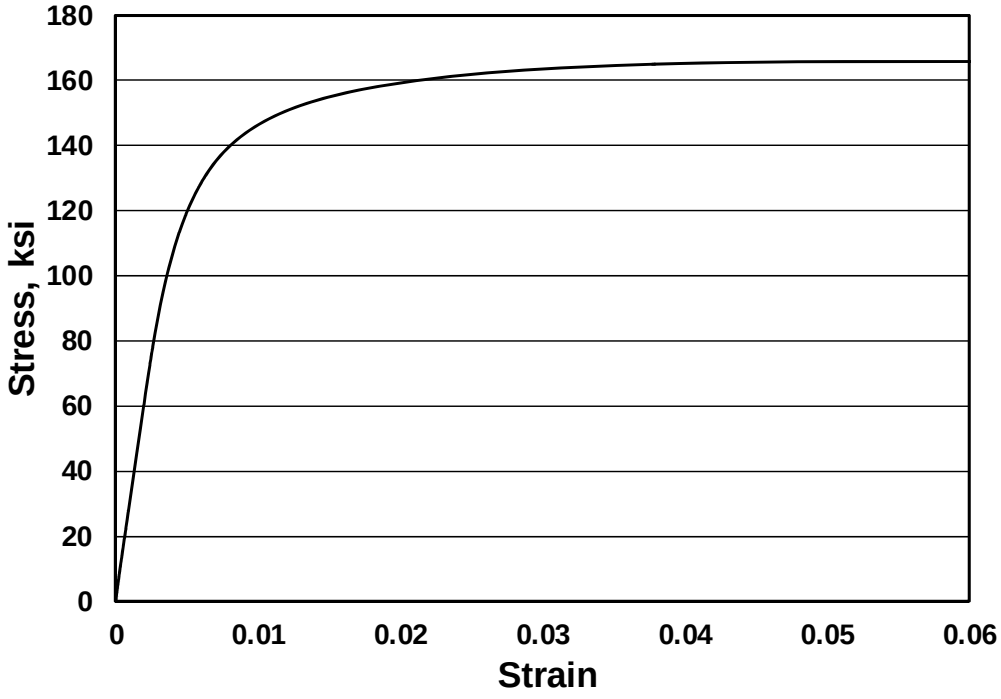


Figure A.5 Stress-strain curve for No. 11 (No. 36) (A1035 steel)

NOTATION FOR DATA TABLES

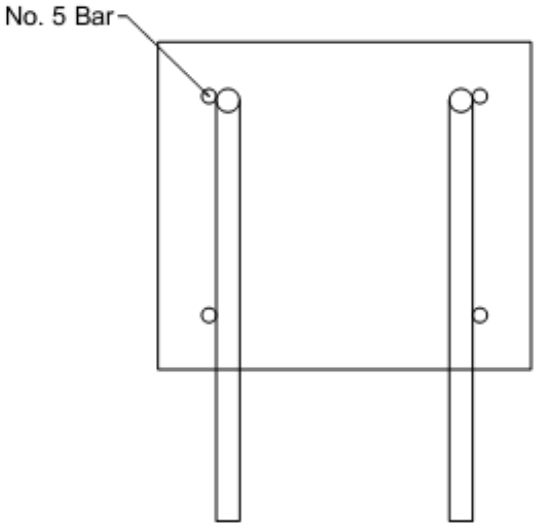
A_h	Area of hooked bar
A_{tr}	Total area of transverse steel inside hook region
A_s	Area of longitudinal steel in the column
A_{cti}	Total area of cross-ties inside the hook region
b	Column width
c_b	Clear cover measured from the center of the hook to the side of the column
c_h	Clear spacing between 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_{eh}	Embedment length measured from the back of the hook to the front 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 peak load on hooked bars
T_c	Contribution of concrete to hooked bar anchorage capacity
T_{calc}	Calculated hooked bar strength
T_{ind}	Peak load on the hooked bar at failure
T_h	Hooked bar anchorage capacity
T_s	Contribution of confining steel in joint region to hooked bar anchorage capacity
T_{test}	Recorded load on hooked bar at failure
T_{total}	Total peak load on hooked bars
T_N	Load on hooked bar at failure multiplied by concrete compressive strength normalized to 5,000 psi
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

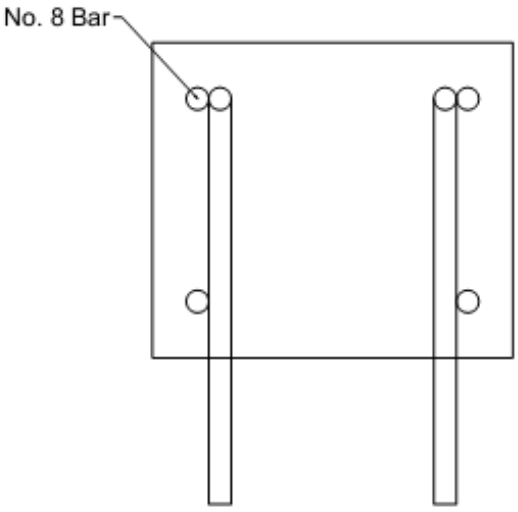
Failure types
FP Front pullout
FB Front blowout
SS Side splitting
SB Side blowout
TK Tail kickout
FL Flexural failure of column
BY Yield or fracture of hooked bars

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 F#G = 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

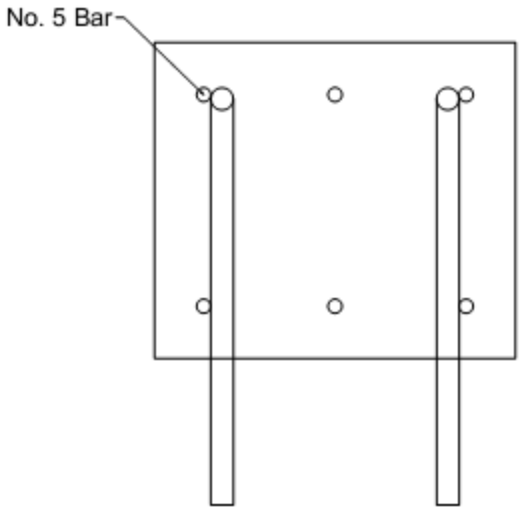
LONGITUDINAL COLUMN STEEL LAYOUTS



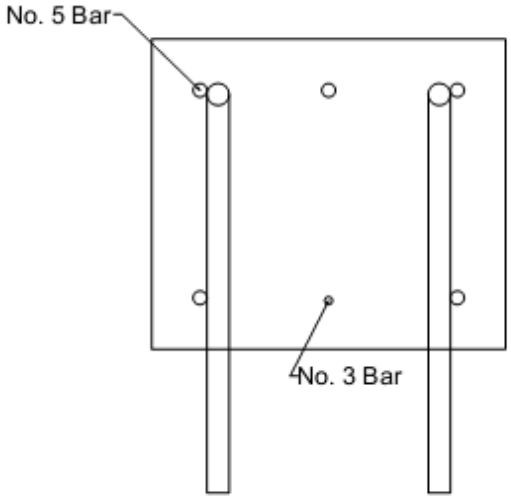
Layout A1: Longitudinal column reinforcement-4 No. 5 bars. Transverse reinforcement not shown.



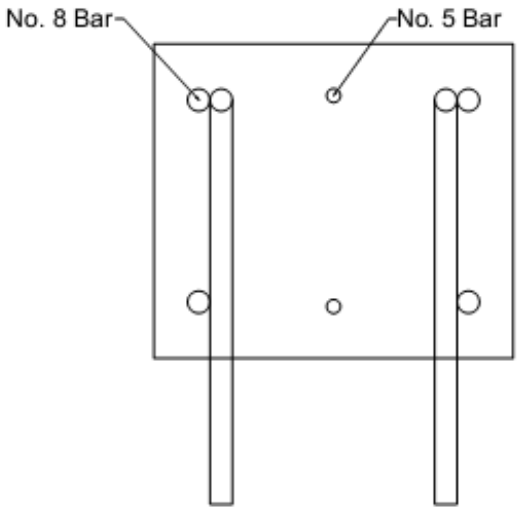
Layout A2: Longitudinal column reinforcement-4 No. 8 bars. Transverse reinforcement not shown.



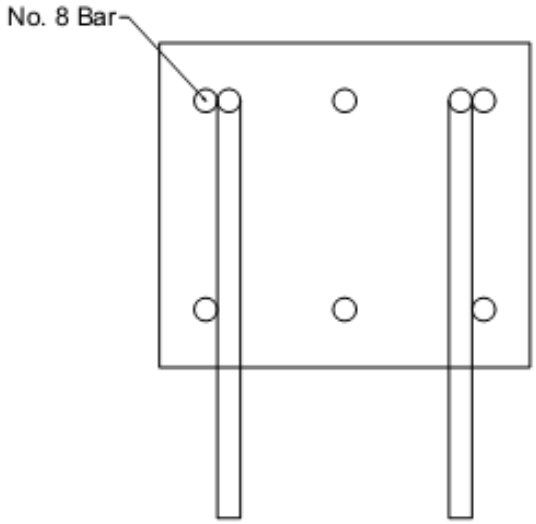
Layout A3: Longitudinal column reinforcement-6 No. 5 bars. Transverse reinforcement not shown.



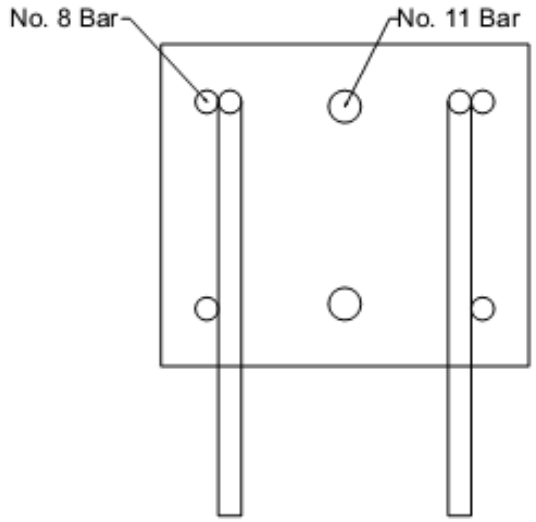
Layout A4: Longitudinal column reinforcement-5 No. 5 bars + 1 No. 3 bar. Transverse reinforcement not shown.



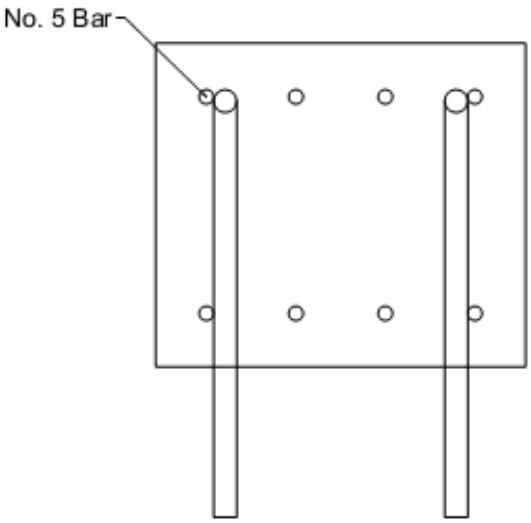
Layout A5: Longitudinal column reinforcement-4 No. 8 bars + 2 No. 5 bars. Transverse reinforcement not shown.



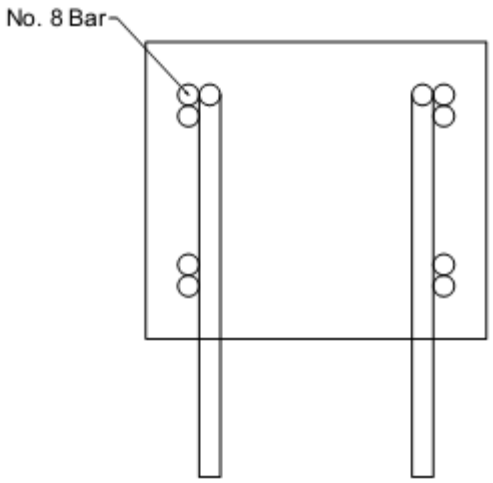
Layout A6: Longitudinal column reinforcement-6 No. 8 bars. Transverse reinforcement not shown.



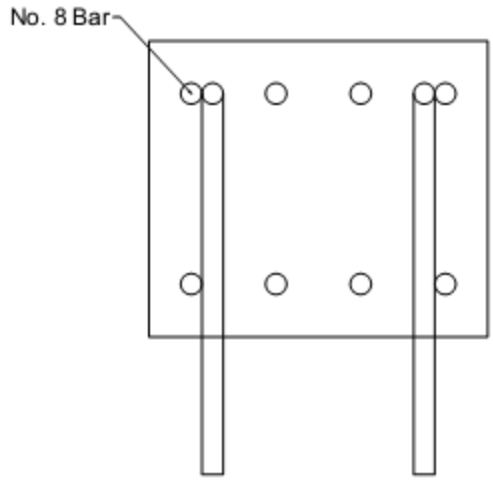
Layout A7: Longitudinal column reinforcement-4 No. 8 bars + 2 No. 11 bars. Transverse reinforcement not shown.



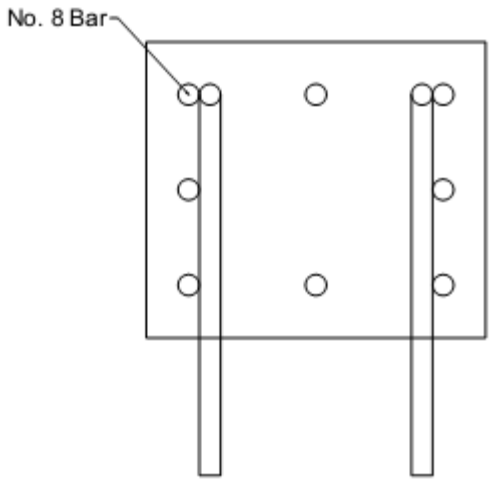
Layout A8: Longitudinal column reinforcement-8 No. 5 bars. Transverse reinforcement not shown.



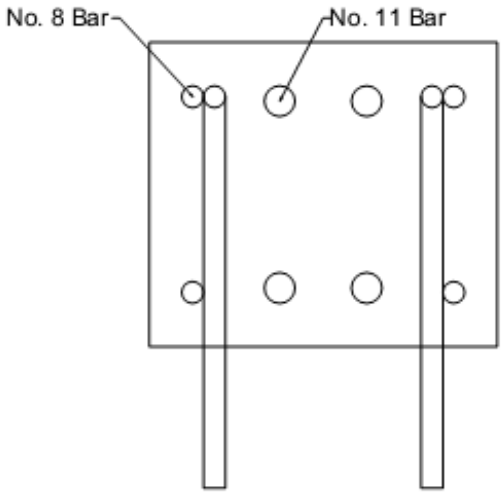
Layout A9: Longitudinal column reinforcement-8 No. 8 bars (four bundles of two bars each). Transverse reinforcement not shown.



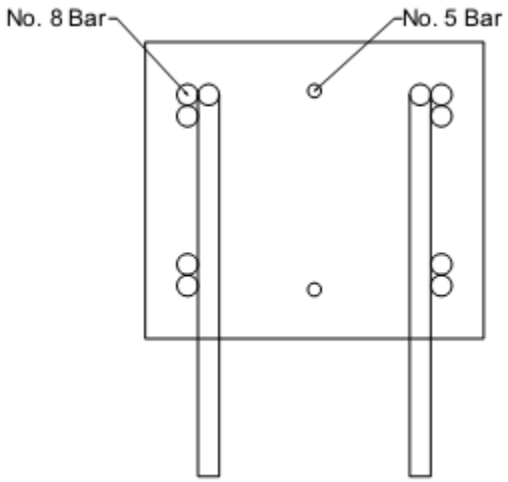
Layout A10: Longitudinal column reinforcement-8 No. 8 bars (distributed across two column faces). Transverse reinforcement not shown.



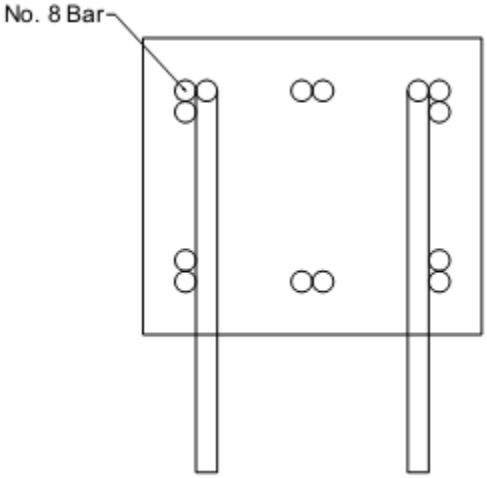
Layout A11: Longitudinal column reinforcement-8 No. 8 bars (distributed across four column faces). Transverse reinforcement not shown.



Layout A12: Longitudinal column reinforcement-4 No. 8 bars + 4 No. 11 bars. Transverse reinforcement not shown.



Layout A13: Longitudinal column reinforcement-8 No. 8 bars + 2 No. 5 bars. Transverse reinforcement not shown.



Layout A14: Longitudinal column reinforcement-12 No. 8 bars. Transverse reinforcement not shown.

Table A.3–Test results for specimens used in bend angle analysis

Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	*Age* days	d_b in.	R_r	*b* in.	h_{cl} in.	h_c in.
5-5-90-0-i-2.5-2-7	A B	90°	Horizontal	A1035	6.9 7.0	6.9	5190	7	0.625	0.073	13	5.25	8.375
5-8-90-0-i-2.5-2-6†	A B	90°	Horizontal	A615	6.8 6.8	6.8	8450	14	0.625	0.073	13	5.25	8.375
5-8-90-0-i-2.5-2-6(1)	A B	90°	Horizontal	A1035	6.1 6.5	6.3	9080	11	0.625	0.073	13	5.25	8.375
5-15-90-0-i-2.5-2-7.5	A B	90°	Horizontal	A1035	7.3 7.3	7.3	15800	62	0.625	0.073	13	5.25	8.375
5-5-90-0-i-3.5-2-7	A B	90°	Horizontal	A1035	7.5 7.6	7.6	5190	7	0.625	0.073	15	5.25	8.375
5-8-90-0-i-3.5-2-6†	A B	90°	Horizontal	A615	6.3 6.4	6.3	8580	15	0.625	0.073	15	5.38	8.375
5-8-90-0-i-3.5-2-6(1)	A B	90°	Horizontal	A1035	6.5 6.6	6.6	9300	13	0.625	0.073	15	5.25	8.375
5-8-90-0-i-3.5-2-8†	A B	90°	Horizontal	A1035	8.6 8.5	8.6	8380	13	0.625	0.060	15	5.25	8.375
5-8-180-0-i-2.5-2-7	A B	180°	Horizontal	A1035	7.4 7.1	7.3	9080	11	0.625	0.073	13	5.25	8.375
5-8-180-0-i-3.5-2-7	A B	180°	Horizontal	A1035	7.4 7.3	7.3	9080	11	0.625	0.073	15	5.25	8.375
5-5-90-2#3-i-2.5-2-8†	A B	90°	Horizontal	A1035	8.0 7.5	7.8	5860	8	0.625	0.073	13	5.38	8.375
5-5-90-2#3-i-2.5-2-6†	A B	90°	Horizontal	A615	6.0 5.8	5.9	5800	9	0.625	0.060	13	5.25	8.375
5-8-90-2#3-i-2.5-2-6†	A B	90°	Horizontal	A1035	6.0 6.0	6.0	8580	15	0.625	0.073	13	5.25	8.375
5-8-90-2#3-i-2.5-2-8†	A B	90°	Horizontal	A1035	8.3 8.5	8.4	8380	13	0.625	0.073	13	5.25	8.375
5-12-90-2#3-i-2.5-2-5	A B	90°	Horizontal	A1035	5.8 5.8	5.8	11090	83	0.625	0.073	13	5.25	8.375
5-15-90-2#3-i-2.5-2-6	A B	90°	Horizontal	A1035	6.3 6.5	6.4	15800	61	0.625	0.073	13	5.25	8.375
5-5-90-2#3-i-3.5-2-6	A B	90°	Horizontal	A1035	6.0 5.8	5.9	5230	6	0.625	0.073	15	5.25	8.375
5-5-90-2#3-i-3.5-2-8	A B	90°	Horizontal	A1035	7.9 7.5	7.7	5190	7	0.625	0.073	15	5.25	8.375
5-8-90-2#3-i-3.5-2-6†	A B	90°	Horizontal	A1035	6.5 6.0	6.3	8580	15	0.625	0.073	15	5.25	8.375
5-8-90-2#3-i-3.5-2-8†	A B	90°	Horizontal	A1035	7.1 7.0	7.1	8710	16	0.625	0.060	15	5.25	8.375
5-5-180-2#3-i-2.5-2-8†	A B	180°	Horizontal	A1035	8.0 8.0	8.0	5670	7	0.625	0.073	13	5.25	8.375
5-5-180-2#3-i-2.5-2-6†	A B	180°	Horizontal	A615	5.8 5.5	5.6	5860	8	0.625	0.060	13	5.25	8.375
5-8-180-2#3-i-2.5-2-7	A B	180°	Horizontal	A1035	7.0 7.3	7.1	9080	11	0.625	0.073	13	5.25	8.375
5-8-180-2#3-i-3.5-2-7	A B	180°	Horizontal	A1035	6.8 6.9	6.8	9080	11	0.625	0.073	15	5.25	8.375

† Specimens had constant 80 kip axial load

Table A.3 Cont.–Test results for specimens used in bend angle analysis

Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	f_{su} psi	$f_{su,avg}$ psi	Lead Slip (Tail Slip) at Failure in.	Failure Type
5-5-90-0-i-2.5-2-7	A B	2.5 2.5	2.5	2.8 2.6	6.8	2	26600 26100	52530	26265	85800 84200	84700	- 0.192	FP/SS FP/SS
5-8-90-0-i-2.5-2-6†	A B	2.8 2.6	2.7	1.3 1.3	6.4	2	27600 32100	59140	29570	89000 103500	95400	- -	FB/SB SB/FB
5-8-90-0-i-2.5-2-6(1)	A B	2.5 2.5	2.5	2.6 2.3	7.0	2	21700 25000	44850	22425	70000 80600	72300	0.296 0.330(0.030)	FP FP
5-15-90-0-i-2.5-2-7.5	A B	2.5 2.5	2.5	2.6 2.6	6.6	2	42000 42500	84400	42200	135500 137100	136100	- -	FB *
5-5-90-0-i-3.5-2-7	A B	3.4 3.5	3.4	1.3 1.1	7.0	2	27200 25900	53030	26515	87700 83500	85500	- -	SS FP/SS
5-8-90-0-i-3.5-2-6†	A B	3.6 3.5	3.6	1.8 1.6	6.6	2	25100 29100	50950	25475	81000 93900	82200	- -	FP/SS FP/SS
5-8-90-0-i-3.5-2-6(1)	A B	3.8 3.8	3.8	2.1 1.9	6.9	2	24400 27500	49080	24540	78700 88700	79200	0.152 0.178(0.150)	FP/SS FP/SS
5-8-90-0-i-3.5-2-8†	A B	3.6 3.5	3.6	1.4 1.5	7.1	2	39100 34300	65490	32745	126100 110600	105600	- -	FB/SS SS
5-8-180-0-i-2.5-2-7	A B	2.5 2.6	2.6	2.1 2.4	6.3	2	26700 35200	54220	27110	86100 113500	87500	0.194 0.146(0.016)	FP/SS SB/FP
5-8-180-0-i-3.5-2-7	A B	3.6 3.4	3.5	1.9 2.0	7.1	2	34100 31400	61510	30755	110000 101300	99200	0.251 0.237(0.021)	SS/FP FP/SS
5-5-90-2#3-i-2.5-2-8†	A B	2.5 2.5	2.5	2.0 2.5	6.6	2	37900 38900	74310	37155	122300 125500	119900	- -	SS/FP SS/FP
5-5-90-2#3-i-2.5-2-6†	A B	2.6 2.6	2.6	2.5 2.8	6.6	2	31800 29200	58890	29445	102600 94200	95000	- -	FP/SS FP/SS
5-8-90-2#3-i-2.5-2-6†	A B	2.8 2.9	2.8	2.0 2.0	6.1	2	33500 30900	61280	30640	108100 99700	98800	- -	FP/SS FP/SS
5-8-90-2#3-i-2.5-2-8†	A B	2.6 2.5	2.6	1.8 1.5	6.5	2	39800 40500	80340	40170	128400 130600	129600	- -	FP/SS FP/SS
5-12-90-2#3-i-2.5-2-5	A B	2.5 2.8	2.6	3.0 3.0	6.5	2	25200 29400	48700	24350	81300 94800	78500	- -	FP/SS FP
5-15-90-2#3-i-2.5-2-6	A B	2.4 2.4	2.4	1.9 1.7	6.6	2	42400 42900	85300	42600	136800 138400	137400	- -	FP FB
5-5-90-2#3-i-3.5-2-6	A B	3.4 3.4	3.4	2.3 2.5	6.5	2	21500 22400	42190	21095	69400 72300	68000	0.183 -	SS/FP SS/FP
5-5-90-2#3-i-3.5-2-8	A B	3.4 3.5	3.4	2.3 2.8	6.8	2	43700 45700	45660	22830	141000 147400	73600	- -	FP FP
5-8-90-2#3-i-3.5-2-6†	A B	3.5 3.8	3.6	1.5 2.0	6.4	2	29900 30100	60070	30035	96500 97100	96900	- -	FP FP/SS
5-8-90-2#3-i-3.5-2-8†	A B	3.5 3.5	3.5	2.9 3.0	6.6	2	38000 28600	57310	28655	122600 92300	92400	- -	FP FP
5-5-180-2#3-i-2.5-2-8†	A B	2.5 2.5	2.5	2.0 2.0	6.9	2	34000 34500	68160	34080	109700 111300	109900	- -	FP/SS FP/SS
5-5-180-2#3-i-2.5-2-6†	A B	2.6 2.6	2.6	2.0 2.3	6.6	2	26900 26900	53460	26730	86800 86800	86200	- -	FP/SS FP
5-8-180-2#3-i-2.5-2-7	A B	2.5 2.5	2.5	2.3 2.1	6.4	2	34600 28700	58460	29230	111600 92600	94300	- 0.369(0.081)	FP/SS FP/SS
5-8-180-2#3-i-3.5-2-7	A B	3.4 3.5	3.4	2.4 2.3	7.0	2	29300 32600	61860	30930	94500 105200	99800	- 0.329(0.028)	FP/SS FP

† Specimens had constant 80 kip axial load
*No failure; equipment malfunction

Table A.3 Cont.–Test results for specimens used in bend angle analysis

Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi	Long. Reinf. Layout°
5-5-90-0-i-2.5-2-7	A B	60	-	-	-	-	0.80	4	2.5	0.500	3.50	-	-	1.27	60	A1
5-8-90-0-i-2.5-2-6†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60	A1
5-8-90-0-i-2.5-2-6(1)	A B	60	-	-	-	-	0.66	6	3.0	0.500	3.00	-	-	1.27	60	A1
5-15-90-0-i-2.5-2-7.5	A B	60	-	-	-	-	-	-	-	0.375	3.50	-	-	3.16	60	A2
5-5-90-0-i-3.5-2-7	A B	60	-	-	-	-	0.80	4	2.5	0.375	3.50	-	-	1.27	60	A1
5-8-90-0-i-3.5-2-6†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60	A1
5-8-90-0-i-3.5-2-6(1)	A B	60	-	-	-	-	0.66	6	3.0	0.500	3.00	-	-	1.27	60	A1
5-8-90-0-i-3.5-2-8†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60	A1
5-8-180-0-i-2.5-2-7	A B	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60	A1
5-8-180-0-i-3.5-2-7	A B	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60	A1
5-5-90-2#3-i-2.5-2-8†	A B	60	0.38	0.2	2	4.00	-	-	-	0.375	4.00	-	-	1.27	60	A1
5-5-90-2#3-i-2.5-2-6†	A B	60	0.38	0.2	2	4.00	-	-	-	0.375	4.00	-	-	1.27	60	A1
5-8-90-2#3-i-2.5-2-6†	A B	60	0.38	0.2	2	4.00	-	-	-	0.500	4.00	-	-	1.27	60	A1
5-8-90-2#3-i-2.5-2-8†	A B	60	0.38	0.2	2	4.00	-	-	-	0.500	4.00	-	-	1.67	60	A5
5-12-90-2#3-i-2.5-2-5	A B	60	0.38	0.2	2	3.30	0.33	3	3.3	0.500	3.00	-	-	1.27	60	A1
5-15-90-2#3-i-2.5-2-6	A B	60	0.38	0.2	2	3.00	-	-	-	0.375	2.75	-	-	3.16	60	A2
5-5-90-2#3-i-3.5-2-6	A B	60	0.38	0.2	2	3.50	0.11	1	3.5	0.375	3.50	-	-	1.27	60	A1
5-5-90-2#3-i-3.5-2-8	A B	60	0.38	0.2	2	3.50	-	-	-	0.375	4.00	-	-	1.27	60	A1
5-8-90-2#3-i-3.5-2-6†	A B	60	0.38	0.2	2	4.00	-	-	-	0.500	4.00	-	-	1.27	60	A1
5-8-90-2#3-i-3.5-2-8†	A B	60	0.38	0.2	2	4.00	-	-	-	0.500	4.00	-	-	1.67	60	A5
5-5-180-2#3-i-2.5-2-8†	A B	60	0.38	0.2	2	2.50	-	-	-	0.375	4.00	-	-	1.27	60	A1
5-5-180-2#3-i-2.5-2-6†	A B	60	0.38	0.2	2	2.50	-	-	-	0.375	4.00	-	-	1.27	60	A1
5-8-180-2#3-i-2.5-2-7	A B	60	0.38	0.2	2	2.00	-	-	-	0.375	3.00	-	-	1.27	60	A1
5-8-180-2#3-i-3.5-2-7	A B	60	0.38	0.2	2	2.00	-	-	-	0.375	3.00	-	-	1.27	60	A5

† Specimens had constant 80 kip axial load

° Longitudinal column configurations shown in Appendix A, Layouts A1 – A14

Table A.3 Cont.–Test results for specimens used in bend angle analysis

Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
8-5-90-0-i-2.5-2-9.5†	A B	90°	Horizontal	A615	9.0 10.3	9.6	5140	8	1	0.078	17	10.5	8.375
8-5-90-0-i-2.5-2-12.5†	A B	90°	Horizontal	A615	13.3 13.3	13.3	5240	9	1	0.078	17	10.5	8.375
8-5-90-0-i-2.5-2-13	A B	90°	Horizontal	A1035[b]	13.3 13.5	13.4	5560	11	1	0.078	17	10.5	8.375
8-8-90-0-i-2.5-2-10	A B	90°	Horizontal	A1035[b]	9.8 9.5	9.6	7700	14	1	0.078	17	10.5	8.375
8-12-90-0-i-2.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	17	10.5	8.375
8-12-90-0-i-2.5-2-12.5	A B	90°	Horizontal	A1035[c]	12.9 12.8	12.8	11850	39	1	0.073	17	10.5	8.375
8-12-90-0-i-2.5-2-12	A B	90°	Horizontal	A1035[c]	12.1 12.1	12.1	11760	34	1	0.073	17	10.5	8.375
8-15-90-0-i-2.5-2-13	A B	90°	Horizontal	A1035[c]	12.8 12.8	12.8	15800	61	1	0.073	17	10.5	8.375
8-5-90-0-i-3.5-2-13	A B	90°	Horizontal	A1035[b]	13.4 13.4	13.4	5560	11	1	0.078	19	10.5	8.375
8-8-90-0-i-3.5-2-10	A B	90°	Horizontal	A1035[b]	8.8 10.8	9.8	7700	14	1	0.078	19	10.5	8.375
8-12-90-0-i-3.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	19	10.5	8.375
8-5-180-0-i-2.5-2-11†	A B	180°	Horizontal	A615	11.0 11.0	11.0	4550	7	1	0.078	17	10.5	8.375
8-5-180-0-i-2.5-2-14†	A B	180°	Horizontal	A1035[b]	14.0 14.0	14.0	4840	8	1	0.078	17	10.5	8.375
8-8-180-0-i-2.5-2-11.5	A B	180°	Horizontal	A1035[b]	9.3 9.3	9.3	8630	11	1	0.078	17	10.5	8.375
8-12-180-0-i-2.5-2-12.5	A B	180°	Horizontal	A1035[c]	12.8 12.5	12.6	11850	39	1	0.073	17	10.5	8.375
8-5-180-0-i-3.5-2-11†	A B	180°	Horizontal	A615	11.6 11.6	11.6	4550	7	1	0.078	17	10.5	8.375
8-5-180-0-i-3.5-2-14†	A B	180°	Horizontal	A1035[b]	14.4 13.9	14.1	4840	8	1	0.078	17	10.5	8.375
8-15-180-0-i-2.5-2-13.5	A B	180°	Horizontal	A1035[c]	13.8 13.5	13.6	16510	88	1	0.073	17	10.5	8.375
8-5-90-2#3-i-2.5-2-12.5†	A B	90°	Horizontal	A615	12.0 12.0	12.0	5240	9	1	0.078	17	10.5	8.375
8-5-90-2#3-i-2.5-2-14	A B	90°	Horizontal	A1035[c]	13.5 14.0	13.8	5450	7	1	0.073	17	10.5	8.375
8-12-90-2#3-i-2.5-2-11	A B	90°	Horizontal	A1035[c]	10.5 11.3	10.9	12010	42	1	0.073	17	10.5	8.375
8-15-90-2#3-i-2.5-2-11	A B	90°	Horizontal	A1035[c]	11.3 10.8	11.0	15800	61	1	0.073	17	10.5	8.375
8-5-90-2#3-i-3.5-2-13	A B	90°	Horizontal	A1035[b]	13.8 13.5	13.6	5560	11	1	0.078	19	10.5	8.375
8-5-180-2#3-i-2.5-2-11†	A B	180°	Horizontal	A615	10.8 10.5	10.6	4550	7	1	0.078	17	10.5	8.375
8-5-180-2#3-i-2.5-2-14†	A B	180°	Horizontal	A1035[b]	13.5 14.0	13.8	4870	9	1	0.078	17	10.5	8.375

† Specimens had constant 80 kip axial load

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

Table A.3 Cont.–Test results for specimens used in bend angle analysis

Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	f_{su} psi	$f_{su,avg}$ psi	Lead Slip (Tail Slip) at Failure in.	Failure Type
8-5-90-0-i-2.5-2-9.5†	A	2.8	2.6	3.0	9.5	2	44600	88970	44485	56500	56300	-	FP
	B	2.5		1.8			65800			83300		-	SS
8-5-90-0-i-2.5-2-12.5†	A	2.8	2.8	1.3	9.8	2	65300	131640	65820	82700	83300	-	SS/B
	B	2.8		1.3			69900			88500		-	SS
8-5-90-0-i-2.5-2-13	A	2.5	2.5	2.0	9.8	2	73100	131080	65540	92500	83000	-	SS
	B	2.5		1.8			65200			82500		-	FP/SS
8-8-90-0-i-2.5-2-10	A	2.8	2.8	2.3	9.0	2	50000	102910	51455	63300	65100	0.195	FP
	B	2.9		2.5			52900			67000		0.185	FP
8-12-90-0-i-2.5-2-9	A	2.8	2.7	2.4	9.6	2	50800	99850	49925	64300	63200	0.219	FP/SS
	B	2.6		2.4			54800			69400			SS/FP
8-12-90-0-i-2.5-2-12.5	A	2.6	2.6	1.7	10.1	2	66000	133900	66950	83500	84700	0.295	FB/SB
	B	2.6		1.8			77400			98000		0.266	FB/SB
8-12-90-0-i-2.5-2-12	A	2.5	2.5	1.9	9.8	2	70700	131800	65900	89500	83400	-	SB/FP
	B	2.4		1.9			65800			83300		0.0119	FB/SS
8-15-90-0-i-2.5-2-13	A	2.4	2.4	2.1	9.9	2	77200	156200	78100	97700	98900	-	FB/SB
	B	2.5		2.0			79000			100000		-	FB
8-5-90-0-i-3.5-2-13	A	3.6	3.5	1.9	9.4	2	69400	136200	68100	87800	86200	-	FP/SS
	B	3.4		1.9			68300			86500		-	SS/FP
8-8-90-0-i-3.5-2-10	A	3.8	3.8	3.3	9.0	2	55200	111130	55565	69900	70300	0.195	FP/SS
	B	3.8		1.3			71900			91000		0.242	SS/FP
8-12-90-0-i-3.5-2-9	A	3.5	3.6	2.4	9.8	2	61400	120480	60240	77700	76300	-	FP
	B	3.8		2.1			68500			86700		0.434	FP/SS
8-5-180-0-i-2.5-2-11†	A	3.0	2.9	2.0	9.8	2	45600	92290	46145	57700	58400	0.275	SS/FP
	B	2.8		2.0			50500			63900		-	SS
8-5-180-0-i-2.5-2-14†	A	2.8	2.7	2.0	9.8	2	49400	98300	49150	62500	62200	0.088	SS
	B	2.6		2.0			69400			87800		0.096	SS
8-8-180-0-i-2.5-2-11.5	A	3.0	3.0	4.5	9.5	2	62800	125600	62800	79500	79500	-	FP/SB
	B	3.0		4.5			80200			101500		-	FP/SS
8-12-180-0-i-2.5-2-12.5	A	3.0	2.8	2.1	9.6	2	74800	150400	75200	94700	95200	0.193	FB/SB
	B	2.5		2.4			92300			116800		0.242	FP
8-5-180-0-i-3.5-2-11†	A	3.8	3.8	1.4	10.0	2	58600	118580	59290	74200	75100	0.372	FP/SS
	B	3.8		1.4			60500			76600		0.239	SS
8-5-180-0-i-3.5-2-14†	A	3.9	3.8	1.6	9.8	2	63700	127010	63505	80600	80400	-	SS
	B	3.8		2.1			78000			98700		-	FB/SS
8-15-180-0-i-2.5-2-13.5	A	2.5	2.5	2.0	10.0	2	90700	179800	89900	114800	113800	-	-
	B	2.5		2.3			89100			112800		-	FB/SB
8-5-90-2#3-i-2.5-2-12.5†	A	2.8	2.8	2.6	9.5	2	74100	144130	72065	93800	91200	-	FP
	B	2.8		2.6			76300			96600		-	FP/SS
8-5-90-2#3-i-2.5-2-14	A	2.8	2.9	2.6	9.3	2	77000	153930	76965	97500	97400	-	SS/FP
	B	3.0		2.1			77500			98100		-	FP/SS
8-12-90-2#3-i-2.5-2-11	A	2.8	2.8	2.4	9.5	2	68100	137400	68700	86200	87000	0.181	FP
	B	2.8		1.6			79800			101000		0.165	FP
8-15-90-2#3-i-2.5-2-11	A	2.5	2.5	1.9	10.0	2	99000	166600	83300	125300	105400	-	FB
	B	2.5		2.4			83600			105800		0.123	FB
8-5-90-2#3-i-3.5-2-13	A	3.1	3.4	1.5	10.3	2	81200	160720	80360	102800	101700	-	SS/FP
	B	3.6		1.8			86900			110000		-	SS/FP
8-5-180-2#3-i-2.5-2-11†	A	2.8	2.6	2.3	9.5	2	64200	120470	60235	81300	76200	0.260	SS/FP
	B	2.5		2.5			61900			78400		0.087	SS/FP
8-5-180-2#3-i-2.5-2-14†	A	2.8	2.8	2.5	9.8	2	87100	152560	76280	110300	96600	0.774	FP
	B	2.8		2.0			76900			97300		0.199	FP/SS

† Specimens had constant 80 kip axial load

Table A.3 Cont.–Test results for specimens used in bend angle analysis

Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} 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_s ksi	Long. Reinf. Layout°
8-5-90-0-i-2.5-2-9.5†	A B	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60	A2
8-5-90-0-i-2.5-2-12.5†	A B	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60	A2
8-5-90-0-i-2.5-2-13	A B	60	-	-	-	-	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60	A2
8-8-90-0-i-2.5-2-10	A B	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60	A2
8-12-90-0-i-2.5-2-9	A B	60	-	-	-	-	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60	A2
8-12-90-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60	A2
8-12-90-0-i-2.5-2-12	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.16	60	A2
8-15-90-0-i-2.5-2-13	A B	60	-	-	-	-	-	-	-	0.38	5.00	-	-	4.74	60	A7
8-5-90-0-i-3.5-2-13	A B	60	-	-	-	-	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60	A2
8-8-90-0-i-3.5-2-10	A B	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60	A2
8-12-90-0-i-3.5-2-9	A B	60	-	-	-	-	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60	A2
8-5-180-0-i-2.5-2-11†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60	A2
8-5-180-0-i-2.5-2-14†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60	A2
8-8-180-0-i-2.5-2-11.5	A B	60	-	-	-	-	0.44	4	3.0	0.50	3.00	-	-	3.16	60	A2
8-12-180-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60	A2
8-5-180-0-i-3.5-2-11†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60	A2
8-5-180-0-i-3.5-2-14†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60	A2
8-15-180-0-i-2.5-2-13.5	A B	60	-	-	-	-	-	-	-	0.50	4.00	-	-	4.74	60	A7
8-5-90-2#3-i-2.5-2-12.5†	A B	60	0.38	0.2	2	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60	A2
8-5-90-2#3-i-2.5-2-14	A B	60	0.38	0.2	2	6.00	0.88	8	3.0	0.50	3.50	0.5	1	3.16	60	A2
8-12-90-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	2.00	-	-	3.16	60	A2
8-15-90-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	5.50	-	-	-	0.38	4.00	-	-	6.32	60	A11
8-5-90-2#3-i-3.5-2-13	A B	60	0.38	0.2	2	8.00	0.44	4	4.0	0.50	3.00	-	-	3.16	60	A2
8-5-180-2#3-i-2.5-2-11†	A B	60	0.38	0.2	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60	A2
8-5-180-2#3-i-2.5-2-14†	A B	60	0.38	0.2	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60	A2

† Specimens had constant 80 kip axial load

° Longitudinal column configurations shown in Layouts A1 – A14

Table A.3 Cont.–Test results for specimens used in bend angle analysis

Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
8-8-180-2#3-i-2.5-2-11.5	A B	180°	Horizontal	A1035[b]	10.5 10.3	10.4	8810	14	1	0.078	17	10.5	8.375
8-12-180-2#3-i-2.5-2-11	A B	180°	Horizontal	A1035[c]	11.1 10.4	10.8	12010	42	1	0.073	17	10.5	8.375
8-5-180-2#3-i-3.5-2-11[†]	A B	180°	Horizontal	A1035[b]	10.1 10.6	10.4	4300	6	1	0.078	17	10.5	8.375
8-5-180-2#3-i-3.5-2-14[†]	A B	180°	Horizontal	A1035[b]	13.5 13.6	13.6	4870	9	1	0.078	17	10.5	8.375
8-15-180-2#3-i-2.5-2-11	A B	180°	Horizontal	A1035[b]	11.1 11.1	11.1	15550	87	1	0.073	17	10.5	8.375
8-5-90-5#3-i-2.5-2-10b[†]	A B	90°	Horizontal	A1035[a]	10.3 10.5	10.4	5440	8	1	0.084	17	10.5	8.375
8-5-90-5#3-i-2.5-2-10c[†]	A B	90°	Horizontal	A1035[a]	10.5 10.5	10.5	5650	9	1	0.084	17	10.5	8.375
8-5-90-5#3-i-2.5-2-10a[†]	B	90°	Horizontal	A1035[a]	10.5	10.5	5270	7	1	0.08	17	10.5	8.375
8-12-90-5#3-i-2.5-2-10	A B	90°	Horizontal	A1035[c]	9.0 9.9	9.4	11800	38	1	0.073	17	10.5	8.375
8-15-90-5#3-i-2.5-2-10	A B	90°	Horizontal	A1035[c]	10.6 9.7	10.1	15800	60	1	0.073	17	10.5	8.375
8-12-180-5#3-i-2.5-2-10	A B	180°	Horizontal	A1035[c]	9.9 9.6	9.8	11800	38	1	0.073	17	10.5	8.375
8-15-180-5#3-i-2.5-2-9.5	A B	180°	Horizontal	A1035[c]	9.6 9.8	9.7	15550	87	1	0.073	17	10.5	8.375
11-5-90-0-i-2.5-2-14	A B	90°	Horizontal	A615	13.5 15.3	14.4	4910	13	1.41	0.069	21.5	19.5	8.375
11-8-90-0-i-2.5-2-17	A B	90°	Horizontal	A1035	17.3 18.0	17.6	9460	9	1.41	0.085	21.5	19.5	8.375
11-8-90-0-i-2.5-2-21	A B	90°	Horizontal	A1035	20.0 21.1	20.6	7870	6	1.41	0.085	21.5	19.5	8.375
11-8-90-0-i-2.5-2-17	A B	90°	Horizontal	A1035	16.3 18.1	17.2	8520	7	1.41	0.085	21.5	19.5	8.375
11-12-90-0-i-2.5-2-17	A B	90°	Horizontal	A1035	16.1 16.9	16.5	11880	35	1.41	0.085	21.5	19.5	8.375
11-12-90-0-i-2.5-2-17.5	A B	90°	Horizontal	A1035	17.6 17.8	17.7	13330	31	1.41	0.085	21.5	19.5	8.375
11-5-90-0-i-3.5-2-17	A B	90°	Horizontal	A1035	18.1 17.6	17.9	5600	24	1.41	0.085	23.5	19.5	8.375
11-5-90-0-i-3.5-2-14	A B	90°	Horizontal	A615	14.8 15.3	15.0	4910	13	1.41	0.069	23.5	19.5	8.375
11-8-180-0-i-2.5-2-21	A B	180°	Horizontal	A1035	21.3 20.9	21.1	7870	6	1.41	0.085	21.5	19.5	8.375
11-8-180-0-i-2.5-2-17	A B	180°	Horizontal	A1035	17.8 18.0	17.9	8520	7	1.41	0.085	21.5	19.5	8.375

[†] Specimens had constant 80 kip axial load

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

Table A.3 Cont.–Test results for specimens used in bend angle analysis

Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	f_{su} psi	$f_{su,avg}$ psi	Lead Slip (Tail Slip) at Failure in.	Failure Type
8-8-180-2#3-i-2.5-2-11.5	A B	2.8 2.8	2.8	2.3 2.5	10.0	2	70100 59500	116340	58170	88700 75300	73600	0.261 0.250(0.027)	FB/SS FP/SS
8-12-180-2#3-i-2.5-2-11	A B	2.5 2.6	2.6	2.1 2.8	9.6	2	73700 66200	129300	64650	93300 83800	81800	- -	FP FB
8-5-180-2#3-i-3.5-2-11†	A B	3.4 3.5	3.4	2.9 2.4	9.8	2	57200 54900	111740	55870	72400 69500	70700	0.167 0.212	SS/FP SS/FP
8-5-180-2#3-i-3.5-2-14†	A B	3.6 3.8	3.7	2.5 2.4	9.8	2	68300 90400	126930	63465	86500 114400	80300	- -	FP/SS FP/SS
8-15-180-2#3-i-2.5-2-11	A B	2.8 2.8	2.8	2.1 2.0	9.8	2	79600 78300	157800	78900	100800 99100	99900	- -	FB/SS FP
8-5-90-5#3-i-2.5-2-10b†	A B	2.8 2.6	2.7	2.0 1.8	9.9	2	78800 66700	139430	69715	99700 84400	88200	0.129 -	FP/SS FP
8-5-90-5#3-i-2.5-2-10c†	A B	2.5 2.5	2.5	2.0 2.0	10.0	2	68900 69600	137670	68835	87200 88100	87100	- -	FP/SS FP/SS
8-5-90-5#3-i-2.5-2-10a†	B	2.5	2.5	1.8	9.8	2	82800	82800	82800	104800	104800	0.164	FP/SS
8-12-90-5#3-i-2.5-2-10	A B	2.6 2.3	2.4	3.2 2.3	9.9	2	66000 64600	129100	64550	83500 81800	81700	0.440 0.547	FB/SS SS/FP
8-15-90-5#3-i-2.5-2-10	A B	2.4 2.4	2.4	1.6 2.4	9.9	2	111600 90200	180000	90000	141300 114200	113900	- 0.407	FB/SS FB/SS
8-12-180-5#3-i-2.5-2-10	A B	2.3 2.8	2.5	2.3 2.6	9.9	2	63000 81400	128200	64100	79700 103000	81100	- 0.339	FP/SS FP
8-15-180-5#3-i-2.5-2-9.5	A B	2.5 2.8	2.6	2.1 1.9	10.0	2	86000 86000	171900	86000	108900 108900	108900	- -	SS FP/SS
11-5-90-0-i-2.5-2-14	A B	2.8 2.8	2.8	2.5 0.8	13.3	2	67200 81400	133180	66590	43100 52200	42700	0.139 -	FP/SS SS
11-8-90-0-i-2.5-2-17	A B	2.5 2.5	2.5	2.0 1.3	13.4	2	132000 141200	264100	132100	84600 90500	84700	- -	FP/TK FB/TK
11-8-90-0-i-2.5-2-21	A B	2.5 2.8	2.6	3.4 2.3	13.0	2	127060 147900	250250	125120	81400 94800	80200	- -	FP/TK FB
11-8-90-0-i-2.5-2-17	A B	2.5 2.5	2.5	3.0 1.1	13.5	2	105630 115170	209560	104780	67700 73800	67200	- -	SS FP
11-12-90-0-i-2.5-2-17	A B	2.5 2.6	2.6	3.1 2.4	13.3	2	148400 120400	239400	119700	95100 77200	76700	- -	SB SB/FP
11-12-90-0-i-2.5-2-17.5	A B	3.8 2.5	3.1	2.1 2.0	13.8	2	123600 125600	249240	124620	79200 80500	79900	- 0.250	SS/TK SS
11-5-90-0-i-3.5-2-17	A B	4.0 3.9	3.9	1.8 2.5	13.1	2	105000 117600	216240	108120	67300 75400	69300	0.187 -	SS/TK SS
11-5-90-0-i-3.5-2-14	A B	3.8 3.9	3.8	1.5 1.0	13.3	2	82600 69000	139030	69515	52900 44200	44600	- -	FP/SS FP/SS/TK
11-8-180-0-i-2.5-2-21	A B	2.9 2.4	2.7	1.8 2.2	13.0	2	137800 126800	256250	128125	88300 81300	82100	- -	FB FB/SB
11-8-180-0-i-2.5-2-17	A B	2.4 2.5	2.4	1.4 1.1	13.8	2	101710 121270	200910	100450	65200 77700	64400	- -	FP FB

† Specimens had constant 80 kip axial load

Table A.3 Cont.–Test results for specimens used in bend angle analysis

Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} 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_s ksi	Long. Reinf. Layout
8-8-180-2#3-i-2.5-2-11.5	A B	60	0.38	0.2	2		-	-	-	0.50	3.00	-	-	3.16	60	A2
8-12-180-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	2.00	-	-	3.16	60	A2
8-5-180-2#3-i-3.5-2-11†	A B	60	0.38	0.2	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60	A2
8-5-180-2#3-i-3.5-2-14†	A B	60	0.38	0.2	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60	A2
8-15-180-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	5.00	-	-	-	0.50	4.00	-	-	4.74	60	A7
8-5-90-5#3-i-2.5-2-10b†	A B	60	0.38	0.6	5	3.00	1.10	10	3.0	0.63	5.00	-	-	3.16	60	A2
8-5-90-5#3-i-2.5-2-10c†	A B	60	0.38	0.6	5	3.00	1.10	10	3.0	0.63	5.00	-	-	3.16	60	A2
8-5-90-5#3-i-2.5-2-10a†	B	60	0.375	0.55	5	3.0	1.10	10	3.0	0.63	3.50	-	-	3.16	60	A2
8-12-90-5#3-i-2.5-2-10	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-15-90-5#3-i-2.5-2-10	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	3.00	-	-	6.32	60	A11
8-12-180-5#3-i-2.5-2-10	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-15-180-5#3-i-2.5-2-9.5	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	4.00	-	-	6.32	60	A10
11-5-90-0-i-2.5-2-14	A B	60	-	-	-	-	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60	A7
11-8-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.48	60	A14
11-8-90-0-i-2.5-2-21	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60	A13
11-8-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60	A8
11-12-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60	A13
11-12-90-0-i-2.5-2-17.5	A B	60	-	-	-	-	2.4	12	4.0	0.50	4.0	-	-	4.74	60	A7
11-5-90-0-i-3.5-2-17	A B	60	-	-	-	-	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60	A7
11-5-90-0-i-3.5-2-14	A B	60	-	-	-	-	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60	A7
11-8-180-0-i-2.5-2-21	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60	A13
11-8-180-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60	A8

† Specimens had constant 80 kip axial load

º Longitudinal column configurations shown in, Layouts A1 – A14

Table A.3 Cont.–Test results for specimens used in bend angle analysis

Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
11-12-180-0-i-2.5-2-17	A B	180°	Horizontal	A1035	16.6 16.6	16.6	11880	35	1.41	0.085	21.5	19.5	8.375
11-5-90-6#3-i-2.5-2-20	A B	90°	Horizontal	A1035	19.5 19.0	19.3	5420	7	1.41	0.085	21.5	19.5	8.375
11-8-90-6#3-i-2.5-2-16	A B	90°	Horizontal	A1035	15.5 16.4	15.9	9120	7	1.41	0.085	21.5	19.5	8.375
11-8-90-6#3-i-2.5-2-15	A B	90°	Horizontal	A1035	15.8 15.3	15.5	7500	5	1.41	0.085	21.5	19.5	8.375
11-8-90-6#3-i-2.5-2-19	A B	90°	Horizontal	A1035	19.1 19.4	19.2	7500	5	1.41	0.085	21.5	19.5	8.375
11-12-90-6#3-i-2.5-2-17	A B	90°	Horizontal	A1035	17.1 16.5	16.8	12370	37	1.41	0.085	21.5	19.5	8.375
11-12-90-6#3-i-2.5-2-16	A B	90°	Horizontal	A1035	14.8 16.0	15.4	13710	31	1.41	0.085	21.5	19.5	8.375
11-5-90-6#3-i-3.5-2-20	A B	90°	Horizontal	A1035	20.5 20.3	20.4	5420	7	1.41	0.085	23.5	19.5	8.375
11-8-180-6#3-i-2.5-2-15	A B	180°	Horizontal	A1035	15.1 15.5	15.3	7500	5	1.41	0.085	21.5	19.5	8.375
11-8-180-6#3-i-2.5-2-19	A B	180°	Horizontal	A1035	19.6 19.9	19.8	7870	6	1.41	0.085	21.5	19.5	8.375
11-12-180-6#3-i-2.5-2-17	A B	180°	Horizontal	A1035	16.9 16.5	16.7	12370	37	1.41	0.085	21.5	19.5	8.375
11-12-180-6#3-i-2.5-2-17	A B	180°	Horizontal	A1035	16.8 16.8	16.8	12370	37	1.41	0.085	21.5	19.5	8.375

Table A.3 Cont.–Test results for specimens used in bend angle analysis

Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	f_{su} psi	$f_{su,avg}$ psi	Slip at Failure in.	Failure Type
11-12-180-0-i-2.5-2-17	A B	3.0 2.5	2.8	2.5 2.5	13.3	2	106700 108200	214900	107500	68400 69400	68900	0.156 -	SB/FP SS
11-5-90-6#3-i-2.5-2-20	A B	2.6 2.6	2.6	2.8 3.3	12.9	2	153100 135000	272540	136270	98100 86500	87400	0.274 -	FP/SS FP/SS
11-8-90-6#3-i-2.5-2-16	A B	2.5 2.5	2.5	2.8 1.9	13.4	2	147500 129700	266000	133000	94600 83100	85300	- -	FP/SS FP/SS
11-8-90-6#3-i-2.5-2-15	A B	2.8 2.5	2.6	1.5 2.0	13.5	2	142300 108000	216600	108300	91200 69200	69400	- -	SS SS/FP
11-8-90-6#3-i-2.5-2-19	A B	2.5 2.6	2.6	2.0 1.7	13.5	2	182700 146100	290900	145400	117100 93700	93200	- -	FB/SS FB/SS
11-12-90-6#3-i-2.5-2-17	A B	2.6 3.0	2.8	1.9 2.6	13.0	2	179700 162300	323300	161600	115200 104000	103600	0.334 -	FB/SB SP/SS
11-12-90-6#3-i-2.5-2-16	A B	2.5 2.5	2.5	3.3 2.0	13.0	2	115100 127500	230390	115195	73800 81700	73800	- 0.952	SS/FP SB/FB
11-5-90-6#3-i-3.5-2-20	A B	3.8 3.9	3.8	1.8 2.0	13.1	2	150200 135300	271640	135820	96300 86700	87100	- -	SS/FP SS
11-8-180-6#3-i-2.5-2-15	A B	2.9 3.1	3.0	2.0 1.6	13.0	2	112400 111000	223400	111700	72100 71200	71600	- -	SS SS
11-8-180-6#3-i-2.5-2-19	A B	2.9 2.9	2.9	1.5 1.3	13.3	2	170000 149000	298000	149000	109000 95500	95500	- -	FB/SS FB/SS
11-12-180-6#3-i-2.5-2-17	A B	2.6 2.8	2.7	2.9 3.3	13.5	2	123100 117600	232700	116400	78900 75400	74600	- 0.379	FP FP/SB
11-12-180-6#3-i-2.5-2-17	A B	2.5 2.8	2.6	2.7 2.6	13.4	2	148900 173000	297400	148700	95400 110900	95300	- -	FP/SS SB/FB

Table A.3 Cont.–Test results for specimens used in bend angle analysis

Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} 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_s ksi	Long. Reinf. Layout
11-12-180-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60	A13
11-5-90-6#3-i-2.5-2-20	A B	60	0.38	0.7	6	4.00	1.2	6	4.0	0.50	4.0	0.375	2	4.74	60	A7
11-8-90-6#3-i-2.5-2-16	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.48	60	A14
11-8-90-6#3-i-2.5-2-15	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60	A13
11-8-90-6#3-i-2.5-2-19	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60	A13
11-12-90-6#3-i-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60	A13
11-12-90-6#3-i-2.5-2-16	A B	60	0.38	0.7	6	4.00	2.4	12	4.0	0.50	4.0	0.375	1	4.74	60	A7
11-5-90-6#3-i-3.5-2-20	A B	60	0.38	0.7	6	4.00	1.2	6	4.0	0.50	4.0	0.375	2	4.74	60	A7
11-8-180-6#3-i-2.5-2-15	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60	A13
11-8-180-6#3-i-2.5-2-19	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60	A13
11-12-180-6#3-i-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	3.0	-	-	4.74	60	A7
11-12-180-6#3-i-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60	A13

º Longitudinal column configurations shown in Layouts A1 – A14

Table A.4–Test results for specimens from previous studies used in bend angle analysis

	Specimen	Bend Angle	ℓ_{eh} in.	f_{cm} psi	f_y psi	d_b in.	b in.
Marques and Jirsa (1975)	J7-180-12-1-H	180°	10.0	4350	64000	0.88	12
	J7-180-15-1-H	180°	13.0	4000	64000	0.88	12
	J 7- 90 -12 -1 - H	90°	10.0	4150	64000	0.88	12
	J 7- 90 -15 -1 - H	90°	13.0	4600	64000	0.88	12
	J 7- 90 -15 -1 - L	90°	13.0	4800	64000	0.88	12
	J 7- 90 -15 -1 - M	90°	13.0	5050	64000	0.88	12
	J 11 - 180 -15 -1 - H	180°	13.1	4400	68000	1.41	12
	J 11- 90 -15 -1 - H	90°	13.1	4900	68000	1.41	12
	J 11- 90 -15 -1 - L	90°	13.1	4750	68000	1.41	12
Pinc et al. (1977)	11-15	90°	13.1	5400	60000	1.41	12
	11-18	90°	16.1	4700	60000	1.41	12
	11-21	90°	19.1	5200	60000	1.41	12
Hamad et al. (1993)	7-90-U	90°	10.0	2570	60000[a]	0.88	12
	7-90-U'	90°	10.0	5400	60000[a]	0.88	12
	11-90-U	90°	13.0	2570	60000[a]	1.41	12
	11-90-U'	90°	13.0	5400	60000[a]	1.41	12
	11-180-U-HS	180°	13.0	7200	60000[a]	1.41	12
	11-90-U-HS	90°	13.0	7200	60000[a]	1.41	12
Ramirez & Russel (2008)	I-2'	90°	15.5	9540	63100	1.41	15
Lee & Park (2010)	H2	90°	11.9	8270	87000	0.88	14.6

[a]Nominal value

Table A.4 Cont.–Test results for specimens from previous studies used in bend angle analysis

Specimen	h_{cl} in.	h_c in.	c_{so} in.	c_{th} in.	c_h in.	N_h	A_h in.^{2}	T lb
J7-180-12-1-H	11.6	6	2.88	2.0	4.5	2	0.60	36600
J7-180-15-1-H	11.6	6	2.88	2.0	4.5	2	0.60	52200
J 7- 90 -12 -1 - H	11.6	6	2.88	2.0	4.5	2	0.60	37200
J 7- 90 -15 -1 - H	11.6	6	2.88	2.0	4.5	2	0.60	54600
J 7- 90 -15 -1 - L	11.6	6	2.88	2.0	4.5	2	0.60	58200
J 7- 90 -15 -1 - M	11.6	6	2.88	2.0	4.5	2	0.60	60000
J 11 - 180 -15 -1 - H	11.3	6	2.88	1.5	3.4	2	1.56	70200
J 11- 90 -15 -1 - H	11.3	6	2.88	1.5	3.4	2	1.56	74880
J 11- 90 -15 -1 - L	11.3	6	2.88	1.5	3.4	2	1.56	81120
11-15	*	*	2.88	1.95	3.4	2	1.56	78000
11-18	*	*	2.88	1.95	3.4	2	1.56	90480
11-21	*	*	2.88	1.95	3.4	2	1.56	113880
7-90-U	11	6	3	2	4.25	2	0.60	25998
7-90-U'	11	6	3	2	4.25	2	0.60	36732
11-90-U	11	6	3	2	3.18	2	1.56	48048
11-90-U'	11	6	3	2	3.18	2	1.56	75005
11-180-U-HS	11	6	3	2	3.18	2	1.56	58843
11-90-U-HS	11	6	3	2	3.18	2	1.56	73788
I-2'	12	6	2.5	2.5	7	2	1.56	105000
H2	*	*	3	2	7	2	0.60	76992

*Not specified

Table A.5–Test results for specimens used in side cover analysis

Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	*Age* days	d_b in.	R_r	*b* in.	h_{cl} in.	h_c in.
5-5-90-0-i-2.5-2-10	A B	90°	Horizontal	A1035	9.4 9.4	9.4	5230	6	0.625	0.073	13	5.25	8.375
5-5-90-0-i-2.5-2-7	A B	90°	Horizontal	A1035	6.9 7.0	6.9	5190	7	0.625	0.073	13	5.25	8.375
5-8-90-0-i-2.5-2-6†	A B	90°	Horizontal	A615	6.8 6.8	6.8	8450	14	0.625	0.073	13	5.25	8.375
5-8-90-0-i-2.5-2-6(1)	A B	90°	Horizontal	A1035	6.1 6.5	6.3	9080	11	0.625	0.073	13	5.25	8.375
5-8-90-0-i-2.5-2-8†	A B	90°	Horizontal	A1035	8.0 7.5	7.8	8580	15	0.625	0.073	13	5.25	8.375
5-12-90-0-i-2.5-2-10	A B	90°	Horizontal	A1035	10.0 11.0	10.5	10290	14	0.625	0.073	13	5.25	8.375
5-12-90-0-i-2.5-2-5	A B	90°	Horizontal	A1035	5.1 4.8	4.9	11600	84	0.625	0.073	13	5.25	8.375
5-15-90-0-i-2.5-2-5.5	A B	90°	Horizontal	A1035	6.1 5.8	5.9	15800	62	0.625	0.073	13	5.25	8.375
5-15-90-0-i-2.5-2-7.5	A B	90°	Horizontal	A1035	7.3 7.3	7.3	15800	62	0.625	0.073	13	5.25	8.375
5-5-90-0-i-3.5-2-10	A B	90°	Horizontal	A1035	10.5 10.4	10.4	5190	7	0.625	0.073	15	5.25	8.375
5-5-90-0-i-3.5-2-7	A B	90°	Horizontal	A1035	7.5 7.6	7.6	5190	7	0.625	0.073	15	5.25	8.375
5-8-90-0-i-3.5-2-6†	A B	90°	Horizontal	A615	6.3 6.4	6.3	8580	15	0.625	0.073	15	5.38	8.375
5-8-90-0-i-3.5-2-6(1)	A B	90°	Horizontal	A1035	6.5 6.6	6.6	9300	13	0.625	0.073	15	5.25	8.375
5-8-90-0-i-3.5-2-8†	A B	90°	Horizontal	A1035	8.6 8.5	8.6	8380	13	0.625	0.060	15	5.25	8.375
5-12-90-0-i-3.5-2-5	A B	90°	Horizontal	A1035	5.5 5.4	5.4	10410	15	0.625	0.073	15	5.25	8.375
5-8-180-0-i-2.5-2-7	A B	180°	Horizontal	A1035	7.4 7.1	7.3	9080	11	0.625	0.073	13	5.25	8.375
5-8-180-0-i-3.5-2-7	A B	180°	Horizontal	A1035	7.4 7.3	7.3	9080	11	0.625	0.073	15	5.25	8.375
5-5-90-2#3-i-2.5-2-8†	A B	90°	Horizontal	A1035	8.0 7.5	7.8	5860	8	0.625	0.073	13	5.38	8.375
5-5-90-2#3-i-2.5-2-6†	A B	90°	Horizontal	A615	6.0 5.8	5.9	5800	9	0.625	0.060	13	5.25	8.375
5-8-90-2#3-i-2.5-2-6†	A B	90°	Horizontal	A1035	6.0 6.0	6.0	8580	15	0.625	0.073	13	5.25	8.375
5-8-90-2#3-i-2.5-2-8†	A B	90°	Horizontal	A1035	8.3 8.5	8.4	8380	13	0.625	0.073	13	5.25	8.375
5-12-90-2#3-i-2.5-2-5	A B	90°	Horizontal	A1035	5.8 5.8	5.8	11090	83	0.625	0.073	13	5.25	8.375
5-15-90-2#3-i-2.5-2-6	A B	90°	Horizontal	A1035	6.3 6.5	6.4	15800	61	0.625	0.073	13	5.25	8.375
5-15-90-2#3-i-2.5-2-4	A B	90°	Horizontal	A1035	3.5 4.0	3.8	15800	61	0.625	0.073	13	5.25	8.375
5-5-90-2#3-i-3.5-2-6	A B	90°	Horizontal	A1035	6.0 5.8	5.9	5230	6	0.625	0.073	15	5.25	8.375

† Specimens had constant 80 kip axial load

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	f_{su} psi	$f_{su,avg}$ psi	Lead Slip (Tail Slip) at Failure in.	Failure Type
5-5-90-0-i-2.5-2-10	A B	2.8 2.6	2.7	2.9 2.9	6.4	2	37400 32900	67170	33585	120600 106100	108300	- -	FP/SS FP/SS
5-5-90-0-i-2.5-2-7	A B	2.5 2.5	2.5	2.8 2.6	6.8	2	26600 26100	52530	26265	85800 84200	84700	- 0.192	FP/SS FP/SS
5-8-90-0-i-2.5-2-6†	A B	2.8 2.6	2.7	1.3 1.3	6.4	2	27600 32100	59140	29570	89000 103500	95400	- -	FB/SB SB/FB
5-8-90-0-i-2.5-2-6(1)	A B	2.5 2.5	2.5	2.6 2.3	7.0	2	21700 25000	44850	22425	70000 80600	72300	0.296 0.330(0.030)	FP FP
5-8-90-0-i-2.5-2-8†	A B	2.5 2.8	2.6	2.0 2.5	6.6	2	31900 35900	63350	31675	102900 115800	102200	- -	SS/FP SS/FP
5-12-90-0-i-2.5-2-10	A B	2.4 2.5	2.4	2.5 1.5	6.6	2	40800 42500	83310	41655	131600 137100	134400	0.191 -	SB FB/SB/TK
5-12-90-0-i-2.5-2-5	A B	2.6 2.6	2.6	2.1 2.5	6.5	2	19400 23170	38440	19220	62600 74700	62000	- -	FP/SS FP
5-15-90-0-i-2.5-2-5.5	A B	2.4 2.4	2.4	1.6 1.9	6.6	2	36200 32400	65000	32500	116800 104500	104800	- -	FP FB
5-15-90-0-i-2.5-2-7.5	A B	2.5 2.5	2.5	2.6 2.6	6.6	2	42000 42500	84400	42200	135500 137100	136100	- -	FB *
5-5-90-0-i-3.5-2-10	A B	3.5 3.5	3.5	1.8 1.9	6.5	2	43200 41100	83850	41925	139400 132600	135200	- -	SB/FP SB/FP
5-5-90-0-i-3.5-2-7	A B	3.4 3.5	3.4	1.3 1.1	7.0	2	27200 25900	53030	26515	87700 83500	85500	- -	SS FP/SS
5-8-90-0-i-3.5-2-6†	A B	3.6 3.5	3.6	1.8 1.6	6.6	2	25100 29100	50950	25475	81000 93900	82200	- -	FP/SS FP/SS
5-8-90-0-i-3.5-2-6(1)	A B	3.8 3.8	3.8	2.1 1.9	6.9	2	24400 27500	49080	24540	78700 88700	79200	0.152 0.178(0.150)	FP/SS FP/SS
5-8-90-0-i-3.5-2-8†	A B	3.6 3.5	3.6	1.4 1.5	7.1	2	39100 34300	65490	32745	126100 110600	105600	- -	FB/SS SS
5-12-90-0-i-3.5-2-5	A B	3.6 3.6	3.6	1.7 1.8	7.0	2	22000 23200	44240	22120	71000 74800	71400	- -	FP FP
5-8-180-0-i-2.5-2-7	A B	2.5 2.6	2.6	2.1 2.4	6.3	2	26700 35200	54220	27110	86100 113500	87500	0.194 0.146(0.016)	FP/SS SB/FP
5-8-180-0-i-3.5-2-7	A B	3.6 3.4	3.5	1.9 2.0	7.1	2	34100 31400	61510	30755	110000 101300	99200	0.251 0.237(0.021)	SS/FP FP/SS
5-5-90-2#3-i-2.5-2-8†	A B	2.5 2.5	2.5	2.0 2.5	6.6	2	37900 38900	74310	37155	122300 125500	119900	- -	SS/FP SS/FP
5-5-90-2#3-i-2.5-2-6†	A B	2.6 2.6	2.6	2.5 2.8	6.6	2	31800 29200	58890	29445	102600 94200	95000	- -	FP/SS FP/SS
5-8-90-2#3-i-2.5-2-6†	A B	2.8 2.9	2.8	2.0 2.0	6.1	2	33500 30900	61280	30640	108100 99700	98800	- -	FP/SS FP/SS
5-8-90-2#3-i-2.5-2-8†	A B	2.6 2.5	2.6	1.8 1.5	6.5	2	39800 40500	80340	40170	128400 130600	129600	- -	FP/SS FP/SS
5-12-90-2#3-i-2.5-2-5	A B	2.5 2.8	2.6	3.0 3.0	6.5	2	25200 29400	48700	24350	81300 94800	78500	- -	FP/SS FP
5-15-90-2#3-i-2.5-2-6	A B	2.4 2.4	2.4	1.9 1.7	6.6	2	42400 42900	85300	42600	136800 138400	137400	- -	FP FB
5-15-90-2#3-i-2.5-2-4	A B	2.5 2.5	2.5	2.6 2.1	6.8	2	18700 21300	37300	18700	60300 68700	60300	- -	FB FP
5-5-90-2#3-i-3.5-2-6	A B	3.4 3.4	3.4	2.3 2.5	6.5	2	21500 22400	42190	21095	69400 72300	68000	0.183 -	SS/FP SS/FP

† Specimens had constant 80 kip axial load

*No failure; equipment malfunction

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi	Long. Reinf. Layout[o]
5-5-90-0-i-2.5-2-10	A B	60	-	-	-	-	0.33	3	3.0	0.375	3.00	-	-	1.89	60	A4
5-5-90-0-i-2.5-2-7	A B	60	-	-	-	-	0.80	4	2.5	0.500	3.50	-	-	1.27	60	A1
5-8-90-0-i-2.5-2-6[†]	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60	A1
5-8-90-0-i-2.5-2-6(1)	A B	60	-	-	-	-	0.66	6	3.0	0.500	3.00	-	-	1.27	60	A1
5-8-90-0-i-2.5-2-8[†]	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60	A1
5-12-90-0-i-2.5-2-10	A B	60	-	-	-	-	0.11	1	7.0	0.375	5.00	-	-	1.89	60	A4
5-12-90-0-i-2.5-2-5	A B	60	-	-	-	-	0.66	6	2.5	0.500	3.00	-	-	1.27	60	A1
5-15-90-0-i-2.5-2-5.5	A B	60	-	-	-	-	-	-	-	0.375	2.50	-	-	1.27	60	A1
5-15-90-0-i-2.5-2-7.5	A B	60	-	-	-	-	-	-	-	0.375	3.50	-	-	3.16	60	A2
5-5-90-0-i-3.5-2-10	A B	60	-	-	-	-	0.33	3	3.0	0.375	3.00	-	-	1.89	60	A4
5-5-90-0-i-3.5-2-7	A B	60	-	-	-	-	0.80	4	2.5	0.375	3.50	-	-	1.27	60	A1
5-8-90-0-i-3.5-2-6[†]	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60	A1
5-8-90-0-i-3.5-2-6(1)	A B	60	-	-	-	-	0.66	6	3.0	0.500	3.00	-	-	1.27	60	A1
5-8-90-0-i-3.5-2-8[†]	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60	A1
5-12-90-0-i-3.5-2-5	A B	60	-	-	-	-	0.66	6	2.5	0.500	3.00	-	-	1.27	60	A1
5-8-180-0-i-2.5-2-7	A B	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60	A1
5-8-180-0-i-3.5-2-7	A B	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60	A1
5-5-90-2#3-i-2.5-2-8[†]	A B	60	0.38	0.2	2	4.00	-	-	-	0.375	4.00	-	-	1.27	60	A1
5-5-90-2#3-i-2.5-2-6[†]	A B	60	0.38	0.2	2	4.00	-	-	-	0.375	4.00	-	-	1.27	60	A1
5-8-90-2#3-i-2.5-2-6[†]	A B	60	0.38	0.2	2	4.00	-	-	-	0.500	4.00	-	-	1.27	60	A1
5-8-90-2#3-i-2.5-2-8[†]	A B	60	0.38	0.2	2	4.00	-	-	-	0.500	4.00	-	-	1.67	60	A5
5-12-90-2#3-i-2.5-2-5	A B	60	0.38	0.2	2	3.30	0.33	3	3.3	0.500	3.00	-	-	1.27	60	A1
5-15-90-2#3-i-2.5-2-6	A B	60	0.38	0.2	2	3.00	-	-	-	0.375	2.75	-	-	3.16	60	A2
5-15-90-2#3-i-2.5-2-4	A B	60	0.38	0.2	2	3.00	-	-	-	0.375	1.75	-	-	2.51	60	A9
5-5-90-2#3-i-3.5-2-6	A B	60	0.38	0.2	2	3.50	0.11	1	3.5	0.375	3.50	-	-	1.27	60	A1

[†] Specimens had constant 80 kip axial load

[o] Longitudinal column configurations shown in, Layouts A1 – A14

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	*Age* days	d_b in.	R_r	*b* in.	h_{cl} in.	h_c in.
5-5-90-2#3-i-3.5-2-8	A B	90°	Horizontal	A1035	7.9 7.5	7.7	5190	7	0.625	0.073	15	5.25	8.375
5-8-90-2#3-i-3.5-2-6†	A B	90°	Horizontal	A1035	6.5 6.0	6.3	8580	15	0.625	0.073	15	5.25	8.375
5-8-90-2#3-i-3.5-2-8†	A B	90°	Horizontal	A1035	7.1 7.0	7.1	8710	16	0.625	0.060	15	5.25	8.375
5-12-90-2#3-i-3.5-2-5	A B	90°	Horizontal	A1035	5.6 5.3	5.4	10410	15	0.625	0.073	15	5.25	8.375
5-5-180-2#3-i-2.5-2-8†	A B	180°	Horizontal	A1035	8.0 8.0	8.0	5670	7	0.625	0.073	13	5.25	8.375
5-5-180-2#3-i-2.5-2-6†	A B	180°	Horizontal	A615	5.8 5.5	5.6	5860	8	0.625	0.060	13	5.25	8.375
5-8-180-2#3-i-2.5-2-7	A B	180°	Horizontal	A1035	7.0 7.3	7.1	9080	11	0.625	0.073	13	5.25	8.375
5-8-180-2#3-i-3.5-2-7	A B	180°	Horizontal	A1035	6.8 6.9	6.8	9080	11	0.625	0.073	15	5.25	8.375
5-5-90-5#3-i-2.5-2-7	A B	90°	Horizontal	A1035	5.6 7.0	6.3	5230	6	0.625	0.073	13	5.25	8.375
5-12-90-5#3-i-2.5-2-5	A B	90°	Horizontal	A1035	5.1 5.8	5.4	10410	15	0.625	0.073	13	5.25	8.375
5-15-90-5#3-i-2.5-2-4	A B	90°	Horizontal	A1035	3.8 4.1	4.0	15800	62	0.625	0.073	13	5.25	8.375
5-15-90-5#3-i-2.5-2-5	A B	90°	Horizontal	A1035	5.0 5.1	5.1	15800	62	0.625	0.073	13	5.25	8.375
5-5-90-5#3-i-3.5-2-7	A B	90°	Horizontal	A1035	7.5 6.8	7.1	5190	7	0.625	0.073	15	5.25	8.375
5-12-90-5#3-i-3.5-2-5	A B	90°	Horizontal	A1035	5.3 4.8	5.0	11090	83	0.625	0.073	15	5.25	8.375
8-5-90-0-i-2.5-2-16†	A B	90°	Horizontal	A1035[b]	16.0 16.8	16.4	4980	7	1	0.078	17	10.5	8.375
8-5-90-0-i-2.5-2-9.5†	A B	90°	Horizontal	A615	9.0 10.3	9.6	5140	8	1	0.078	17	10.5	8.375
8-5-90-0-i-2.5-2-12.5†	A B	90°	Horizontal	A615	13.3 13.3	13.3	5240	9	1	0.078	17	10.5	8.375
8-5-90-0-i-2.5-2-18	A B	90°	Horizontal	A1035[b]	19.5 17.9	18.7	5380	11	1	0.078	17	10.5	8.375
8-5-90-0-i-2.5-2-13	A B	90°	Horizontal	A1035[b]	13.3 13.5	13.4	5560	11	1	0.078	17	10.5	8.375
8-5-90-0-i-2.5-2-15(1)	A B	90°	Horizontal	A1035[b]	14.5 15.3	14.9	5910	14	1	0.073	17	10.5	8.375
8-5-90-0-i-2.5-2-15	A B	90°	Horizontal	A1035[b]	15.3 14.4	14.8	6210	8	1	0.073	17	10.5	8.375
8-8-90-0-i-2.5-2-8	A B	90°	Horizontal	A1035[b]	8.9 8.0	8.4	7910	15	1	0.078	17	10.5	8.375
8-8-90-0-i-2.5-2-10	A B	90°	Horizontal	A1035[b]	9.8 9.5	9.6	7700	14	1	0.078	17	10.5	8.375
8-8-90-0-i-2.5-2-8(1)	A B	90°	Horizontal	A1035[b]	8.0 8.0	8.0	8780	13	1	0.078	17	10.5	8.375
8-8-90-0-i-2.5-2-9‡	A B	90°	Horizontal	A615	9.5 9.5	9.5	7710	25	1	0.073	17	10.5	8.375

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	f_{su} psi	$f_{su,avg}$ psi	Lead Slip (Tail Slip) at Failure in.	Failure Type
5-5-90-2#3-i-3.5-2-8	A	3.4	3.4	2.3	6.8	2	43700	45660	22830	141000	73600	-	FP
	B	3.5		2.8			45700			147400		-	FP
5-8-90-2#3-i-3.5-2-6†	A	3.5	3.6	1.5	6.4	2	29900	60070	30035	96500	96900	-	FP
	B	3.8		2.0			30100			97100		-	FP/SS
5-8-90-2#3-i-3.5-2-8†	A	3.5	3.5	2.9	6.6	2	38000	57310	28655	122600	92400	-	FP
	B	3.5		3.0			28600			92300		-	FP
5-12-90-2#3-i-3.5-2-5	A	3.8	3.6	1.8	6.6	2	27900	56730	28365	90000	91500	-	FP
	B	3.5		2.2			28900			93200		0.349	FP
5-5-180-2#3-i-2.5-2-8†	A	2.5	2.5	2.0	6.9	2	34000	68160	34080	109700	109900	-	FP/SS
	B	2.5		2.0			34500			111300		-	FP/SS
5-5-180-2#3-i-2.5-2-6†	A	2.6	2.6	2.0	6.6	2	26900	53460	26730	86800	86200	-	FP/SS
	B	2.6		2.3			26900			86800		-	FP
5-8-180-2#3-i-2.5-2-7	A	2.5	2.5	2.3	6.4	2	34600	58460	29230	111600	94300	-	FP/SS
	B	2.5		2.1			28700			92600		0.369(0.081)	FP/SS
5-8-180-2#3-i-3.5-2-7	A	3.4	3.4	2.4	7.0	2	29300	61860	30930	94500	99800	-	FP/SS
	B	3.5		2.3			32600			105200		0.329(0.028)	FP
5-5-90-5#3-i-2.5-2-7	A	2.8	2.8	3.6	6.5	2	32100	63390	31695	103500	102200	-	FP
	B	2.8		2.3			31300			101000		-	FP/SS
5-12-90-5#3-i-2.5-2-5	A	2.6	2.6	2.1	6.5	2	33900	68840	34420	109400	111000	0.292	FP/SS
	B	2.6		1.5			34900			112600		0.295	SS/FP
5-15-90-5#3-i-2.5-2-4	A	2.4	2.4	2.2	6.6	2	31300	62600	31360	101000	101200	0.603	FP
	B	2.5		1.9			31300			101000		0.378	FP
5-15-90-5#3-i-2.5-2-5	A	2.4	2.4	2.1	6.8	2	38600	78300	39200	124500	126500	-	FP
	B	2.3		1.9			46200			149000		-	BY
5-5-90-5#3-i-3.5-2-7	A	3.4	3.4	2.0	7.0	2	44300	72050	36025	142900	116200	-	FP
	B	3.5		2.8			35200			113500		-	FP
5-12-90-5#3-i-3.5-2-5	A	3.3	3.3	2.5	6.6	2	31500	60880	30440	101600	98200	-	FP
	B	3.3		1.5			31300			101000		-	FP
8-5-90-0-i-2.5-2-16†	A	2.8	2.8	1.8	9.5	2	83300	166480	83240	105400	105400	-	FP/SB
	B	2.8		1.4			86100			109000		-	FB/TK
8-5-90-0-i-2.5-2-9.5†	A	2.8	2.6	3.0	9.5	2	44600	88970	44485	56500	56300	-	FP
	B	2.5		1.8			65800			83300		-	SS
8-5-90-0-i-2.5-2-12.5†	A	2.8	2.8	1.3	9.8	2	65300	131640	65820	82700	83300	-	SS/B
	B	2.8		1.3			69900			88500		-	SS
8-5-90-0-i-2.5-2-18	A	2.5	2.5	0.8	10.5	2	100200	161760	80880	126800	102400	-	FB/SS/TK
	B	2.5		2.4			79800			101000		0.153	FB/SS/TK
8-5-90-0-i-2.5-2-13	A	2.5	2.5	2.0	9.8	2	73100	131080	65540	92500	83000	-	SS
	B	2.5		1.8			65200			82500		-	FP/SS
8-5-90-0-i-2.5-2-15(1)	A	2.5	2.5	2.8	9.6	2	64500	127530	63765	81600	80700	-	FB/SB
	B	2.6		2.0			87300			110500		-	SB
8-5-90-0-i-2.5-2-15	A	2.5	2.6	2.0	9.5	2	76300	150960	75480	96600	95500	-	SS/FP
	B	2.6		2.9			80700			102200		-	SB/FP
8-8-90-0-i-2.5-2-8	A	2.8	2.8	1.1	8.6	2	54700	90490	45245	69200	57300	-	FP/TK
	B	2.9		2.0			45200			57200		-	FP/SS
8-8-90-0-i-2.5-2-10	A	2.8	2.8	2.3	9.0	2	50000	102910	51455	63300	65100	0.195	FP
	B	2.9		2.5			52900			67000		0.185	FP
8-8-90-0-i-2.5-2-8(1)	A	2.8	2.8	2.8	9.5	2	38000	73640	36820	48100	46600	0.387	FP/SS
	B	2.8		2.8			37700			47700		0.229	FP/SS
8-8-90-0-i-2.5-2-9‡	A	2.5	2.6	1.5	10.0	2	35500	70	35100	44937	44430	0.104	FB
	B	2.8		1.5			34700			43924		0	FB

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi	Long. Reinf. Layout°
5-5-90-2#3-i-3.5-2-8	A B	60	0.38	0.2	2	3.50	-	-	-	0.375	4.00	-	-	1.27	60	A1
5-8-90-2#3-i-3.5-2-6†	A B	60	0.38	0.2	2	4.00	-	-	-	0.500	4.00	-	-	1.27	60	A1
5-8-90-2#3-i-3.5-2-8†	A B	60	0.38	0.2	2	4.00	-	-	-	0.500	4.00	-	-	1.67	60	A5
5-12-90-2#3-i-3.5-2-5	A B	60	0.38	0.2	2	3.33	0.33	3	3.3	0.500	3.00	-	-	1.27	60	A1
5-5-180-2#3-i-2.5-2-8†	A B	60	0.38	0.2	2	2.50	-	-	-	0.375	4.00	-	-	1.27	60	A1
5-5-180-2#3-i-2.5-2-6†	A B	60	0.38	0.2	2	2.50	-	-	-	0.375	4.00	-	-	1.27	60	A1
5-8-180-2#3-i-2.5-2-7	A B	60	0.38	0.2	2	2.00	-	-	-	0.375	3.00	-	-	1.27	60	A1
5-8-180-2#3-i-3.5-2-7	A B	60	0.38	0.2	2	2.00	-	-	-	0.375	3.00	-	-	1.27	60	A1
5-5-90-5#3-i-2.5-2-7	A B	60	0.38	0.6	5	1.75	-	-	-	0.500	3.50	-	-	1.27	60	A1
5-12-90-5#3-i-2.5-2-5	A B	60	0.38	0.6	5	1.67	-	-	-	0.500	3.00	-	-	1.27	60	A1
5-15-90-5#3-i-2.5-2-4	A B	60	0.38	0.6	5	1.75	-	-	-	0.375	1.75	-	-	2.51	60	A9
5-15-90-5#3-i-2.5-2-5	A B	60	0.38	0.6	5	1.75	-	-	-	0.375	2.25	-	-	3.16	60	A2
5-5-90-5#3-i-3.5-2-7	A B	60	0.38	0.6	5	1.75	-	-	-	0.500	3.50	-	-	1.27	60	A1
5-12-90-5#3-i-3.5-2-5	A B	60	0.38	0.6	5	1.70	-	-	-	0.500	3.00	-	-	1.27	60	A1
8-5-90-0-i-2.5-2-16†	A B	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60	A2
8-5-90-0-i-2.5-2-9.5†	A B	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60	A2
8-5-90-0-i-2.5-2-12.5†	A B	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60	A2
8-5-90-0-i-2.5-2-18	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.4	1	3.78	60	A6
8-5-90-0-i-2.5-2-13	A B	60	-	-	-	-	1.00	5	3.0	0.50	3.00	0.4	1	3.16	60	A2
8-5-90-0-i-2.5-2-15(1)	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.4	2	3.16	60	A2
8-5-90-0-i-2.5-2-15	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.4	2	3.16	60	A2
8-8-90-0-i-2.5-2-8	A B	60	-	-	-	-	1.60	8	4.0	0.50	1.75	-	-	3.16	60	A2
8-8-90-0-i-2.5-2-10	A B	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60	A2
8-8-90-0-i-2.5-2-8(1)	A B	60	-	-	-	-	1.60	8	4.0	0.50	1.50	-	-	3.16	60	A2
8-8-90-0-i-2.5sc-2tc-9‡	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.16	60	A2

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

° Longitudinal column configurations shown in Layouts A1 – A14

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
8-12-90-0-i-2.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	17	10.5	8.375
8-12-90-0-i-2.5-2-12.5	A B	90°	Horizontal	A1035[c]	12.9 12.8	12.8	11850	39	1	0.073	17	10.5	8.375
8-12-90-0-i-2.5-2-12	A B	90°	Horizontal	A1035[c]	12.1 12.1	12.1	11760	34	1	0.073	17	10.5	8.375
8-15-90-0-i-2.5-2-8.5	A B	90°	Horizontal	A1035[c]	8.8 8.9	8.8	15800	61	1	0.073	17	10.5	8.375
8-15-90-0-i-2.5-2-13	A B	90°	Horizontal	A1035[c]	12.8 12.8	12.8	15800	61	1	0.073	17	10.5	8.375
8-5-90-0-i-3.5-2-18	A B	90°	Horizontal	A1035[b]	19.0 18.0	18.5	5380	11	1	0.078	19	10.5	8.375
8-5-90-0-i-3.5-2-13	A B	90°	Horizontal	A1035[b]	13.4 13.4	13.4	5560	11	1	0.078	19	10.5	8.375
8-5-90-0-i-3.5-2-15(2)	A B	90°	Horizontal	A1035[c]	15.6 14.9	15.3	5180	8	1	0.073	19	10.5	8.375
8-5-90-0-i-3.5-2-15(1)	A B	90°	Horizontal	A1035[c]	15.4 15.1	15.3	6440	9	1	0.073	19	10.5	8.375
8-8-90-0-i-3.5-2-8(1)	A B	90°	Horizontal	A1035[b]	7.8 7.8	7.8	7910	15	1	0.078	19	10.5	8.375
8-8-90-0-i-3.5-2-10	A B	90°	Horizontal	A1035[b]	8.8 10.8	9.8	7700	14	1	0.078	19	10.5	8.375
8-8-90-0-i-3.5-2-8(2)	A B	90°	Horizontal	A1035[b]	8.5 8.0	8.3	8780	13	1	0.078	19	10.5	8.375
8-12-90-0-i-3.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	19	10.5	8.375
8-5-180-0-i-2.5-2-11†	A B	180°	Horizontal	A615	11.0 11.0	11.0	4550	7	1	0.078	17	10.5	8.375
8-5-180-0-i-2.5-2-14†	A B	180°	Horizontal	A1035[b]	14.0 14.0	14.0	4840	8	1	0.078	17	10.5	8.375
8-8-180-0-i-2.5-2-11.5	A B	180°	Horizontal	A1035[b]	9.3 9.3	9.3	8630	11	1	0.078	17	10.5	8.375
8-12-180-0-i-2.5-2-12.5	A B	180°	Horizontal	A1035[c]	12.8 12.5	12.6	11850	39	1	0.073	17	10.5	8.375
8-5-180-0-i-3.5-2-11†	A B	180°	Horizontal	A615	11.6 11.6	11.6	4550	7	1	0.078	17	10.5	8.375
8-5-180-0-i-3.5-2-14†	A B	180°	Horizontal	A1035[b]	14.4 13.9	14.1	4840	8	1	0.078	17	10.5	8.375
8-15-180-0-i-2.5-2-13.5	A B	180°	Horizontal	A1035[c]	13.8 13.5	13.6	16510	88	1	0.073	17	10.5	8.375
8-5-90-2#3-i-2.5-2-16†	A B	90°	Horizontal	A1035[b]	15.0 15.8	15.4	4810	6	1	0.078	17	10.5	8.375
8-5-90-2#3-i-2.5-2-9.5†	A B	90°	Horizontal	A615	9.0 9.3	9.1	5140	8	1	0.078	17	10.5	8.375
8-5-90-2#3-i-2.5-2-12.5†	A B	90°	Horizontal	A615	12.0 12.0	12.0	5240	9	1	0.078	17	10.5	8.375
8-5-90-2#3-i-2.5-2-8.5	A B	90°	Horizontal	A1035[c]	8.9 9.6	9.3	5240	6	1	0.073	17	10.5	8.375
8-5-90-2#3-i-2.5-2-14	A B	90°	Horizontal	A1035[c]	13.5 14.0	13.8	5450	7	1	0.073	17	10.5	8.375

† Specimens had constant 80 kip axial load

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

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	c_{so}	$c_{so,avg}$	c_{th}	c_h	N_h	T_{ind}	T_{total}	T	f_{su}	$f_{su,avg}$	Lead Slip (Tail Slip) at Failure	Failure Type
		in.	in.	in.	in.		lb	lb	lb	psi	psi	in.	
8-12-90-0-i-2.5-2-9	A	2.8	2.7	2.4	9.6	2	50800	99850	49925	64300	63200	0.219	FP/SS
	B	2.6		2.4			54800			69400		-	SS/FP
8-12-90-0-i-2.5-2-12.5	A	2.6	2.6	1.7	10.1	2	66000	133900	66950	83500	84700	0.295	FB/SB
	B	2.6		1.8			77400			98000		0.266	FB/SB
8-12-90-0-i-2.5-2-12	A	2.5	2.5	1.9	9.8	2	70700	131800	65900	89500	83400	-	SB/FP
	B	2.4		1.9			65800			83300		0.0119	FB/SS
8-15-90-0-i-2.5-2-8.5	A	2.5	2.5	2.0	10.0	2	43100	87200	43600	54600	55200	-	FP
	B	2.5		1.9			44100			55800		-	FP
8-15-90-0-i-2.5-2-13	A	2.4	2.4	2.1	9.9	2	77200	156200	78100	97700	98900	-	FB/SB
	B	2.5		2.0			79000			100000		-	FB
8-5-90-0-i-3.5-2-18	A	3.8	3.6	1.4	9.4	2	96000	190740	95370	121500	120700	0.181	FP/SS/TK
	B	3.4		2.4			105100			133000		-	FB/SS
8-5-90-0-i-3.5-2-13	A	3.6	3.5	1.9	9.4	2	69400	136200	68100	87800	86200	-	FP/SS
	B	3.4		1.9			68300			86500		-	SS/FP
8-5-90-0-i-3.5-2-15(2)	A	3.5	3.5	1.6	9.5	2	106200	175420	87710	134400	111000	-	SS
	B	3.5		2.4			85500			108200		-	SS/FP
8-5-90-0-i-3.5-2-15(1)	A	3.3	3.3	1.8	10.1	2	71200	141300	70650	90100	89400	-	SS/FP
	B	3.4		2.0			79400			100500		-	SB
8-8-90-0-i-3.5-2-8(1)	A	3.5	3.6	2.3	9.0	2	43700	87690	43845	55300	55500	0.144	SS/FP
	B	3.8		2.3			44000			55700		0.156	SS/FP
8-8-90-0-i-3.5-2-10	A	3.8	3.8	3.3	9.0	2	55200	111130	55565	69900	70300	0.195	FP/SS
	B	3.8		1.3			71900			91000		0.242	SS/FP
8-8-90-0-i-3.5-2-8(2)	A	3.6	3.7	2.1	10.0	2	41200	84070	42035	52200	53200	0.133	FP
	B	3.8		2.6			42900			54300		0.201	FP
8-12-90-0-i-3.5-2-9	A	3.5	3.6	2.4	9.8	2	61400	120480	60240	77700	76300	-	FP
	B	3.8		2.1			68500			86700		0.434	FP/SS
8-5-180-0-i-2.5-2-11†	A	3.0	2.9	2.0	9.8	2	45600	92290	46145	57700	58400	0.275	SS/FP
	B	2.8		2.0			50500			63900		-	SS
8-5-180-0-i-2.5-2-14†	A	2.8	2.7	2.0	9.8	2	49400	98300	49150	62500	62200	0.088	SS
	B	2.6		2.0			69400			87800		0.096	SS
8-8-180-0-i-2.5-2-11.5	A	3.0	3.0	4.5	9.5	2	62800	125600	62800	79500	79500	-	FP/SB
	B	3.0		4.5			80200			101500		-	FP/SS
8-12-180-0-i-2.5-2-12.5	A	3.0	2.8	2.1	9.6	2	74800	150400	75200	94700	95200	0.193	FB/SB
	B	2.5		2.4			92300			116800		0.242	FP
8-5-180-0-i-3.5-2-11†	A	3.8	3.8	1.4	10.0	2	58600	118580	59290	74200	75100	0.372	FP/SS
	B	3.8		1.4			60500			76600		0.239	SS
8-5-180-0-i-3.5-2-14†	A	3.9	3.8	1.6	9.8	2	63700	127010	63505	80600	80400	-	SS
	B	3.8		2.1			78000			98700		-	FB/SS
8-15-180-0-i-2.5-2-13.5	A	2.5	2.5	2.0	10.0	2	90700	179800	89900	114800	113800	-	-
	B	2.5		2.3			89100			112800		-	FB/SB
8-5-90-2#3-i-2.5-2-16†	A	2.8	2.8	2.9	9.5	2	80000	159260	79630	101300	100800	-	SS/FP
	B	2.9		2.1			92800			117500		-	FP
8-5-90-2#3-i-2.5-2-9.5†	A	2.5	2.5	2.6	10.0	2	54900	107240	53620	69500	67900	-	FP
	B	2.5		2.3			53600			67800		-	FP
8-5-90-2#3-i-2.5-2-12.5†	A	2.8	2.8	2.6	9.5	2	74100	144130	72065	93800	91200	-	FP
	B	2.8		2.6			76300			96600		-	FP/SS
8-5-90-2#3-i-2.5-2-8.5	A	3.0	3.0	1.8	9.1	2	52900	101100	50550	67000	64000	-	FP/SS
	B	3.0		1.1			48400			61300		-	SS
8-5-90-2#3-i-2.5-2-14	A	2.8	2.9	2.6	9.3	2	77000	153930	76965	97500	97400	-	SS/FP
	B	3.0		2.1			77500			98100		-	FP/SS

† Specimens had constant 80 kip axial load

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} 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_s ksi	Long. Reinf. Layout°
8-12-90-0-i-2.5-2-9	A B	60	-	-	-	-	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60	A2
8-12-90-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60	A2
8-12-90-0-i-2.5-2-12	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.16	60	A2
8-15-90-0-i-2.5-2-8.5	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.78	60	A5
8-15-90-0-i-2.5-2-13	A B	60	-	-	-	-	-	-	-	0.38	5.00	-	-	4.74	60	A6
8-5-90-0-i-3.5-2-18	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	1	3.78	60	A5
8-5-90-0-i-3.5-2-13	A B	60	-	-	-	-	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60	A2
8-5-90-0-i-3.5-2-15(2)	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60	A2
8-5-90-0-i-3.5-2-15(1)	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60	A2
8-8-90-0-i-3.5-2-8(1)	A B	60	-	-	-	-	1.60	8	4.0	0.50	1.75	-	-	3.16	60	A2
8-8-90-0-i-3.5-2-10	A B	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60	A2
8-8-90-0-i-3.5-2-8(2)	A B	60	-	-	-	-	1.60	8	4.0	0.50	1.50	-	-	3.16	60	A2
8-12-90-0-i-3.5-2-9	A B	60	-	-	-	-	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60	A2
8-5-180-0-i-2.5-2-11†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60	A2
8-5-180-0-i-2.5-2-14†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60	A2
8-8-180-0-i-2.5-2-11.5	A B	60	-	-	-	-	0.44	4	3.0	0.50	3.00	-	-	3.16	60	A2
8-12-180-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60	A2
8-5-180-0-i-3.5-2-11†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60	A2
8-5-180-0-i-3.5-2-14†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60	A2
8-15-180-0-i-2.5-2-13.5	A B	60	-	-	-	-	-	-	-	0.50	4.00	-	-	4.74	60	A6
8-5-90-2#3-i-2.5-2-16†	A B	60	0.38	0.2	2	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60	A2
8-5-90-2#3-i-2.5-2-9.5†	A B	60	0.38	0.2	2	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60	A2
8-5-90-2#3-i-2.5-2-12.5†	A B	60	0.38	0.2	2	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60	A2
8-5-90-2#3-i-2.5-2-8.5	A B	60	0.38	0.2	2	7.50	2.00	10	2.5	0.50	3.25	0.5	1	3.16	60	A2
8-5-90-2#3-i-2.5-2-14	A B	60	0.38	0.2	2	6.00	0.88	8	3.0	0.50	3.50	0.5	1	3.16	60	A2

† Specimens had constant 80 kip axial load

° Longitudinal column configurations shown in Layouts A1 – A14

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
8-8-90-2#3-i-2.5-2-8	A B	90°	Horizontal	A1035[b]	8.0 8.5	8.3	7700	14	1	0.078	17	10.5	8.375
8-8-90-2#3-i-2.5-2-10	A B	90°	Horizontal	A1035[b]	9.9 9.5	9.7	8990	17	1	0.078	17	10.5	8.375
8-12-90-2#3-i-2.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	17	10.5	8.375
8-12-90-2#3-i-2.5-2-11	A B	90°	Horizontal	A1035[c]	10.5 11.3	10.9	12010	42	1	0.073	17	10.5	8.375
8-15-90-2#3-i-2.5-2-6	A B	90°	Horizontal	A1035[c]	5.8 6.4	6.1	15800	61	1	0.073	17	10.5	8.375
8-15-90-2#3-i-2.5-2-11	A B	90°	Horizontal	A1035[c]	11.3 10.8	11.0	15800	61	1	0.073	17	10.5	8.375
8-5-90-2#3-i-3.5-2-17	A B	90°	Horizontal	A1035[b]	17.5 17.0	17.3	5570	12	1	0.078	19	10.5	8.375
8-5-90-2#3-i-3.5-2-13	A B	90°	Horizontal	A1035[b]	13.8 13.5	13.6	5560	11	1	0.078	19	10.5	8.375
8-8-90-2#3-i-3.5-2-8	A B	90°	Horizontal	A1035[b]	8.0 8.1	8.1	8290	16	1	0.078	19	10.5	8.375
8-8-90-2#3-i-3.5-2-10	A B	90°	Horizontal	A1035[b]	8.8 8.8	8.8	8990	17	1	0.078	19	10.5	8.375
8-12-90-2#3-i-3.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	19	10.5	8.375
8-5-180-2#3-i-2.5-2-11†	A B	180°	Horizontal	A615	10.8 10.5	10.6	4550	7	1	0.078	17	10.5	8.375
8-5-180-2#3-i-2.5-2-14†	A B	180°	Horizontal	A1035[b]	13.5 14.0	13.8	4870	9	1	0.078	17	10.5	8.375
8-8-180-2#3-i-2.5-2-11.5	A B	180°	Horizontal	A1035[b]	10.5 10.3	10.4	8810	14	1	0.078	17	10.5	8.375
8-12-180-2#3-i-2.5-2-11	A B	180°	Horizontal	A1035[c]	11.1 10.4	10.8	12010	42	1	0.073	17	10.5	8.375
8-5-180-2#3-i-3.5-2-11†	A B	180°	Horizontal	A1035[b]	10.1 10.6	10.4	4300	6	1	0.078	17	10.5	8.375
8-5-180-2#3-i-3.5-2-14†	A B	180°	Horizontal	A1035[b]	13.5 13.6	13.6	4870	9	1	0.078	17	10.5	8.375
8-15-180-2#3-i-2.5-2-11	A B	180°	Horizontal	A1035[b]	11.1 11.1	11.1	15550	87	1	0.073	17	10.5	8.375
8-5-90-5#3-i-2.5-2-10b†	A B	90°	Horizontal	A1035[a]	10.3 10.5	10.4	5440	8	1	0.084	17	10.5	8.375
8-5-90-5#3-i-2.5-2-10c†	A B	90°	Horizontal	A1035[a]	10.5 10.5	10.5	5650	9	1	0.084	17	10.5	8.375
8-5-90-5#3-i-2.5-2-15	A B	90°	Horizontal	A1035[b]	15.3 15.8	15.5	4850	7	1	0.078	17	10.5	8.375
8-5-90-5#3-i-2.5-2-13	A B	90°	Horizontal	A1035[b]	13.8 13.5	13.6	5560	11	1	0.078	17	10.5	8.375
8-5-90-5#3-i-2.5-2-12(1)	A B	90°	Horizontal	A1035[c]	11.5 11.1	11.3	5090	7	1	0.073	17	10.5	8.375

† Specimens had constant 80 kip axial load

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

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	f_{su} psi	$f_{su,avg}$ psi	Lead Slip (Tail Slip) at Failure in.	Failure Type
8-8-90-2#3-i-2.5-2-8	A	3.0	2.9	2.0	9.0	2	46200	95750	47875	58500	60600	-	FP/SS
	B	2.9		1.5			55400			70100		-	FP/SS
8-8-90-2#3-i-2.5-2-10	A	2.8	2.8	2.1	8.5	2	60700	122050	61025	76800	77200	0.186	FP
	B	2.8		2.5			67000			84800		0.152	FB
8-12-90-2#3-i-2.5-2-9	A	2.9	2.8	2.3	9.5	2	61800	122030	61015	78200	77200	0.345	FP/SS
	B	2.6		2.3			60300			76300		0.361	SS/FP
8-12-90-2#3-i-2.5-2-11	A	2.8	2.8	2.4	9.5	2	68100	137400	68700	86200	87000	0.181	FP
	B	2.8		1.6			79800			101000		0.165	FP
8-15-90-2#3-i-2.5-2-6	A	2.5	2.4	2.3	9.9	2	37400	75100	37600	47300	47600	-	FP
	B	2.4		1.8			37700			47700		-	FP
8-15-90-2#3-i-2.5-2-11	A	2.5	2.5	1.9	10.0	2	99000	166600	83300	125300	105400	-	FB
	B	2.5		2.4			83600			105800		0.123	FB
8-5-90-2#3-i-3.5-2-17	A	3.3	3.4	1.8	10.1	2	102600	179830	89915	129900	113800	-	SS
	B	3.5		2.3			88600			112200		-	SS/FP
8-5-90-2#3-i-3.5-2-13	A	3.1	3.4	1.5	10.3	2	81200	160720	80360	102800	101700	-	SS/FP
	B	3.6		1.8			86900			110000		-	SS/FP
8-8-90-2#3-i-3.5-2-8	A	3.6	3.7	2.0	8.5	2	48300	97550	48775	61100	61700	0.310	FP
	B	3.8		1.9			49300			62400		0.340(0.147)	FP
8-8-90-2#3-i-3.5-2-10	A	3.6	3.7	3.3	8.5	2	54000	107770	53885	68400	68200	-	SS
	B	3.8		3.3			53800			68100		-	FP
8-12-90-2#3-i-3.5-2-9	A	3.6	3.8	2.3	9.6	2	50300	99550	49775	63700	63000	0.150	FP/SS
	B	4.0		2.4			49300			62400			FP/SS
8-5-180-2#3-i-2.5-2-11†	A	2.8	2.6	2.3	9.5	2	64200	120470	60235	81300	76200	0.260	SS/FP
	B	2.5		2.5			61900			78400		0.087	SS/FP
8-5-180-2#3-i-2.5-2-14†	A	2.8	2.8	2.5	9.8	2	87100	152560	76280	110300	96600	0.774	FP
	B	2.8		2.0			76900			97300		0.199	FP/SS
8-8-180-2#3-i-2.5-2-11.5	A	2.8	2.8	2.3	10.0	2	70100	116340	58170	88700	73600	0.261	FB/SS
	B	2.8		2.5			59500			75300		0.25(0.027)	FP/SS
8-12-180-2#3-i-2.5-2-11	A	2.5	2.6	2.1	9.6	2	73700	129300	64650	93300	81800	-	FP
	B	2.6		2.8			66200			83800		-	FB
8-5-180-2#3-i-3.5-2-11†	A	3.4	3.4	2.9	9.8	2	57200	111740	55870	72400	70700	0.167	SS/FP
	B	3.5		2.4			54900			69500		0.212	SS/FP
8-5-180-2#3-i-3.5-2-14†	A	3.6	3.7	2.5	9.8	2	68300	126930	63465	86500	80300	-	FP/SS
	B	3.8		2.4			90400			114400		-	FP/SS
8-15-180-2#3-i-2.5-2-11	A	2.8	2.8	2.1	9.8	2	79600	157800	78900	100800	99900	-	FB/SS
	B	2.8		2.0			78300			99100		-	FP
8-5-90-5#3-i-2.5-2-10b†	A	2.8	2.7	2.0	9.9	2	78800	139430	69715	99700	88200	0.129	FP/SS
	B	2.6		1.8			66700			84400		-	FP
8-5-90-5#3-i-2.5-2-10c†	A	2.5	2.5	2.0	10.0	2	68900	137670	68835	87200	87100	-	FP/SS
	B	2.5		2.0			69600			88100		-	FP/SS
8-5-90-5#3-i-2.5-2-15	A	2.8	2.6	1.9	9.9	2	77100	146750	73375	97600	92900	0.196	FP/SS
	B	2.5		1.4			72600			91900		-	FP/SS
8-5-90-5#3-i-2.5-2-13	A	2.5	2.4	1.5	10.3	2	93100	164750	82375	117800	104300	-	SS/FP
	B	2.4		1.8			81300			102900		-	FP/SS
8-5-90-5#3-i-2.5-2-12(1)	A	2.5	2.5	2.6	9.8	2	66700	132730	66365	84400	84000	-	SS/FP
	B	2.5		3.0			75900			96100		-	SS/FP

† Specimens had constant 80 kip axial load

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} 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_s ksi	Long. Reinf. Layout°
8-8-90-2#3-i-2.5-2-8	A B	60	0.38	0.2	2	7.13	1.20	6	4.0	0.50	1.50	-	-	3.16	60	A2
8-8-90-2#3-i-2.5-2-10	A B	60	0.38	0.2	2	7.13	1.20	6	4.0	0.63	3.50	-	-	3.16	60	A2
8-12-90-2#3-i-2.5-2-9	A B	60	0.38	0.2	2	8.00	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60	A2
8-12-90-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	2.00	-	-	3.16	60	A2
8-12-90-2#3vr-i-2.5-2-11	A B	60	0.38	0.2	2	2.67	-	-	-	0.50	2.00	-	-	3.16	60	A2
8-15-90-2#3-i-2.5-2-6	A B	60	0.38	0.2	2	6.00	-	-	-	0.38	2.75	-	-	6.32	60	A10
8-15-90-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	5.50	-	-	-	0.38	4.00	-	-	6.32	60	A10
8-5-90-2#3-i-3.5-2-17	A B	60	0.38	0.2	2	8.00	0.80	4	4.0	0.50	4.00	0.375	1	3.16	60	A2
8-5-90-2#3-i-3.5-2-13	A B	60	0.38	0.2	2	8.00	0.44	4	4.0	0.50	3.00	-	-	3.16	60	A2
8-8-90-2#3-i-3.5-2-8	A B	60	0.38	0.2	2	7.13	1.20	6	4.0	0.50	1.50	-	-	3.16	60	A2
8-8-90-2#3-i-3.5-2-10	A B	60	0.38	0.2	2	7.13	1.20	6	4.0	0.63	3.50	-	-	3.16	60	A2
8-12-90-2#3-i-3.5-2-9	A B	60	0.38	0.2	2	8.00	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60	A2
8-5-180-2#3-i-2.5-2-11†	A B	60	0.38	0.2	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60	A2
8-5-180-2#3-i-2.5-2-14†	A B	60	0.38	0.2	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60	A2
8-8-180-2#3-i-2.5-2-11.5	A B	60	0.38	0.2	2		-	-	-	0.50	3.00	-	-	3.16	60	A2
8-12-180-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	2.00	-	-	3.16	60	A2
8-12-180-2#3vr-i-2.5-2-11	A B	60	0.38	0.2	2	2.67	-	-	-	0.50	2.00	-	-	3.16	60	A2
8-5-180-2#3-i-3.5-2-11†	A B	60	0.38	0.2	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60	A2
8-5-180-2#3-i-3.5-2-14†	A B	60	0.38	0.2	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60	A2
8-15-180-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	5.00	-	-	-	0.50	4.00	-	-	4.74	60	A6
8-5-90-5#3-i-2.5-2-10b†	A B	60	0.38	0.6	5	3.00	1.10	10	3.0	0.63	5.00	-	-	3.16	60	A2
8-5-90-5#3-i-2.5-2-10c†	A B	60	0.38	0.6	5	3.00	1.10	10	3.0	0.63	5.00	-	-	3.16	60	A2
8-5-90-5#3-i-2.5-2-15	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.375	2	3.16	60	A2
8-5-90-5#3-i-2.5-2-13	A B	60	0.38	0.6	5	3.00	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60	A2
8-5-90-5#3-i-2.5-2-12(1)	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.5	2	3.16	60	A2

† Specimens had constant 80 kip axial load

° Longitudinal column configurations shown in Layouts A1 – A14

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
8-5-90-5#3-i-2.5-2-12	A B	90°	Horizontal	A1035[c]	11.3 12.3	11.8	5960	7	1	0.073	17	10.5	8.375
8-5-90-5#3-i-2.5-2-12(2)	A B	90°	Horizontal	A1035[c]	12.4 12.0	12.2	5240	6	1	0.073	17	10.5	8.375
8-5-90-5#3-i-2.5-2-8	A B	90°	Horizontal	A1035[c]	7.8 7.4	7.6	5240	6	1	0.073	17	10.5	8.375
8-5-90-5#3-i-2.5-2-10a†	B	90°	Horizontal	A1035[a]	10.5	10.5	5270	7	1	0.08	17	10.5	8.375
8-8-90-5#3-i-2.5-2-8	A B	90°	Horizontal	A1035[b]	7.3 7.3	7.3	8290	16	1	0.078	17	10.5	8.375
8-8-90-5#3-i-2.5-2-9‡	A B	90°	Horizontal	A615	8.6 9.0	8.8	7710	25	1	0.073	17	10.5	8.375
8-12-90-5#3-i-2.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	17	10.5	8.375
8-12-90-5#3-i-2.5-2-10	A B	90°	Horizontal	A1035[c]	9.0 9.9	9.4	11800	38	1	0.073	17	10.5	8.375
8-12-90-5#3-i-2.5-2-12‡	A B	90°	Horizontal	A1035[c]	12.2 12.3	12.2	11760	34	1	0.073	17	10.5	8.375
8-15-90-5#3-i-2.5-2-6	A B	90°	Horizontal	A1035[c]	6.5 6.1	6.3	15800	60	1	0.073	17	10.5	8.375
8-15-90-5#3-i-2.5-2-10	A B	90°	Horizontal	A1035[c]	10.6 9.7	10.1	15800	60	1	0.073	17	10.5	8.375
8-5-90-5#3-i-3.5-2-15	A B	90°	Horizontal	A1035[b]	15.8 15.8	15.8	4850	7	1	0.078	19	10.5	8.375
8-5-90-5#3-i-3.5-2-13	A B	90°	Horizontal	A1035[b]	13.3 13.0	13.1	5570	12	1	0.078	19	10.5	8.375
8-5-90-5#3-i-3.5-2-12(1)	A B	90°	Horizontal	A1035[c]	12.8 12.3	12.5	5090	7	1	0.073	19	10.5	8.375
8-5-90-5#3-i-3.5-2-12	A B	90°	Horizontal	A1035[c]	12.5 11.8	12.1	6440	9	1	0.073	19	10.5	8.375
8-8-90-5#3-i-3.5-2-8	A B	90°	Horizontal	A1035[b]	8.0 8.0	8.0	7910	15	1	0.078	19	10.5	8.375
8-12-90-5#3-i-3.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	19	10.5	8.375
8-12-180-5#3-i-2.5-2-10	A B	180°	Horizontal	A1035[c]	9.9 9.6	9.8	11800	38	1	0.073	17	10.5	8.375
8-15-180-5#3-i-2.5-2-9.5	A B	180°	Horizontal	A1035[c]	9.6 9.8	9.7	15550	87	1	0.073	17	10.5	8.375
11-5-90-0-i-2.5-2-14	A B	90°	Horizontal	A615	13.5 15.3	14.4	4910	13	1.41	0.069	21.5	19.5	8.375
11-5-90-0-i-2.5-2-26	A B	90°	Horizontal	A1035	26.0 26.0	26.0	5360	6	1.41	0.085	21.5	19.5	8.375
11-8-90-0-i-2.5-2-17	A B	90°	Horizontal	A1035	17.3 18.0	17.6	9460	9	1.41	0.085	21.5	19.5	8.375

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	f_{su} psi	$f_{su,avg}$ psi	Lead Slip (Tail Slip) at Failure in.	Failure Type
8-5-90-5#3-i-2.5-2-12	A	2.5	2.4	3.0	9.8	2	84900	156900	84900	107500	107500	-	SS
	B	2.4		2.0			72000			91100		-	SS
8-5-90-5#3-i-2.5-2-12(2)	A	2.5	2.6	1.8	9.0	2	72400	142940	71470	91600	90500	-	FP/SS
	B	2.6		2.1			77400			98000		-	FP/SS
8-5-90-5#3-i-2.5-2-8	A	2.8	2.8	2.6	9.0	2	48000	94960	47480	60800	60100	-	FP
	B	2.9		2.9			47000			59500		0.321	FP
8-5-90-5#3-i-2.5-2-10a†	B	2.5	2.5	1.8	9.8	2	82800	82800	82800	104800	104800	0.164	FP/SS
8-8-90-5#3-i-2.5-2-8	A	2.9	2.8	2.8	8.5	2	56000	100530	50265	70900	63600	0.300	FP
	B	2.8		2.8			51200			64800		0.375 (0.092)	FP
8-8-90-5#3-i-2.5-2-9‡	A	2.8	3.0	2.4	9.8	2	64800	129	64390	82025	81506	0.047	FB
	B	3.3		2.0			64800			82025		-	FB
8-12-90-5#3-i-2.5-2-9	A	2.5	2.6	2.5	9.5	2	66500	129510	64755	84200	82000	0.224	FP/SS
	B	2.6		2.5			63100			79900		0.252	FP/SS
8-12-90-5#3-i-2.5-2-10	A	2.6	2.4	3.2	9.9	2	66000	129100	64550	83500	81700	0.440	FB/SS
	B	2.3		2.3			64600			81800		0.547	SS/FP
8-12-90-5#3-i-2.5-2-12‡	A	2.4	2.4	2.0	10.0	2	90500	175400	87700	114600	111000	-	FB/SS
	B	2.5		1.9			86500			109500		-	SS/FP
8-15-90-5#3-i-2.5-2-6	A	2.6	2.6	1.8	9.8	2	48300	97000	48500	61100	61400	-	FP
	B	2.6		2.2			48700			61600		-	FP
8-15-90-5#3-i-2.5-2-10	A	2.4	2.4	1.6	9.9	2	111600	180000	90000	141300	113900	-	FB/SS
	B	2.4		2.4			90200			114200		0.407	FB/SS
8-5-90-5#3-i-3.5-2-15	A	3.6	3.5	1.3	10.3	2	81200	160680	80340	102800	101700	0.214(0.026)	SS/FP
	B	3.5		1.3			87100			110300		-	SS/FP
8-5-90-5#3-i-3.5-2-13	A	3.4	3.4	2.1	10.4	2	89600	154140	77070	113400	97600	-	SS
	B	3.5		2.4			76000			96200		-	SS/FP
8-5-90-5#3-i-3.5-2-12(1)	A	3.5	3.5	1.6	9.8	2	78900	152860	76430	99900	96700	-	SS/FP
	B	3.4		2.1			75900			96100		-	SS
8-5-90-5#3-i-3.5-2-12	A	3.4	3.4	1.7	9.8	2	79200	158300	79150	100300	100200		FP
	B	3.5		2.4			79300			100400		0.162	FP/SS
8-8-90-5#3-i-3.5-2-8	A	3.5	3.6	2.0	8.9	2	55400	111620	55810	70100	70600	-	FP
	B	3.6		2.0			56200			71100		-	FP
8-12-90-5#3-i-3.5-2-9	A	3.3	3.3	2.5	9.5	2	68800	135660	67830	87100	85900		FP/SS
	B	3.4		2.5			82200			104100		0.415	FP/SS
8-12-180-5#3-i-2.5-2-10	A	2.3	2.5	2.3	9.9	2	63000	128200	64100	79700	81100	-	FP/SS
	B	2.8		2.6			81400			103000		0.339	FP
8-15-180-5#3-i-2.5-2-9.5	A	2.5	2.6	2.1	10.0	2	86000	171900	86000	108900	108900	-	SS
	B	2.8		1.9			86000			108900		-	FP/SS
11-5-90-0-i-2.5-2-14	A	2.8	2.8	2.5	13.3	2	67200	133180	66590	43100	42700	0.139	FP/SS
	B	2.8		0.8			81400			52200		-	SS
11-5-90-0-i-2.5-2-26	A	2.5	2.7	2.1	13.3	2	165700	297450	148725	106200	95300	-	FB/SS
	B	2.9		2.1			146800			94100		-	FB/SS/TK
11-8-90-0-i-2.5-2-17	A	2.5	2.5	2.0	13.4	2	132000	264100	132100	84600	84700	-	FP/TK
	B	2.5		1.3			141200			90500		-	FB/TK

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} 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_s ksi	Long. Reinf. Layout°
8-5-90-5#3-i-2.5-2-12	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.5	2	3.16	60	A2
8-5-90-5#3-i-2.5-2-12(2)	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.375	1	3.16	60	A2
8-5-90-5#3-i-2.5-2-8	A B	60	0.38	0.6	5	3.00	1.55	5	3.0	0.50	3.00	0.5	1	3.16	60	A2
8-5-90-5#3-i-2.5-2-10a†	B	60	0.375	0.55	5	3.0	1.10	10	3.0	0.63	3.50	-	-	3.16	60	A2
8-8-90-5#3-i-2.5-2-8	A B	60	0.38	0.6	5	3.00	1.20	6	3.0	0.50	1.50	-	-	3.16	60	A2
8-8-90-5#3-i-2.5-2-9‡	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	3.16	120	A2
8-12-90-5#3-i-2.5-2-9	A B	60	0.38	0.6	5	3.00	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60	A2
8-12-90-5#3-i-2.5-2-10	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-12-90-5#3-i-2.5-2-12‡	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	3.16	120	A2
8-12-90-5#3vr-i-2.5-2-10	A B	60	0.38	0.6	5	1.75	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-12-90-4#3vr-i-2.5-2-10	A B	60	0.38	0.4	4	2.25	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-15-90-5#3-i-2.5-2-6	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	2.75	-	-	6.32	60	A10
8-15-90-5#3-i-2.5-2-10	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	3.00	-	-	6.32	60	A10
8-5-90-5#3-i-3.5-2-15	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.375	2	3.16	60	A2
8-5-90-5#3-i-3.5-2-13	A B	60	0.38	0.6	5	3.00	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60	A2
8-5-90-5#3-i-3.5-2-12(1)	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.5	2	3.16	60	A2
8-5-90-5#3-i-3.5-2-12	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.5	2	3.16	60	A2
8-8-90-5#3-i-3.5-2-8	A B	60	0.38	0.6	5	3.00	1.20	6	3.0	0.50	1.50	-	-	3.16	60	A2
8-12-90-5#3-i-3.5-2-9	A B	60	0.38	0.6	5	3.00	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60	A2
8-12-180-5#3-i-2.5-2-10	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-12-180-5#3vr-i-2.5-2-10	A B	60	0.38	0.6	5	1.75	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-12-180-4#3vr-i-2.5-2-10	A B	60	0.38	0.4	4	2.25	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-15-180-5#3-i-2.5-2-9.5	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	4.00	-	-	6.32	60	A9
11-5-90-0-i-2.5-2-14	A B	60	-	-	-	-	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60	A6
11-5-90-0-i-2.5-2-26	A B	60	-	-	-	-	1.86	6	4.0	0.50	4.0	0.375	1	6.32	60	A11
11-8-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.48	60	A14

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

° Longitudinal column configurations shown in Layouts A1 – A14

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
11-8-90-0-i-2.5-2-21	A B	90°	Horizontal	A1035	20.0 21.1	20.6	7870	6	1.41	0.085	21.5	19.5	8.375
11-8-90-0-i-2.5-2-17	A B	90°	Horizontal	A1035	16.3 18.1	17.2	8520	7	1.41	0.085	21.5	19.5	8.375
11-12-90-0-i-2.5-2-17	A B	90°	Horizontal	A1035	16.1 16.9	16.5	11880	35	1.41	0.085	21.5	19.5	8.375
11-12-90-0-i-2.5-2-17.5	A B	90°	Horizontal	A1035	17.6 17.8	17.7	13330	31	1.41	0.085	21.5	19.5	8.375
11-12-90-0-i-2.5-2-25	A B	90°	Horizontal	A1035	24.9 24.4	24.6	13330	34	1.41	0.085	21.5	19.5	8.375
11-15-90-0-i-2.5-2-24	A B	90°	Horizontal	A1035	24.0 24.8	24.4	16180	62	1.41	0.085	21.5	19.5	8.375
11-15-90-0-i-2.5-2-10‡	A B	90°	Horizontal	A615	9.5 9.5	9.5	14050	76	1.41	0.085	21.5	19.5	8.375
11-15-90-0-i-2.5-2-15‡	A B	90°	Horizontal	A1035	14.0 14.0	14.0	14050	77	1.41	0.085	21.5	19.5	8.375
11-5-90-0-i-3.5-2-17	A B	90°	Horizontal	A1035	18.1 17.6	17.9	5600	24	1.41	0.085	23.5	19.5	8.375
11-5-90-0-i-3.5-2-14	A B	90°	Horizontal	A615	14.8 15.3	15.0	4910	13	1.41	0.069	23.5	19.5	8.375
11-5-90-0-i-3.5-2-26	A B	90°	Horizontal	A1035	26.3 25.8	26.0	5960	8	1.41	0.085	23.5	19.5	8.375
11-8-180-0-i-2.5-2-21	A B	180°	Horizontal	A1035	21.3 20.9	21.1	7870	6	1.41	0.085	21.5	19.5	8.375
11-8-180-0-i-2.5-2-17	A B	180°	Horizontal	A1035	17.8 18.0	17.9	8520	7	1.41	0.085	21.5	19.5	8.375
11-12-180-0-i-2.5-2-17	A B	180°	Horizontal	A1035	16.6 16.6	16.6	11880	35	1.41	0.085	21.5	19.5	8.375
11-5-90-2#3-i-2.5-2-17	A B	90°	Horizontal	A1035	17.4 17.8	17.6	5600	24	1.41	0.085	21.5	19.5	8.375
11-5-90-2#3-i-2.5-2-14	A B	90°	Horizontal	A615	13.5 13.8	13.6	4910	13	1.41	0.069	21.5	19.5	8.375
11-12-90-2#3-i-2.5-2-17.5	A B	90°	Horizontal	A1035	18.0 17.5	17.8	13710	30	1.41	0.085	21.5	19.5	8.375
11-15-90-2#3-i-2.5-2-23	A B	90°	Horizontal	A1035	23.5 23.5	23.5	16180	62	1.41	0.085	21.5	19.5	8.375
11-15-90-2#3-i-2.5-2-10‡	A B	90°	Horizontal	A615	10.0 10.0	10.0	14045	76	1.41	0.085	21.5	19.5	8.375
11-15-90-2#3-i-2.5-2-15‡	A B	90°	Horizontal	A1035	14.0 14.3	14.1	14045	80	1.41	0.085	21.5	19.5	8.375
11-5-90-2#3-i-3.5-2-17	A B	90°	Horizontal	A1035	17.5 17.8	17.6	7070	28	1.41	0.085	23.5	19.5	8.375
11-5-90-2#3-i-3.5-2-14	A B	90°	Horizontal	A615	14.5 13.4	13.9	4910	12	1.41	0.069	23.5	19.5	8.375
11-5-90-6#3-i-2.5-2-20	A B	90°	Horizontal	A1035	19.5 19.0	19.3	5420	7	1.41	0.085	21.5	19.5	8.375
11-8-90-6#3-i-2.5-2-16	A B	90°	Horizontal	A1035	15.5 16.4	15.9	9120	7	1.41	0.085	21.5	19.5	8.375
11-8-90-6#3-i-2.5-2-22a	A B	90°	Horizontal	A1035	21.3 21.5	21.4	9420	8	1.41	0.085	21.5	19.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	f_{su} psi	$f_{su,avg}$ psi	Lead Slip (Tail Slip) at Failure in.	Failure Type
11-8-90-0-i-2.5-2-21	A B	2.5 2.8	2.6	3.4 2.3	13.0	2	127060 147900	250250	125120	81400 94800	80200	- -	FP/TK FB
11-8-90-0-i-2.5-2-17	A B	2.5 2.5	2.5	3.0 1.1	13.5	2	105630 115170	209560	104780	67700 73800	67200	- -	SS FP
11-12-90-0-i-2.5-2-17	A B	2.5 2.6	2.6	3.1 2.4	13.3	2	148400 120400	239400	119700	95100 77200	76700	- -	SB SB/FP
11-12-90-0-i-2.5-2-17.5	A B	3.8 2.5	3.1	2.1 2.0	13.8	2	123600 125600	249240	124620	79200 80500	79900	- 0.250	SS/TK SS
11-12-90-0-i-2.5-2-25	A B	2.5 2.5	2.5	2.4 2.9	13.1	2	205100 198100	399490	199745	131500 127000	128000	- -	SB SB
11-15-90-0-i-2.5-2-24	A B	2.5 2.5	2.5	2.0 1.3	13.5	2	212600 231300	426500	213300	136300 148300	136700	- -	SB/TK SB/TK
11-15-90-0-i-2.5-2-10‡	A B	2.8 2.7	2.7	2.5 2.5	13.6	2	52100 50900	103	51500	33397 32628	33013	- -	FP FP
11-15-90-0-i-2.5-2-15‡	A B	2.8 2.8	2.8	3.0 3.0	13.0	2	93300 91000	184	92200	59808 58333	59103	- -	SB SB
11-5-90-0-i-3.5-2-17	A B	4.0 3.9	3.9	1.8 2.5	13.1	2	105000 117600	216240	108120	67300 75400	69300	0.187 -	SS/TK SS
11-5-90-0-i-3.5-2-14	A B	3.8 3.9	3.8	1.5 1.0	13.3	2	82600 69000	139030	69515	52900 44200	44600	- -	FP/SS FP/SS/TK
11-5-90-0-i-3.5-2-26	A B	3.8 3.8	3.8	2.1 2.6	13.5	2	198300 181700	364510	182255	127100 116500	116800	- -	SB/FB FB/SB
11-8-180-0-i-2.5-2-21	A B	2.9 2.4	2.7	1.8 2.2	13.0	2	137800 126800	256250	128125	88300 81300	82100	- -	FB FB/SB
11-8-180-0-i-2.5-2-17	A B	2.4 2.5	2.4	1.4 1.1	13.8	2	101710 121270	200910	100450	65200 77700	64400	- -	FP FB
11-12-180-0-i-2.5-2-17	A B	3.0 2.5	2.8	2.5 2.5	13.3	2	106700 108200	214900	107500	68400 69400	68900	0.156 -	SB/FP SS
11-5-90-2#3-i-2.5-2-17	A B	2.5 2.6	2.6	2.3 1.8	13.4	2	108400 103200	201390	100695	69500 66200	64500	- -	SS/FP SS/FP
11-5-90-2#3-i-2.5-2-14	A B	2.8 2.9	2.8	2.5 2.3	13.3	2	77700 77200	154840	77420	49800 49500	49600	0.206 -	FP/SS SS
11-12-90-2#3-i-2.5-2-17.5	A B	2.5 2.5	2.5	1.5 2.0	13.3	2	133200 129900	260780	130390	85400 83300	83600	- -	SS SS
11-15-90-2#3-i-2.5-2-23	A B	2.8 2.8	2.8	1.5 1.5	13.0	2	232100 206900	419200	209600	148800 132600	134400	- -	SB SB/FB
11-15-90-2#3-i-2.5-2-10‡	A B	2.8 3.0	2.9	2.0 2.0	13.4	2	64300 63900	128	63900	41218 40962	40962	-	FP FP
11-15-90-2#3-i-2.5-2-15‡	A B	2.6 2.6	2.6	3.0 2.8	13.6	2	115600 114800	230	115200	74103 73590	73846	- -	FP/SB FP/SB
11-5-90-2#3-i-3.5-2-17	A B	3.6 3.6	3.6	2.1 2.0	13.4	2	107800 111500	219290	109645	69100 71500	70300	- -	SS/FP/TK SS
11-5-90-2#3-i-3.5-2-14	A B	3.8 3.9	3.8	1.6 2.8	13.3	2	92700 81800	164550	82275	59400 52400	52700	- -	FP/SS SS/FP/TK
11-5-90-6#3-i-2.5-2-20	A B	2.6 2.6	2.6	2.8 3.3	12.9	2	153100 135000	272540	136270	98100 86500	87400	0.274 -	FP/SS FP/SS
11-8-90-6#3-i-2.5-2-16	A B	2.5 2.5	2.5	2.8 1.9	13.4	2	147500 129700	266000	133000	94600 83100	85300	- -	FP/SS FP/SS
11-8-90-6#3-i-2.5-2-22	A B	2.5 2.6	2.6	2.8 2.6	13.5	2	205000 183200	369100	184600	131400 117400	118300	- -	* SS

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

*No failure; equipment malfunction

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} 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_s ksi	Long. Reinf. Layout[o]
11-8-90-0-i-2.5-2-21	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60	A12
11-8-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60	A7
11-12-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60	A12
11-12-90-0-i-2.5-2-17.5	A B	60	-	-	-	-	2.4	12	4.0	0.50	4.0	-	-	4.74	60	A6
11-12-90-0-i-2.5-2-25	A B	60	-	-	-	-	3.6	18	4.0	0.50	4.0	0.5	1	6.32	60	A11
11-15-90-0-i-2.5-2-24	A B	60	-	-	-	-	-	-	-	0.50	3.5	-	-	6.32	60	A10
11-15-90-0-i-2.5-2-10[‡]	A B	60	-	-	-	-	-	-	-	0.50	4.5	-	-	6.94	120	A13
11-15-90-0-i-2.5-2-15[‡]	A B	60	-	-	-	-	-	-	-	0.50	4.5	-	-	6.94	120	A13
11-5-90-0-i-3.5-2-17	A B	60	-	-	-	-	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60	A6
11-5-90-0-i-3.5-2-14	A B	60	-	-	-	-	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60	A6
11-5-90-0-i-3.5-2-26	A B	60	-	-	-	-	1.86	6	4.0	0.50	4.0	0.375	1	6.32	60	A11
11-8-180-0-i-2.5-2-21	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60	A12
11-8-180-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60	A7
11-12-180-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60	A12
11-5-90-2#3-i-2.5-2-17	A B	60	0.38	0.2	2	8.00	2	10	4.0	0.50	4.0	0.375	2	4.74	60	A6
11-5-90-2#3-i-2.5-2-14	A B	60	0.38	0.2	2	8.00	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60	A6
11-12-90-2#3-i-2.5-2-17.5	A B	60	0.38	0.2	2	12.00	2.4	12	4.0	0.50	4.0	-	-	4.74	60	A6
11-15-90-2#3-i-2.5-2-23	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	3.0	-	-	6.32	60	A10
11-15-90-2#3-i-2.5-2-10[‡]	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	4.5	-	-	6.94	120	A13
11-15-90-2#3-i-2.5-2-15[‡]	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	4.5	-	-	6.94	120	A13
11-5-90-2#3-i-3.5-2-17	A B	60	0.38	0.2	2	8.00	2	10	4.0	0.50	4.0	0.375	2	4.74	60	A6
11-5-90-2#3-i-3.5-2-14	A B	60	0.38	0.2	2	8.00	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60	A6
11-5-90-6#3-i-2.5-2-20	A B	60	0.38	0.7	6	4.00	1.2	6	4.0	0.50	4.0	0.375	2	4.74	60	A6
11-8-90-6#3-i-2.5-2-16	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.48	60	A14
11-8-90-6#3-i-2.5-2-22	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	2.5	-	-	6.32	60	A10

[‡] Specimen contained A1035 Grade 120 for column longitudinal steel
[o] Longitudinal column configurations shown in, Layouts A1 – A14

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
11-8-90-6#3-i-2.5-2-22b	A B	90°	Horizontal	A1035	21.9 22.0	21.9	9420	8	1.41	0.085	21.5	19.5	8.375
11-8-90-6#3-i-2.5-2-15	A B	90°	Horizontal	A1035	15.8 15.3	15.5	7500	5	1.41	0.085	21.5	19.5	8.375
11-8-90-6#3-i-2.5-2-19	A B	90°	Horizontal	A1035	19.1 19.4	19.2	7500	5	1.41	0.085	21.5	19.5	8.375
11-12-90-6#3-i-2.5-2-17	A B	90°	Horizontal	A1035	17.1 16.5	16.8	12370	37	1.41	0.085	21.5	19.5	8.375
11-12-90-6#3-i-2.5-2-16	A B	90°	Horizontal	A1035	14.8 16.0	15.4	13710	31	1.41	0.085	21.5	19.5	8.375
11-12-90-6#3-i-2.5-2-22	A B	90°	Horizontal	A1035	21.9 21.5	21.7	13710	31	1.41	0.085	21.5	19.5	8.375
11-15-90-6#3-i-2.5-2-22	A B	90°	Horizontal	A1035	22.3 22.4	22.3	16180	62	1.41	0.085	21.5	19.5	8.375
11-15-90-6#3-i-2.5-2-10a‡	A B	90°	Horizontal	A615	9.5 10.0	9.8	14045	76	1.41	0.085	21.5	19.5	8.375
11-15-90-6#3-i-2.5-2-10b‡	A B	90°	Horizontal	A615	9.5 9.8	9.6	14050	77	1.41	0.085	21.5	19.5	8.375
11-15-90-6#3-i-2.5-2-15‡	A B	90°	Horizontal	A1035	14.5 15.0	14.8	14045	80	1.41	0.085	21.5	19.5	8.375
11-5-90-6#3-i-3.5-2-20	A B	90°	Horizontal	A1035	20.5 20.3	20.4	5420	7	1.41	0.085	23.5	19.5	8.375
11-8-180-6#3-i-2.5-2-15	A B	180°	Horizontal	A1035	15.1 15.5	15.3	7500	5	1.41	0.085	21.5	19.5	8.375
11-8-180-6#3-i-2.5-2-19	A B	180°	Horizontal	A1035	19.6 19.9	19.8	7870	6	1.41	0.085	21.5	19.5	8.375
11-12-180-6#3-i-2.5-2-17	A B	180°	Horizontal	A1035	16.9 16.5	16.7	12370	37	1.41	0.085	21.5	19.5	8.375
11-12-180-6#3-i-2.5-2-17	A B	180°	Horizontal	A1035	16.8 16.8	16.8	12370	37	1.41	0.085	21.5	19.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	f_{su} psi	$f_{su,avg}$ psi	Lead Slip (Tail Slip) at Failure in.	Failure Type
11-8-90-6#3-i-2.5-2-22	A B	2.6 2.9	2.8	2.3 2.2	13.4	2	200000 191300	382100	191000	128200 122600	122400	- -	* SB/FB
11-8-90-6#3-i-2.5-2-15	A B	2.8 2.5	2.6	1.5 2.0	13.5	2	142300 108000	216600	108300	91200 69200	69400	- -	SS SS/FP
11-8-90-6#3-i-2.5-2-19	A B	2.5 2.6	2.6	2.0 1.7	13.5	2	182700 146100	290900	145400	117100 93700	93200	- -	FB/SS FB/SS
11-12-90-6#3-i-2.5-2-17	A B	2.6 3.0	2.8	1.9 2.6	13.0	2	179700 162300	323300	161600	115200 104000	103600	0.334 -	FB/SB SP/SS
11-12-90-6#3-i-2.5-2-16	A B	2.5 2.5	2.5	3.3 2.0	13.0	2	115100 127500	230390	115195	73800 81700	73800	- 0.952	SS/FP SB/FB
11-12-90-6#3-i-2.5-2-22	A B	2.9 3.1	3.0	2.4 2.8	13.3	2	200100 199200	402380	201190	128300 127700	129000	- -	SS/FB FB
11-15-90-6#3-i-2.5-2-22	A B	3.0 2.5	2.8	1.8 1.6	13.5	2	227500 195700	395600	197800	145800 125400	126800	- -	FB/SS SB/FB
11-15-90-6#3-i-2.5-2-10a‡	A B	2.6 2.8	2.7	2.5 2.0	13.4	2	83600 81800	165	82700	53590 52436	53013	- -	FP FP
11-15-90-6#3-i-2.5-2-10b‡	A B	2.8 2.8	2.8	2.5 2.3	13.0	2	76600 74600	151	75600	49103 47821	48462	 -	FP FP
11-15-90-6#3-i-2.5-2-15‡	A B	2.6 2.6	2.6	2.5 2.0	13.6	2	145700 144900	291	145300	93397 92885	93141	- -	FP FP
11-5-90-6#3-i-3.5-2-20	A B	3.8 3.9	3.8	1.8 2.0	13.1	2	150200 135300	271640	135820	96300 86700	87100	- -	SS/FP SS
11-8-180-6#3-i-2.5-2-15	A B	2.9 3.1	3.0	2.0 1.6	13.0	2	112400 111000	223400	111700	72100 71200	71600	- -	SS SS
11-8-180-6#3-i-2.5-2-19	A B	2.9 2.9	2.9	1.5 1.3	13.3	2	170000 149000	298000	149000	109000 95500	95500	- -	FB/SS FB/SS
11-12-180-6#3-i-2.5-2-17	A B	2.6 2.8	2.7	2.9 3.3	13.5	2	123100 117600	232700	116400	78900 75400	74600	- 0.379	FP FP/SB
11-12-180-6#3-i-2.5-2-17	A B	2.5 2.8	2.6	2.7 2.6	13.4	2	148900 173000	297400	148700	95400 110900	95300	- -	FP/SS SB/FB

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

*No failure; equipment malfunction

Table A.5 Cont.–Test results for specimens used in side cover analysis

Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} 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_s ksi	Long. Reinf. Layout°
11-8-90-6#3-i-2.5-2-22	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.48	60	A14
11-8-90-6#3-i-2.5-2-15	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60	A12
11-8-90-6#3-i-2.5-2-19	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60	A12
11-12-90-6#3-i-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60	A12
11-12-90-6#3-i-2.5-2-16	A B	60	0.38	0.7	6	4.00	2.4	12	4.0	0.50	4.0	0.375	1	4.74	60	A6
11-12-90-6#3-i-2.5-2-22	A B	60	0.38	0.7	6	4.00	3.06	12	4.0	0.50	4.0	0.375	2	6.32	60	A11
11-15-90-6#3-i-2.5-2-22	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	3.0	-	-	6.32	60	A9
11-15-90-6#3-i-2.5-2-10a‡	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	4.5	-	-	6.94	120	A13
11-15-90-6#3-i-2.5-2-10b‡	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	4.5	-	-	6.32	120	A9
11-15-90-6#3-i-2.5-2-15‡	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	4.5	-	-	6.94	120	A13
11-5-90-6#3-i-3.5-2-20	A B	60	0.38	0.7	6	4.00	1.2	6	4.0	0.50	4.0	0.375	2	4.74	60	A6
11-8-180-6#3-i-2.5-2-15	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60	A12
11-8-180-6#3-i-2.5-2-19	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60	A12
11-12-180-6#3-i-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	3.0	-	-	4.74	60	A6
11-12-180-6#3-i-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60	A12

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

° Longitudinal column configurations shown in, Layouts A1 – A14

Table A.6–Test results for specimens with horizontal and vertical ties

Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
8-12-90-0-i-2.5-2-12.5	A B	90°	Horizontal	A1035[c]	12.9 12.8	12.8	11850	39	1	0.073	17	10.5	8.375
8-12-180-0-i-2.5-2-12.5	A B	180°	Horizontal	A1035[c]	12.8 12.5	12.6	11850	39	1	0.073	17	10.5	8.375
8-12-90-2#3-i-2.5-2-11	A B	90°	Horizontal	A1035[c]	10.5 11.3	10.9	12010	42	1	0.073	17	10.5	8.375
8-12-90-2#3vr-i-2.5-2-11	A B	90°	Vertical	A1035[c]	10.9 10.4	10.6	12010	42	1	0.073	17	10.5	8.375
8-12-180-2#3-i-2.5-2-11	A B	180°	Horizontal	A1035[c]	11.1 10.4	10.8	12010	42	1	0.073	17	10.5	8.375
8-12-180-2#3vr-i-2.5-2-11	A B	180°	Vertical	A1035[c]	10.9 10.9	10.9	12010	42	1	0.073	17	10.5	8.375
8-12-90-5#3-i-2.5-2-10	A B	90°	Horizontal	A1035[c]	9.0 9.9	9.4	11800	38	1	0.073	17	10.5	8.375
8-12-90-5#3vr-i-2.5-2-10	A B	90°	Vertical	A1035[c]	10.3 10.2	10.2	11800	38	1	0.073	17	10.5	8.375
8-12-90-4#3vr-i-2.5-2-10	A B	90°	Vertical	A1035[c]	10.6 10.3	10.4	11850	39	1	0.073	17	10.5	8.375
8-12-180-5#3-i-2.5-2-10	A B	180°	Horizontal	A1035[c]	9.9 9.6	9.8	11800	38	1	0.073	17	10.5	8.375
8-12-180-5#3vr-i-2.5-2-10	A B	180°	Vertical	A1035[c]	11.1 10.5	10.8	11800	38	1	0.073	17	10.5	8.375
8-12-180-4#3vr-i-2.5-2-10	A B	180°	Vertical	A1035[c]	10.5 10.0	10.3	11850	39	1	0.073	17	10.5	8.375

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

Table A.6 Cont.–Test results for specimens with horizontal and vertical ties

Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	f_{su} psi	$f_{su,avg}$ psi	Lead Slip (Tail Slip) at Failure in.	Failure Type
8-12-90-0-i-2.5-2-12.5	A B	2.6 2.6	2.6	1.7 1.8	10.1	2	66000 77400	133900	66950	83500 98000	84700	0.295 0.266	FB/SB FB/SB
8-12-180-0-i-2.5-2-12.5	A B	3.0 2.5	2.8	2.1 2.4	9.6	2	74800 92300	150400	75200	94700 116800	95200	0.193 0.242	FB/SB FP
8-12-90-2#3-i-2.5-2-11	A B	2.8 2.8	2.8	2.4 1.6	9.5	2	68100 79800	137400	68700	86200 101000	87000	0.181 0.165	FP FP
8-12-90-2#3vr-i-2.5-2-11	A B	2.5 2.3	2.4	2.1 2.6	9.8	2	50700 66800	105300	52650	64200 84600	66600	- 0.130	FP/SS FP
8-12-180-2#3-i-2.5-2-11	A B	2.5 2.6	2.6	2.1 2.8	9.6	2	73700 66200	129300	64650	93300 83800	81800	- -	FP FB
8-12-180-2#3vr-i-2.5-2-11	A B	2.8 2.6	2.7	2.4 2.4	9.8	2	67100 87100	131600	65800	84900 110300	83300	- 0.369	SS/FP FB/SB
8-12-90-5#3-i-2.5-2-10	A B	2.6 2.3	2.4	3.2 2.3	9.9	2	66000 64600	129100	64550	83500 81800	81700	0.440 0.547	FB/SS SS/FP
8-12-90-5#3vr-i-2.5-2-10	A B	2.5 2.4	2.4	1.7 1.7	9.8	2	59400 64100	120400	60200	75200 81100	76200	0.236 0.246	FP FP
8-12-90-4#3vr-i-2.5-2-10	A B	2.5 2.5	2.5	1.8 2.1	9.0	2	80300 59300	118500	59250	101600 75100	75000	0.123 0.101	FP/SS FP
8-12-180-5#3-i-2.5-2-10	A B	2.3 2.8	2.5	2.3 2.6	9.9	2	63000 81400	128200	64100	79700 103000	81100	- 0.339	FP/SS FP
8-12-180-5#3vr-i-2.5-2-10	A B	2.5 2.5	2.5	1.3 1.9	9.8	2	67500 68000	135600	67800	85400 86100	85800	- 0.321	FP FB
8-12-180-4#3vr-i-2.5-2-10	A B	2.8 2.5	2.6	1.8 2.3	9.8	2	69700 68800	138400	69200	88200 87100	87600	- -	FP FP

Table A.6 Cont.–Test results for specimens with horizontal and vertical ties

Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} 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_s ksi	Long. Reinf. Layout°
8-12-90-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60	A2
8-12-180-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60	A2
8-12-90-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	2.00	-	-	3.16	60	A2
8-12-90-2#3vr-i-2.5-2-11	A B	60	0.38	0.2	2	2.67	-	-	-	0.50	2.00	-	-	3.16	60	A2
8-12-180-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	2.00	-	-	3.16	60	A2
8-12-180-2#3vr-i-2.5-2-11	A B	60	0.38	0.2	2	2.67	-	-	-	0.50	2.00	-	-	3.16	60	A2
8-12-90-5#3-i-2.5-2-10	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-12-90-5#3vr-i-2.5-2-10	A B	60	0.38	0.6	5	1.75	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-12-90-4#3vr-i-2.5-2-10	A B	60	0.38	0.4	4	2.25	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-12-180-5#3-i-2.5-2-10	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-12-180-5#3vr-i-2.5-2-10	A B	60	0.38	0.6	5	1.75	-	-	-	0.50	1.75	-	-	3.16	60	A2
8-12-180-4#3vr-i-2.5-2-10	A B	60	0.38	0.4	4	2.25	-	-	-	0.50	1.75	-	-	3.16	60	A2

° Longitudinal column configurations shown in Layouts A1 – A14