ANCHORAGE STRENGTH OF CONVENTIONAL AND HIGH-STRENGTH HOOKED BARS IN CONCRETE

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ABSTRACT

Key factors affecting the anchorage strength of hooked bars are investigated and design guidelines for the development length of hooked bars that apply to both conventional and high-strength steel and concrete are presented. In this study, 337 beam-column joint specimens were tested. Parameters included number of hooks (2, 3, or 4), concrete compressive strength (4,300 to 16,510 psi [30 to 114 MPa]), bar stress at failure (22,800 to 141,600 psi [157 to 976 MPa]), bar diameter (No. 5, 8, and 11 [No. 19, 25, and 36]), concrete side cover (1.5 to 4 in. [38 to 102 mm]), quantity of confining reinforcement in the joint region, hooked bar spacing (3 to 11 bar diameters measured center-to-center), hook bend angle (90° or 180°), placement of the hook (inside or outside the column core, and inside or outside of the column compressive region), and embedment length. Using a subset of 214 simulated exterior beam-column joints, expressions are developed to characterize the anchorage capacity of hooked bars as a function of embedment length, concrete compressive strength, bar diameter, and amount and orientation of confining reinforcement.

The results of this study show that front failure plays an important role in the behavior of hooked bars, which contrasts with the findings of previous studies. The provisions in the 2014 ACI Building Code become less conservative as the concrete compressive strength and bar diameter increase. The contribution of concrete compressive strength to the anchorage capacity of hooked bars can be represented by the concrete compressive strength to the 0.29 power, in contrast to the 0.5 power currently used in the ACI 318-14 Code. Confining reinforcement, expressed as the area of confining reinforcement per confined hooked bar, provides in an incremental rather than percentage increase in the anchorage capacity of hooked bars. Confining reinforcement parallel to the straight portion of the hooked bars contributes to the anchorage capacity of both 90° and 180°

hooked bars. The contribution of confining reinforcement oriented perpendicular to the straight portion of the hooked bar differs from that of confining reinforcement parallel to the straight portion of the hooked bar and may be similar to the contribution of confining reinforcement to the development and splice strength of straight bars. Hooked bars with 90° and 180° bend angles produce similar anchorage capacities and can be used interchangeably. Increasing concrete side cover from 2.5 to 3.5 in. (64 to 89 mm) does not increase the anchorage capacity of hooked bars. These observations are incorporated into a new design equation that allows for the conservative design of hooked bars at concrete strengths up to 16,000 psi and steel stresses up to 120 ksi, well above current Code limits.

Key words: anchorage, beam-column joints, bond and development, concrete, high-strength concrete, high-strength steel, hooks, reinforcement, reinforced concrete, side cover, bend angle, reliability, variability

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CHAPTER 1: INTRODUCTION

1.1 GENERAL

In reinforced concrete structures, the embedded reinforcing steel and surrounding concrete must be bonded together to transfer forces between the two materials. The bond between deformed steel bars and concrete is the result of chemical adhesion, friction, and bearing. Chemical adhesion results from the attraction of the cement paste to the reinforcing steel. Friction arises due to contact between the reinforcing steel and concrete when the bar moves. Bearing is provided by the deformations of the reinforcing bar bearing against the surrounding concrete. A loss in bond between reinforcing steel and concrete can lead to sudden failure of the concrete member.

When reinforcing steel is terminated, adequate length must be provided to develop the yield strength of the steel at the critical section. This development length is a function of the characteristics of the reinforcing bar and surrounding concrete. In most cases, the development length can be provided within the member. There are cases, however, where the straight bar development length cannot be provided within the member, such as at an external beam-column connection. In this case, the bar must be anchored by another means. This is generally accomplished by the use of a hooked bar with a bend angle of either 90° or 180°. The anchorage provided by a hooked bar is generally believed to be shared by the straight and bent portions of the bar, but as the tensile load is increased and the bond along the straight portion is degraded, the bent portion of the bar becomes increasingly more active in resisting the tensile load.

It is fairly well understood that the bond strength of straight deformed reinforcing bars is a function of concrete cover, bar size, bar spacing, concrete compressive strength, confining reinforcement, and relative rib area (ratio of area of projections to area of bar). For hooked bars, the factors affecting bond strength are not as well understood. The bearing of the hook on the concrete adds another level of complexity to the problem of hooked bar anchorage. Based on prior studies, it is believed that the anchorage capacity of hooked bars is a function of embedment length, concrete compressive strength, and bar size. Relatively little is understood, however, about the anchorage of hooks in high strength concrete or of hooks made with high strength steel. The current provisions of the ACI 318 Building Code, ACI 349 Code Requirements for Nuclear Safety-Related Concrete Structures, and AASHTO Bridge Specifications for the development length of hooked bars are based on tests reported in 1977. These tests involved reinforcing steel with yield strengths of 64 and 68 ksi and concrete compressive strengths between 3,750 and 5,100 psi (26 and 35 MPa). Since the time of those tests, the use of reinforcing steel with yield strengths of 75 and 80 ksi (517 and 552 MPa) has become common, as well as using concrete with compressive strengths between 10,000 and 15,000 psi (69 and 103 MPa). Bars with yield strengths up to 120 ksi (830 MPa) are now available; however, the Code limits the yield strength to 80 ksi (552 MPa), except for steel used as spiral reinforcement in columns, where the limit is 100 ksi (690 MPa). The design expressions allow the use of steel strengths greater than those used to develop those design expressions, but neither the accuracy nor the safety of those expressions have been validated for high strength steel. In addition, the Code limits the use of high-strength concrete to 10,000 psi (69 MPa) for use in calculating straight and hooked bar development, but the safety of using higher-strength concrete has not been validated for hooked bars. The use of high-strength concrete and steel allows the reduction in member sizes and congestion of reinforcing steel, as well as a greater useable floor space. Thus, it is important to understand the behavior of high-strength steel and concrete, especially when developing reinforcing bars.

This project focuses on expanding the knowledge of hooked bar development. The effects of high-strength steel and concrete are studied, as well as the effects of embedded length, concrete cover, bend angle, bar size, confining reinforcement, hook placement (inside or outside the column core or column compression region), and number and spacing of hooked bars. Equations that characterize hook anchorage capacity are developed, and using probability techniques, an appropriate capacity reduction factor (ϕ) is developed to formulate a design equation.

1.2 OVERVIEW OF PREVIOUS WORK

1.2.1 Bond Strength

The first documented study on bond of reinforcing bars was performed by Abrams (1913). In his study, 1,500 pullout specimens and 110 beam specimens were tested. Abrams tested both plain and deformed reinforcing bars. For plain bars, he found that bond is a combination of adhesion prior to slipping and friction after slipping, with adhesion being the more significant factor.

In his tests on deformed bars, Abrams found bond behavior to be very similar to that of plain bars until the initial slip occurred. Once slip occurred, Abrams observed that the deformations become active in resisting slip of the bar. Bond strength is then principally provided by bearing between the projections and the concrete. The bearing stress is resisted by shear strength of the concrete enveloping the projections. Abrams also found that spiral reinforcement surrounding the bars being developed greatly increases the bond resistance of deformed bars. When adequate spiral reinforcement is used to prevent splitting, the shearing resistance of the concrete key [the concrete between the ribs (Figure 1.1)] becomes the limiting factor for bond resistance. A failure of this type is known as bar pullout. The spacing, height, and angle of the ribs (Figure 1.1) are all important in the bond resistance. These geometric properties help provide a good balance of bearing to shear forces in the concrete. Abrams recommended a ratio of area of projections to area of bar of 0.20 to 0.25.

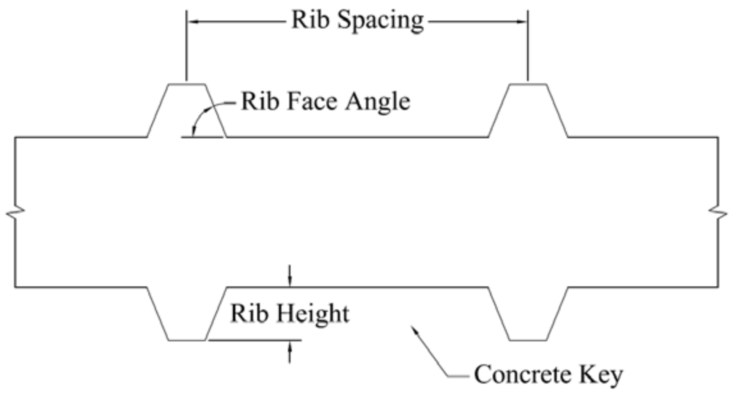


Figure 1.1 Geometry of deformed reinforcing bars

Abrams (1913) also tested pull-out specimens of plain bars with hooks. Two main groups of hooked bars were used, ¾ and 1-in. (19 and 25-mm) plain round bars with the free end bent to ¼ or ½ the circumference of a 3 in. (76 mm) diameter circle and 2-in. (51-mm) lengths at the free end of a bar bent at 45°, 90°, 135°, or 180° angles with respect to the projected axis of the bar. The specimens contained spiral reinforcement to prevent splitting. Abrams found that, when the load reached 70 to 90% the maximum, there was evidence of the straightening out of the hooks, except for those with 180° bends. The hooked bars had high resistance to pullout due to the bearing stresses developed in the concrete ahead of the bends. Abrams found that, although the specimens were reinforced against splitting, there was significant damage to the concrete resulting from high bearing and bursting stresses at the bend of the hook. Abrams suggested the use of circular bends with larger radii to help mitigate the effects of the bearing and bursting stresses.

Menzel (1939) used pullout tests to find the influence of a number of factors on the bond strength of reinforcing bars. These factors include the bar surface, embedment length, type and position of deformations, concrete cover, and position of bar with respect to placing of the concrete. The major conclusions from Menzel's study are that bond resistance increases with increasing surface roughness, embedment length, and concrete cover. He also found that transverse deformations (transverse to the longitudinal axis of the bar) provide greater bond resistance than longitudinal ribs. The transverse deformations provide bearing area for mechanical interaction in the direction of the pullout force. Menzel found that the casting position has an effect on the pullout strength of deformed bars. Vertical bars were strongest when the direction of concrete flow during casting was opposite to the direction of pull during testing and weakest when the direction of flow and pull were the same. Thus, bars pulled vertically upward exhibited higher bond forces than bars pulled vertically downward. The strength of the bars cast horizontally was intermediate to the strength of the bars cast vertically. This difference in strengths is attributed to the settlement and bleeding of concrete below the bar. The settlement and bleed water result in poorer quality concrete just below the bar or deformations depending on casting position.

Clark (1946, 1949) performed pullout and beam tests on 17 deformed bars with different deformation patterns. The variables were depth of concrete under the bar, embedment length, concrete compressive strength, and bar diameter. His work is the basis for the deformation patterns used in the United States today. Clark evaluated the bond characteristics by comparing the bond forces developed at preselected values of bar slip for both the pullout and beam tests. Based upon his work, tentative specification ASTM A305-47T was developed and later modified (ASTM A305-49) to include maximum average spacing of the deformations of 70% of the nominal bar diameter and a minimum height of deformations of 4% for bars with a nominal diameter of ½ in. (13 mm) or smaller, 4.5% for bars with a diameter of $^5/_8$ in. (16 mm), and 5% for larger bars. In addition to his recommendations for rib spacing and height, Clark recommended a ratio of shearing area between ribs (bar perimeter times distance between ribs) to a rib bearing area (projected area of rib) of a maximum of 10 and optimally 5 or 6. The inverse of this criterion is used today and is known as the relative rib area R_r. Taking the inverse of Clark's recommendations, the optimum relative rib area is 0.17 to 0.20 with a minimum of 0.10. Clark's recommendations for relative rib area were not adopted in ASTM A305-49. Deformed bars today have relative rib areas from 0.057 to 0.084 (Choi et al. 1990). The most significant impact of Clark's work was to remove the weakest deformation patterns rather than to find the optimum deformation patterns. In addition, Clark concluded that top cast bars had lower bond strength than bottom cast bars.

Studies by Lutz, Gergely, and Winter (1966) and Lutz and Gergely (1967) on the bond strength of deformed reinforcing bars indicate that the contributing factors to bond are chemical adhesion, friction, and mechanical interaction between the concrete and steel. In these studies, tests were performed on reinforcing bars with single and multiple ribs. According to Lutz et al. (1966), increasing the height of the rib can cause an increase in the bond strength and slip resistance. This is due to the reduction of the bearing pressure on the rib. Ribs with face angles (Figure 1.1) of 30° to 40° will slip relative to the adjacent concrete by wedging action, whereas ribs with face angles of 40° to 45° will slip by crushing the concrete under the rib. It was found that a reduction in the rib spacing could significantly improve the bond strength and slip resistance. It was also found that with increasing confinement, either by the use of stirrups or concrete cover, the ultimate bond force per unit length of the bar depends increasingly on the bar diameter.

Skorobogatov and Edwards (1979) conducted a study on bars with rib face angles of 48.5° and 57.8° with respect to the axis of the bar. The major conclusion of their study was that the rib face angle does not affect the maximum bond strength due to the observation that the large face angle will produce a wedge of crushed concrete that will reduce the effective face angle of the ribs. This finding supports the work by Lutz et al. (1966).

Studies by Donahey and Darwin (1985) and Brettmann, Darwin, and Donahey (1986) investigated the effect of concrete slump, consolidation practice, concrete cover, bar position, and the use of superplasticizer on the bond capacity of reinforcing bars. They observed that for concrete with the same compressive strength, an increase in slump led to a decrease in bond capacity for top-cast bars, most likely due to increased bleed. They also observed that high-density internal vibration improves the bond strength and that the amount of improvement increases with increasing slump, suggesting that greater consolidation may overcome some of the extra settlement that occurs with high slump concrete. Bars with a higher concrete cover had a higher bond strength, which was found to be independent of bar size, slump, and vibration density. They observed that as the amount of concrete below the bar increases, the bond strength decreases. They also found that the effect of casting position on the bond strength was greatly influenced not only by the amount of concrete below the bar but also above the bar. They refer to this as the upper surface effect, which occurs when there is a small (< 3 in. [76 mm]) cover above the bar and more than 2 in. (51 mm) of concrete below the bar. Superplasticizer was used to obtain a high slump concrete with temperatures of 53°F or 84°F (12°C or 29°C). Brettmann et al. (1986) found that the use of concrete with superplasticizer, in general, decreases the bond capacity when compared with concrete with medium-slump and no superplasticizer. This decrease in bond strength is exaggerated when the concrete is not vibrated or the concrete temperature is low.

A study on the bond performance of reinforcing bars in high strength concrete was performed by Azizinamini, Stark, Roller and Ghosh (1993) and Azizinamini, Chisala, and Ghosh (1995). Azizinamini et al. (1993) hypothesized that the assumption that at ultimate strength the bond stress distribution is uniform over the development length is incorrect when high strength concrete is used. To test the bond performance in high strength concrete, twelve beam splice specimens containing No. 11 (No. 36) reinforcing bars were tested. A failure hypothesis was presented that explains the observed behavior of the tests with high strength concrete. This hypothesis is shown graphically in Figure 1.2. As the bar is placed in tension, the first rib begins to bear on the concrete. The horizontal component of this bearing force produces bond stress. As the load increases (Figure 1.2b), crushing of the concrete in front of the ribs occurs and allows the adjacent rib to start bearing on the concrete and resist the applied load. It is assumed that at the ultimate applied load, the bond stress distribution is uniform, implying that all the ribs of the reinforcing bar are active in bearing against the concrete (Figure 1.2c). Azizinamini et al. reasoned that for normal strength concrete this is a rational assumption, but for high strength concrete, the distribution of bond stress is not uniform because increasing the compressive strength of concrete results in a greater increase in bearing capacity than tensile capacity. Thus, the higher bearing capacity of the concrete keys (Figure 1.1) results in failure by splitting of concrete induced by ring tensile stresses before uniform bond distribution can occur. Because of this non-uniform bond stress distribution, a longer splice length may not work to develop the full yield strength of the bar when high strength concrete and small cover are used. In this case, transverse reinforcement over the splice region is needed to help confine the splitting stresses.

Azizinamini et al. (1993) found that top-cast bars in high-strength concrete have a slightly higher bond capacity than bottom cast bars. This is in contrast to studies (Menzel 1939, Donahey and Darwin 1985, and Brettmann et al. 1986) in which top-cast bars exhibited lower bond capacity. A possible explanation given by Azizinamini et al. (1993) is that the bleeding of concrete under the bar will result in lower quality concrete underneath the reinforcement that will limit the bearing capacity of the concrete and allow more ribs to participate in resisting the tensile load. The increase in bond capacity is produced by the participation of more ribs.

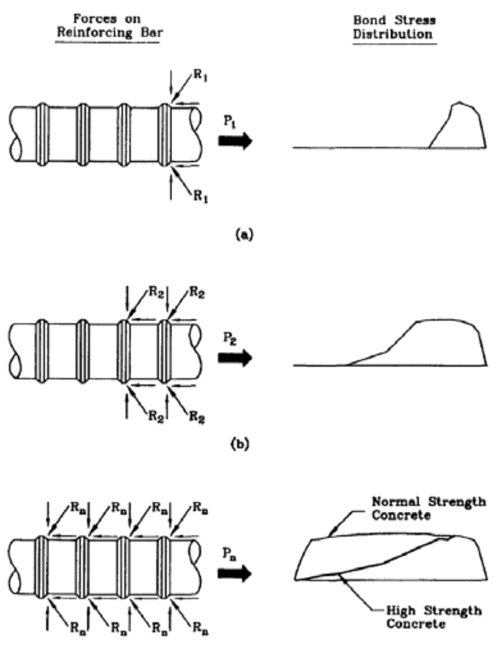


Figure 1.2 Idealization of behavior of deformed reinforcing bars embedded in concrete and subjected to tension (figure from Azizinamini et al. (1995))

Darwin and Graham (1993) used beam-end specimens (now described in ASTM A944-10) to study the effect of deformation pattern on the bond strength of reinforcing bars. They tested 1-

in. (25-mm) diameter machined bars with relative rib areas of 0.20, 0.10, and 0.05. Deformation heights of 0.05, 0.075, and 0.10 in. (1.3, 2.0, and 2.5 mm) were used and deformation spacings ranged from 0.26 to 2.2 in. (6.6 to 56 mm). They also tested conventional reinforcing bars with a relative rib area of 0.07. Three levels of confinement were used: (1) 2-in. (51-mm) cover without transverse stirrups, (2) 2-in. (51-mm) cover with confining transverse stirrups, and (3) 3-in. (76-mm) cover without confining transverse stirrups. Darwin and Graham (1993) found that independent of the specific combination of rib height and rib spacing, bond load-slip response is a function of the relative rib area and that for all conditions of confinement, the initial stiffness of the load-slip curves increases with increasing relative rib area. When splitting failure governs (that is, in case of low confinement) bond strength is independent of the deformation pattern. When additional confinement is provided either by transverse reinforcement or additional concrete cover, bond strength increases relative to bars with less confinement, and the magnitude of the increase in bond strength increases with the relative rib area.

Darwin, Zuo, Tholen, and Idun (1996) performed a statistical analysis of 133 splice and development specimens in which the bars did not have confining transverse reinforcement and 166 specimens in which the bars were confined by transverse reinforcement to develop a design expression for splice and development length. The design expression is a function of concrete strength, cover, bar spacing, development/splice length, transverse reinforcement, and geometric properties of the developed/spliced bars. The analyses demonstrated that the relationship between development or splice length and bond force is linear but not proportional, meaning that to increase the bond force by a given percentage, the development/splice length must be increased by more than that percentage. Darwin et al. (1996) found that $f_c'^{1/2}$ does not accurately represent the effect of concrete compressive strength on the bond strength, but rather the ¼ power is a better representation of the contribution of the concrete based on the analysis of concrete strengths ranging from 2,500 to 16,000 psi (17 to 110 MPa). The effect of transverse reinforcement is a function of the number of transverse reinforcing bars that cross the developed/spliced bar, the area of the transverse reinforcement, the number of bars developed or spliced at one location, the relative rib area of the developed/spliced bar, and the size of the developed/spliced bar. The effect of transverse reinforcement, however, does not depend on the yield strength of the transverse reinforcement. The design expressions developed by Darwin et al. (1996) apply to both development length and splice length, which was a departure from ACI 318-95, as well as the current ACI Code (ACI Committee 318 2014), where the development length is multiplied by 1.3 to find the splice length of Class B splices (splices in which the area of steel provided is less than two times the area of steel required or where more than 50% of the steel is spliced).

Zuo and Darwin (2000) expanded on the work of Darwin et al. (1996). They investigated the effects of concrete strength, coarse aggregate quantity and type, and reinforcing geometry on splice strength. They tested 64 splice specimens with reinforcing bars with 10 different deformation patterns with relative rib areas ranging from 0.069 to 0.141, concrete strengths ranging from 4,250 to 15,650 psi (39 to 108 MPa), and quantities of basalt and limestone coarse aggregate ranging from 1,586 to 1,908 lb/yd^3 (941 to 1,130 kg/m^3). Zuo and Darwin (2000) found that for splices not confined by stirrups, the results showed a difference in splice strength based on the type of coarse aggregate, regardless of coarse aggregate quantity or concrete strength. The increase in splice strength with the higher strength aggregate was attributed to the higher fracture energy provided by the basalt, which resulted in an increased resistance to crack propagation that delayed splitting failure and increased the splice strength (Kozul and Darwin 1997, Barham and Darwin 1999). Like Darwin et al. (1996), Zuo and Darwin found that $f_c'^{1/4}$ accurately represents the contribution of the concrete strength on bond strength in specimens with no confining transverse reinforcement. For specimens with transverse reinforcement, it was found that the quantity of coarse aggregate can have a significant effect on the contribution of the steel to the bond strength, with higher quantities producing a greater contribution of the transverse reinforcement to the splice strength. For splices with transverse reinforcement, $f_c'^{3/4}$ characterizes the contribution of the concrete strength on the additional strength provided by the reinforcement. Zuo and Darwin (2000) also found that splice strength of bars confined by transverse reinforcement increases with an increase in relative rib area and bar diameter.

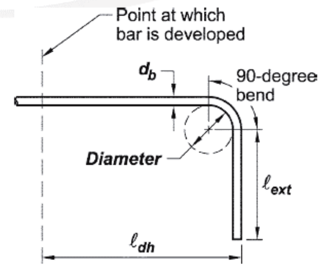
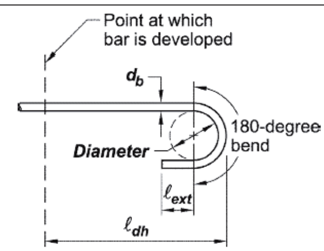
Seliem et al. (2009) studied the bond characteristics of ASTM A1035 reinforcing bars using large-scale beam-splice specimens with normal-strength concrete. The parameters studied were splice length, bar size, concrete cover, concrete strength, and level of confining transverse reinforcement. A total of 69 beam-splice specimens were tested. The results indicate that using longer splice lengths without confining transverse reinforcement is not an efficient way to develop high stress levels. The bond stresses at the lead end of a splice begin to drop off before the bond along the rest of the splice can be fully developed. Thus, it is not possible to mobilize high bond stresses along the entire length of a long splice. When transverse reinforcement is added, however, higher stresses can be developed along the splice length. The addition of transverse reinforcement also increases the ultimate load and corresponding deflection.

According to these studies on straight bar development, the major factors affecting the bond between reinforcing steel and concrete are development/splice length, degree of confinement, concrete compressive strength, relative rib area, bar position, and degree of vibration, especially for top bars and high slump concrete. Other factors not mentioned in these studies are the use of epoxy coating for bars in concrete subject to corrosive environments and lightweight concrete. Epoxy coating, in addition to reducing the friction between the concrete and steel, reduces the effective rib height and spacing. This corresponds to a decrease in bond capacity. Lightweight concrete is weaker in tension and shear than normalweight concrete with an equivalent compressive strength. This reduced tensile and shear strength results in a lower bond capacity.

1.2.2 Standard Hooked Bars

Many times, for example at exterior beam-column joints, the member dimensions will not be adequate for straight development to anchor a reinforcing bar. In many of these cases, hooks are placed at the end of the bars to provide the required anchorage. Hooked bars achieve anchorage through a combination of bond and direct bearing of the hook on the concrete.

The ACI Building Code provides standard dimensions for hooks with 90° and 180° bends, shown in Figure 1.3. Throughout this report a hook that meets the dimensions specified in the ACI Code will be referred to as a “standard hook.”

Type of standard hook	Bar size	Minimum inside bend diameter, in.	Straight extension[1] ℓ_{ext}, in.	Type of standard hook
90-degree hook	No. 3 through No. 8	$6d_b$	$12d_b$	
	No. 9 through No. 11	$8d_b$		
	No. 14 and No. 18	$10d_b$		
180-degree hook	No. 3 through No. 8	$6d_b$	Greater of $4d_b$ and 2.5 in.	
	No. 9 through No. 11	$8d_b$		
	No. 14 and No. 18	$10d_b$		

[1]A standard hook for deformed bars in tension includes the specific inside bend diameter and straight extension length. It shall be permitted to use a longer straight extension at the end of a hook. A longer extension shall not be considered to increase the anchorage capacity of the hook.

Figure 1.3 Standard hook details (figure from ACI 318-14)

The stresses in the region of a standard hook are shown in Figure 1.4. The concrete in front of the hook is typically crushed at full development of the bar (Minor and Jirsa 1975). For 90° hooks, the hook tends to be pulled straight through the bend of the bar; thus, it is important that the tail of the hook be well confined to avoid spalling of the cover behind the hook, known as tail kickout. For 180° hooks, the hook tends to be pulled forward as a unit without slipping around the bend of the hook. According to studies on hooked bar anchorage, an anchorage failure of a hooked bar typically involves spalling of the side concrete cover resulting from cracks that form in the plane of the hook. Test results from the current study, however, suggest that the failure is more three-dimensional in that cracks originating from a hooked bar are not only splitting cracks in the plane of the hook but also form outside the plane of the hook so that the failure surface is a cone of concrete being pulled out the front of the column. For small forces, the straight portion of the bar is active and resists the tensile load in much the same way as straight bars. Once the splitting cracks develop along the straight length, the hook starts to engage the concrete and create the cone shaped failure surface. This behavior under small loads was first recognized by Minor and Jirsa (1975). Minor and Jirsa (1975) found that the initial force applied to a hooked bar is transferred to the concrete by the lead end of the hook and anchorage stresses over the tail of the hook are negligible.

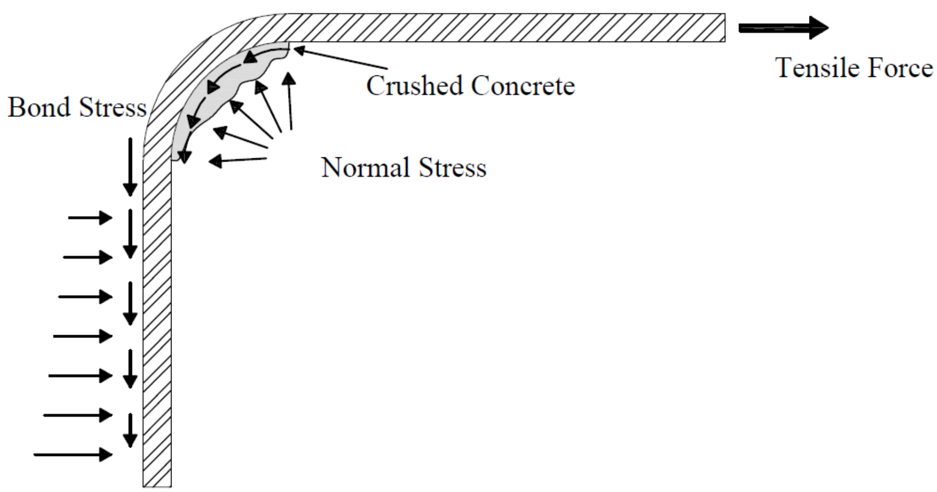


Figure 1.4 Stresses in region of a hooked bar (figure adapted from Minor and Jirsa 1975)

Minor and Jirsa (1975) tested a total of 80 specimens. The test parameters were bar size (No. 5, 7, and 9 [No. 16, 22, and 29]), bend angle (0°, 45°, 90°, 135°, and 180°), and radius of bend (1.0 in. to 5.0 in. [25 mm to 127 mm]). All specimens contained one bar in a concrete block with no confining transverse reinforcement. Bond was prevented over a length *c* by a loose-fitting plastic tube that was sealed to prevent cement paste from entering the tube, with *c* equal to 6 in., 8 in., or 7.5 in. (152, 203, 191 mm) for No. 5, 7, or 9 bars (No. 16, 22, or 29), respectively. This "bond breaker" started at the point of horizontal tangency of the bend of the hook and continued along the straight portion of the bar to the edge of the concrete block. The concrete compressive strength for all specimens containing No. 5 (No. 16) bars ranged from 2,400 to 5,500 psi (17 to 38 MPa) and the bonded length ranged from 1.6 in. to 6.0 in. (41 to 152 mm). For the specimens containing No. 7 (No. 22) bars, the range of the compressive strength of the concrete was 3,500 to 6,600 psi (24 to 46 MPa) and the bonded lengths ranged between 4.3 in. and 8.5 in. (109 mm and 216 mm). For the specimens containing No. 9 (No. 29) bars, the compressive strength ranged from 2,700 to 3,900 psi (19 to 27 MPa) and the bonded length was 8.3 in. (211 mm) for all specimens. The bonded length was measured from the point of horizontal tangency of the bend of the hook and followed the curve of the hook.

Minor and Jirsa (1975) found that for equal bond length to bar diameter ratios, both a larger angle of bend and smaller ratio of radius of bend to bar diameter contribute to greater bar slip for a given stress. These results show that it is better to use 90° hooks than 180° hooks in order to reduce slip and maintain joint stiffness.

Marques and Jirsa (1975) tested 22 specimens that simulated a typical exterior beam-column joint. Each specimen contained either two No. 7 (No. 22) or two No. 11 (No. 36) hooked bars with 90° or 180° bend angles. The effects of axial load, hooked bar placement (inside or outside the column longitudinal bars), concrete side cover, lateral confining transverse reinforcement in the joint region, and embedment length of the hooked bar were investigated. The specimens were cast in concrete with compressive strengths of 3,600 to 5,100 psi (25 to 35 MPa). Nominal axial loads of 135, 270, 420, or 540 kips (600, 1,200, 1,870, or 2,400 kN) (corresponding to a range in stress of 750 to 3,000 psi [5.2 to 21 MPa]) were used to investigate the effect of axial confinement on the anchorage capacity of the hooked bars. For the specimens with transverse reinforcement in the joint, No. 3 ties spaced at 2.5 in. or 5 in. (64 mm or 127 mm) were used. The hooked bars were tested both inside and outside the column longitudinal steel with either 1½ or $2^7/_8$ in. (38 or 73 mm) side cover. The clear spacing between the hooks ranged from 3.4 to 7.25 in. (86 to 184 mm). Hydraulic jacks were used to apply the load for both the axial compression and the hooked bars.

Cracking first occurred on the front face of the column with cracks radiating outward from the hooked bars. Cracks on the sides of the specimen then appeared as loading was increased. In general, failure was sudden and resulted in the entire side face of the column spalling. The slip between the bar and the concrete produced splitting cracks, which progressively travelled backward until reaching the bend of the hook. At failure, the straight lead embedment was not active in transferring any stress to the concrete. This induced large compressive stresses at the inside surface of the bend and produced a stress condition that tended to split the concrete, adding to the splitting caused by the straight lead embedment. Near failure and as slip progressed, the hook acted like a wedge forcing the concrete side cover to spall.

Marques and Jirsa concluded that variations in axial load make little difference in failure load and behavior of hooked bars and that there are no significant differences in behavior between hooks with 90° and 180° bend angles. The placement of the hooked bars (inside or outside the column core) had very little influence on the type of failure or the stress at failure, but the thickness of the concrete cover had a significant effect on the slip and stress at failure. If the hooked bars, however, are placed inside the column core and a 1½ in. (38 mm) clear cover on the column reinforcement is maintained, the effect of concrete cover will not be as significant. It was found that increasing the total embedment length increases the capacity of the hooked bar. For the specimens with No. 11 (No. 36) hooked bars and ties through the joint, the stress reached yield before failure in all cases, indicating that closely spaced ties are especially beneficial for large anchored bars. They also hypothesized that a combination of ties through the joint and column bars outside the hooks would further increase the capacity of the hooks, but such a combination was not tested.

Based on their findings, Marques and Jirsa proposed the following design equation:

$$f_h = 700(1-0.3d_b)\psi\sqrt{f_c'} \leq f_y \tag{1.1}$$

where f_h is the tensile stresses developed in a standard hook in psi, d_b is the diameter of the hooked bar in in., and f_y is the yield strength of the hooked bar in psi. The value of ψ ranges from 1.0 to 1.8 depending on the amount of lateral confining transverse reinforcement provided. If additional development length is required, the straight lead embedment length ℓ_l measured from the critical section to the beginning of the hook, can be calculated through Eq. (1.2):

$$\ell_l = \left(\frac{0.04A_b\left(f_y - f_h\right)}{\sqrt{f_c'}}\right) + \ell' \tag{1.2}$$

where ℓ' is the greater of $4d_b$ or 4 in. and A_b is the area of the hooked bar. The first term in Eq. (1.2) is the length of straight bar needed to develop a stress of $f_y - f_h$ in accordance with the provisions of ACI 318-71. Thus, the calculated hooked bar anchorage length is a combination of straight bar development length and the stress that can be developed by the hook.

Pinc, Watkins, and Jirsa (1977) tested 16 beam-column joint specimens, four with normalweight concrete and No. 9 (No. 29) bar hooks, four with normalweight concrete and No. 11 (No. 36) bar hooks, two with lightweight concrete and No. 7 (No. 22) bar hooks, and six with lightweight concrete and No. 11 (No. 36) bar hooks. Each specimen was cast with two hooked bars. The columns were 12 in. (305 mm) wide with different depths depending on the lead embedment length of the hooked bar. For the No. 9 (No. 29) bar specimens, the column dimensions varied from 12×12 in. to 12×21 in. (305×305 mm to 305×533 mm), and for the No. 11 (No. 36) specimens, the column dimensions varied from 12×15 in. to 12×24 in. (305×381 mm to 305×610 mm). The column dimensions increased in 3 in. (76 mm) increments. No lateral confining transverse reinforcement was used in the hook region for any of the specimens. Concrete strengths ranged from 3,600 to 5,400 psi (25 to 37 MPa). A constant side cover of $2^7/_8$ in. (73 mm) was used for all specimens, and the clear spacing of the hooked bars ranged from 3.4 to 4.0 in. (86 to 102 mm). During the test, a constant axial load was applied to the specimen. The axial load varied from 108 to 230 kips (480 to 1,020 kN) depending on the specimen corresponding to a range in stress of 640 to 800 psi (4.4 to 5.5 MPa).

The load transfer and failure patterns observed by Pinc et al. (1977) were very similar to those observed by Marques and Jirsa (1975). Crack formation followed a similar pattern for all specimens. As the tensile load was applied, the first crack appeared on the front face of the specimen radiating from the anchored bars followed by vertical cracks that terminated in the compression zone of the beam. Horizontal cracks also originated from the anchored bars, forming a crack extending from the bars and out to the edges of the specimen. In all cases, failure was sudden, with the load dropping immediately, accompanied by severe cracking and spalling of the side cover. At failure, no stress was being transferred to the concrete by the lead embedment, but rather all the stress was being transferred through the bend and tail of the hook, although the stress in the tail of the hook was generally less than 20 ksi (138 MPa). Pinc et al. (1977) concluded that failure of hooked bars was primarily the result of loss of side cover rather than by pulling a wedge of concrete out the front face of the column. Based on their work and the work done by Marques and Jirsa (1975), Pinc et al. (1977) concluded that the principal factors affecting the strength of the anchored bars are lead embedment and degree of lateral confinement of the joint. Pinc et al. (1977) proposed a design equation for hooked bars that no longer considered the lead length as separate from the hook. Their proposed equation is given by:

$$\ell_{dh} = \frac{0.02 d_b f_y}{\psi \sqrt{f_c'}} \tag{1.3}$$

where ℓ_{dh} is the development length of a hooked bar in in., d_b is the diameter of the hooked bar in in., f_y is the yield strength of the hooked bar in psi, and f_c' is the concrete compressive strength in psi. The value of ψ ranges from 1.0 to 1.8 depending on cover and transverse reinforcement provided to the hooked bars.

Soroushian et al. (1988) tested seven beam-column joint specimens with 90° standard hooks. The main parameters of the test were hooked bar diameter, confining transverse reinforcement in the joint, and concrete compressive strength. One specimen contained two No. 6 (No. 19) hooked bars, five specimens contained two No. 8 (No. 25) hooked bars, and one specimen contained two No. 10 (No. 32) hooked bars. All anchored bars were cast inside the column core in specimens with 12×14 in. (305×356 mm) cross sections. The concrete compressive strength ranged from 3,780 to 6,050 psi (26 to 42 MPa). A plastic tube was used to prevent bonding of the concrete to the anchored bar along the straight portion of the bar so that the tensile loads were only resisted by the hooked portion of the bar. A plastic sheet was placed horizontally at the level of the hooked bars to simulate the radial cracks that would have occurred if the straight portion of the bar had been bonded to the concrete. Confining transverse reinforcement in the joint region consisted of

No. 3 or No. 4 (No. 10 or 13) bars spaced at 3 or 4 in. (76 or 102 mm) in accordance with the requirements in ACI 318-83 for reinforced concrete frames in high-seismic risk zones.

The load was applied using two hydraulic actuators bearing on the concrete column, with one above and one below the anchored bars. Cracking patterns were similar for all specimens with cracks starting in the plane of the two anchored bars at approximately half the ultimate load. The cracks continued to grow and extend along the hooked bars as the load increased. Cracks normal to the plane of the hooks appeared on the front face of the column at higher loads and as the ultimate load was approached, the specimens exhibited a tendency to expand in the direction normal to the plane of the hooks. Spalling of the concrete cover was determined to be the cause of failure. Confining transverse reinforcement was also found to have increased the anchorage capacity of the hooked bars. Soroushian et al. (1988) concluded that hook anchorage capacity increases with increasing bar diameter and confining transverse reinforcement in the joint region. They also concluded that the reduction of clear spacing between the bars might adversely affect the anchorage strength of the hooked bars, and that concrete compressive strength did not significantly influence the behavior or anchorage capacity of hooked bars.

Hamad et al. (1993) tested 24 beam-column joint specimens, 12 with epoxy-coated hooked bars and 12 with conventional hooked bars. The specimens were similar to those tested by Marques and Jirsa (1975), with two hooks cast in a short column. The main parameters were bar size (No. 7 and No. 11 [No. 22 and 36]), concrete compressive strength (2,570 to 7,200 psi [18 to 50MPa]), concrete side cover ($2^7/_8$ in. and $1^7/_8$ in. [73 mm and 48 mm]), hook bend geometry (90° and 180°), and amount of confining transverse reinforcement in the joint region (no reinforcement, No. 3 [No. 10] bars at 6 in. [152 mm] on center, and No. 3 [No. 10] bars at 4 in. [102 mm] on center). Two column sizes were used based on the embedment length of the anchored bars–12×12 in. and 12×15 in. (305×305 mm and 305×381 mm] Cracking patterns were similar for all specimens with the first crack appearing in the vicinity of the assumed compression zone of the beam and extending downward and upward at approximately 45° angles. Cracks also appeared in the side cover near the bent portion of the hooked bar. Cracks were seen on the front face of the column spreading horizontally and vertically from the hooked bars. At failure, the cracks widened and increased in number. Failure was sudden with the load dropping immediately to a fraction of the ultimate level. In specimens with 90° hooks, Hamad et al. reported the formation of horizontal cracks on the back of the specimen near the tail of the hook. They felt that this was the result of the tendency of the hooked bars to straighten and the tail of the hook to kick out. The cracks were small, however, implying that a 2-in. (51-mm) cover on the tail of the hook is sufficient for design purposes. Hamad et al. (1993) found that anchorage capacity increases with concrete compressive strength, side cover, and amount of confining transverse reinforcement. They also observed that No. 7 (No. 22) hooked bars consistently had less slip at a given stress than No. 11 (No. 36) hooked bars; 90° hooked bars were found to have less slip at high loads than companion 180° hooked bars; and when epoxy coating was used, the hooked bars consistently developed lower anchorage capacities than uncoated hooked bars. Unlike Marques and Jirsa (1975) who found no significant difference in capacity between 90° and 180° hooked bars, Hamad et al. (1993) found that 90° hooked bars developed higher anchorage capacities than 180° hooked bars.

Joh, Goto, and Shibata (1993) performed tests on 19 beam-column joints. The main variables were embedment length, distance to the reaction representing the compression zone of the beam, column depth, spacing of the bars, concrete side cover, number of bar layers, lateral reinforcement ratio in the joint, column axial stress, loading type (cyclic or monotonic), and concrete compressive strength. All hooked bars had a diameter of 19 mm (0.75 in.) and a bend angle of 90°. Each specimen contained four bars in one layer, except for one specimen, which contained eight bars in two layers of four. The center-to-center spacing of the bars ranged from 47.5 to 66.5 mm (1.87 to 2.62 in.), and the cover to the center of the bar ranged from 64.5 to 114.5 mm (2.54 to 14.5 in.). The embedment length ranged from 133 to 330 mm (5.24 to 13.0 in.). The concrete compressive strength ranged from 316 to 754 kgf/cm^2 (4,490 to 10,720 psi). The distance to the compression zone of the assumed beam ranged from 228 to 428 mm (8.98 to 16.9 in.), and the transverse reinforcement ratio of the joint was either 0.2%, 0.4%, or 0.8%. The column axial stress ranged from zero to 132.7 kgf/cm^2 (1,890 psi).

Joh et al. (1993) characterized beam-column joint failures under monotonic loading into three main failure modes—"side split failure," "local compression failure," and "raking-out failure." A diagram of each failure mode is shown in Figure 1.5. A side split failure (Figure 1.5a) will occur when the concrete cover on the side of the hooked bar is small enough that the cover will spall off near the bend of the hook with the shape of a disk. This is the result of the wedging action of the bend of the bar, which causes splitting stresses in the side cover. Joh et al. (1993) classified the failure type of the specimens in the study by Pinc et al. (1977) as side split failures. A local compression failure (Figure 1.5b) occurs when the side cover is large, there are only a few hooked bars that are spaced far apart so that the raking out failure is prevented, and the radius of the bend of the hook is "too small." This is a gradual failure mode, and is prevented by the use of minimum bend diameters. The final failure mode discussed by Joh et al. (1993) is the raking-out failure (Figure 1.5c). A raking-out failure is caused by having several closely spaced hooked bars and/or providing a short embedment length. In this failure mode, all hooked bars lose their resistance at the same time. A crack will develop along the bend and tail of the hooked bars that runs across the entire joint width, causing the whole joint to fail at once. All of the beam-column joints in the study by Joh et al. (1993) were designed to have a raking-out type failure.

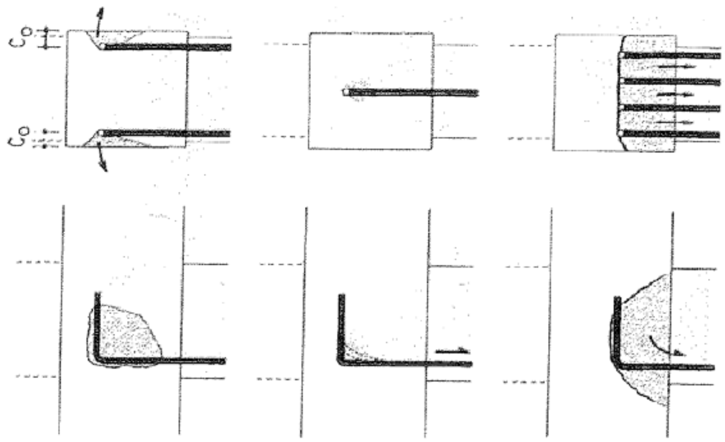


Figure 1.5 Failure modes for beam-column joints (figure from Joh et al. 1993)

The cracking patterns were slightly different for each specimen; however, there were three main cracks appearing on each specimen (Figure 1.6)—a diagonal crack starting at the end of the bend of the hook and progressing to the compression zone of the assumed beam, a vertical crack along the tail of the hook, and an inclined crack starting from the bend of the hook and continuing away from the compression region. In all specimens, the concrete block formed by these three cracks was pulled out and the anchorage failed at once without yielding of the hooked bars. Generally, this concrete block was in the shape of a trapezoid, but it became more triangular with a decrease in strut angle, which is shown as the angle θ in Figure 1.7.

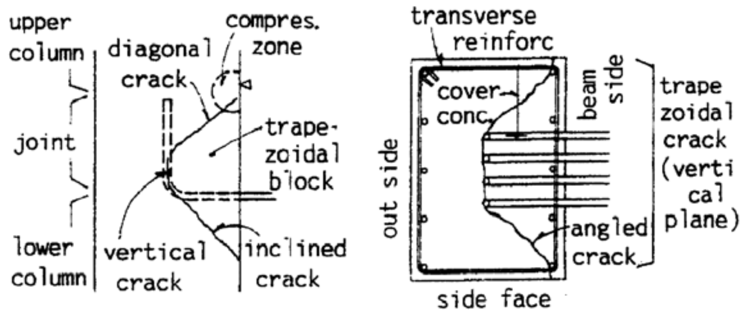


Figure 1.6 Cracking pattern seen in tests by Joh et al. (1993) (figure from Joh and Shibata 1996)

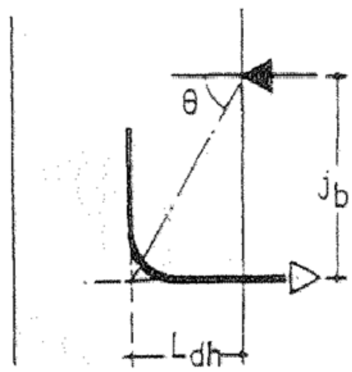


Figure 1.7 Strut angle as defined by Joh et al. (1993)

The main conclusions drawn from the study were that the force at failure is almost proportional to the effective joint width (joint width minus the diameter of the hooked bars times the number of hooked bars), axial stress increases the anchorage strength up to an axial stress of one-sixth the concrete compressive strength, anchorage capacity is proportional to the square root of the concrete compressive strength and the reciprocal of the sine of the strut angle (as defined in Figure 1.7), and the addition of lateral reinforcement produces a proportional increase in anchorage capacity.

Some of the findings of Joh et al. (1993) are similar to those of earlier studies (Marques and Jirsa 1975, Pinc et al. 1977, Soroushian et al. 1988, and Hamad et al. 1983). However, unlike Marques and Jirsa (1975), Joh et al. found that increasing axial stress does increase the anchorage strength of hooked bars, at least over a small range. The specimens tested by Marques and Jirsa were vastly different in that Joh et al. (1993) tested multiple hooked bars that were closely spaced. This caused the nature of the failure to change from that of side splitting to that of “raking-out.” This change in failure type could result in different factors contributing to the failure of the hooked bars.

Joh and Shibata (1996) expanded on the work done by Joh et al. (1993). In this study, 13 beam-column joints were tested, each containing four 19 mm (0.75 in.) 90° hooked bars. Of the thirteen specimens, eight were used to further investigate the effect of column axial stress on the anchorage capacity of the hooked bars, and five were used to investigate the effect of large side covers on the anchorage capacity. The concrete compressive strength ranged from 238 to 567 kgf/cm^2 (3,380 to 8,060 psi). The spacing between the bars was 57 mm (2.24 in.), and the side cover was varied from 64.5 to 264.5 mm (2.54 to 10.4 in.). The axial stress ranged from zero to 130.8 kgf/cm^2 (1,860 psi).

Cracking patterns were similar to those in the previous study (Joh et al. 1993) with three main cracks forming a trapezoidal type failure surface (Figure 1.6). For specimens with large side covers, however, the trapezoidal failure surface was not large enough to intercept the sides of the column, as shown in Figure 1.8. The angle of the inclined cracks propagating from the hooked bars are approximately 40° measured from the axis of the bar. Joh and Shibata found that transverse reinforcement becomes less effective in increasing the anchorage capacity when the side cover is so large that these cracks do not intersect the side of the column but surface on the face of the column. In this configuration (Figure 1.8), the ties are so far away from the hooked bars that the cracks never intercepted them and, thus, did not activate to help resist the crack propagation.

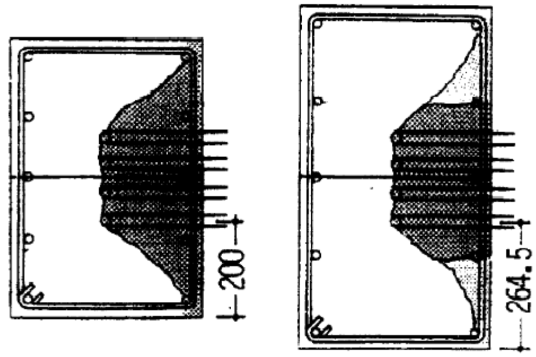


Figure 1.8 Failure surface for specimens with large side cover tested by Joh and Shibata (1996)

In addition, Joh and Shibata (1996) found that anchorage strength increases with an increase in axial stress up to 8% of the concrete compressive strength, as opposed to one-sixth of the compressive strength (Joh et al. 1993) and is constant thereafter. They proposed a relationship describing the increase in anchorage capacity:

$$1 + 0.020\sigma_{oe} \tag{1.4}$$

where, σ_{oe} is the minimum of σ_o and $0.08\sigma_B$, σ_o is the applied column axial stress in kgf/cm^2, and σ_B is the concrete compressive strength in kgf/cm^2. The greatest increase in capacity observed in the study due to axial stress was approximately 50% from the case with no axial stress to an axial stress of $0.08\sigma_B$. This effect of axial stress may be due to the fact that the hooks were not anchored in the compression region of the column, as was the case for the hooks tested by Marques and Jirsa (1975), Pinc et al. (1977), Soroushian et al. (1988), and Hamad et al. (1993).

Ramirez and Russell (2008) tested 21 beam-column joint specimens, 10 of which were epoxy-coated hooked bars. The main variables were bar size (No. 6 and No. 11 [No. 19 and No.

36]), concrete compressive strength (8,910 to 16,500 psi [61 to 114 MPa]), and amount of confining transverse reinforcement in the joint region (no confinement and ties spaced at $3d_b$). The specimens were similar to those tested by Marques and Jirsa (1975). The column size was 9×15 in. (229×381 mm) for specimens with No. 6 (No. 19) hooked bars and 15×15 in. (381×381 mm) for specimens with No. 11 (No. 36) hooked bars. Loading differed from that used by Marques and Jirsa (1975) in that the columns were tested as cantilevers without axial load.

The cracking patterns were similar for all specimens, with the first crack (horizontal flexural crack) appearing on the back face of the specimen at the tail end of the hook. Inclined shear cracks then appeared on the side of the specimen. At approximately 90% of the peak load, vertical cracks appeared along the front column longitudinal steel. For specimens without transverse reinforcement in the joint region, the failure was a pullout type failure with a block of concrete being pulled out the front face of the column. For specimens with transverse reinforcement, a pullout type failure occurred, combined with spalling of the concrete side cover. At failure, the tail of the hook tended to kick out, splitting the concrete behind the hook. The splitting cracks, however, were very small, and the cover of 2.5 in. (64 mm) over the tail was deemed sufficient for design purposes. They further concluded that the tail cover could be reduced to one bar diameter when transverse reinforcement is used.

Ramirez and Russell (2008) stated that the ACI 318 Code provisions could be extended to include concrete compressive strengths up to 15 ksi (103 MPa) as long as ties spaced at $3d_b$ are provided. In a comparison with the provisions for hooked bar development length in ACI 318-05, Ramirez and Russell (2008) found that 10 out of 11 specimens with No. 11 (No. 36) bar hooks had test-to-calculated ratios (ratio of peak stress during the test to stress calculated using ACI 318-05 provisions) less than 1.0, with a minimum of 0.83. They also found that the test-to-calculated ratio decreases with an increase in concrete compressive strength, which does not support their statement that the ACI 318 Code provisions could be extended to include greater concrete compressive strengths. To increase the test-to-calculated ratios, they proposed a modification factor of 0.8 instead of 0.7 be used for No. 11 (No. 36) and smaller 90° hooks with a minimum side cover of 2.5 in. (64 mm) and tail cover of 2 in. (51 mm). As in previous research, they found the anchorage strength of epoxy-coated hooks to be less than that of uncoated bars.

Shahrooz et al. (2011) tested eighteen ASTM A1035 hooked bar anchorage specimens. The main variables were concrete compressive strength (6,020 and 9,710 psi [42 and 67 MPa]), bar size (No. 4, No. 5, and No. 8 [No. 13, No. 16, and No. 25]), confining transverse reinforcement (no confining reinforcement and ties spaced less than or equal to $3d_b$), and embedment length (6 to 25 in.[152 to 635 mm]). The No. 4 (No. 13) specimens had a bend angle of 180°, and the No. 5 and No. 8 (No. 16 and No. 25) specimens had a bend angle of 90°. Each specimen contained one hooked bar placed in the middle of a 12-in. (305-mm) wide concrete block. The first 3 in. (76 mm) of the hooked bar were wrapped with foam pipe insulation to mitigate the pullout of a cone of concrete at the surface and provide additional concrete depth to preclude a shear failure.

In all cases where failure occurred, the failure of the specimens was bar rupture or concrete shear failure(for some specimens, the test was stopped prior to failure due to safety considerations). Shahrooz et al. (2011) concluded that present AASHTO requirements for hooked bar development length can be extended to develop bar stresses up to 125 ksi (862 MPa) for concretes with strengths up to 10,000 psi (69 MPa). They also recommended that confining reinforcement spaced less than or equal to $3d_b$ should always be used when developing, splicing, or anchoring ASTM A1035 steel.

1.2.3 Reliability-Based Design

Reliability-based design was implemented by the American Concrete Institute in the 1956 and 1963 Building Codes (ACI 318-56, ACI 318-63). Reliability-based design uses the concepts of probability to design a system or element to have a target reliability that takes into account various sources of uncertainty. Load and strength reduction factors (ϕ-factors) are used to provide the target reliability. These factors account for the inherent variability in expected loads and predicted strength of structural members and work in concert to increase the predicted loads and reduce the predicted strength of elements.

The principal reasons why load and ϕ-factors are used instead of safety factors are (1) variability in strength (the actual strength of a member is almost always different from the predicted strength due to variation in nominal dimensions and/or variation in materials), (2) variability in loads (actual loads can be significantly different from those used in design), and (3) consequences of failure (potential loss of life and property). The variability of the applied load and the variability of the actual strength of a member can lead to overload or understrength. To minimize overload and understrength, load and resistance factors are used and result in structures that are designed for greater than predicted loads and lower than predicted strength. The reliability of the structure can be represented by the reliability index β, which is the number of standard deviations separating the mean margin of safety from the value representing failure. In general, the higher the value of the reliability index, the greater the reliability of the member. Typical values for β for concrete structures are 3.0 to 3.5, which, if a normal distribution is assumed, correspond to a probability of failure on the order of 0.1% for β of 3.0 and 0.02% for β of 3.5.

There are different techniques for establishing load and strength reduction factors. One technique that is widely used in structural reliability is Monte Carlo analysis. This tool is especially useful for complex problems with many random variables that are related in a nonlinear fashion. It is used to determine the approximate probability of a certain event that is the result of many random variables. In a Monte Carlo simulation, a risk analysis is executed by substituting a range of values for any factor that has an inherent uncertainty. The process is repeated, each time using different values for the random variables based on their respective probability distributions. The technique generates the variability associated with the event being investigated. An overview of the development of load and resistance factors for the design of concrete structures follows.

Allen (1970) used probability techniques to find the ultimate moment and ductility ratio (curvature at ultimate to curvature at yield) of reinforced concrete beams in bending. Using probabilistic assumptions about material properties and dimensions, Allen (1970) used Monte Carlo simulation to conclude that (1) the variability of the expected ultimate moment increases when either the member is thin or the percentage of steel is high, (2) the variability of the ultimate moment is highly dependent on depth to reinforcement and percentage of steel but not on the rate of loading, and (3) the variability of the ductility ratio is high and greatly influenced by the probability of the beam failing in compression even when the section is under-reinforced according to ACI 318-63. The variability in ultimate moment and ductility ratio can be reduced considerably by good workmanship.

MacGregor (1976) addressed the decision to adopt common load factors for all materials and the need to develop new ϕ-factors to maintain an acceptable margin against failure. He studied a number of different techniques for establishing safety provisions for structures and found that procedures based on probability of failure gave the most satisfactory results. MacGregor (1976) also developed a probabilistic procedure for computing ϕ-factors and load factors based on an appropriate reliability index β.

Grant, Mirza, and MacGregor (1978) used Monte Carlo simulation to study the effects of variations in concrete strength, steel strength, cross-sectional dimensions, and location of steel reinforcement on the strength of short rectangular reinforced concrete tied columns. Grant et al. (1978) assumed a beta distribution for the mill test yield strength of reinforcing bars, a normal distribution for concrete strength and geometric imperfections, and a modified lognormal distribution for the ratio of the specified area to required area of reinforcing steel. The lognormal distribution was that proposed by Mirza and MacGregor (1979). The results of the study indicated that concrete strength and steel ratio have the most significant impacts on the variability of the strength ratios (theoretical strength to strength calculated according to the provisions of ACI 318-71). For small changes in reinforcement ratio, however, they observed that the effect on the strength ratio is insignificant. The variability of the concrete compressive strength is more significant when the eccentricity is small and compression failure controls, and the variability in steel strength is more significant when the eccentricity is large and tension failure dominates.

Mirza and MacGregor (1979) performed a study on the variability of dimensions of cast-in-place and precast concrete members and proposed representative distributions for estimating the effects of dimensional variability on the strength of the members. They also studied the effect of the difference between required and specified areas of reinforcement on the variability of the capacity of flexural and compression members. Mirza and MacGregor (1979) recommended normal distributions for the probability models of all geometric imperfections. They proposed values for mean deviations from nominal dimensions and the corresponding standard deviations for slabs, beams, and columns. They recommended that the probability model for the ratio of specified area to required area of reinforcing steel be represented by a modified lognormal distribution.

Mirza, Hatzinikolas, and MacGregor (1979) developed probabilistic descriptions of concrete strength. The variability of concrete strength is caused by the variability in material properties and proportions of the concrete mixture; the variability in transporting, placing, and curing methods; the variability in testing procedures; and the variability due to concrete being in a structure rather than in test cylinders. Mirza et al. (1979) studied the effects of these parameters on the compressive strength, tensile strength, and modulus of elasticity in both tension and compression of concrete and found that the probability distributions for all concrete properties can be modeled using a normal distribution. Mirza et al. (1979) developed equations to describe these probability distributions.

Ellingwood, Galambos, MacGregor, and Cornell (1980), Galambos, Ellingwood, MacGregor, and Cornell (1982), and Ellingwood, MacGregor, Galambos, and Cornell (1982) developed load factors and load combinations for the 1980 proposed version of American National Standard A58. They also proposed the use of the reliability index β for the development of appropriate ϕ-factors. They found that the existing design criteria indicated that the reliability index varied according to material, member type and failure mode, and load combination; and that β associated with wind or earthquake load combinations was smaller than for gravity load combinations. They recommended reliability indices for different structural members and presented charts for use in determining ϕ-factors for given values of β that would be consistent with the recommended load factors.

Mirza and MacGregor (1986) and Mirza (1987) studied the effects of the variability of concrete and steel strengths and steel placement on the bond strength of bottom tension reinforcing bars in flexural members and, using Monte Carlo analysis, proposed probability distributions of ultimate bond strength for use in calculating ϕ-factors for bond strength. They studied the effects of side cover to the center of the tension steel, spacing and number of stirrups, concrete strength, grade of flexural steel, quality of construction, and loading. Each of these parameters were varied using a Monte Carlo simulation and compared to both the ACI 318-83 Building Code requirements and the then ACI Committee 408 equation (ACI Committee 408 1979). It was found that the ACI 408 equation produced less variation in the mean ratios than did the ACI 318-83 equation. In addition, the concrete cover, amount of confining steel, bar size, and the quality of construction influenced the bond strength ratios (ratio of theoretical bond strength to bond strength computed from the design expression in ACI 318-83 or the proposed expression in ACI Committee 408). They also found that the effects of the concrete strength, steel grade, and seismic loading on the strength ratios for bond strength may be neglected. Mirza (1987) presented suggested mean values and coefficients of variation of bond strength ratios for typical beams.

Darwin, Idun, Zuo, and Tholen (1998) used the results of 133 development and splice tests of bottom-cast bars without confining reinforcement and 166 tests with confining reinforcement to develop strength-reduction factors for the development and splice length equations developed in the study by Darwin et al. (1996). Using Monte Carlo simulation and a reliability index of 3.5, Darwin et al. (1998) developed ϕ-factors using (1) nominal live-to-dead load ratios of 0.5, 1.0, and 1.5; (2) combinations of dead and live load factors of 1.4 and 1.7, respectively or 1.2 and 1.6, respectively; (3) bars with relative rib areas of 0.0727 and 0.1275; and (4) members with and without confining transverse reinforcement. The beams used in the Monte Carlo simulation had variable widths, depths, concrete compressive strengths, number and size of bars being developed, and size and spacing of stirrups. Darwin et al. (1998) found that an increase in the live load-to-dead load ratio results in a reduction in the ϕ-factor. A strength-reduction factor of 0.9 was obtained for the design expressions of Darwin et al. (1996) using a probability of failure in bond equal to one-fifth the probability of failure in bending or combined bending and compression. The strength-reduction factor developed by Darwin et al. (1996) assumed a strength-reduction for bending of 0.8 for the load case of 1.2 and 1.6 for dead and live load, respectfully. The actual strength reduction factor that was used for bending when the ACI Building Code switched to the new load factors is 0.9. This difference in strength-reduction factors for bending causes a decrease in the strength-reduction factor associated with bond. This reduction is implemented in the ACI 408 equation (ACI 408R-03).

Nowak and Szerszen (2003) and Szerszen and Nowak (2003) recalibrated the ACI 318 resistance factors using Monte Carlo simulation to better represent the change in the variability of material properties from the work done by Ellingwood et al. (1980). These resistance factors were designed to be consistent with the load factors and combinations that were specified in ASCE 7-98 and the reliability indexes already inherent in ACI 318-99. Three structural types were considered—beams, structural slabs, and columns. The resistance factors were developed using material strength variability of ordinary concrete, lightweight concrete, high-strength concrete (6,000 psi to 12,000 psi [42 to 83 MPa]), reinforcing steel (No. 3 to No. 11 [No. 10 to No. 36]), and prestressing strands. They updated the material factors using data gathered from associations representing ready-mixed concrete and reinforcing steel fabricators from across the nation to ensure a representative sample. The statistical factors for fabrication and professional analysis (the ratio of actual to predicted behavior of structural elements) were taken from work done by Ellingwood et al. (1980). Using these statistical parameters for material, fabrication, and professional analysis, Szerszen and Nowak (2003) developed the resistance factors used in ACI 318-02. They determined that the variation in material strength was reduced when compared to the work done by Ellingwood et al. (1980) and that the most significant differences between the two data sets were the concrete strength and yield strength of reinforcing steel. It was observed that the ratio of the mean to the nominal value for concrete compressive strength decreases for higher values of concrete strength and that the reliability index varies for different design cases. They also suggested that the number of different resistance factors in the Code be minimized.

Nowak et al. (2012) expanded the work done by Nowak and Szerszen (2003) to include No. 3 to No. 14 (No. 10 to No. 43) Grade 60 (Grade 420) reinforcing bars. With the addition of this data, Nowak et al. (2012) found that over the past 30 years [from the work done by Ellingwood et al. (1980) to the work done by Nowak et al. (2012)] the bias factors (ratio of mean to nominal value) have increased and the coefficients of variation (COV) have decreased. Nowak et al. (2012) found that the flexural capacity of beams is affected by the strength of the reinforcing steel more than the concrete compressive strength, and that the reinforcement ratio has a small effect on the bias factor and COV of beam resistance. For shear resistance, the bias factor and COV decrease with concrete strength, but for larger reinforcement ratios, the resistance is affected more by the reinforcing steel properties than the strength of the concrete. The latter finding supports the results of Grant et al. (1978). Bearing capacity resistance parameters (bias factor and COV) decrease with an increase in concrete compressive strength. They also found that the bias factor and COV of flexural resistance of a one-way slab do not depend on the slab thickness, and the bias factor and COV of shear resistance of a one-way slab increase with increasing concrete compressive strength. In addition, the load-carrying parameters of concrete columns decrease with increasing concrete compressive strength.

1.3 DISCUSSION

Prior to 1983, design methodology was based on calculating the anchorage strength of hooked bars as a combination of the stress that could be developed by the straight lead embedment and the hook. The stress developed in a hook was a function of bar size, yield strength, and bar position (top bar or other bar). However, this produced inconsistent results for the same bar size but different grades of steel, leading Marques and Jirsa to develop an alternative equation for the stress developed by a hook f_h for calculating hooked bar anchorage strength. However, the straight bar length was still used to calculate the development length of the hook. Work by Pinc et al. (1977) provided additional data and resulted in the design approach used today. This approach uncoupled the hooked bar anchorage provisions from the straight bar development length provisions and resulted in the total embedment length needed. The understanding of the behavior of hooked bars was that the failure is due to splitting the concrete cover parallel to the plane of the hook. The splitting originates at the inside of the bend where the local stress concentrations are very high.

Since the work done by Pinc et al. (1977), there have been other studies conducted to find the strength of epoxy-coated hooked bars, multiple hooked bars that are closely spaced, hooked bars in high-strength concrete, and high-strength hooked bars. Yet, despite these studies, relatively little is known about the behavior of hooked bars, especially high-strength steel hooked bars, hooked bars in high-strength concrete, or hooked bars with confining reinforcement. In addition, there has been very little focus on improving the design expression for hooked bars in the ACI 318 Building Code. There have been numerous studies on the bond strength of straight deformed reinforcing bars. For this reason, the causes of failure of straight bars are relatively well understood. However, the low number of studies conducted on the bond strength of hooked bars has led to more questions than answers.

1.4 OBJECTIVE AND SCOPE

Currently, the ACI Code provisions for the development of hooked bars are based on the tests performed by Marques and Jirsa (1975) and Pinc et al. (1977). These tests included steels with yield strengths of 64 and 68 ksi (441 and 469 MPa) and concrete compressive strengths between 3,750 and 5,100 psi (26 and 35 MPa). The objective of this study is to expand the knowledge of anchorage capacity of hooked bars to cover both high strength steels and high strength concretes. Other variables include the amount of confining transverse reinforcement, side concrete cover, bend angle (90° or 180°), number and spacing of hooked bars, and embedment length. These variables are studied for hooked bars both inside and outside the column core. This report covers the design and testing of 337 simulated beam-column joint specimens—276 with two hooked bars and 61 with more than two hooked bars. Selected results of the 276 specimens with two hooked bars are analyzed to determine the effects of embedment length, concrete side cover, bend angle, and amount and orientation of confining reinforcement on the anchorage capacity.

The analytical portion of this study focuses on obtaining characterizing and design expressions for hooked bar anchorage with and without transverse reinforcement. Linear regression techniques are employed to determine these expressions based on the variables listed above. Using Monte Carlo simulation, an appropriate ϕ-factor is determined for use with the design equation for hooked bar development length.

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CHAPTER 2: TEST RESULTS

2.1 INTRODUCTION

In reinforced concrete members, reinforcement must be bonded or anchored to the concrete so that it can develop its yield strength at sections subjected to maximum stresses. This is often accomplished by embedding the reinforcement far enough on either side of the critical section so that it is anchored by a combination of mechanical interlock and friction with the surrounding concrete. In many cases, however, such as exterior beam-column joints, the concrete dimensions are not adequate to fully develop the yield strength of the bar. In these cases, anchorage may be obtained through the use of hooked bars. Hooked bars are commonly used in reinforced concrete construction, but the anchorage strength of hooked bars has not been studied as extensively as other aspects of reinforced concrete design. Current design provisions for reinforced concrete including the ACI 318 Building Code Requirements for Structural Concrete (2014), ACI 349 Code Requirements for Nuclear Safety-Related Concrete Structures (2006), and the AASHTO LRFD Bridge Design Specifications (2012) have requirements for the development of bars with standard hooks that are based on tests conducted by Minor and Jirsa (1975), Marques and Jirsa (1975), and Pinc et al. (1977). These experimental studies included only a small number of specimens that contained standard hooks, and the range of material properties used in the specimens was limited and did not include high-strength steel bars or high-strength concrete. The main cause of failure for the specimens was observed to be the loss of side cover.

The purpose of this and subsequent papers is to describe the findings of an investigation into the key parameters affecting the anchorage strength of standard hooked bars (as defined in Section 25.3 of ACI 318-14). This paper describes the test program and compares the results with the development length provisions for hooked bars in ACI 318-14. Part 2 of this paper describes the analysis of the test results and the development of characterizing equations for hooked bar development. Subsequent papers will examine specific parameters affecting hooked bar anchorage, such as side cover and spacing of hooked bars, and develop proposed Code provisions.

2.2 RESEARCH SIGNIFICANCE

The use of high-strength steel and concrete has become increasingly preferred due to the benefits of lower congestion, smaller member dimensions, and increased useable floor area. Current Code provisions for hooked bar anchorage, however, are based on tests reported in 1975 and 1977 of Grade 60 (Grade 420) steel reinforcement used in conjunction with concrete with compressive strengths between 3,600 and 5,400 psi (24.8 and 37.2 MPa); thus, there is no basis for modifying them to include higher strength materials. This study includes a greatly expanded database of test results that incorporates both conventional and higher-strength materials to evaluate the accuracy and safety of the current Code development length provisions for hooked bars over the full range of steel and concrete strengths currently used and planned for use in reinforced concrete construction.

2.3 TEST PROGRAM

A total of 337 beam-column joint specimens, 276 with two hooked bars and 61 with more than two hooked bars, were tested to investigate the anchorage capacity of hooked bars. The parameters investigated were bar size, bar stress at failure, embedment length, side cover, amount of transverse reinforcement, location of hook (inside or outside the column core and within the depth of the member), concrete compressive strength, hooked bar size, hook spacing, number of hooks, and hook bend angle. No. 5, 8, and 11 (No. 16, 25, and 36) hooked bars were tested in normalweight concrete with compressive strengths ranging from 4,300 to 16,510 psi (30 to 114 MPa). Nominal clear cover from the outside of the bar to the outside of the column (side covers) ranged from 1.5 to 4 in. (38 to 102 mm) and hook center-to-center spacing ranged from 3 to 11 bar diameters (d_b). Bar stresses at failure ranged from 22,800 to 141,600 psi (157 to 976 MPa). The results for these tests are reported and used in conjunction with results from previous studies to develop descriptive equations relating the key parameters to anchorage strength.

2.3.1 Test Specimens

A diagram of a typical specimen simulating a beam-column joint is shown in Figure 2.1. The specimens were designed to represent exterior beam-column joints and were cast without the beam. For the standard two-hook specimens used in this study (the majority of specimens tested), the out-to-out spacing of the bars was fixed for a given bar diameter—8 in., 12 in., and 16.5 in. (203 mm, 305 mm, and 419 mm) for specimens with No. 5, No. 8, and No. 11 (No. 16, No. 25, and No. 36) hooked bars, respectively. This spacing varied for specimens with more than two hooked bars (multiple hook specimens) and for two-hook specimens where close hook spacing was investigated. The column depth equaled the sum of the tail cover and the embedment length. For this paper, embedment length ℓ_{eh} refers to the distance measured from the front of the column face to the back of the tail of the hook, while development length ℓ_{dh} refers to the minimum length of anchorage required by Section 25.4.3 of ACI 318-14 to ensure that a bar can develop its yield strength. During specimen design, embedment lengths ℓ_{eh} were chosen to ensure anchorage failure prior to bar failure. Early on in the testing program, this objective was accomplished by using an embedment length equal to 80% of the development length defined in ACI 318-14; later specimens were designed by extrapolating trends from prior test results.

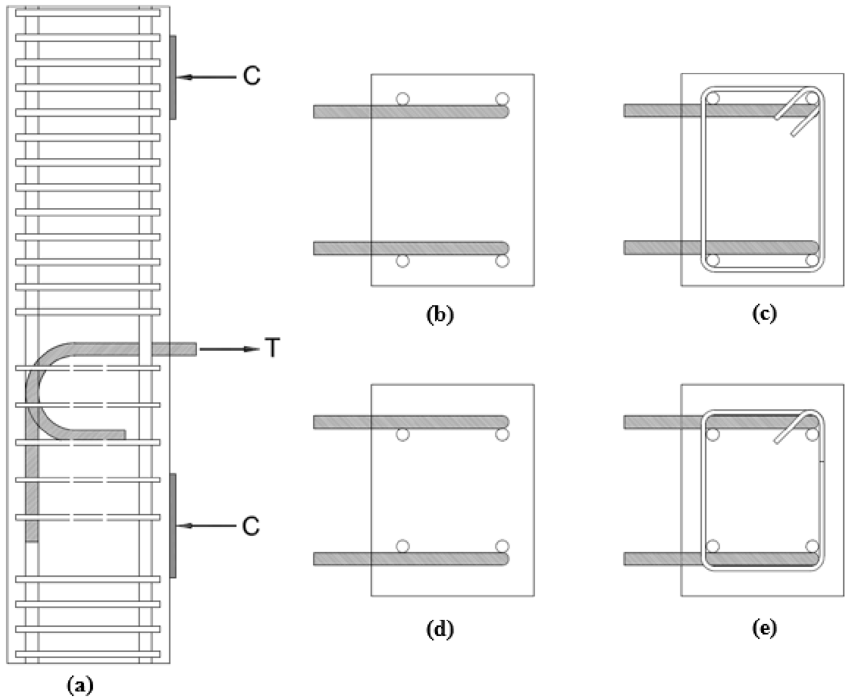
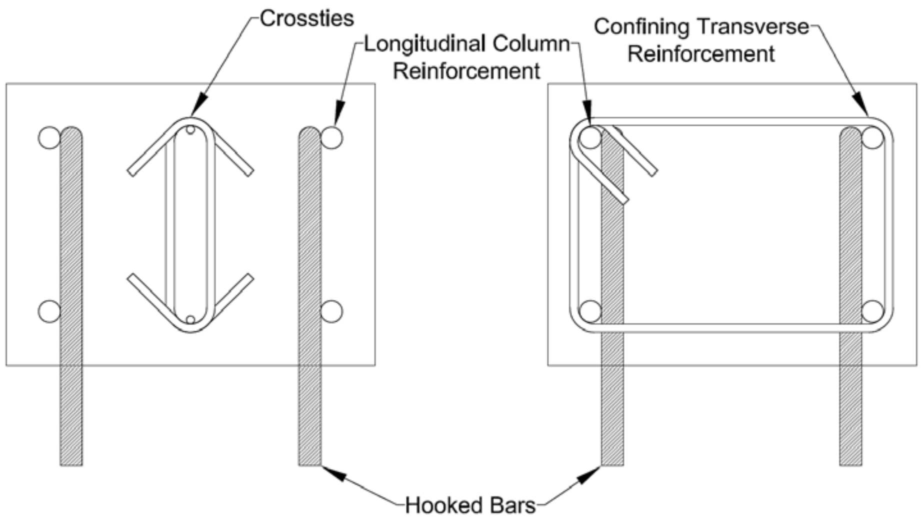


Figure 2.1 Schematic of specimens (a) side view of specimen (b) cross-section of specimen with hooks inside column core and without confining transverse reinforcement (c) cross-section of specimen with hooks inside column core and with transverse reinforcement (d) cross-section of specimen with hooks outside column core and without confining transverse reinforcement and (e) cross-section of specimen with hooks outside the column core and with confining transverse reinforcement

After the dimensions of the specimen were selected, the maximum shear and moment in the specimen were determined assuming all hooked bars reached their maximum failure load simultaneously. These loads were used to proportion the column reinforcement. Preliminary calculations showed that some specimens would be expected to have shear demands greater than the combined capacity of the concrete and the transverse reinforcement in the joint (or the concrete alone when there was no transverse reinforcement). For these specimens, cross-ties were placed in the center of the column oriented in the direction of the beam longitudinal reinforcement, as shown in Figure 2.2a. No. 3 (No. 10) longitudinal reinforcing bars were added to the column to hold the crossties in place when the moment demand on the specimen was not large enough to require more than four longitudinal column reinforcing bars. The use of cross-ties was found to be unnecessary and was discontinued in later tests to minimize interference of the ties with the expected failure surface and to provide a more realistic column reinforcement configuration. A specimen without cross-ties is shown in Figure 2.2b. Figures 2.1 and 2.2 are representative of typical two-hook specimens. Multiple and closely-spaced hooked bar specimens will be discussed in a separate paper and are described by Sperry et al. (2015).



(a) (b)

Figure 2.2 Cross-section of specimens (a) with cross-ties and no confining transverse reinforcement and (b) without cross-ties and with confining transverse reinforcement

For the majority of the specimens tested, hooks were placed inside the column longitudinal reinforcement (that is, within the column core). Some specimens were tested with hooks placed outside the column core to simulate a hook in unconfined concrete, such as at the free end of a cantilever beam. Figure 2.1 shows the differences between the two cases. The width of the specimen, side cover, and hook spacing were kept the same; only the location of the column longitudinal reinforcement changed between the specimens. The effects of hooked bar placement will be addressed in a separate paper and are presented by Sperry et al. (2015).

The majority of the specimens contained one of three quantities of transverse reinforcement, oriented horizontally (parallel to the straight portion of the hook): (1) no transverse reinforcement, (2) two No. 3 (No. 10) ties spaced at $8d_b$ for No. 5 (No. 16) and No. 8 (No. 25) hooked bars and $8.5d_b$ for No. 11 (No. 36) hooked bars, or (3) No. 3 (No. 10) ties spaced at $3d_b$ along the tail and the bend of the hook, where d_b is the diameter of the hooked bar. No. 3 (No. 10) ties spaced at $3d_b$ provide the minimum amount of transverse reinforcement required to allow the use of the 0.8 reduction factor in development length of hooked bars in accordance with Section 25.4.3 of ACI 318-14. For No. 5 (No. 16) and No. 8 (No. 25) standard hooks, this is equal to five No. 3 (No. 10) ties spaced along the length of the tail and bend, while for a No. 11 (No. 36) standard hook, this is equal to six No. 3 (No. 10) ties. For cases (2) and (3), the first tie was placed $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar). Additional specimens were fabricated with other transverse reinforcement configurations ranging from a single No. 3 (No. 10) tie to confinement in accordance with ACI 318-14 Section 18.8.3 for joints in special moment frames [four or five No. 4 (No. 13) ties with No. 4 (No. 13) crossties in both directions]. In addition, six specimens were tested with vertical ties, such as shown in Figure 2.3. Of the six, two contained two No. 3 (No. 10) ties, two contained four No. 3 (No. 10) ties, and two contained five No. 3 (No. 10) ties. Both of the latter two cases qualify for the 0.8 reduction factor in Section 25.4.3 of ACI 318-14. Full specimen details are presented in the Appendix B.

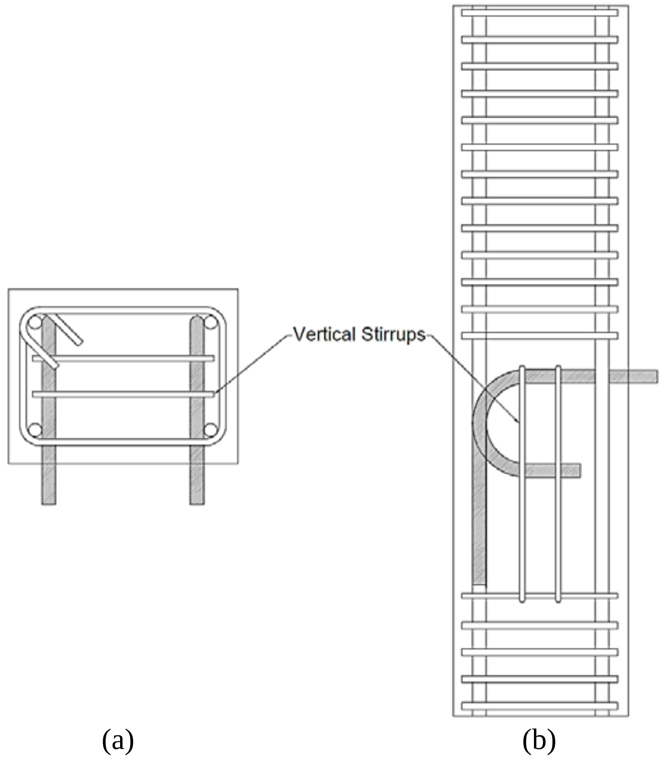


Figure 2.3 Details of specimen with vertical ties (a) cross-section and (b) side view

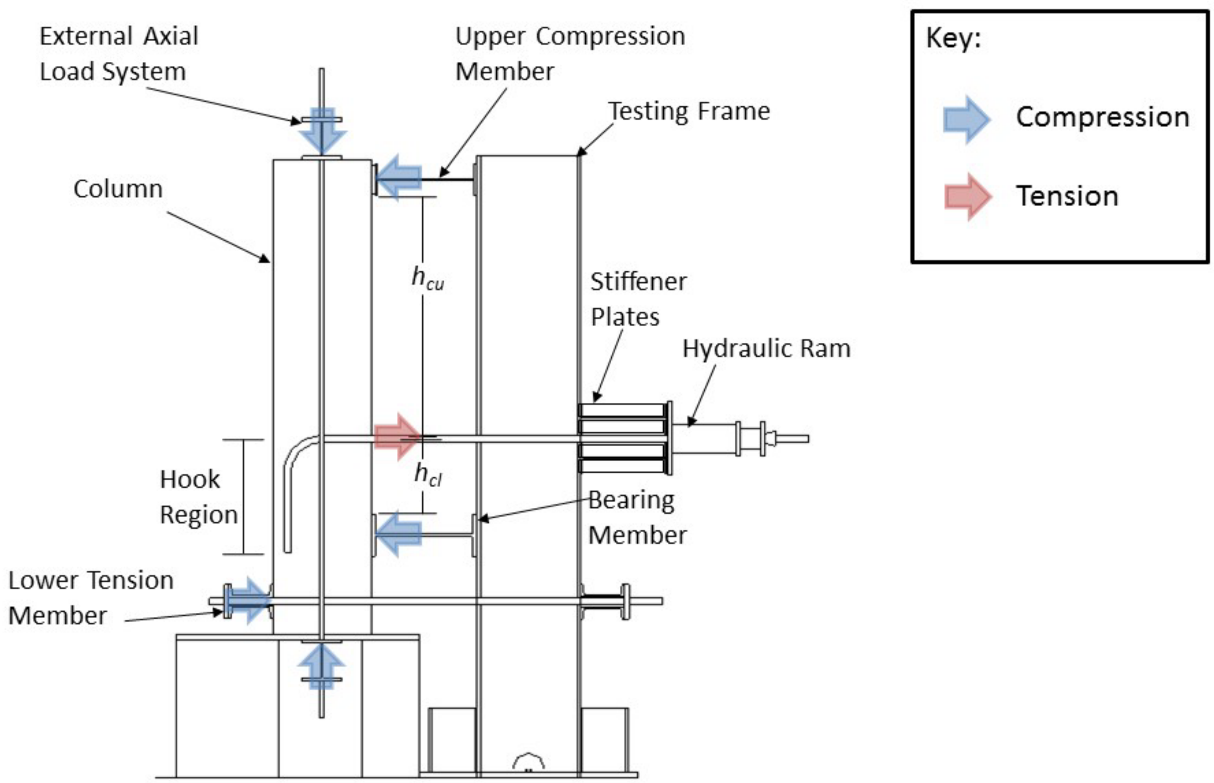


Figure 2.4 Testing frame and forces applied to specimens during testing

The heights of specimens were chosen so that the support reactions from the test frame did not interfere with the hook region during testing, as shown in Figure 2.4. The column height was 52¾ 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 distance to the bearing member and upper compression member are given in Table 2.1.

Table 2.1 Location of reaction forces

	No. 5 Hook	**No. 8 Hook**	**No. 11 Hook**
Height of Specimen, (in.)	52¾	52¾	96
Distance from Center of Hook to Top of Bearing Member Flange, h_{cl} (in.)[1]	5.25	10	19.5
Distance from Center of Hook to Bottom of Upper Compression Member Flange, h_{cu} (in.)[1]	18.5	18.5	48.5

[1]See Figure 2.4, 1 in. = 25.4 mm

2.3.2 Material Properties

Specimens were cast using non-air-entrained ready-mix concrete with nominal compressive strengths of 5,000, 8,000, 12,000, and 15,000 psi (34.5, 55, 83, and 103 MPa). Actual strengths ranged from 4,300 to 16,510 psi (30 to 114 MPa). The concrete contained Type I/II portland cement, crushed limestone or granite with a maximum size of ¾ in. (19 mm), Kansas River sand, and a high-range water-reducing admixture. Pea gravel was incorporated in the 12,000 psi (83 MPa) concrete to improve the workability of the mix. Class C fly ash and silica fume were added as supplementary cementitious materials for the 15,000 psi (103 MPa) concrete. ADVA 140 was used in the 5,000 and 8,000-psi (34.5 and 55-MPa) concrete and ADVA 575 was used in the

12,000 and 15,000-psi (83 and 103-MPa) concrete; both products are produced by W.R. Grace. Mixture proportions are listed in Table 2.2.

Table 2.2 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
Crushed Limestone, lb/yd^3	1734	1683	1796	-
Granite, lb/yd^3	-	-	-	1693
Pea Gravel, lb/yd^3	-	-	316	-
Kansas River Sand, lb/yd^3	1396	1375	1050	1138
Estimated Air Content, %	1	1	1	1
High-Range Water-Reducer, oz (US)	30[1]	171[1]	104[2]	205[2]
w/cm ratio	0.44	0.32	0.29	0.24

[1]ADVA 140, [2]ADVA 575, 1 psi = 0.00689 MPa, 1 lb/yd^3 = 0.593 kg/m^3, 1 oz = 29.6 mL

Except for a few early tests that used ASTM A615 Grade 60 (420 MPa) reinforcement, ASTM A615 Grade 80 (550 MPa) and A1035 Grade 120 (830 MPa) bars were used for the hooked bars. To provide maximum flexibility in the tests, the majority of specimens were cast with hooked bars made of A1035 steel to ensure that anchorage strength was not limited by steel strength. For most specimens, the ancillary steel for column and transverse reinforcement consisted of ASTM A615 Grade 60 (420 MPa) reinforcing bars. Some specimens had a greater flexural demand than could be satisfied using ASTM A615 Grade 60 (420 MPa) reinforcing bars. For those specimens, ASTM A1035 Grade 120 (830 MPa) bars were used as the column longitudinal steel. 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 Table 2.3.

Table 2.3 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

2.3.3 Test Procedure

Specimens were tested using a self-reacting system configured to simulate the axial, tensile, and compressive forces in a beam-column joint (Figure 2.4). The test frame is a modified version of the apparatus used by Marques and Jirsa (1975). The locations of reactions on the testing apparatus can be altered to accommodate different-sized specimens, as listed in Table 2.1. The flange width of the upper compression member and the bearing member were $6^5/_8$-in. (168.3 mm) and $8^3/_8$-in. (212.7 mm), respectively.

For specimens with No. 5 and No. 8 (No. 16 and No. 25) hooked bars, a constant 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 (0.621 to 3.17 MPa) (for early tests, a constant force of 80,000 lb [356 kN] was used, corresponding to a range in axial stress of 505 to 1,930 psi [3.48 to 13.3 MPa]). Specimens with No. 11 hooked bars had a constant axial stress of 280 psi (1.93 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 3,000 psi resulted in negligible changes in the anchorage strength of the hooked bars.

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. The bearing member located below the hooked bars simulated the compression zone of the beam and the horizontal reactions at the top and bottom of the specimen were used to prevent overturning. A detailed description of the test frame and testing procedure is provided by Peckover and Darwin (2013).

2.4 TEST RESULTS

2.4.1 Cracking Patterns

Figure 2.5 shows the typical crack progression observed in the specimens. Cracking almost always began with a horizontal crack on the front face of the column at the level of the hooked bars, slightly extending around the side of the column (Figure 2.5a). This cracking pattern is similar to cracking observed with bond failures for straight bar reinforcement in reinforced concrete beams and is likely associated with slip of the straight portion of the bar. As the load increased, the horizontal crack continued to grow along the side face of the column until it reached a depth approximately equal to the location of the bend of the hooked bar (Figure 2.5b), at which point radial cracks formed on the front of the column starting from the hooked reinforcement. Vertical and diagonal cracks also formed along the length of the horizontal crack on the side of the column. These cracks continued to grow towards the front of the column (Figure 2.5c). Cracks below the level of the hooked bar extended towards the compression reactions (Figure 2.5d), where the bottom reaction represented the compression zone of the beam in a beam-column joint. Cracks above the level of the hooked bar extended to a location just below the top reaction of the column.

Near failure (Figure 2.5e), the inclined cracks on the side of the column extended across the front of the column and widened as concrete pulled out of the front of the column. The amount of cracking and spalling varied depending on the failure type, as described next.

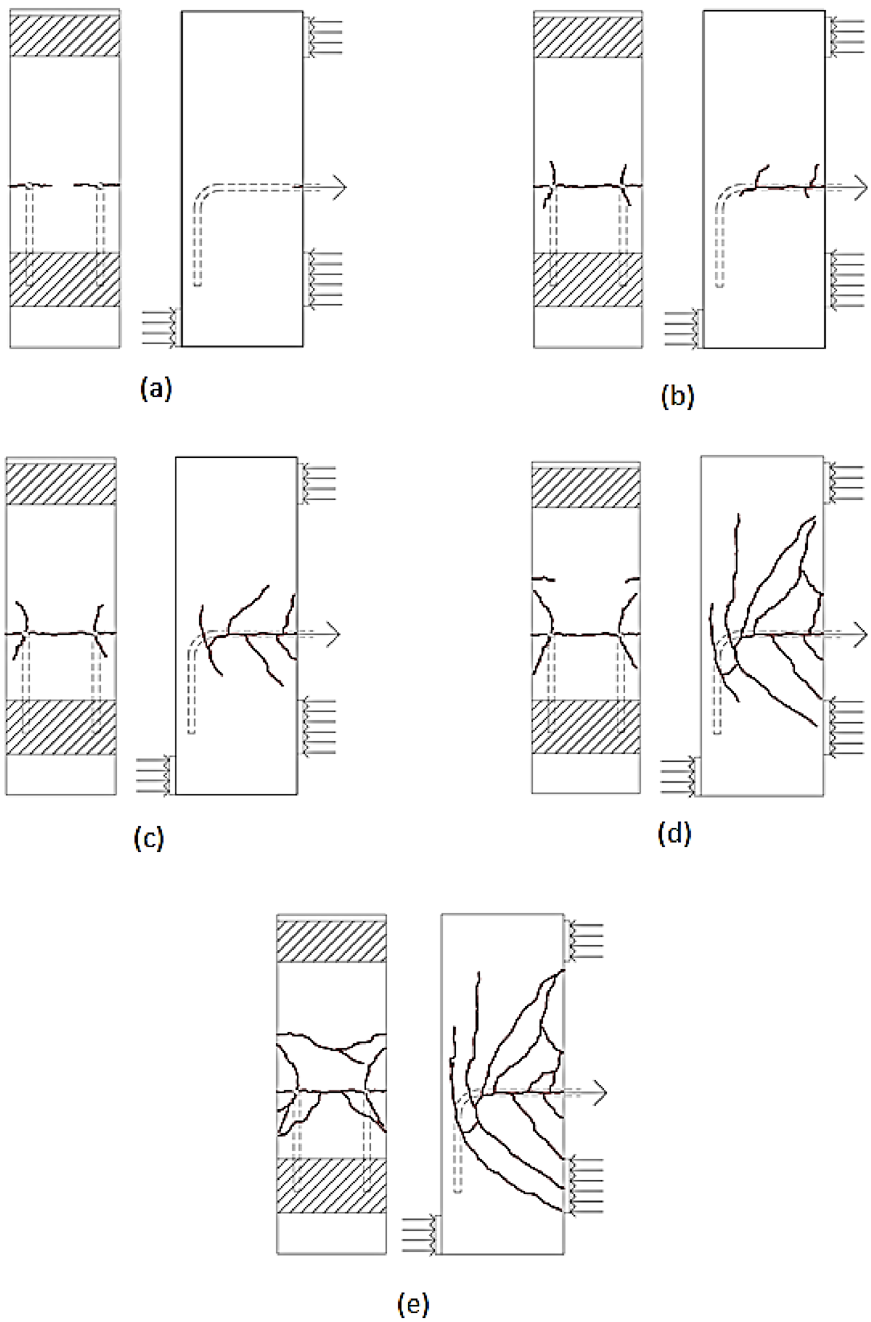


Figure 2.5 Front and side views of specimens indicating typical crack progression

2.4.2 Failure Modes

A front pullout failure (Figure 2.6a), represented by FP in the tables of the appendix, was characterized by a mass of concrete being pulled forward with the hook from the front face of the column. This failure mode was often coupled with side splitting or side blowout.

A front blowout (FB) failure (Figure 2.6b) was similar to a front pullout failure; front blowout failures, however, were more sudden in nature, with a larger release of energy and bar slip than in front pullout failures. Likewise, front blowout failures were associated with spalling of the concrete on the front face of the column at failure. This failure mode was often coupled with side blowout or side splitting. Both front pullout and front blowout failures suggest that the hooked portion of the bar is providing the primary anchorage after slip has occurred along the straight portion of the bar.

A side splitting (SS) failure (Figure 2.6c) occurred when the concrete cover on the side of the hooked bar cracked and separated from the column as the hooked anchorage lost strength. The splitting plane for this failure mode was in line with the vertical plane passing through the hooked bar. Often a long vertical crack on the back face of the column was observed at failure due to side splitting, as shown in Figure 2.6c. This failure type was often coupled with front pullout or front blowout.

Side blowout (SB) (Figure 2.6d) is a more energetic form of side splitting in the same way that front blowout is a more energetic form of front pullout. Side blowout failures were more sudden in nature with a higher amount of energy released at failure than a side splitting failure. Also, during a side blowout failure, there was often a loss of concrete side cover to the outside reinforcement on the column (that is, if transverse reinforcement was present, the ties were exposed after failure; otherwise, the hooked bar was exposed after failure). This failure type was often coupled with front blowout or front pullout. Both side splitting and side blowout suggest that the hooked bar serves as a wedge, forcing a crack in the plane of the hook, as the bar undergoes slip.

Tail kickout (TK) (Figure 2.6e) was observed in a small number of specimens. This failure occurred when the tail extension of 90° hooked bars pushed the concrete cover off the back of the column, often exposing the tail of the hooked bar. It commonly occurred for hooked bars without transverse reinforcement and was observed primarily for No. 8 or No. 11 (No. 25 or No. 36) 90° hooked bars, although one No. 5 (No. 16) 90° hooked bar also exhibited tail kickout at failure. Tail kickout was often sudden in nature and was observed in conjunction with other failure types—it did not appear to be the main cause of failure for any specimen.

In addition to the failure modes just described, two other failure modes were observed—bar yield (BY) and flexural failure of column longitudinal reinforcement (FL). Bar yield occurred when the stress on the hooked bar approached the tensile strength of the steel. When this occurred, tests were stopped as a safety precaution to ensure that the bars did not fracture. Flexural failure occurred when longitudinal reinforcement on the tensile face of the column yielded prior to an anchorage failure. These two failure modes were not considered an anchorage failure of the hook and were not included in the analyses of the data.

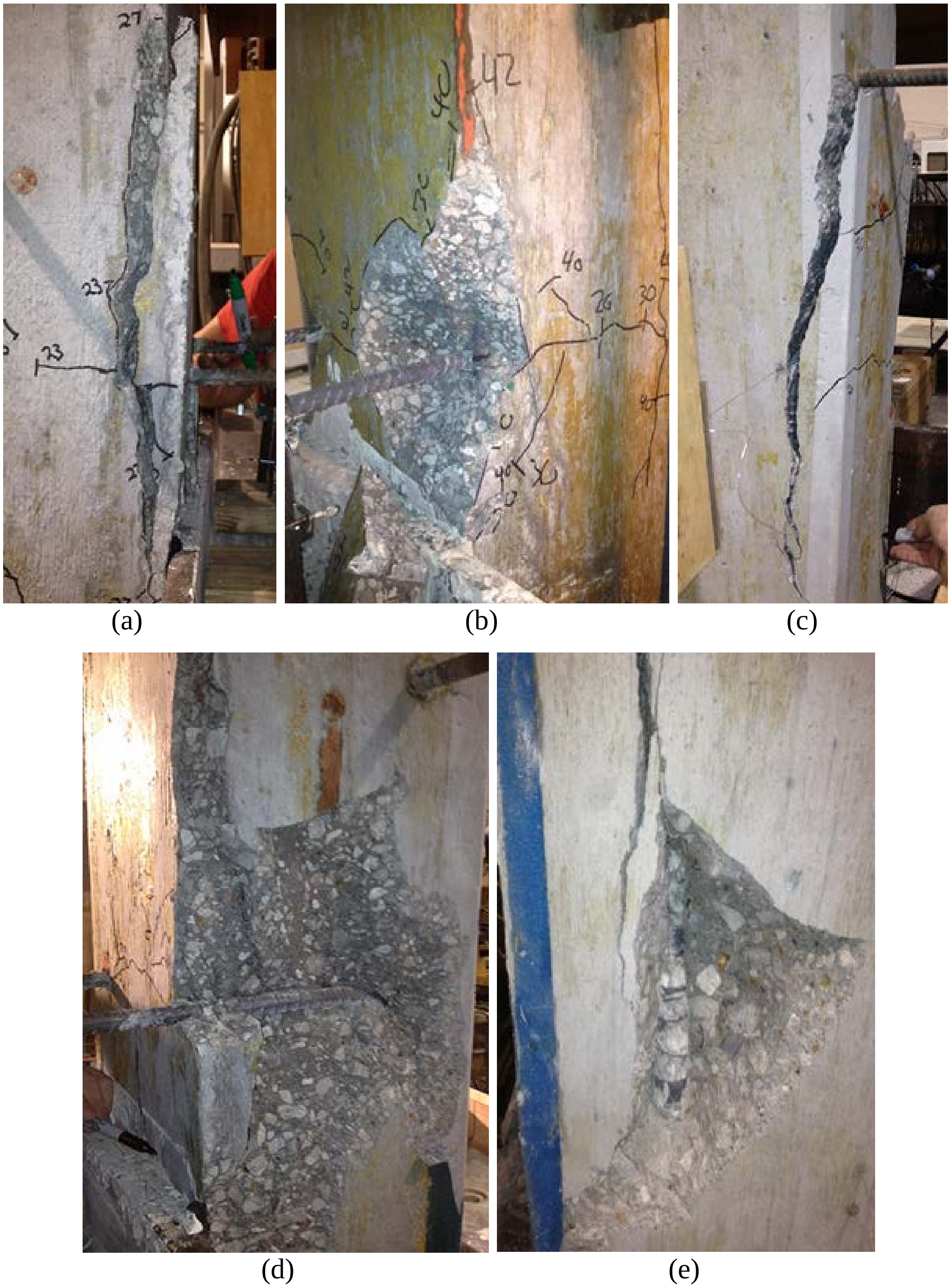


Figure 2.6 Failure modes (a) front pullout, (b) front blowout, (c) side splitting, (d) side blowout, and (e) tail kickout

Figure 2.7 presents the percentage of hooked bars exhibiting the different failure modes (excluding bar yield and flexural failures). The percentage is based on individual hooked bars rather than specimens since individual hooked bars in a specimen can exhibit different failure modes. For simplicity, front pullout and front blowout are combined into "front failures;" side splitting and side blowout are combined into "side failures." When multiple failure modes were involved, the dominant failure mode was distinguished based on the relative amount of cracking and concrete movement observed on the side and front faces after failure. The dominant failure mode was defined as a front failure if the front face of the column exhibited greater damage; otherwise, the dominant failure mode was defined as a side failure. Due to the nature of the failures, the distinction between a dominant front and a dominant side failure was subjective.

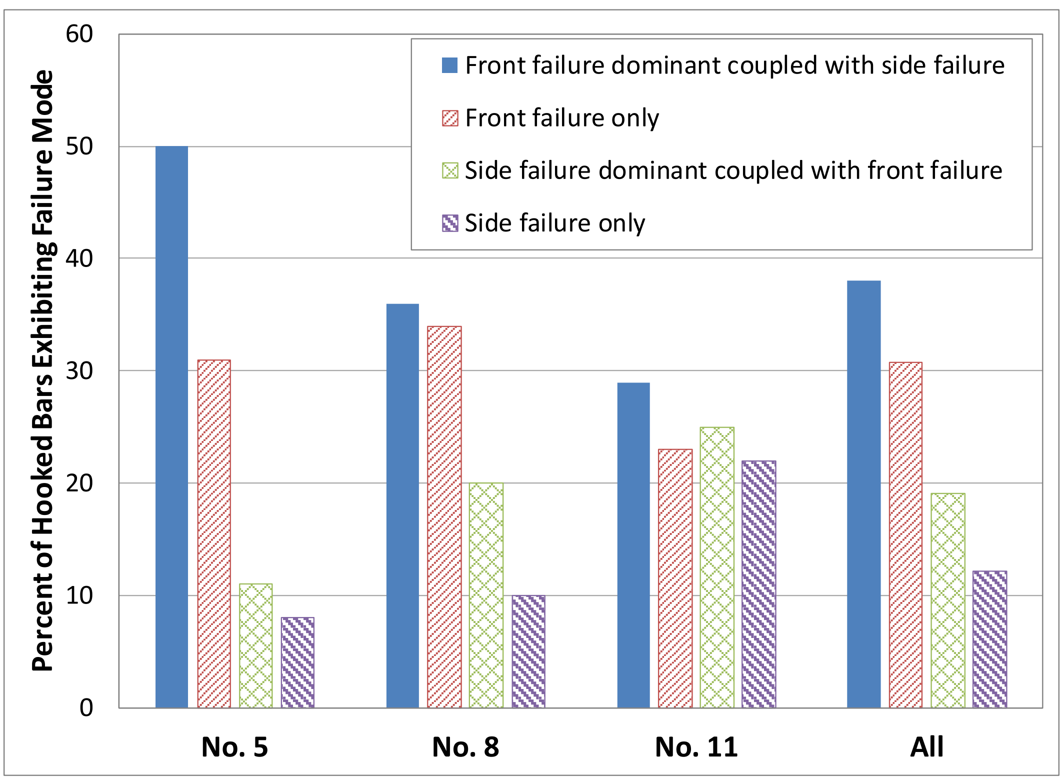


Figure 2.7 Percent of hooked bars exhibiting each failure mode

For the majority of hooked bars (57%), both front and side failure were involved. Of that 57%, three quarters of the hooked bars exhibited front failure as the dominant failure mode. For hooked bars with only one failure mode, more hooked bars exhibited front failures (31%) than side failures (12%).

For the No. 5 (No. 16) hooked bars, 81% of hooked bars exhibited front failure as the primary failure mode (50% exhibited a front failure coupled with a side failure, and 31% exhibited a front failure only), and 19% exhibited side failure as the primary failure mode. For the No. 8 (No. 25) hooked bars, 70% of the hooked bars exhibited front failure as the primary failure mode (36% with front failure coupled with side failure, and 34% exhibited front failure only). For the No. 11 (No. 36) hooked bars, only 52% of the hooked bars exhibited front failure as the primary failure mode (29% exhibited front failure coupled with side failure, and 23% exhibited front failure only). This indicates that the percentage of hooked bars exhibiting side failures as the primary failure mode increased as the bar size increased. This behavior is likely due to the fact that side cover was kept constant for the majority of the specimens; thus, the ratio of cover to bar diameter decreased as bar size increased. For each bar size, however, failure involved front failure as the primary failure mode coupled with a secondary side failure. Thus, front failure plays an important role in the behavior of hooked bars. These observations are in contrast to the findings of Marques and Jirsa (1975) and Pinc et al. (1977) in which all specimens failed due to side splitting.

2.4.3 Comparison of Test Results with ACI 318-14

Test results from this and earlier studies were compared with anchorage strengths derived from the provisions for hooked bars in ACI 318-14. The data set used for this analysis includes test results from this study as well as data from tests performed by Marques and Jirsa (1975), Pinc et al. (1977), Hamad et al. (1993), Ramirez and Russell (2008), and Lee and Park (2010). Included in this evaluation were specimens with two hooked bars cast inside the column longitudinal reinforcement with side cover ranging from 2.5 to 3.5 in. (64 to 89 mm). Excluded from the analysis were specimens with more than two hooked bars, hooked bars cast outside the column core (outside the longitudinal column reinforcement), hooked bars anchored outside the compression region of the column (hooked bars anchored in the middle of the column), and hooked bars anchored in columns with high reinforcement ratios (> 0.04); results for these test specimens will be included in later papers. A regression analysis technique based on dummy variables (Draper and Smith 1981), referred to in this paper as a dummy variables analysis, was 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.

In Section 25.4.3.1(a) of ACI 318-14, the development length of a hooked bar ℓ_{dh} is expressed as a function of the yield strength of the reinforcement f_y, the compressive strength of the concrete f_c', and the bar diameter d_b. As shown in Eq. (2.1), the expression for ℓ_{dh} also includes factors for the effects of epoxy coating ψ_e, cover ψ_c, confining reinforcement ψ_r, and lightweight concrete λ. The development length ℓ_{dh} represents the minimum embedment length required to develop the yield strength of the bar. While ℓ_{dh} is an important parameter in the context of design, for the purposes of evaluating the test results it is more useful to derive the bar stress $f_{s,\text{ACI}}$ as a function of the embedment length ℓ_{eh}. To obtain $f_{s,\text{ACI}}$, the development length ℓ_{dh} in Eq. (2.1) is replaced by embedment length ℓ_{eh}, yield strength f_y is replaced by bar stress $f_{s,\text{ACI}}$, the specified compressive strength f'_c is replaced by the measured compressive strength f_{cm}, and the equation is solved for $f_{s,ACI}$, as shown in Eq. (2.2). Because all of the specimens in this study were constructed with uncoated bars and normalweight concrete, ψ_e and λ are taken as 1.0.

$$\ell_{dh} = \left(\frac{f_y \psi_e \psi_c \psi_r}{50\lambda\sqrt{f'_c}} \right) d_b \tag{2.1}$$

$$f_{s,\text{ACI}} = \frac{50\ell_{eh}\sqrt{f_{cm}}}{\psi_c \psi_r d_b} \tag{2.2}$$

Figures 2.8 through 2.10 compare the ratio of measured average bar stress at failure f_{su} to $f_{s,\text{ACI}}$, as a function of the concrete compressive strength f_{cm}. Each data point represents an individual test, and the trend lines are obtained using a dummy variables analysis with the data separated based on the size of the hooked bar. Figure 2.8 shows the results for No. 5, No. 6, No. 7, No. 8, No. 9, and No. 11 (No. 16, No. 19, No. 22, No. 25, No. 29, and No. 36) bars without confining transverse reinforcement in the joint region. Figure 2.9 shows the results for hooked bars with two No. 3 (No. 10) ties as confining transverse reinforcement, and Figure 2.10 shows the results for hooked bars with No. 3 (No. 10) ties spaced at $3d_b$ as confining transverse reinforcement.

The values for ℓ_{eh} and f_{cm} used in Eq. (2.2) used to calculate $f_{s,\text{ACI}}$ were those measured, not the nominal values. The figures include results for specimens with 2.5-in. (63.5-mm) or 3.5-in. (88.9-mm) clear side cover along with hooked bars with 90° or 180° bend angles. As will be described in a follow-on paper and as described by Sperry et al. (2015), the anchorage strength of hooked bars is largely unaffected by differences in clear side cover between 2.5-in. (63.5-mm) and 3.5-in. (88.9-mm) or by the bend angle for 90° or 180° hooks. In these comparisons, the 100 psi

(8.3 MPa) upper limit on $\sqrt{f_c'}$ (10,000 psi (68.9 MPa) on f_c') in Section 25.4.1.4 of ACI 318-14 was not applied.

The values of $f_{s,\text{ACI}}$ shown in Figures 2.8 through 2.10 include the cover factor ψ_c = 0.7 for No. 11 bars and smaller with at least 2.5 in. (63.5 mm) of clear cover to the side of the hook and 2 in. (50.8 mm) of clear cover to the tail of the hook. The values of $f_{s,ACI}$ shown in Figure 2.10 include the confining reinforcement factor ψ_r = 0.8 for hooked bars confined by stirrups or ties parallel or perpendicular to the bar being developed and spaced no further than three bar diameters apart. Because the nominal dimensions of the specimens provided at least a 2.5-in. (63.5 mm) side cover and a 2-in. (50.8 mm) tail cover, the 0.7 factor was applied to all calculations of $f_{s,\text{ACI}}$, although some specimens, due to fabrication tolerances, had actual side and tail covers slightly less than 2.5 in. (63.5 mm) and 2 in. (50.8 mm), respectively.

Figure 2.8 includes results for 99 beam-column joint specimens without confining transverse reinforcement in the joint region. Sixty-eight of the specimens are from the current investigation. Although test data for high-strength concrete are not available for all bar sizes, the trend lines from the dummy variables analysis indicate that the ratio $f_{su}/f_{s,\text{ACI}}$ decreases with increasing compressive strength. The trend lines also show that $f_{su}/f_{s,\text{ACI}}$ decreases with bar size. The trend line for the ratio of $f_{su}/f_{s,\text{ACI}}$ falls below 1.0 for No. 6 (No. 19) hooked bars at approximately 13,500 psi (93.1 MPa), for No. 7 (No. 22) and No. 8 (No. 25) hooked bars at approximately 11,500 psi (79.3 MPa), for No. 9 (No. 29) hooked bars at approximately 8,000 psi (55.2 MPa), and for No. 11 (No. 36) hooked bars at approximately 6,000 psi (41.4 MPa). In the last two cases, the concrete compressive strength at which the $f_{su}/f_{s,\text{ACI}}$ ratio drops below 1.0 occurs below the 10,000 psi (68.9 MPa) limit on f_c' in ACI 318-14. These results indicate that current

Code provisions for development length may result in unconservative designs for No. 9 (No. 29) and larger bars when used with concrete with compressive strengths as low as 6,000 psi (41.4 MPa).

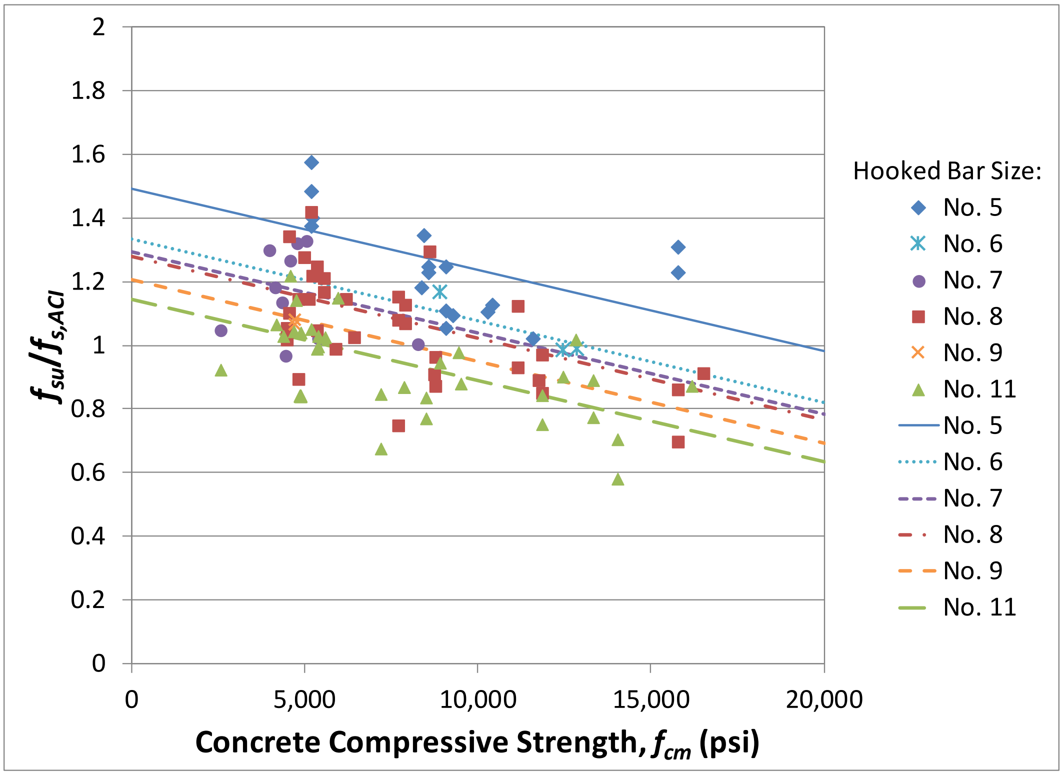


Figure 2.8 Ratio of test-to-calculated stress $f_{su}/f_{s,ACI}$ versus f_{cm} for hooked bars without confining transverse reinforcement

Figure 2.9 shows the experimental results from this study for 50 beam-column joints with two hooked bars and two No. 3 (No. 10) column ties in the joint region. As for the hooked bars without confining transverse reinforcement in the joint region, the ratio $f_{su}/f_{s,\mathrm{ACI}}$ decreases as bar size and concrete compressive strength increase. The values of $f_{su}/f_{s,\mathrm{ACI}}$ shown in Figure 2.9 are higher than those shown in Figure 2.8, an indication that the two ties in the joint region contribute to increased anchorage strength, an effect that is not accounted for in ACI 318-14 [Eq. (2.1) and (2.2)].

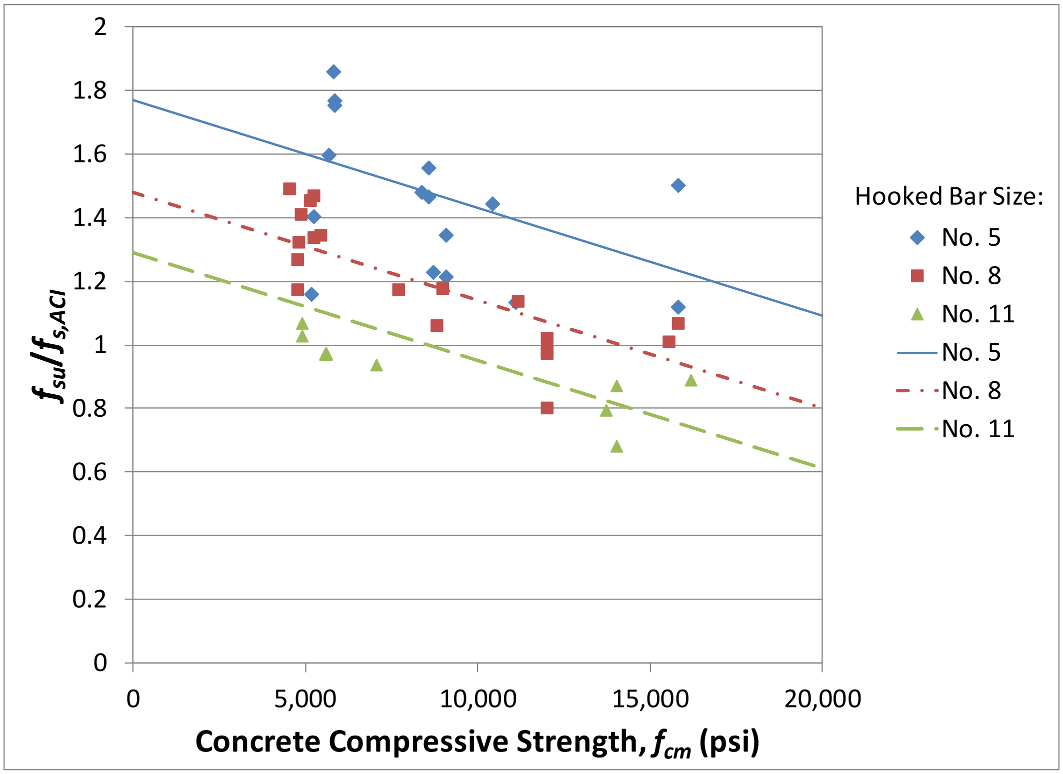


Figure 2.9 Ratio of test-to-calculated stress $f_{su}/f_{s,ACI}$ versus f_{cm} for hooked bars 2 No. 3 ties as confining transverse reinforcement

As shown in Figure 2.9, the trend line for No. 8 (No. 25) bars drops below 1.0 for compressive strengths above approximately 14,500 psi (100 MPa), and for No. 11 (No. 36) bars for compressive strengths above approximately 9,000 psi (62.1 MPa). As with the hooked bars without confining transverse reinforcement in the joint region, these results indicate that the provisions for hooked bar development length in ACI 318-14 do not accurately reflect the effects of concrete compressive strength and bar diameter on anchorage strength, and can lead to unconservatively short development lengths for No. 11 (No. 36) hooked bars when used with concrete with compressive strengths above 9,000 psi (62.1 MPa).

Figure 2.10 shows results for 59 beam column joints (53 from the current investigation) with No. 3 (No. 10) ties spaced at $3d_b$ or less within the joint region. The $3d_b$ spacing of the confining transverse reinforcement permits the use of the confining reinforcement factor $\psi_r = 0.8$

for development length in accordance with Section 25.4.3.2 of ACI 318-14. As in Figure 2.8, the parallel trend lines from the dummy variables analysis have a negative slope and the intercepts of the trend lines decrease as bar size increases. An exception to this trend based on bar size is the line corresponding to a single data point for No. 7 (No. 22) bars from the study by Lee and Park (2010), which is below the lines corresponding to No. 8 (No. 25) and No. 11 (No. 36) bars.

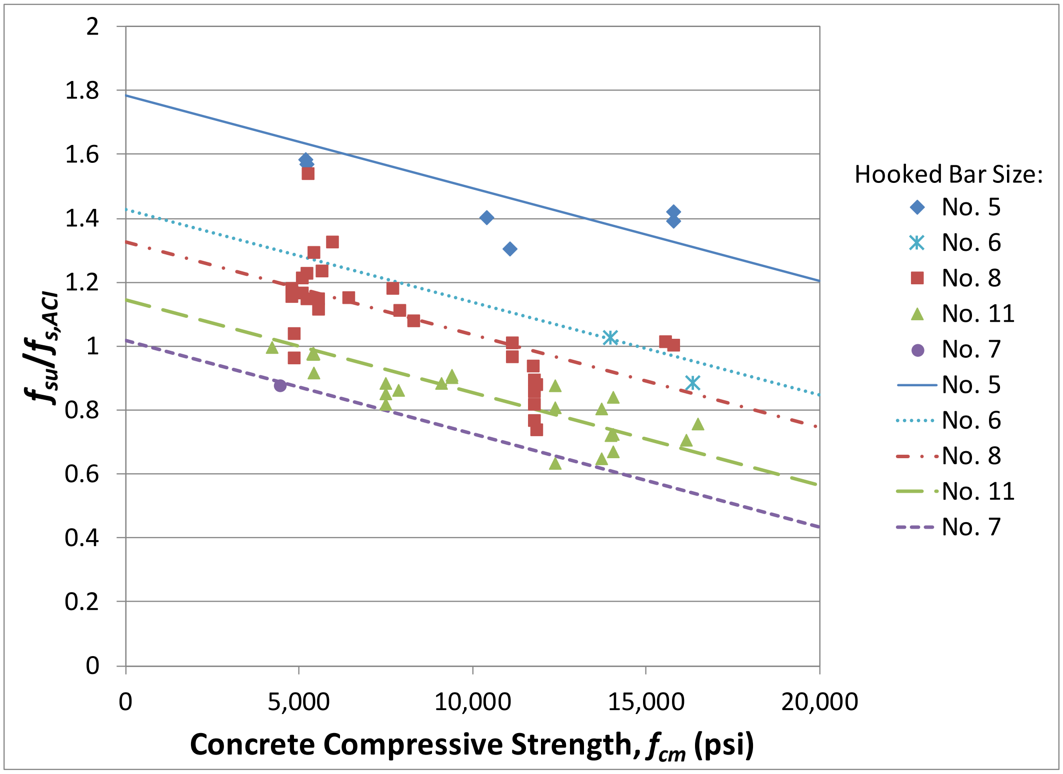


Figure 2.10 Ratio of test-to-calculated stress $f_{su}/f_{s,ACI}$ versus f_{cm} for hooked bars No. 3 ties spaced at $3d_b$ as confining transverse reinforcement

For the No. 6 (No. 19) hooked bars, the trend line for $f_{su}/f_{s,\text{ACI}}$ reaches a value of 1.0 at a compressive strength of approximately 14,500 psi (100 MPa). For the No. 8 and 11 (No. 25 and 36) hooked bars, the trend lines reach a value of 1.0 at respective concrete compressive strengths of approximately 11,000 and 5,000 psi (75.8 and 34.5 MPa). As previously stated, the development length provisions for hooked bars in ACI 318-14 limit the value of concrete compressive strength used in the calculations to a maximum of 10,000 psi (68.9 MPa). Ramirez and Russell (2008) recommended allowing the use of higher concrete compressive strengths in the calculations in conjunction with the development length reduction factors that now appear in ACI 318-14 Section 25.4.3.2. The test results shown in Figure 2.10 indicate that this practice would produce unsafe designs for No. 8 (No. 25) hooked bars with concrete compressive strengths greater than 11,000 psi (75.8 MPa). When the development length reduction factors are applied to No. 11 (No. 36) bars, the provisions produce unconservative designs for concrete compressive strengths as low as 5,000 psi (34.5 MPa). This matches earlier results by Ramirez and Russell (2008) who also found these reduction factors produce unconservative designs.

For specimens with No. 3 (No. 10) ties spaced at $3d_b$ within the joint region, specimens with two No. 3 (No. 10) ties in the joint region, and specimens without confining transverse reinforcement, the trend lines for $f_{su}/f_{s,\mathrm{ACI}}$ decrease with increasing bar size and concrete compressive strength, and the current design provisions appear to result in unconservative designs for No. 11 (No. 36) bars with concrete compressive strengths as low as 5,000 psi (34.5 MPa). These observations indicate that the provisions in ACI 318-14 for the design of hooked bars should be adjusted to more accurately represent the effects of concrete compressive strength and bar size.

Figures 2.11 and 2.12 compare the failure load T_{test} with the calculated failure load T_{calc} based on the provisions of Section 25.4.3.1(a) of ACI 318-14 [and as Eq. (2.2) in this chapter] for hooked bars without and with confining transverse reinforcement, respectively. T_{calc} incorporates all reduction factors, as applicable, along with the limit of 10,000 psi (69 MPa) on the concrete compressive strength. The results for the specimens with two hooked bars anchored inside the column longitudinal bars are presented. The dashed lines in the figures represent cases in which the T_{test} and T_{calc} are equal, while the solid line represents the best fit line for the tests results. As demonstrated in the figures, the ACI provisions are conservative ($T_{test} > T_{calc}$) for smaller bar sizes, but unconservative ($T_{test} < T_{calc}$) for a significant number of specimens with No. 8 (No. 25) hooked bars and the majority of specimens with No. 11 (No. 36) hooked bars. The ACI provisions become increasingly unconservative as the failure load increases. The average, maximum, and minimum values of T_{test}/T_{calc} were 1.09, 1.64, and 0.68 for specimens with no transverse reinforcement and 1.24, 1.89, and 0.71 for specimens with transverse reinforcement. Figures 2.11 and 2.12 further demonstrate that the effect of bar size is not accurately represented by the development length provisions of ACI 318-14 Section 25.4.3.1(a).

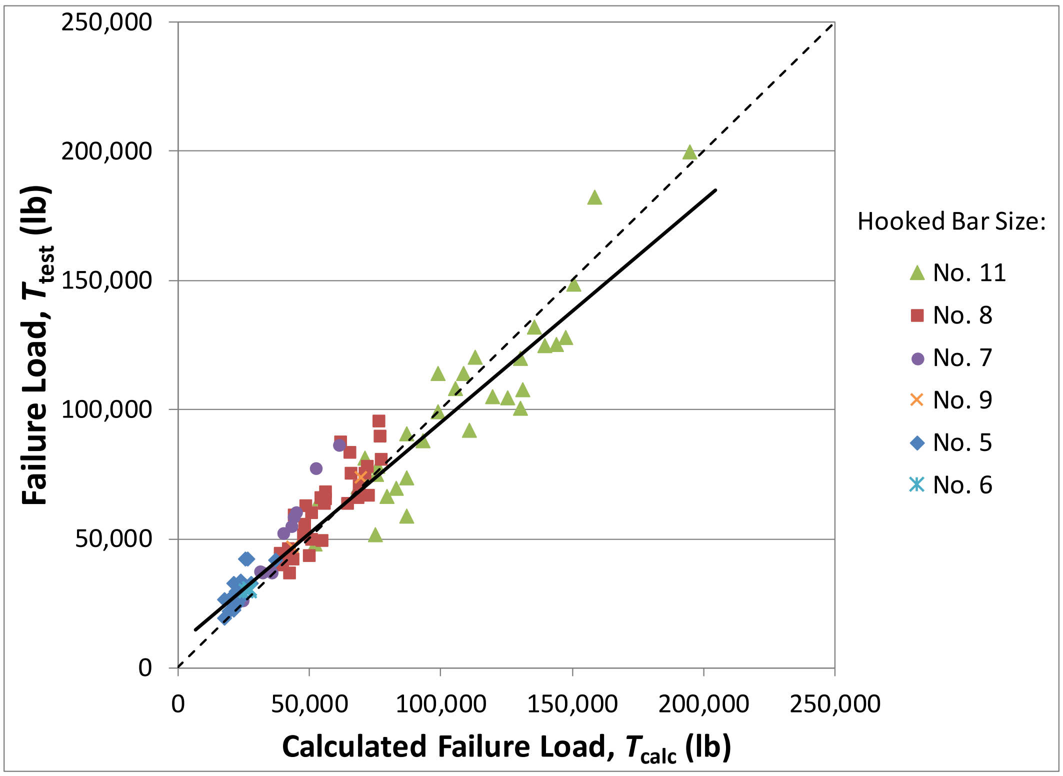


Figure 2.11 Load at failure versus calculated failure load for hooked bars without confining transverse reinforcement, with T_{calc} based on ACI 318-14 Section 25.4.3.1(a)

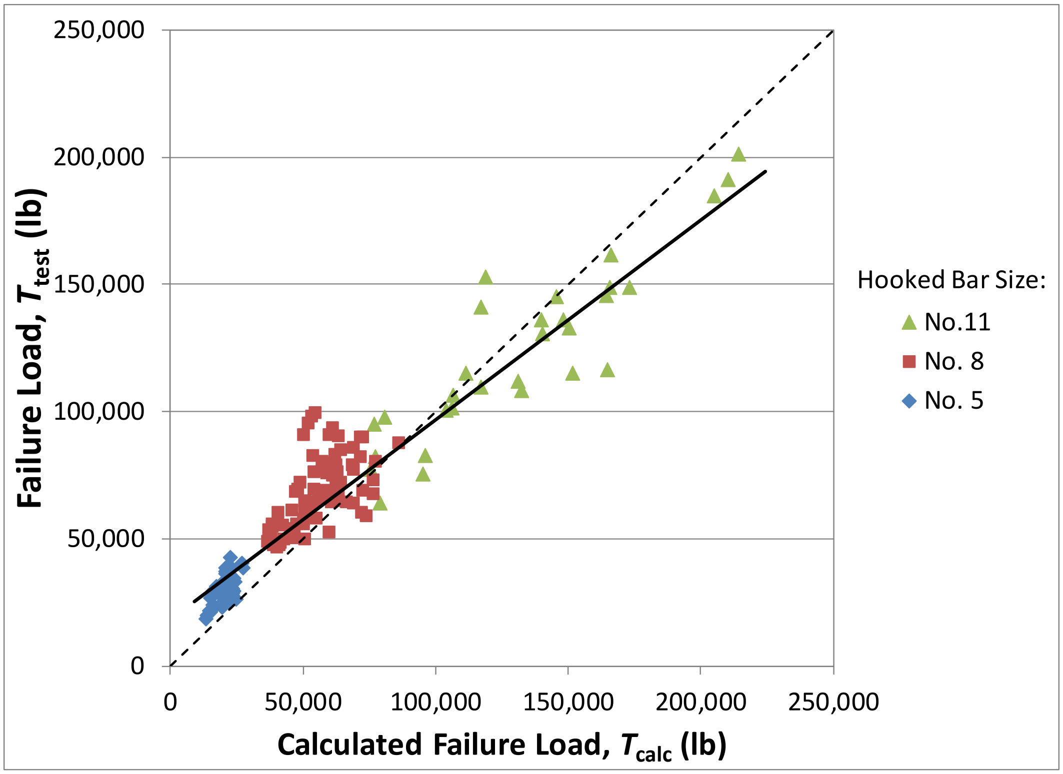


Figure 2.12 Load at failure versus calculated failure load for hooked bars with confining transverse reinforcement, with T_{calc} based on ACI 318-14 Section 25.4.3.1(a)

2.5 SUMMARY AND CONCLUSIONS

In this study, 337 simulated exterior beam-column joints were tested to investigate the anchorage capacity of hooked bars. Of the 337 beam-column joints, 276 contained two hooked bars, and 61 contained more than two hooked bars. The beam-column joint specimens with two hooked bars cast inside the column longitudinal steel were used to evaluate the applicability of the current Code provisions to high-strength steel or concrete. The effects of concrete side cover to the hooked bar, hook bend angle, hooked bar spacing, hooked bar placement, and transverse reinforcement orientation are discussed by Sperry et al. (2015) and will be addressed in subsequent papers. No. 5, No. 8, and No. 11 (No. 16, 25, and 36) hooked bars were tested with both 90° and 180° bend angles. The nominal clear concrete side cover ranged from 1.5 in. to 4 in. (38.1 to 101.6 mm), with most values in the 2.5 to 3.5 in. (63.5 to 88.9 mm) range, and the hook center-to-center spacing ranged from $3d_b$ to $11d_b$. The specimens were cast with normalweight concrete with compressive strengths ranging from 4,300 to 16,510 psi (30 to 134 MPa). Bar stresses at failure ranged from 22,800 to 141,600 psi (157 to 976 MPa). To determine the effect of transverse reinforcement on joint capacity, specimens were constructed with either no transverse reinforcement or transverse reinforcement ranging from 1 No. 3 (No. 10) tie to transverse reinforcement in accordance with ACI 318-14 Section 18.8.3 for joints in special moment frames. Data from prior studies were included in the analysis. Results were compared to the provisions of ACI 318-14 Section 25.4.3 for hooked bar development length.

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

1. Both a front and side failure were involved for the majority of hooked bars, with front failure being the dominant failure mode in a greater percentage of the tests.
2. Of hooked bars exhibiting only one failure mode, a greater number exhibited front failure than side failure.
3. Front failure plays an important role in the behavior of hooked bars, which is in contrast to findings of previous studies.
4. As the bar size increases, the percentage of hooked bars exhibiting side failure as the primary failure mode increases.
5. The provisions of ACI 318-14 overpredict the anchorage strength of larger hooked bars, the effect of concrete compressive strength, and the effect of confining transverse reinforcement on the anchorage capacity of hooked bars in tension.
6. The reduction factors as applied in Section 25.4.3.2 of ACI 318-14 for concrete cover and confining transverse reinforcement are unconservative.

2.6 NOTATION

d_b Nominal bar diameter of the hooked bar

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} Average peak stress in hooked bars at failure

h_c Width of bearing member flange

h_{cl} Height measured from the center of the hook to the top of the bearing member flange

h_{cu} Height measured from the center of the hook to the bottom of the upper compression member

ℓ_{dh} Development length in tension of deformed bar with a standard hook, measured from the outside end of hook, point of tangency, toward critical section

ℓ_{eh} Embedment length measured from the back of the hook to the front of the column

T_{calc} Calculated hooked bar strength

T_{test} Measured load on hooked bar at failure

λ Modification factor to reflect the reduced mechanical properties of lightweight concrete to normalweight concrete of the same compressive strength

ψ_c Factor used to modify development length based on cover as defined in ACI 318-14 Section 25.4.3.2

ψ_e Factor used to modify development length based on coating as defined in ACI 318-14 Section 25.4.3.2

ψ_r Factor used to modify development length based on confining reinforcement in the hook region as defined in ACI 318-14 Section 25.4.3.2

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CHAPTER 3: ANALYSIS OF RESULTS

3.1 INTRODUCTION

When reinforcing steel is terminated, such as in a splice or at an exterior beam-column joint, an adequate length of bar must be embedded in the concrete to develop the yield strength of the steel at the critical section. This development length is a function of the characteristics of the reinforcing bar and surrounding concrete. In most cases, the development length can be provided within the member with a straight length of bar. There are cases, however, where the straight bar development length cannot be provided within the member, such as at an external beam-column connection. In this case, the bar must be anchored by other means. One option is to use a hooked bar with a bend angle of 90° or 180°.

Extensive research has been done on the development and splice strength of straight deformed bars (Abrams 1913, Lutz and Gergely 1967, Azizinamini et al. 1993, Darwin and Graham 1993, Darwin et al. 1996, Zuo and Darwin 2000, to name a few), which has resulted in equations that accurately characterize bond over the full range of steel yield strengths and concrete compressive strengths currently used and planned for use in concrete structures (Darwin et al. 1996, Zuo and Darwin 2000, ACI Committee 408R-03). Similar characterizing equations, however, have yet to be formulated for hooked bars. When trying to describe the strength or behavior of hooked bars, researchers typically compare test results with strengths calculated using the provisions of the ACI Building Code (ACI 318-14) for hooked bar development length. This approach is less than ideal, however, because the provisions in ACI 318 are based on a small data set that does not include high-strength steel or high-strength concrete. In addition, the development length equation is a design equation not meant to characterize the behavior of hooked bars but rather to provide a safe design. Thus, the actual behavior of hooked bars, especially when using high-strength materials, cannot be accurately represented using the development length equation of ACI 318-14, as demonstrated by Sperry et al. (2015, 201X). Thus, the need arises to develop an expression that is applicable to the full range of concrete and steel strengths that are used in practice, one that can ultimately be used to develop design provisions.

The equation for development length ℓ_{dh} in the ACI Code (ACI 318-14) [Eq.(3.1)] assumes that the stress developed in a hooked bar is proportional to the square root of the concrete compressive strength and inversely proportional to the bar diameter. This can be demonstrated, starting with the equation in ACI 318-14 for ℓ_{dh}.

$$\ell_{dh} = \left(\frac{f_y \psi_e \psi_c \psi_r}{50\lambda\sqrt{f'_c}} \right) d_b \tag{3.1}$$

where ℓ_{dh} = Development length in tension of a deformed bar with a standard hook, measured from the outside end of hook, point of tangency, toward critical section, f_y = Yield strength of hooked bar, ψ_e = Factor used to modify development length based on coating as defined in ACI 318-14 Section 25.4.3.2, ψ_c = Factor used to modify development length based on cover as defined in ACI 318-14 Section 25.4.3.2, ψ_r = Factor used to modify development length based on confining reinforcement in the hook region as defined in ACI 318-14 Section 25.4.3.2, d_b = Nominal bar diameter of hooked bar, λ = Modification factor to reflect the reduced mechanical properties of lightweight concrete to normalweight concrete of the same compressive strength, and f'_c = specified concrete compressive strength.

Substituting the calculated stress $f_{s,ACI}$ for f_y, the embedment length ℓ_{eh} for ℓ_{dh}, and the measured concrete compressive strength f_{cm} for f'_c, and taking ψ_e and $\lambda = 1.0$ gives

$$f_{s,\mathrm{ACI}} = \frac{50\ell_{eh}\sqrt{f_{cm}}}{\psi_c \psi_r d_b} \tag{3.2}$$

In Chapter 2, it was shown that the assumptions in ACI 318-14 relative to compressive strength and bar diameter produce unconservative designs; that is, as the concrete compressive strength and bar diameter increase, the development length Eq. (3.1) becomes progressively unconservative. Dealing first with compressive strength, these observations indicate that the square root of the compressive strength overstates the effect of concrete compressive strength on the anchorage strength. This matches observations for straight bars, where it has been found that the stress developed in a bar is not proportional to the square root of the concrete compressive strength but rather the fourth root, that is, the compressive strength raised to the quarter power (Darwin et al. 1996, Zuo and Darwin 2000). The analysis in Chapter 2 also demonstrated that Eq. (3.1) and (3.2) underpredict the stresses developed in small hooked bars and overpredict the stresses in larger hooked bars, indicating that the assumption embodied in Eq. (3.1) and (3.2), that the stress that can be developed in a hooked bar is inversely proportional to the diameter of the hooked bar d_b, is incorrect. Sperry et al. (2015, 201X) also observed that the reduction factors for side cover and confining transverse reinforcement in Section 25.4.3.2 of ACI 318-14 (0.7 and 0.8, respectively) are unconservative, especially when used with high-strength concrete and larger diameter bars.

In this chapter, equations will be developed that accurately characterize the effects of concrete compressive strength, bar diameter, and confining transverse reinforcement on the anchorage strength of hooked bars. The effects of hook bend angle, clear concrete side cover to the hooked bar, hooked bar placement inside or outside the column core, as well as within the depth of the member, and closely spaced hooked bars are covered by Sperry et al. (2015) and in subsequent papers.

3.2 RESEARCH SIGNIFICANCE

Equations have been developed that accurately characterize the development and splice strength of straight deformed bars that apply equally well to conventional strength and high-strength steel and concrete. There are, however, no such equations for hooked deformed bars. In addition, prior to this study, the knowledge of the behavior of hooked bars has been limited due to the low number of experimental studies. This paper focuses on characterizing the anchorage strength of hooked bars across the full range of material strengths currently in use and planned for use in concrete structures. The effects of key parameters on hooked bar development are analyzed and used to develop characterizing equations.

3.3 TEST PROGRAM

A database of 214 test results was selected from a larger study of hooked bar anchorage (Sperry et al. 2015) to study the following variables: reinforcing steel stress at hook failure, embedment length, side cover, amount of confining reinforcement, concrete compressive strength, hooked bar size, and hook bend angle. All specimens had two hooked bars cast inside the column core. No. 5, 8, and 11 (No. 16, 25, and 36) hooked bars were tested in normalweight concrete with compressive strengths ranging from 4,300 to 16,510 psi (29.6 to 113.8 MPa). The test specimens, simulated beam-column joints, were cast as reinforced concrete columns without the beam, shown in Figure 3.1. The longitudinal beam reinforcing bars protruded from the face of the column, and the compression region of the beam was simulated using the testing frame (Figure 3.2). Nominal clear cover from the outside of the bar to the outside of the column (side covers) ranged from 2.5 to 3.5 in. (64 to 89 mm) and hook center-to-center spacing was $11d_b$, where d_b is the diameter of the hooked bar. Bar stresses ranged from 33,000 to 137,400 psi (228 to 947 MPa). The results of these tests are used in conjunction with results from 31 exterior beam-column joint specimens from previous studies to develop descriptive equations relating the key parameters to anchorage strength. This paper describes the development of characterizing equations for hooked bar anchorage. The details and results of the specimens used to develop the characterizing equations were presented in Chapter 2 and by Sperry et al. (2015).

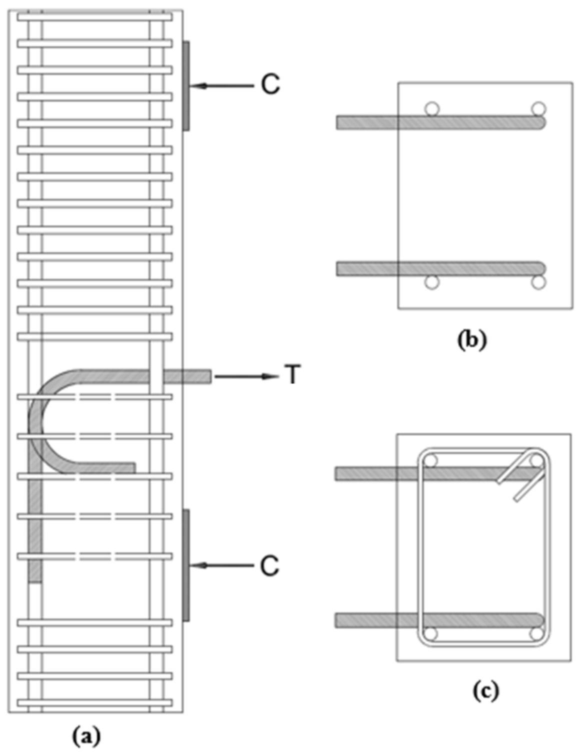

Figure 3.1 Schematic of specimens (a) side view of specimen (b) cross-section of specimen with hooks inside column core and without confining transverse reinforcement (c) cross-section of specimen with hooks inside column core and with confining reinforcement

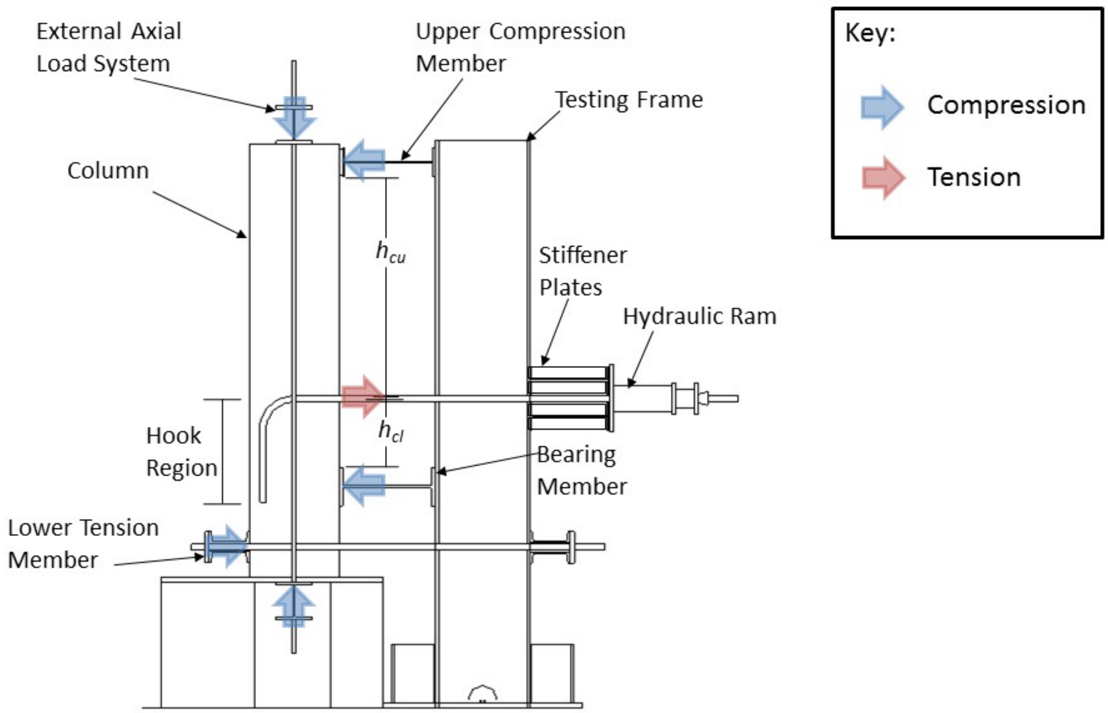

Figure 3.2 Testing frame and forces applied to specimens during testing

3.4 ANALYSIS OF TEST RESULTS

A series of iterative analyses was conducted to determine the effects of key parameters (embedment length, concrete compressive strength, hooked bar diameter, and quantity of confining transverse reinforcement) on hooked bar anchorage strength using experimental results from this and other studies. The effects of hook bend angle, side cover, and tie orientation (parallel or perpendicular to the straight portion of the hooked bar) will be discussed in a follow-on paper. Two cases were addressed throughout the analyses: hooked bars without confining transverse reinforcement in the joint region and hooked bars with differing quantities of confining transverse reinforcement within the joint region. All specimens used in these analyses contained two hooked bars cast inside the column longitudinal reinforcement. In all analyses, the average bar force at failure T was defined as the peak load on the specimen divided by the number of hooked bars, and the embedment length ℓ_{eh} was defined as the average distance from the front face of the column to the back of the tail of the hooks within a specimen. In this paper, ℓ_{eh} refers to the embedded length of the bar and is a measured property, whereas ℓ_{dh} refers to the minimum length of anchorage required by ACI 318-14 Section 25.4.3 to ensure that a bar can develop its yield strength.

3.4.1 Descriptive Equation for Hooked Bars without Confining Reinforcement

Figure 3.3 shows the results for 99 beam-column joint specimens without confining transverse reinforcement. The figure shows the average bar force at failure T as a function of embedment length ℓ_{eh}. The average bar forces at failure T range from 19,200 to 213,300 lb (85.4 to 949 kN), the bars stresses range from 30,800 to 136,700 psi (212 to 943 MPa), the embedment lengths ℓ_{eh} range from 4.9 to 26.0 in. (124 to 660 mm), and the concrete compressive strengths range from 2,570 to 16,510 psi (17.7 to 114 MPa). The general trend shows that an increase in embedment length produces an increase in anchorage capacity. This representation of the data, however, does not show the effects of concrete compressive strength.

Using a least squares regression technique known as dummy variables analysis (Draper and Smith 1981) in which differences in populations can be compensated for when formulating relationships between principal variables (described more fully in Chapter 2), the results shown in Figure 3.3 were re-plotted with the load at failure normalized with respect to the compressive strength to the power p_1, $T/f_{cm}^{p_1}$. The value of p_1 was varied to obtain the linear relationship that minimized the relative intercept. The relative intercept is defined as the difference in the maximum and minimum intercepts of the dummy variables lines normalized to the difference in the maximum and minimum values of $T/f_{cm}^{p_1}$. Using this method, the value of p_1 was found to be 0.29. The average intercept of the individual dummy variables lines was used to develop Eq.(3.3), where

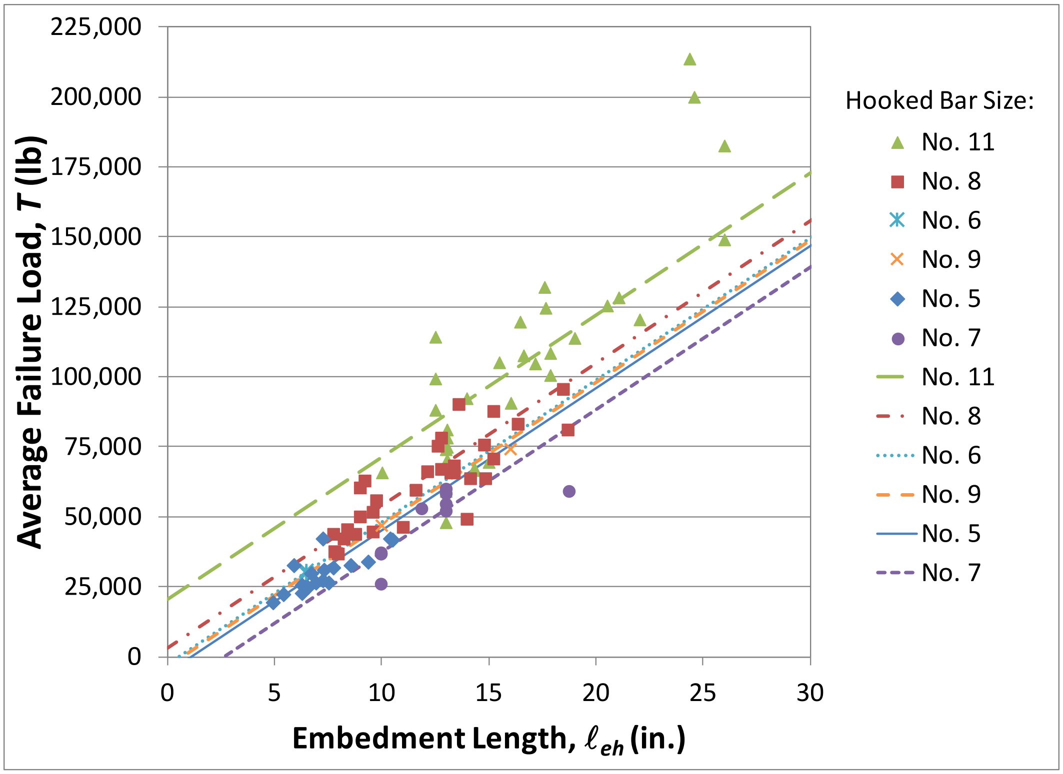

Figure 3.3 Average bar force at failure versus embedment length for hooked bars without confining transverse reinforcement

T_c represents the calculated anchorage capacity of a hooked bar without confining transverse reinforcement.

$$\frac{T_c}{f_{cm}^{0.29}} = 430\ell_{eh} - 460 \tag{3.3}$$

Figures 3.4 and 3.5 show the results of this analysis. In Figure 3.4, $T/f_{cm}^{p_1}$ is plotted as a function of embedment length. In Figure 3.5, the ratios of the bar force at failure to the bar force calculated based on Eq. (3.3), T_{test}/T_{calc}, are plotted with respect to f_{cm}. The mean ratio is 1.0, with a range of 0.681 to 1.49 and a standard deviation and coefficient of variation of 0.185. The intercepts range from 0.812 to 1.20.

A clear pattern in the dummy variable lines is observed in Figures 3.4 and 3.5, with the larger bar sizes above the smaller bar sizes, indicating that, for a *given embedment length*, larger hooked bars provide greater anchorage strength.

In Figure 3.5, the dummy variables lines are horizontal, showing that the ratio of test-to-calculated failure load does not vary with concrete compressive strength. This consistency with respect to concrete compressive strength indicates that p_1 = 0.29 appropriately captures the effect of concrete compressive strength.

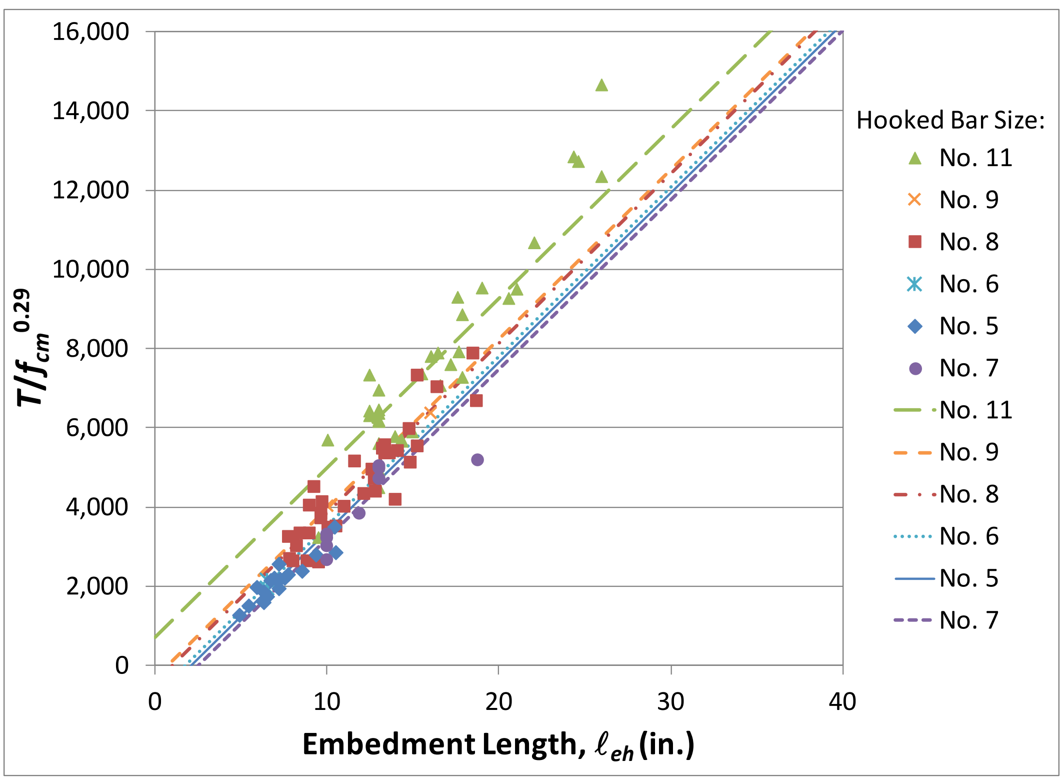

Figure 3.4 Average bar force at failure normalized to $f_{cm}^{0.29}$ versus embedment length for hooked bars without confining transverse reinforcement

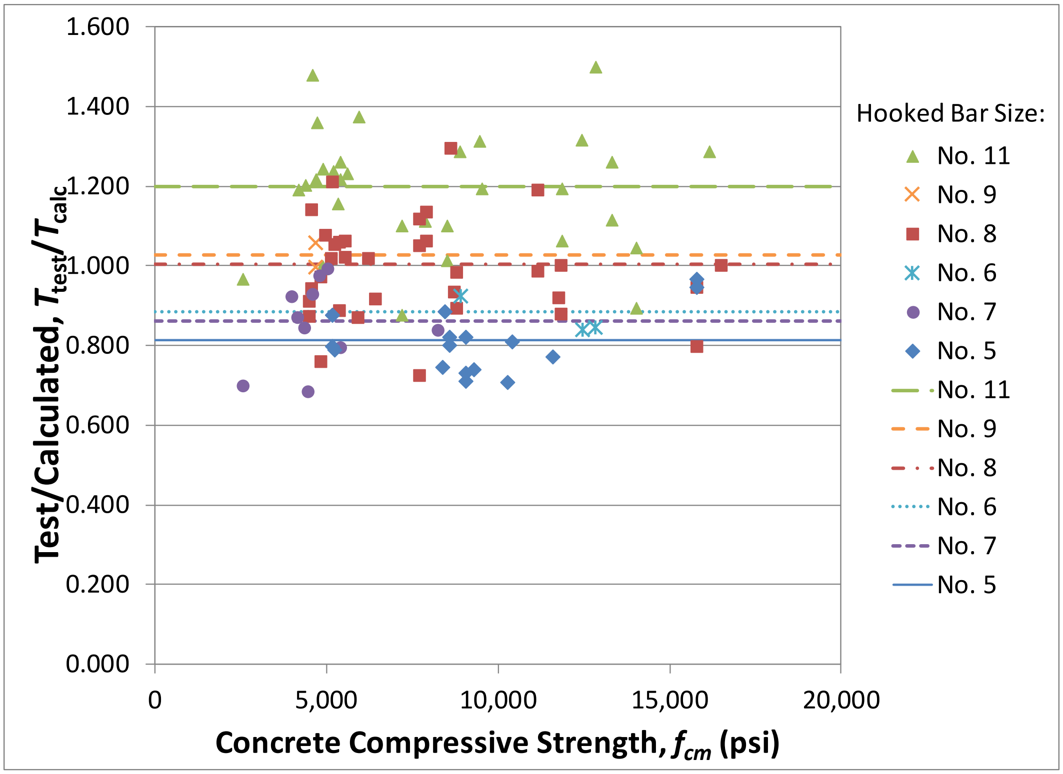

Figure 3.5 Ratio of test-to-calculated failure load versus concrete compressive strength for specimens without confining transverse reinforcement, with T_{calc} based on Eq. (3.3)

The fact that the power of f'_c, p_1, is significantly less than ½ (the value used in the ACI Code [ACI 318-14] to represent the contribution of the effect of concrete compressive strength on bond and anchorage capacity) is in concert with observations of the effect of concrete compressive strength on the development and splice strength of straight reinforcement, where a power of 0.25 has been found to provide a close match with experimental results (Darwin et al. 1996, Zuo and Darwin 2000). Like the bond strength of straight reinforcement, hook strength is governed by the combined effects of concrete tensile strength, which controls initial crack formation, and fracture energy, which controls crack propagation. While the tensile strength of concrete increases with the compressive strength to a power between ½ and $^2/_3$, the fracture energy of concrete is independent of compressive strength (Darwin et al. 2001). The combined effect is a power well below ½.

The next step in developing an equation to characterize hook strength was to determine the effect of bar diameter on anchorage strength for hooks without confining transverse reinforcement. To accomplish this, the average bar force T normalized to $f_{cm}^{0.29}$ was plotted versus embedment length times the bar diameter raised to the p_2 power. Dummy variables lines were calculated for each bar diameter, with the power p_2 = 0.47 minimizing the relative intercept (spread) of the dummy variables lines; this result is shown in Figure 3.6. The resulting dummy variables lines are closely spaced, indicating that $d_b^{0.47}$ reflects the contribution of bar diameter to anchorage force. Using the average intercept of the dummy variables lines, the descriptive equation for hooked bars without confining transverse reinforcement is

$$\frac{T_c}{f_{cm}^{0.29}} = 422\ell_{eh}d_b^{0.47} - 417 \tag{3.4}$$

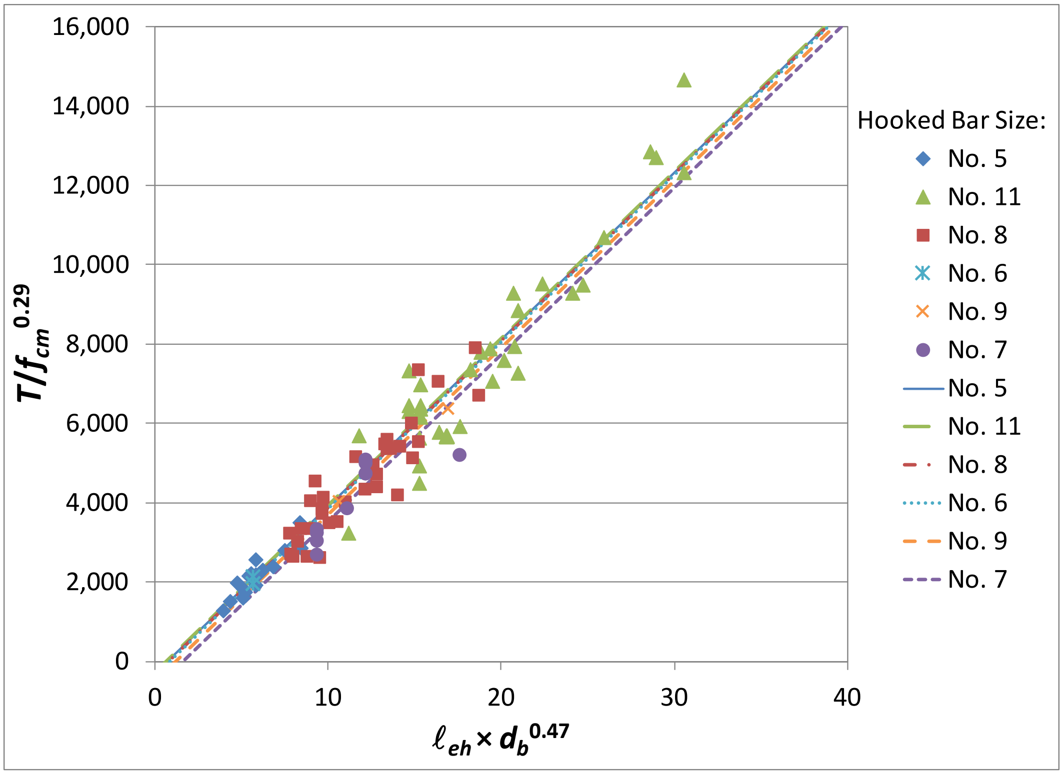

Figure 3.6 Average bar force at failure normalized to $f_{cm}^{0.29}$ versus embedment length and bar diameter for hooked bars without confining transverse reinforcement

The intercepts of the trend lines for the bar sizes evaluated are –288 for No. 5 (No. 16) hooked bars, –368 for No. 6 (No. 19) hooked bars, –698 for No. 7 (No. 22) hooked bars, –348 for No. 8 (No. 25) hooked bars, –504 for No. 9 (No. 29) hooked bars, and –288 for No. 11 (No. 36) hooked bars. These intercepts represent a major improvement when compared to those in Figure 3.4.

The ratios of the bar force at failure to the bar force calculated based on Eq. (3.4) are plotted with respect to f_{cm} in Figure 3.7. The figure exhibits much less scatter than Figure 3.5 as a result of including the effect of the bar size in Eq. (3.4). The mean ratio is 1.0, the coefficient of variation is 0.121, and the ratios of test-to-calculated failure load range from 0.728 to 1.30. The slopes of the dummy variables lines are approximately zero, confirming that with the inclusion of bar size, $f_{cm}^{0.29}$ continues to capture the effect of concrete compressive strength on anchorage strength. The intercepts of the individual trend lines range from 0.94 to 1.07.

Figure 3.8 shows the relationship between the ratio of test-to-calculated failure load [using Eq. (3.4)] and bar diameter d_b. The nearly zero slope of the dummy variables lines confirms that the effect of bar diameter on anchorage strength T is reasonably represented by $d_b^{0.47}$. The intercepts of the dummy variables trend lines range from 0.93 to 1.06.

Up to this point, the analyses were based on the assumption that the relationship between the anchorage strength of hooked bars and embedment length ℓ_{eh} is linear. There are several trends in the data, however, that indicate a nonlinear relationship. For example, in Figure 3.6, three of the four data points corresponding to the greatest embedment lengths and highest anchorage forces deviate from the linear trend on the high side. In addition, the intercepts of the dummy variables lines are negative, when they should actually be equal to zero. To capture this nonlinear behavior,

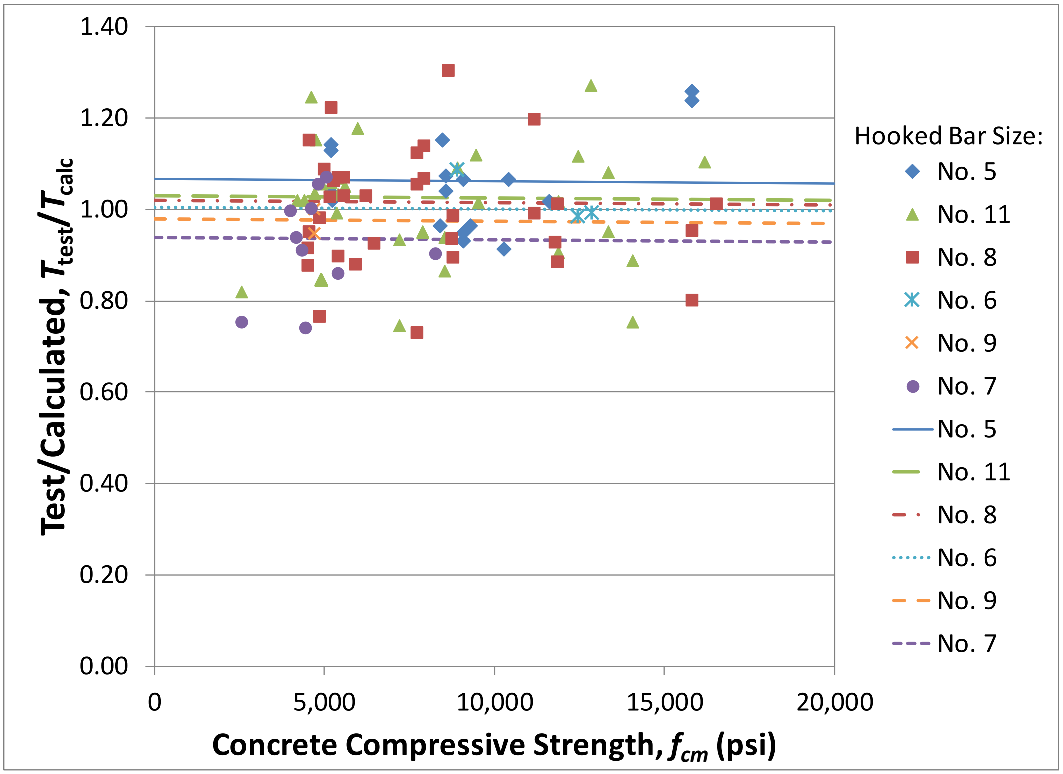

Figure 3.7 Ratio of test failure load to calculated failure load based on Eq. (3.4) versus concrete compressive strength for beam-column specimens without confining transverse reinforcement

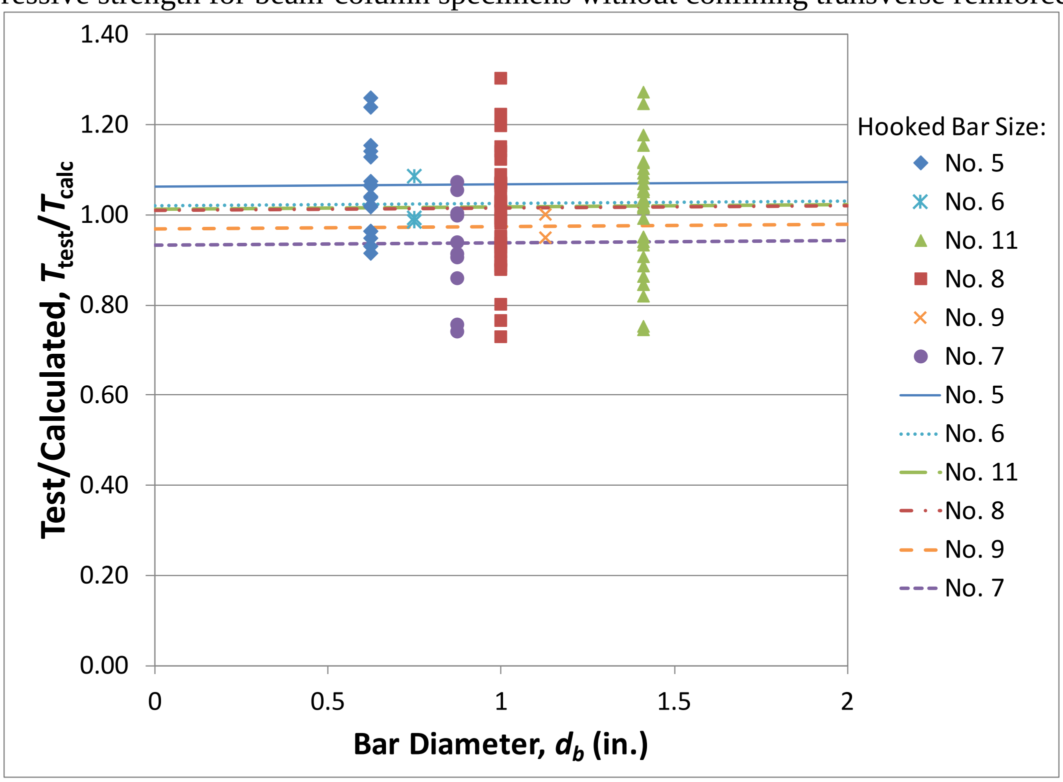

Figure 3.8 Ratio of measured to calculated bar force versus bar diameter for beam-column specimens without confining transverse reinforcement

the data were reanalyzed by raising ℓ_{eh} and d_b to the powers that minimized the sum of the squared differences $(1-T/T_c)^2$. The resulting equation is given by

$$\frac{T_c}{f_{cm}^{0.29}} = 332\ell_{eh}^{1.06}d_b^{0.54} \tag{3.5}$$

This nonlinear relationship, with a power of ℓ_{eh} slightly greater than 1.0, is in concert with the failure modes, front breakout and blowout and side breakout and blowout, described in Chapter 2, that involve progressively more concrete as the embedment length increases. It should be noted, however, that a power of 1.06 produces similar results to a power of 1.0. Thus, for design, it would be justified to use the power of 1.0 for the embedment length. The experimental results are compared with the failure loads calculated using Eq. (3.5) in Figure 3.9, where the dashed line is the 45° line where the calculated failure load exactly equals the measured failure load and the solid line is the best fit line for the data set. The fact that the two lines are very close indicates that Eq. (3.5) provides a good estimate of anchorage strength for the entire range of test results.

The average test-to-calculated ratio based on Eq. (3.5) is 1.0 with a coefficient of variation of 0.119. The maximum and minimum ratios are, respectively, 1.30 and 0.731. These compare to the nearly identical respective values for Eq. (3.4) of 1.0, 0.121, 1.30 and 0.728.

Because Eq. (3.5) provides a somewhat more accurate representation of the data than Eq. (3.4), Eq. (3.5) was used in subsequent calculations to represent the contribution of the concrete to the anchorage capacity of hooked bars T_c. The following section addresses the strength of specimens that contain confining reinforcement in the region of the hook.

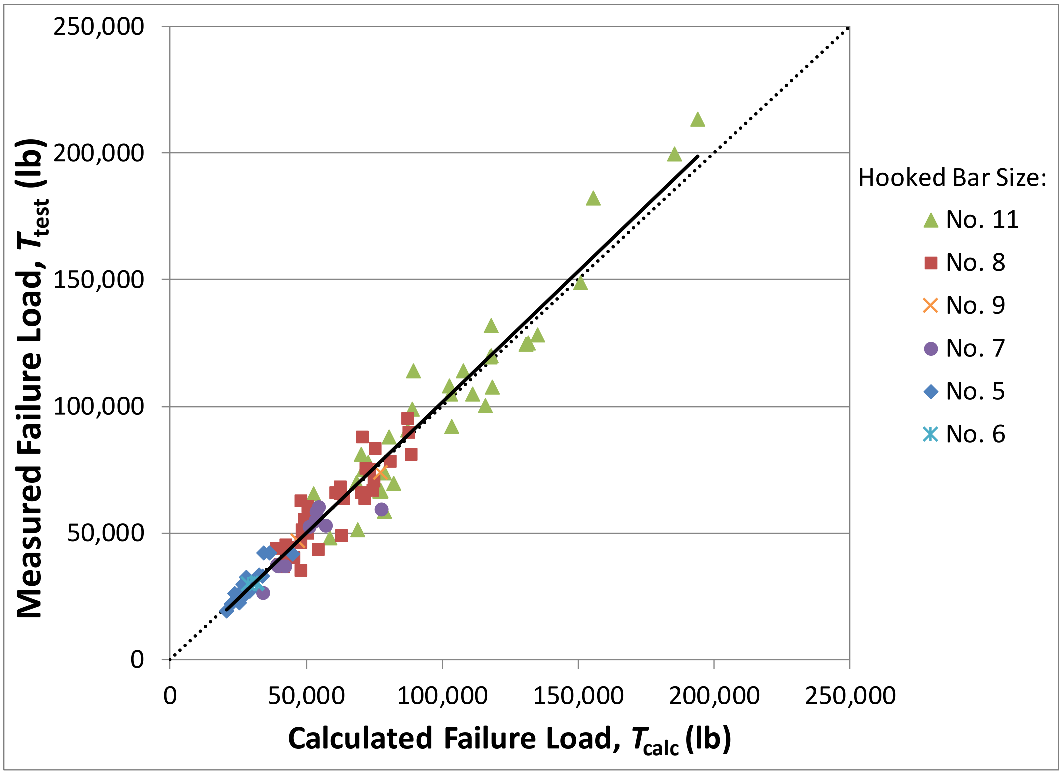

Figure 3.9 Measured versus calculated bar force at failure for hooked bars with confining transverse reinforcement, with T_{calc} based on Eq. (3.5)

3.4.2 Descriptive Equation for Hooked Bars with Confining Reinforcement

ACI 318-14 permits a reduction in the development length of hooked bars if the bars are confined by No. 3 (No. 10) bars or larger spaced at $3d_b$ or less; the confining reinforcement may be perpendicular or parallel to the straight portion of the hooked bars for 90° hooks, but only confining reinforcement perpendicular the straight portion of a hook may be used to reduce the development length of 180° hooks. In the current analysis, confining reinforcement with both orientations was found to contribute the anchorage capacity of both 90° and 180° hooked bars.

For specimens with confining transverse reinforcement within the joint region, the bar force calculated with the equation characterizing the anchorage strength of specimens without confining transverse reinforcement T_c [from Eq. (3.5)] was subtracted from the measured bar force at failure T. This difference was assumed to represent the contribution of the confining reinforcement T_s to the anchorage capacity of the hooked bars. On average, the value of T_c represents 82 percent of the total capacity of the hooked bar. Due to the relatively small number of specimens (12) containing standard hooks confined by confining reinforcement tested prior to this study (Marques and Jirsa 1975, Hamad et al. 1993, Ramirez and Russell 2008, and Lee and Park 2010) and the inherent variability in the contribution of the confining steel to the capacity of the hooked bars and differences in specimen design, only specimens that were tested in this study were used to develop an expression for T_s.

The difference between T and T_c was plotted as a function of NA_{tr}/n, a term representative of the quantity of confining reinforcement effective in the hook region, where N is the number of legs parallel to the straight portion of the hooked bar within $8d_b$ of the top of the hooked bar for No. 3 through No. 8 (No. 10 through No. 25) bars or within $10d_b$ of the top of the hooked bar for No. 9 through No. 11 (No. 29 through No. 36) bars (the out-to-out dimensions of a 180° hooked bar under the provisions of ACI 318-14) or the number of legs perpendicular to the straight portion of the hooked bar over the length being developed, A_{tr} is the area of a single leg of confining reinforcement, and n is the number of hooked bars. For example, for a member with two hooked bars and three No. 3 (No. 10) ties within $8d_b$ or $10d_b$ of the top of the hook, oriented parallel to the straight portion of the bars (this would be provided by ties spaced at $3d_b$), $NA_{tr}/n = (6 \times 0.11)/2 = 0.33\ \text{in.}^2/\text{hook}$ (213 mm^2/hook). For the hooked bars discussed in this section, the value of NA_{tr}/n ranges from 0.11 to 0.60 in.^{2}/hook (71 to 387 mm^2/hook) with a maximum value of N equal to 6.

This definition of N differs from that used by Sperry et al. (2015) due to the observation that some of the ties confining hooks are not in the region of the failure but rather in the region of the compression stress block of the beam, shown in Figure 3.10. Several definitions of *N* as applied to NA_{tr}/n were systematically applied to the dataset. It was found that using the out-to-out dimension of a 180° hook to define the region where ties are effective in resisting the pull-out force of the hook (for both 90° and 180° hooks) resulted in the least scatter in the resulting equation. This definition of *N* is also supported by observations of the specimens after failure. The crack progression shown in Figure 3.10, particularly the crack patterns observed at failure, demonstrate that the majority of the cracks were confined by the ties within $8d_b$ or $10d_b$, as appropriate, of the straight portion of the hooked bar. Some side cracks did extend through the ties within the region of compressive stress, but the concrete failure cone on the front face did not extend below the compression region. This crack behavior suggests that the majority of the confining tensile force will be carried by the ties closest to the hook—that is, outside the compression region.

Based on the cracking patterns and the observed failure modes described in Chapter 2, the confining reinforcement not only prevents cracks in the plane of the hook from widening, but appears to hold regions of the failing concrete together. The nature of the failures observed in the tests suggests that horizontal confining reinforcement acts to anchor the failure cone that is pulled out at failure by the hooked bars and, thus, that anchorage strength should be proportional to the quantity of confining reinforcement in the direction of the bar being developed.

Confining reinforcement placed perpendicular to the bar over the length being developed was also investigated. This orientation is required by ACI 318-14 for 180° hooked bars and allowed for 90° hooked bars. Although this orientation also provides confinement to the hooked

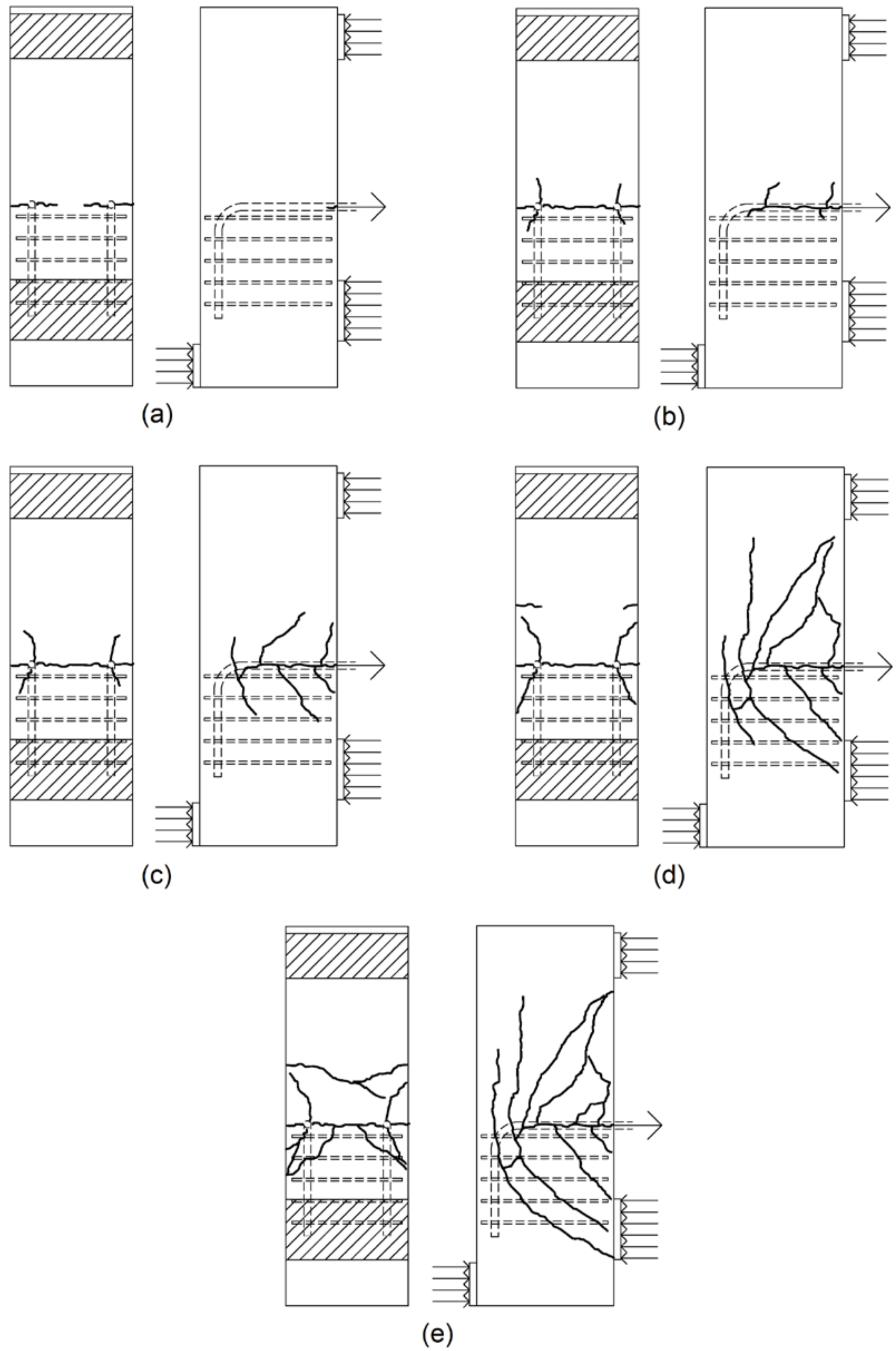

Figure 3.10 Front and side view of specimens indicating typical crack progression with respect to confining reinforcement in joint region (lower shaded region indicates compression region)

bars, it appears that its contribution to anchorage capacity differs from that of reinforcement parallel to the straight portion of the hook, with behavior that is more akin to that of confining reinforcement in the development of straight bars (Darwin et al. 1996, Zuo and Darwin 2000, ACI Committee 408R-03). Thus, the two cases will be discussed in turn and handled separately in the analysis.

Parallel Confining Reinforcement—Figure 3.11 shows the relationship between the ratio of anchorage strength for hooks confined by confining reinforcement parallel to the straight portion of the hooked bars to the calculated anchorage strength provided by concrete [Eq. (3.5)] T/T_c and the parameter NA_{tr}/n. The strength in excess of the concrete contribution $T - T_c$ is compared to the parameter NA_{tr}/n in Figure 3.12. The figures include the results from 140 specimens with various quantities of confining reinforcement. The average bar forces at failure ranged from 18,700 to 209,600 lb (83.1 to 932 kN) corresponding to a range in stress from 41,000 to 137,400 psi (283 to 947 MPa), the embedment lengths ranged from 3.75 to 23.5 in. (95.3 to 597 mm), and concrete compressive strengths ranged from 4,300 to 16,180 psi (29.6 to 112 MPa). In the figures, values of NA_{tr}/n of 0.33 in.^{2}/hook (213 mm^2/hook) correspond to No. 3 (No. 10) ties spaced at $3d_b$ (which qualify for a 0.8 reduction in development length in accordance with Section 25.4.3.2 in ACI 318-14), and values of 0.4 in.^{2}/hook (258 mm^2/hook) for No. 8 (No. 25) bars and 0.6 in.^{2}/hook (387 mm^2/hook) for No. 11 (No. 36) bars correspond to the higher quantities of confining reinforcement required by ACI 318-14 Section 18.8.3 for joints in special moment frames. The trend lines in Figures 3.11 and 3.12 are, respectively, the best-fit and dummy variable lines based on bar size.

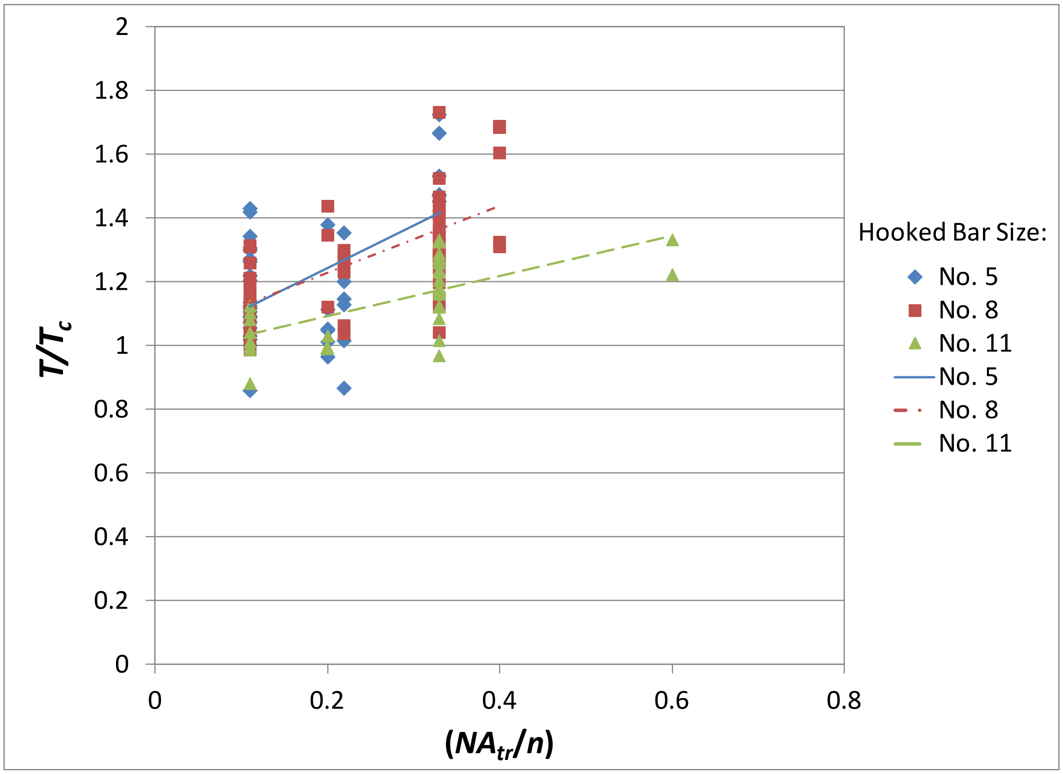

Figure 3.11 Ratio of anchorage strength for hooks confined by confining reinforcement to anchorage strength provided by concrete, with T_c based on Eq. (3.5)

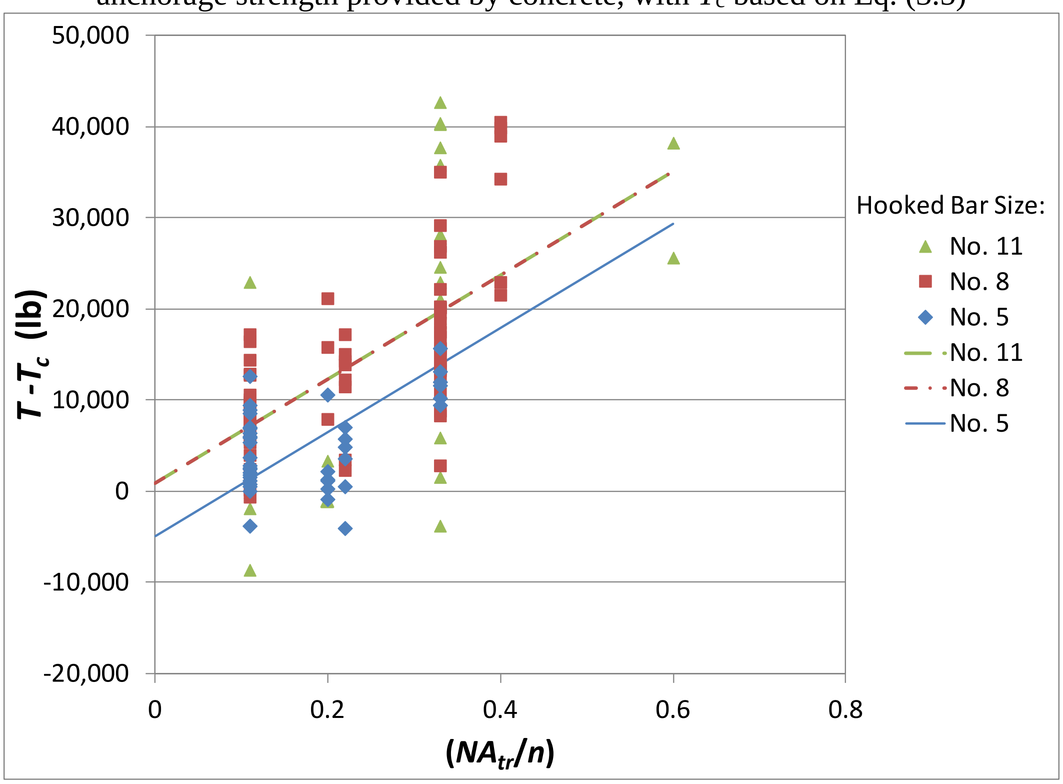

Figure 3.12 Anchorage strength in excess of the concrete contribution versus amount of confining reinforcement, with T_c based on Eq. (3.5)

As shown in Figure 3.11, T/T_c increases with an increase in NA_{tr}/n, with smaller bars exhibiting a greater relative increase in anchorage strength than the larger bars. Based on this comparison, it becomes clear that the increase in strength of hooked bars provided by confining transverse reinforcement spaced at $\leq 3d_b$ cannot be expressed as a single percentage of the strength without confinement T_c for all bar sizes as is implied by the use of the 0.8 reduction factor for development length in accordance with Section 25.4.3.2 of ACI 318-14.

Figure 3.12 shows that $T - T_c$ increases with an increase in NA_{tr}/n. As can be seen, there is a lot of scatter in $T - T_c$. This is to be expected since there is scatter in T and $T - T_c$ is a small portion (on average 18%) of T. The value of $T - T_c$ as a function of NA_{tr}/n is, in general, similar for the three bar sizes, with No. 8 and No. 11 (No. 25 and No. 36) hooked bars exhibiting somewhat more benefit from the confining reinforcement than No. 5 (No. 16) hooked bars. To determine the effect of bar size on the increase in anchorage strength provided by confining reinforcement, an analysis similar to that used for specimens without confining reinforcement was implemented. To do this, the confining reinforcement parameter NA_{tr}/n was multiplied by the diameter of the hooked bar d_b to a power p_3. A least-squares approach was used to find the value of the power p_3 (= 0.60) that minimized the range of intercepts of the trend lines on the $T - T_c$ axis.

The results of this analysis are shown in Figures 3.13, 3.14, and 3.15. Figure 3.13 shows the relationship between $T - T_c$ and $\left(NA_{tr}/n\right)d_b^{0.60}$. The spread of the intercepts of the trend lines corresponding to the individual bar sizes is smaller with the addition of the d_b term, and the dummy variables lines do not appear in order of descending bar diameter. Using the average intercept of the dummy variables lines, the equation describing the effect of the confining reinforcement is

$$T_s = 55{,}500\frac{NA_{tr}}{n}d_b^{0.60} - 1{,}200 \tag{3.6}$$

Figure 3.14 shows the ratios of measured to the calculated bar force at failure T_{test}/T_{calc} as a function of the hooked bar diameter d_b, where $T_{calc} = T_c + T_s$ with T_c from Eq. (3.5) and T_s from Eq. (3.6). The values of T_{test}/T_{calc} range between 0.69 and 1.28. The intercepts of the trend lines are 0.98 for specimens with No. 5 (No. 16) bars, 1.04 for specimens with No. 8 (No. 25) bars, and 0.98 for specimens with No. 11 (No. 36) bars. The nearly zero slope of the lines suggests that $d_b^{0.60}$ captures the effect of the hooked bar diameter on the anchorage capacity provided by confining transverse reinforcement. The mean value of T_{test}/T_{calc} is 1.00, with a coefficient of variation of 0.122.

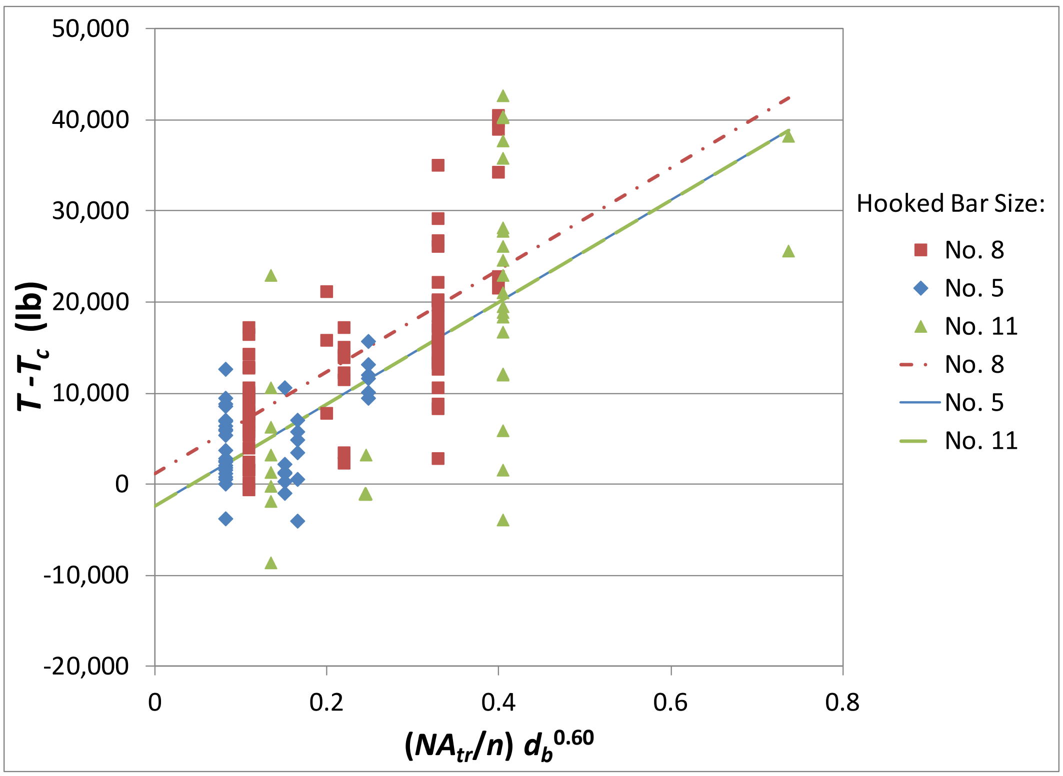

Figure 3.13 Anchorage strength in excess of the concrete contribution versus amount of confining reinforcement and hooked bar diameter, with T_c based on Eq. (3.5)

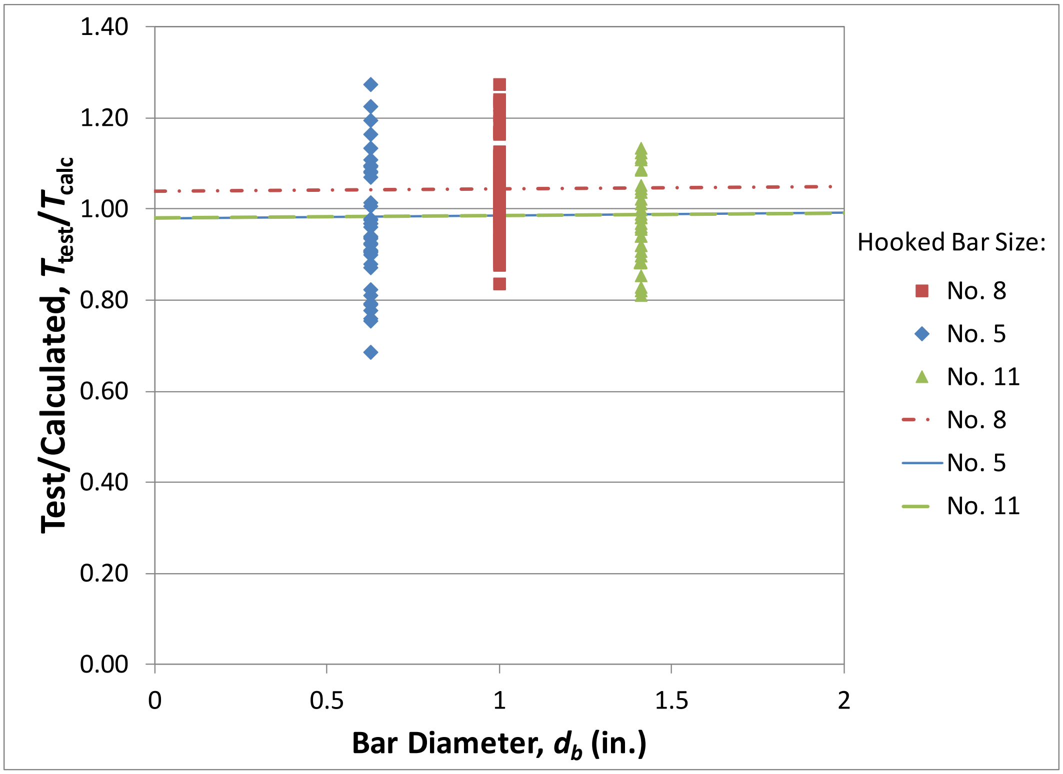

Figure 3.14 Test-to-calculated anchorage strength ratio versus bar diameter for hooked bars with confining transverse reinforcement, with T_{calc} based on Eq. (3.5) and (3.6)

Figure 3.15 shows the relationship between T_{test}/T_{calc} and concrete compressive strength f_{cm} for the specimens with confining transverse reinforcement. The nearly zero slope of the trend lines indicates that the effect of concrete compressive strength is accurately accounted for by the parameter $f_{cm}^{0.29}$ for hooks confined by confining reinforcement, as it is for hooks without confining reinforcement. For the test results shown in Figure 3.15, the concrete term T_c represents (on average) 82% of the capacity of the hooked bars. The intercepts of the trend lines are 0.99 for specimens with No. 5 (No. 16) bars, 1.04 for specimens with No. 8 (No. 25) hooked bars, and 0.99 for specimens with No. 11 (No. 36) hooked bars.

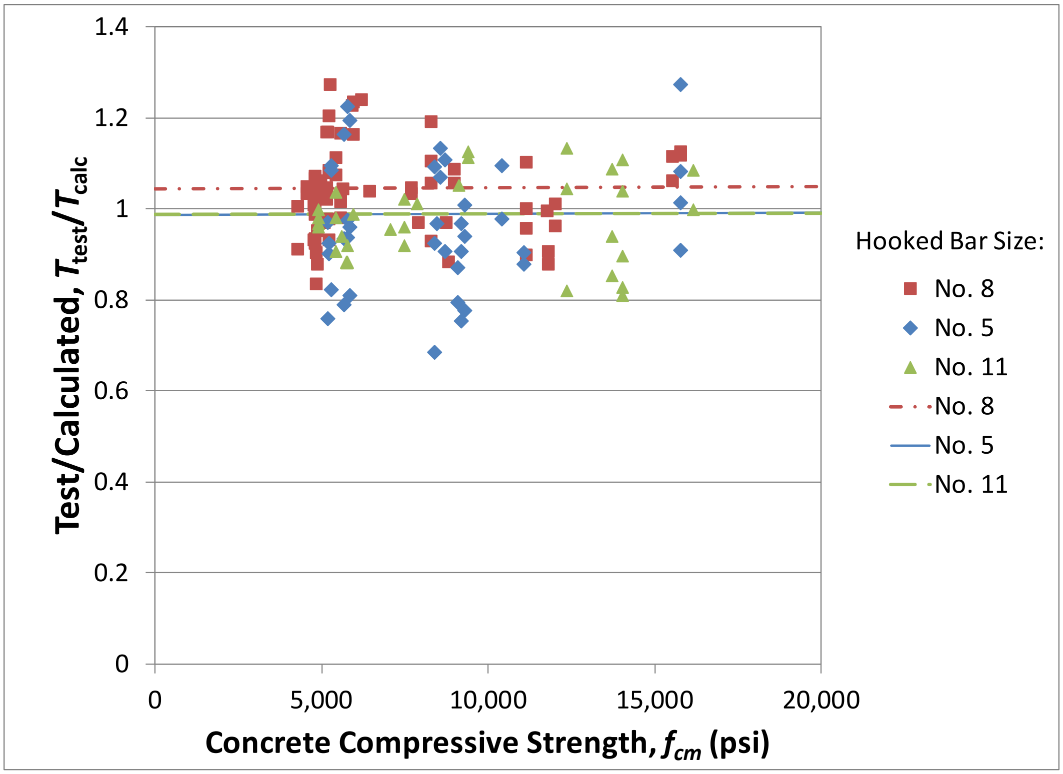

Figure 3.15 Test-to-calculated anchorage strength ratio versus concrete compressive strength for hooked bars with confining transverse reinforcement, based on Eq. (3.5) and (3.6)

As with the concrete contribution T_c, the negative intercept of Eq. (3.6) suggests that the relationship between T_s and NA_{tr}/n is not precisely linear. To capture this behavior, the data were reanalyzed by raising NA_{tr}/n and d_b to powers that minimized the sum of the squared differences $\left[(T-T_c)-T_s\right]^2$. The resulting equation is

$$T_s = 54{,}250\left(\frac{NA_{tr}}{n}\right)^{1.06} d_b^{\,0.59} \tag{3.7}$$

As before, using a power of 1.06 on NA_{tr}/n produces results that are comparable to that of using a power of 1.0, indicating that the relationship with respect to NA_{tr}/n is close enough to linear to use a linear relationship for design.

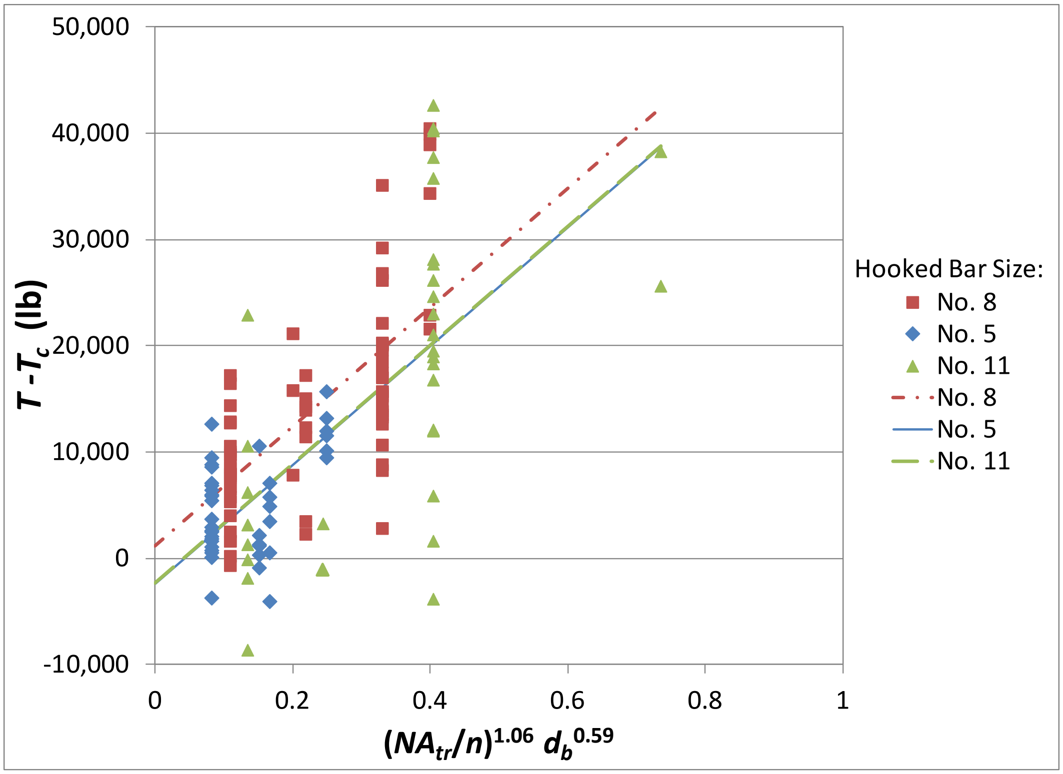

Figure 3.16 Anchorage strength in excess of the concrete contribution versus amount of confining transverse reinforcement and hooked bar diameter, with T_c based on Eq. (3.5)

An equation for the anchorage strength of hooked bars with confining transverse reinforcement in exterior beam-column joints was obtained by adding the terms corresponding to the contributions of concrete and the confining transverse reinforcement given by Eq. (3.5) and (3.7).

$$T_h = 332 f_{cm}^{0.29} \ell_{eh}^{1.06} d_b^{0.54} + 54{,}250\left(\frac{NA_{tr}}{n}\right)^{1.06} d_b^{0.59} \tag{3.8}$$

Figure 3.17 shows T_{test}/T_{calc} as a function of hooked bar diameter d_b based on Eq. (3.8). The dummy variables trend lines are nearly horizontal and the intercepts for trend lines corresponding to specimens with No. 5, 8, and 11 (No. 16, 25, and 36) bars are 0.97, 1.04, and 0.99, respectively. The mean test-to-calculated strength ratio is 1.0, and the coefficient of variation and standard deviation are 0.113. The test-to-calculated anchorage strength ratio ranges between 0.681 and 1.28.

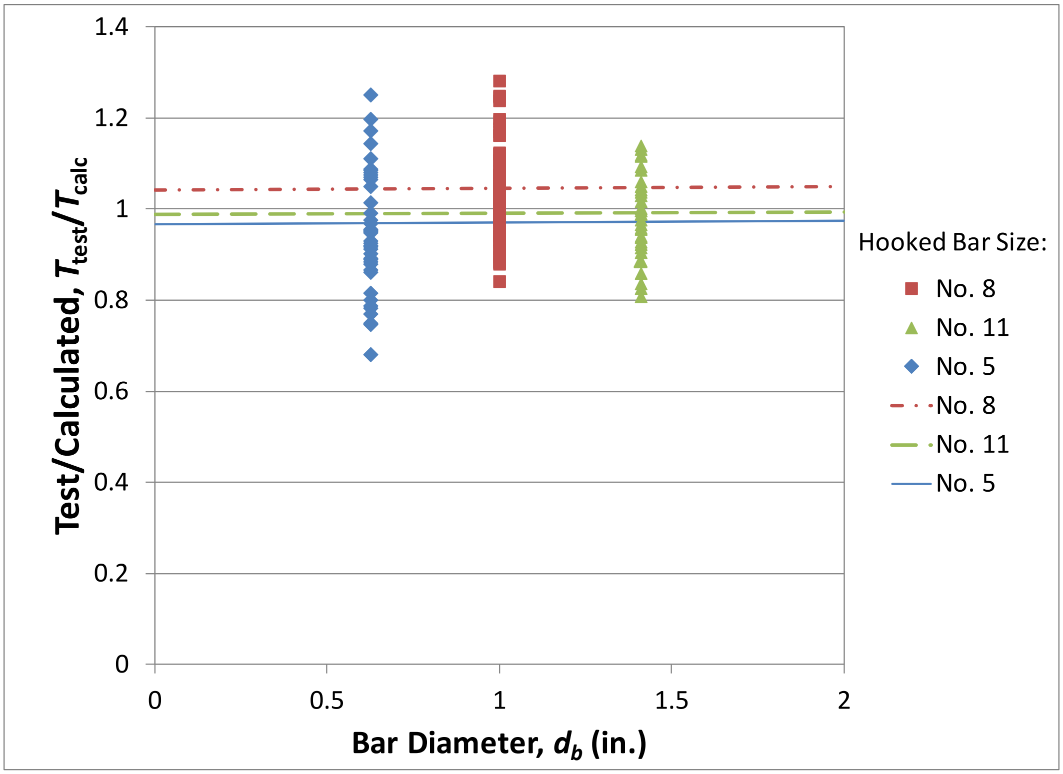

Figure 3.17 Test-to-calculated anchorage strength ratio versus bar diameter for hooked bars with confining transverse reinforcement, with T_{calc} based on Eq. (3.8)

T_{test}/T_{calc} is plotted as a function of concrete compressive strength f_{cm} in Figure 3.18. Anchorage strength is calculated using Eq. (3.8) for the specimens with confining transverse reinforcement. Once again, the dummy variables trend lines are nearly horizontal, showing that the effect of concrete compressive strength is adequately represented by Eq. (3.8). The intercepts of the trend lines corresponding to specimens with No. 5, 8, and 11 (No. 16, 25, and 36) bars are 0.97, 1.05, and 1.00, respectively.

Figure 3.19 compares the anchorage forces measured in the tests to those calculated using Eq. (3.8). The dashed line represents cases in which the measured and calculated strengths are equal, while the solid line represents the best fit line for the data set. The two lines nearly match indicating that Eq. (3.8) provides an adequate estimate of anchorage strength over the entire range of tests.

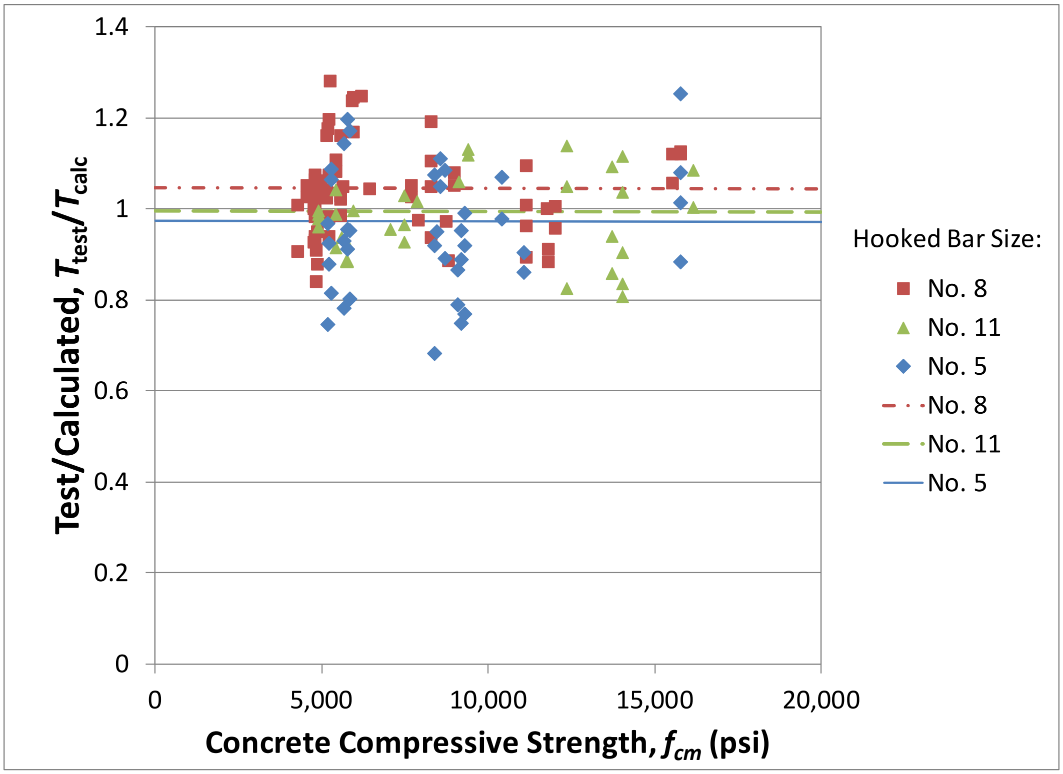

Figure 3.18 Test-to-calculated anchorage strength ratio versus concrete compressive strength for hooked bars with confining transverse reinforcement, with T_{calc} based on Eq. (3.8)

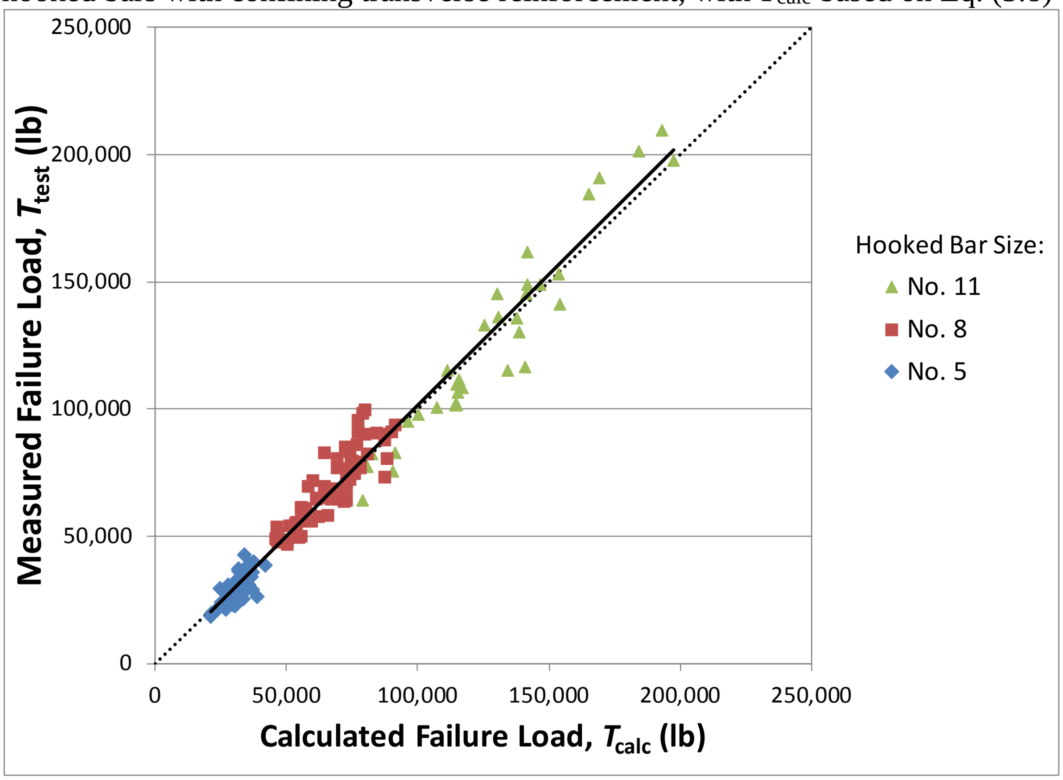

Figure 3.19 Measured versus calculated bar force at failure for hooked bars with confining transverse reinforcement, with T_{calc} based on Eq. (3.8)

Perpendicular Confining Reinforcement**—**As mentioned earlier, confining reinforcement oriented perpendicular to the straight portion of the hooked bar helps limit splitting stresses, whereas confining reinforcement oriented parallel to the straight portion of the hooked bar helps anchor the failure cone by resisting the direct tensile force. The role of perpendicular confining reinforcement may be similar to the role of confinement provided by transverse reinforcement when developing and splicing straight bars. This, in turn, suggests that the term representing the contribution of confining reinforcement perpendicular to the straight portion of a hooked bar to anchorage strength will be a function of NA_{tr}/n, d_b, and f_{cm} (ACI 408R-03).

To investigate the validity of this assumption, twelve specimens were tested with confining reinforcement oriented horizontally or vertically (that is, parallel or perpendicular to the straight portion of the hooked bar, respectively). Each specimen with confining reinforcement oriented horizontally had a companion specimen with confining reinforcement oriented vertically. The details of this group of specimens can be found in Appendix A of Chapter 2 and in Sperry et al. (2015).

Due to the limited number of specimens with vertical ties (six), it was not possible to reanalyze the powers on NA_{tr}/n, d_b, and f_{cm}; therefore, the powers established for these variables in Eq. (3.8) were used. To remain consistent, the equation representing the additional capacity for these six specimens was fit to express the same average test-to-calculated ratio as those specimens cast in the same group with horizontal ties. Based on Eq. (3.8), the average test-to-calculated ratio for the specimens with horizontal ties is 0.94, reflecting the fact that this group of specimens was among the weakest of all specimens tested in this study. Using this approach, the additional capacity provided by confining reinforcement oriented vertically is given by

$$T_{svr} = 983\left(\frac{NA_{tr}}{n}\right)^{1.06} d_b^{0.59} f_{cm}^{0.29} \tag{3.9}$$

The value 983 was obtained using an iterative analysis that resulted in an average test-to-calculated ratio of 0.94 for the six specimens containing vertical ties. In principle, a larger database would result in an average test-to-calculated ratio of 1.0.

Since the study of the contribution of confining reinforcement perpendicular to the straight portion of the bar was limited in scope and no other research on vertical ties is available, it is clear that more research is needed to confidently establish the contribution to anchorage strength of confining reinforcement with this orientation.

Equations (3.5), (3.8), and (3.9) were developed to characterize the test results for specimens containing two hooked bars without and with confining transverse reinforcement. Analyses of other aspects, such as hooked bar spacing, hooked bar placement within a member, and the use of more than two hooked bars within a section will be presented in follow-on papers.

3.5 SUMMARY AND CONCLUSIONS

Equations were developed to characterize the anchorage capacity of hooked bars with and without confining transverse reinforcement. The equations are based on the test results for 245 beam-column joint specimens containing two hooked bars, 99 without confining transverse reinforcement and 146 with confining transverse reinforcement. Results from studies by Marques and Jirsa (1975), Pinc et al. (1977), Hamad et al. (1993), Ramirez and Russell (2008), and Lee and Park (2010) were used in conjunction with tests reported by Sperry et al. (2015, 201X). Bar stresses ranged from 30,800 to 137,400 psi (212 to 947 MPa), and concrete compressive strengths ranged from 2,570 to 16,510 psi (17.7 to 114 MPa).

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

1. The contribution of concrete to the anchorage capacity of hooked bars can be represented as a function of concrete compressive strength to the 0.29 power.
2. Confining reinforcement, expressed as the area of confining reinforcement per confined hooked bar, provides an incremental rather than percentage increase in the anchorage capacity of hooked bars.
3. For a given embedment length, the anchorage capacity of hooked bars without and with confining transverse reinforcement increases as the bar diameter increases.
4. The contribution of confining reinforcement oriented perpendicular to the straight portion of the hooked bar differs from that of confining reinforcement parallel to the straight portion of the hooked bar and may be similar to the contribution of confining reinforcement to the development and splice strength of straight bars.

3.6 NOTATION

d_b Nominal bar diameter of the hooked bar

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} Average peak stress in hooked bars at failure

f_y Yield strength of hooked bar

h_c Width of bearing member flange

h_{cl} Height measured from the center of the hook to the top of the bearing member flange

h_{cu} Height measured from the center of the hook to the bottom of the upper compression member

ℓ_{dh} Development length in tension of deformed bar with a standard hook, measured from the outside end of hook, point of tangency, toward critical section

ℓ_{eh} Embedment length measured from the back of the hook to the front of the column

n Number of hooked bars confined by N legs

N Number of legs of confining transverse reinforcement in joint region

T Average peak load on hooked bars

T_c Contribution of concrete to hooked bar anchorage capacity

T_{calc} Calculated hooked bar strength

T_h Hooked bar anchorage capacity

T_s Contribution to hooked bar anchorage capacity of confining reinforcement in the joint region oriented parallel to the straight portion of the hooked bar

T_{svr} Contribution to hooked bar anchorage capacity of confining reinforcement in the joint region oriented perpendicular to the straight portion of the hooked bar

T_{test} Recorded load on hooked bar at failure

λ Modification factor to reflect the reduced mechanical properties of lightweight concrete to normalweight concrete of the same compressive strength

ψ_c Factor used to modify development length based on cover as defined in ACI 318-14 Section 25.4.3.2

ψ_e Factor used to modify development length based on coating as defined in ACI 318-14 Section 25.4.3.2

ψ_r Factor used to modify development length based on confining reinforcement in the hook region as defined in ACI 318-14 Section 25.4.3.2

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CHAPTER 4: EFFECTS OF BEND ANGLE, CONCRETE SIDE COVER, AND CONFINING REINFORCEMENT ORIENTATION ON THE ANCHORAGE CAPACITY OF HOOKED BARS

4.1 INTRODUCTION

Hooked bars are commonly used in reinforced concrete construction, but the anchorage strength of hooked bars has not been studied as extensively as other aspects of reinforced concrete design. Current design provisions (ACI 318-14, ACI 349-06, AASHTO 2012) for anchorage of hooked bars in reinforced concrete are based on several assumptions about the behavior of hooks; among others, hooks with 90° and 180° bend angles are assumed to have similar strength, hooks with side cover of 2.5 in. (64 mm) or greater have similar strengths, and transverse reinforcement oriented parallel or perpendicular to the straight portion of a 90° hook is assumed equally effective at providing confinement, but only transverse reinforcement oriented perpendicular to the straight portion of a 180° hook is assumed to be effective at providing confinement. The Code provisions are based on 38 tests by Marques and Jirsa (1975) and Pinc et al. (1977) of beam-column joint specimens containing Grade 60 (Grade 420) No. 7, No. 9, or No. 11 (No. 22, No. 29, or No. 36) standard hooks and concrete with compressive strengths ranging between 3,600 and 5,400 psi (24.8 and 27.2 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. (64 mm). None of the test specimens in the earlier studies contained transverse reinforcement perpendicular to straight portion of the hooked bars.

To validate the applicability of the earlier findings, tests were performed to evaluate the effects of hook bend angle, concrete clear cover, and orientation of confining reinforcement on hook anchorage capacity 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. (2015, 201Xa, 201Xb).

4.2 RESEARCH SIGNIFICANCE

The use of high strength steel and concrete has increased recently due to its ability to provide lower congestion, smaller member dimensions, less material use, and increased useable floor area. The current Code provisions for hooked bar anchorage make certain assumptions about the effects of hook bend angle, side cover, and transverse reinforcement orientation on hooked bar anchorage. Verifying the validity of these assumptions, especially when using high-strength materials, is necessary to understand the behavior and strength of hooked bar anchorage and to provide safe designs for the full range of material strengths used in practice.

4.3 EXPERIMENTAL INVESTIGATION

As part of a larger research program, tests of 166 specimens with two hooked bars were used to investigate the effect of bend angle, side cover, and reinforcement orientation. No. 5, 8, and 11 (No. 16, 25, and 36) hooked bars were tested in normalweight concrete with compressive strengths ranging from 4,300 to 16,510 psi (29.6 to 114 MPa). Nominal clear cover from the outside of the bar to the outside of the column (side covers) ranged from 2.5 to 3.5 in. (64 to 89 mm). Bar stresses ranged from 33,000 to 137,400 psi (228 to 947 MPa). The results of these tests are reported and used in conjunction with previous studies to determine the effects of bend angle, concrete side cover, and transverse reinforcement orientation.

4.3.1 Test Specimens

A diagram of a typical specimen simulating a beam-column joint is shown in Figure 4.1. Specimens were designed to represent exterior beam-column joints and were cast without the beam. The specimens described in this paper contained two hooked bars cast inside the column longitudinal reinforcement. The out-to-out spacing of the hooked bars was fixed for a given bar diameter—8 in., 12 in., and 16.5 in. (203 mm, 305 mm, and 419 mm) for specimens with No. 5, No. 8, and No. 11 hooked bars (No. 16, 25, and 36), respectively. The column depth equaled the sum of the tail cover and the embedment length. As used in this paper, embedment length ℓ_{eh} refers to the distance measured from the front of the column face to the back of the tail of the hook, 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 to ensure that a bar can develop its yield strength. Column reinforcement was provided to resist the shear and moment demand on the column assuming all hooked bars reached their maximum failure load simultaneously.

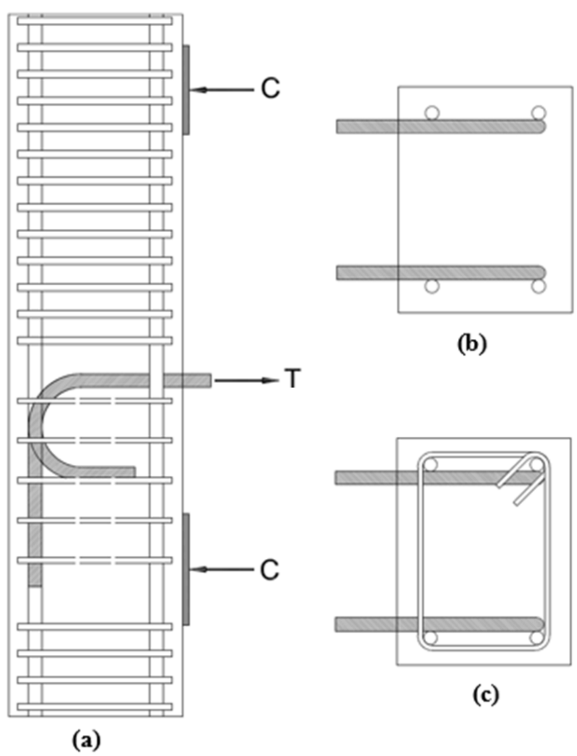
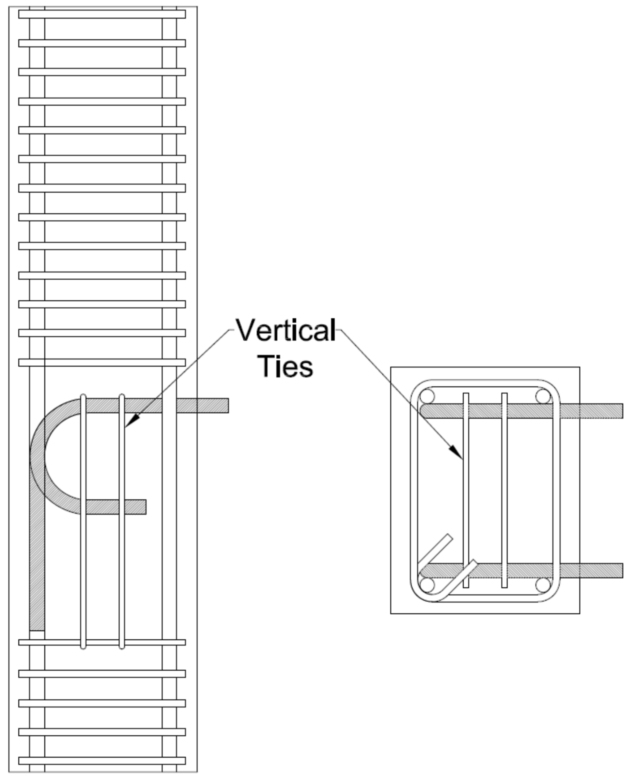


Figure 4.1 Schematic of specimens (a) side view of specimen (b) cross-section of specimen with hooks inside column core and without confining transverse reinforcement (c) cross-section of specimen with hooks inside column core and with transverse reinforcement

The specimens contained one of three quantities of transverse reinforcement, in most cases oriented horizontally (parallel to the straight portion of the hooked bar): (1) no transverse reinforcement, (2) two No. 3 (No. 10) ties spaced along the length of the tail of the hook, or (3) No. 3 (No. 10) ties spaced at $3d_b$ along the tail and the bend of the hook, where d_b is the diameter of the hooked bar. No. 3 (No. 10) ties spaced at $3d_b$ represents the amount of transverse reinforcement required to allow the use of the 0.8 reduction factor in development length of hooked bars in accordance with Section 25.4.3 of ACI 318-14 and is provided by five No. 3 (No. 10) ties for No. 5 (No. 16) and No. 8 (No. 25) standard hooks and six No. 3 (No. 10) ties for a No. 11 (No. 36) standard hooks. For case (3), the first tie was placed $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar). To evaluate the effect of reinforcement orientation, six specimens were tested with vertical ties as shown in Figure 4.2. Of the six, two contained 2 No. 3 (No. 10) ties, two contained 4 No. 3 (No. 10) ties, and two contained 5 No. 3 (No. 10) ties. The latter two cases both qualify for the 0.8 reduction factor in Section 25.4.3.2 of ACI 318-14.



(a) (b)

Figure 4.2 Details of specimen with vertical ties (a) side view and (b) cross-section

The heights of specimens were chosen so that the support reactions from the test frame did not interfere with the hook region during testing, as shown in Fig. 3. The column height was 52¾ 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 distance from the center of the hooked bar to the bearing member and upper compression member are given in Table 4.1.

Table 4.1 Location of reaction forces

	No. 5 Hook	**No. 8 Hook**	**No. 11 Hook**
Height of Specimen, (in.)	52¾	52¾	96
Distance from Center of Hook to Top of Bearing Member Flange, h_{cl} (in.)[1]	5.25	10	19.5
Distance from Center of Hook to Bottom of Upper Compression Member Flange, h_{cu} (in.)[1]	18.5	18.5	48.5

[1]See Fig. 4.3, 1 in. = 25.4 mm

4.3.2 Material Properties

Specimens were cast using non-air-entrained ready-mix concrete with nominal compressive strengths of 5,000, 8,000, 12,000, and 15,000 psi (35, 55, 83, and 103 MPa). Actual strengths ranged from 4,300 to 16,510 psi (29.6 to 114 MPa). The concrete contained Type I/II portland cement, crushed limestone or granite with a maximum size of 0.75 in. (19.1 mm), Kansas River sand, and a high-range water-reducing admixture. ADVA 140 was used in the 5,000 and 8,000-psi (34.5 and 55-MPa) concrete and ADVA 575 was used in the 12,000 and 15,000-psi (83 and 103-MPa) concrete; both products are produced by W.R. Grace. Pea gravel was incorporated in the 12,000 psi (82.7 MPa) concrete to improve the workability of the mix. For the 15,000-psi (103-MPa) concrete, silica fume and Class C fly ash were used as supplementary cementitious materials. Mixture proportions are listed in Table 4.2.

Except for a few early tests that used ASTM A615 Grade 60 (420 MPa) reinforcement for the hooked bars, ASTM A615 Grade 80 (550 MPa) and A1035 Grade 120 (830 MPa) bars were used for the study to provide maximum flexibility in the tests. For most specimens, the ancillary steel for column and transverse reinforcement consisted of ASTM A615 Grade 60 (420 MPa) reinforcing bars. Some specimens had a greater flexural demand than could be satisfied using ASTM A615 Grade 60 (420 MPa) reinforcing bars. For those specimens, ASTM A1035 Grade 120 (830 MPa) bars were used as the column longitudinal steel. Yield strength, nominal diameter, rib spacing, rib height, gap width, and relative rib area for the deformed steel bars used as hooked bars is presented in Table 4.3.

Table 4.2 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
Crushed Limestone, lb/yd^3	1734	1683	1796	-
Granite, lb/yd^3	-	-	-	1693
Pea Gravel, lb/yd^3	-	-	316	-
Kansas River Sand, lb/yd^3	1396	1375	1050	1138
Estimated Air Content, %	1	1	1	1
High-Range Water-Reducer, oz (US)	30 [1]	171 [1]	104 [2]	205 [2]
w/cm ratio	0.44	0.32	0.29	0.24

[1] ADVA 140, [2]ADVA 575, 1 psi = 0.00689 MPa, 1 lb/yd^3 = 0.593 kg/m^3, 1 oz = 29.6 mL

Table 4.3 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

4.3.3 Test Procedure

Specimens were tested using a self-reacting system configured to simulate the axial, tensile, and compressive forces in a beam-column joint (Figure 4.3). The test frame is a modified version of the apparatus used by Marques and Jirsa (1975). The locations of reactions on the testing apparatus can be altered to accommodate different-sized specimens as shown in Table 4.1. The flange width of the upper compression member and the bearing member were $6^{5}/_{8}$-in. (168.3 mm) and $8^{3}/_{8}$-in. (212.7 mm), respectively.

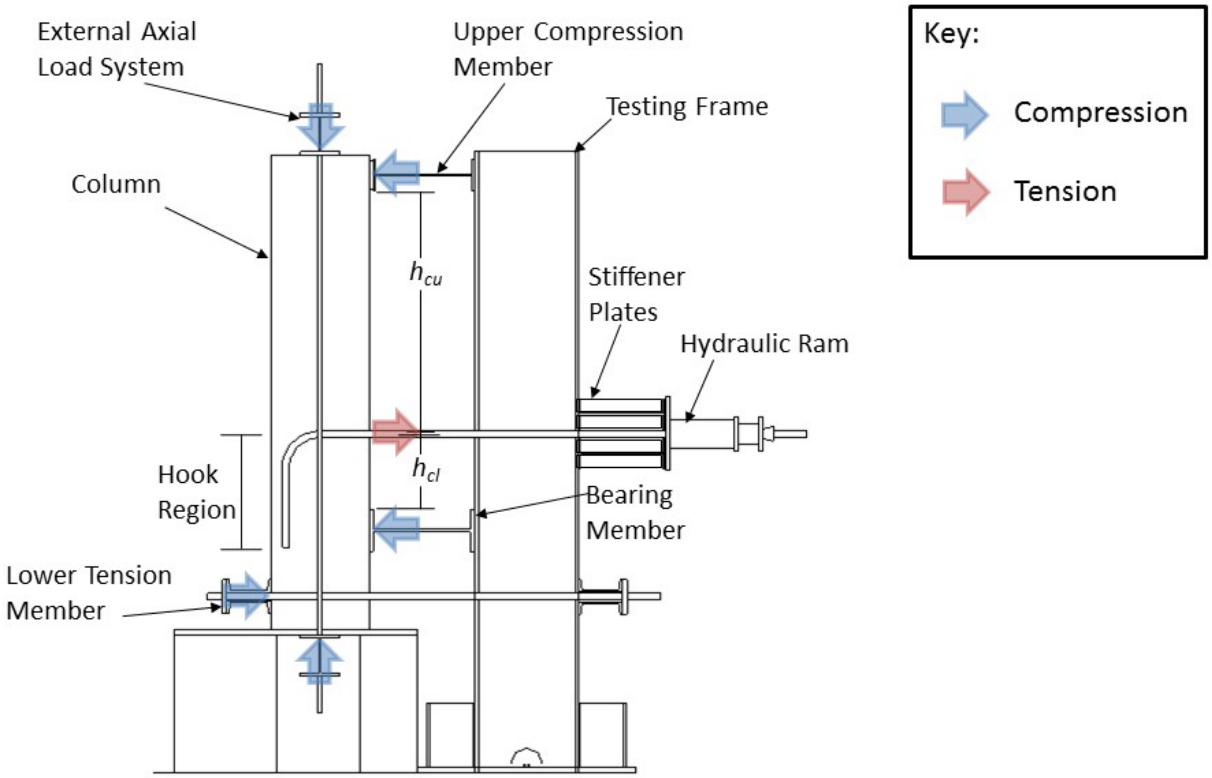


Figure 4.3 Testing frame and forces applied to specimens during testing

For specimens with No. 5 and No. 8 (No. 16 and No. 25) hooked bars, a constant 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 (0.621 to 3.17 MPa) (for early tests, a constant force of 80,000 lb [356 kN] was used, corresponding to a range in axial stress of 505 to 1,930 psi [3.48 to 13.3 MPa]). Specimens with No. 11 hooked bars had a constant axial stress of 280 psi (1.93 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 3,000 psi (21 MPa) resulted in negligible changes in the anchorage strength of the hooked bars.

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. The bearing member located below the hooked bars simulated the compression zone of the beam and the horizontal reactions at the top and bottom of the specimen were used to prevent overturning. A detailed description of the test frame and testing procedure is provided by Peckover and Darwin (2013).

4.4 RESULTS AND ANALYSIS

To evaluate the effect of hook bend angle, concrete side cover, and transverse reinforcement orientation, results from 166 beam-column joint specimens with two No. 5, No. 8, or No. 11 (No. 16, No. 25, and No. 36) hooked bars cast inside the column core were selected from the data presented by Sperry et al. (2015, 201Xa). The test results of these specimens are presented in Appendix B. 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 following sections present the effects of bend angle, side cover, and transverse reinforcement orientation on hooked bar anchorage capacity.

To limit the effects of differences in concrete compressive strength and simplify the comparisons, the average bar forces at failure were normalized with respect to a concrete compressive strength of 5,000 psi by multiplying the average bar forces at failure T by $\left(5000/f_{cm}\right)^{p_1}$ to give normalized average failure loads T_N. The value of p_1 was selected based on the observation by Sperry et al. (2015, 201Xa) that the power of 0.5, as is currently used by ACI 318-14, overpredicts the effect of concrete compressive strength. Test results for straight bar development indicate that a value of p_1 = 0.25 adequately characterizes the effect of concrete compressive strength on the bond strength (Darwin et al. 1996, Zuo and Darwin 2000, ACI Committee 408R-03). Thus, a value of p_1 equal to 0.25 is used to normalize the failure loads.

In the comparisons that follow, a regression analysis technique based on dummy variables (Draper and Smith 1981) was 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.

4.4.1 Effect of Bend Angle

Figure 4.4 shows the normalized average failure loads T_N as a function of embedment length, and includes test results for 58 beam-column specimens (39 from the current study) containing No. 5, No. 7, No. 8, and No. 11 (No. 16, No. 22, No. 25, and No. 36) hooked bars without confining transverse reinforcement in the joint region, with bend angles of 90° and 180°. The test results for the No. 7 (No. 22) hooked bars and some of the No. 11 (No. 36) hooked bars 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 correspond to trend lines for 90° hooked bars while the broken lines correspond to 180° hooked bars. Both trend lines and data points are color coded according to bar size. In this figure and those that follow, the order of results in the legend coincides with order of the lines in the figure. For each bar size, the range of embedment lengths is similar for 90° and 180° hooked bars. The embedment lengths ℓ_{eh} ranged from 6.31 to 21.1 in. (160 to 536 mm), and normalized average bar forces at failure ranged from

19,300 to 114,400 lb (84 to 509 kN). The measured concrete compressive strengths ranged from 2,570 to 16,510 psi (17.7 to 114 MPa).

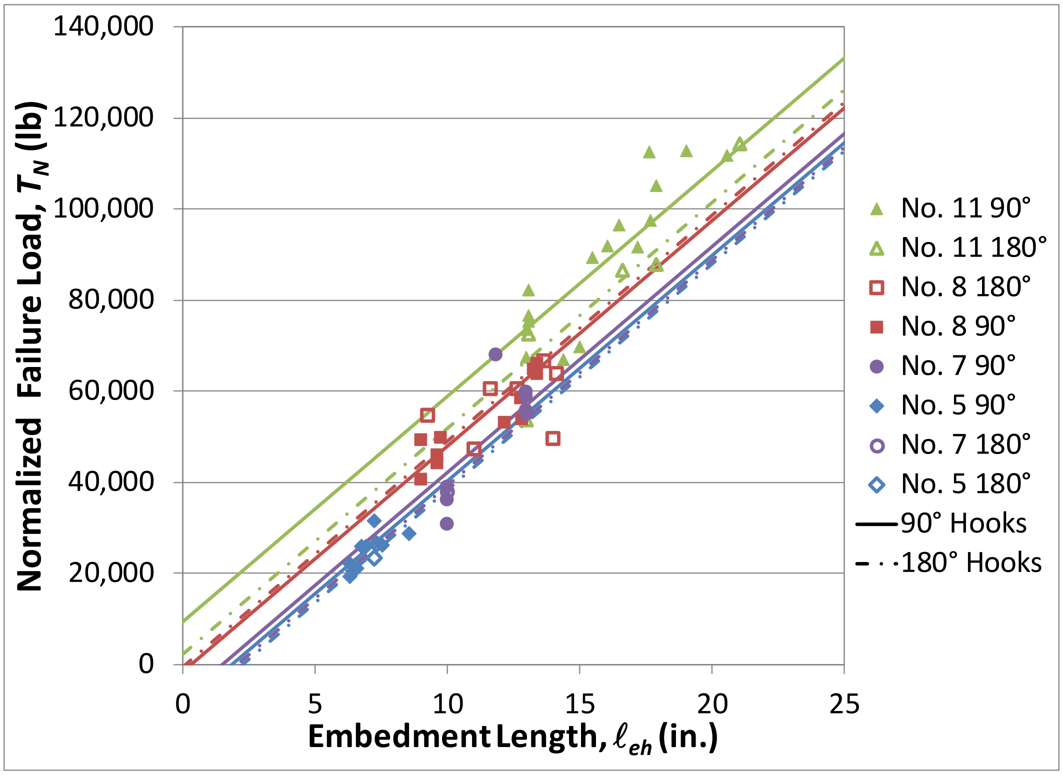


Figure 4.4 Bar force at failure normalized to 5,000 psi concrete versus embedment length for hooked bars without confining transverse reinforcement

As shown in Figure 4.4, an increase in embedment length is associated with an increase in the normalized average bar force at failure, as expected. The results in Figure 4.4 indicate that there is no clear correlation between anchorage strength and bend angle. For No. 5, 7, and 11 (No. 16, 22, 36) hooked bars, the trend line corresponding to a 90° bend angle has a higher intercept than the trend line corresponding to a 180° bend angle. The opposite trend is observed for No. 8 (No. 25) hooked bars. The magnitude of the difference in intercepts is greater for the No. 11 (No. 36) bars than for the smaller bar sizes. The results are compared using Student's t-test to compare intercepts with the T_N axis obtained by extending lines through each data point parallel to the dummy variables trend lines. Student's t-test indicates that none of the differences in anchorage strength between 90° and 180° hooked No. 5, No. 7, No. 8, and No. 11 (No. 16, No. 22, No. 25, and No. 36) bars is statistically significant (α = 0.48, 0.44, 0.80, and 0.13, respectively) using α = 0.05 as the threshold for statistical significance.

Figure 4.5 compares the anchorage strengths of 26 beam-column specimens (all from the current study) containing 90° and 180° No. 5 and No. 8 (No. 16 and 25) hooked bars with two No. 3 (No. 10) ties in the joint region as a function of embedment length. The two ties were placed in the direction parallel to the straight portion of the hooked bars for both 90° and 180° hooks. Two ties is insufficient to satisfy ACI Code (ACI 318-14) requirements for the use of a development length reduction factor for hooked bars, and ties 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 180° hooks. Contrary to this Code provision, the ties placed parallel to the straight portion of the hooked bars provided similar increases in anchorage strength for both 90° and 180° hooks.

The embedment lengths ℓ_{eh} ranged from 5.6 to 13.75 in. (142 to 349 mm), the normalized average bar forces sat failure T_N ranged from 20,000 to 78,300 lb (89 to 348 kN), and the concrete compressive strengths ranged from 4,300 to 15,800 psi (29.6 to 109 MPa). The figure shows that the dummy variables trend lines for anchorage strength nearly coincide for the 90° and 180° No. 5 (No. 16) hooked bars, while the 180° No. 8 (No. 25) hooked bars had a slightly lower strength than the 90° No. 8 (No. 25) hooked bars. The results of a Student's t-test show that the differences in anchorage strength between 90° and 180° No. 5 and No. 8 (No. 16 and 25) hooked bars are not statistically significant, with α = 0.81 and 0.12, respectively.

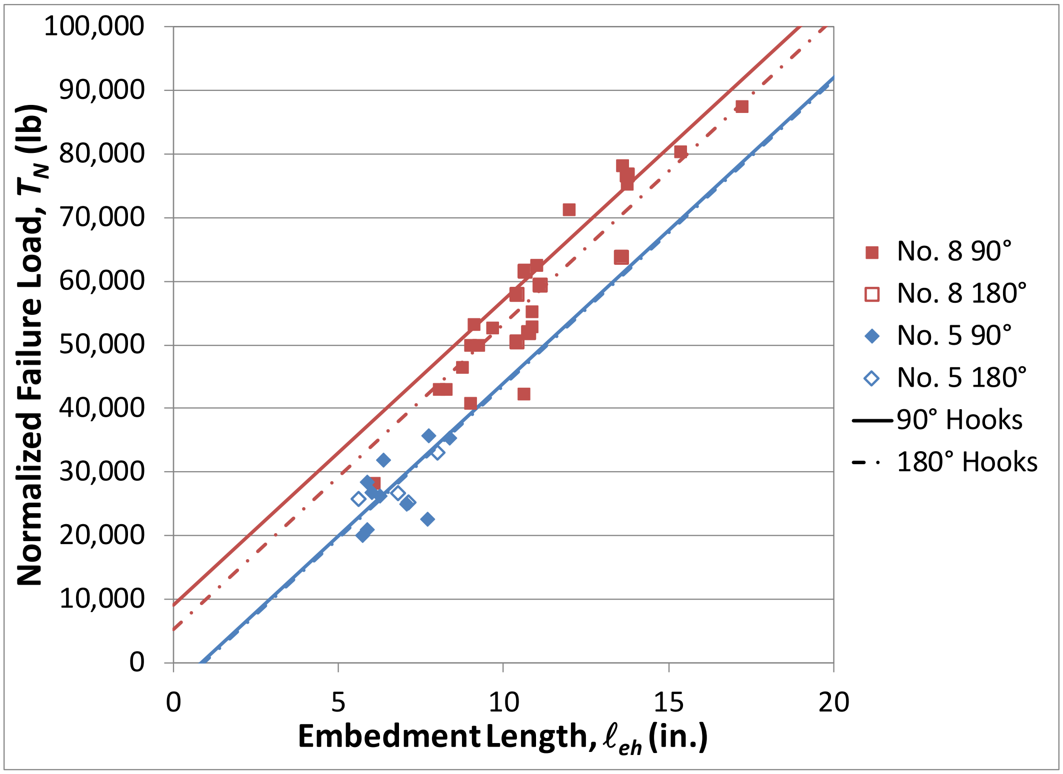


Figure 4.5 Bar force at failure normalized to 5,000 psi concrete versus embedment length for hooked bars confined by two No. 3 (No. 10) ties

Figure 4.6 compares the anchorage strengths of 90° and 180° No. 8 and No. 11 (No. 25 and 36) hooked bars with No. 3 (No. 10) ties spaced at $3d_b$, which satisfies the requirements for the use of the 0.8 development length reduction factor in ACI 318-14 Section 25.4.3.2. The results represent 18 specimens tested in the current study. 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 595 kN), and the concrete compressive strengths ranged from 5,420 to 15,800 psi (37.4 to 109 MPa). For both the No. 8 and No. 11 (No. 25 and 36) hooked bars, the anchorage strength of the 180° hooks was slightly lower than the strength of the 90° hooks. The results of Student's t-test, however, show that the differences in anchorage strengths for No. 8 and No. 11 (No. 25 and 36) hooked bars are not statistically significant (α = 0.54 and 0.50, respectively).

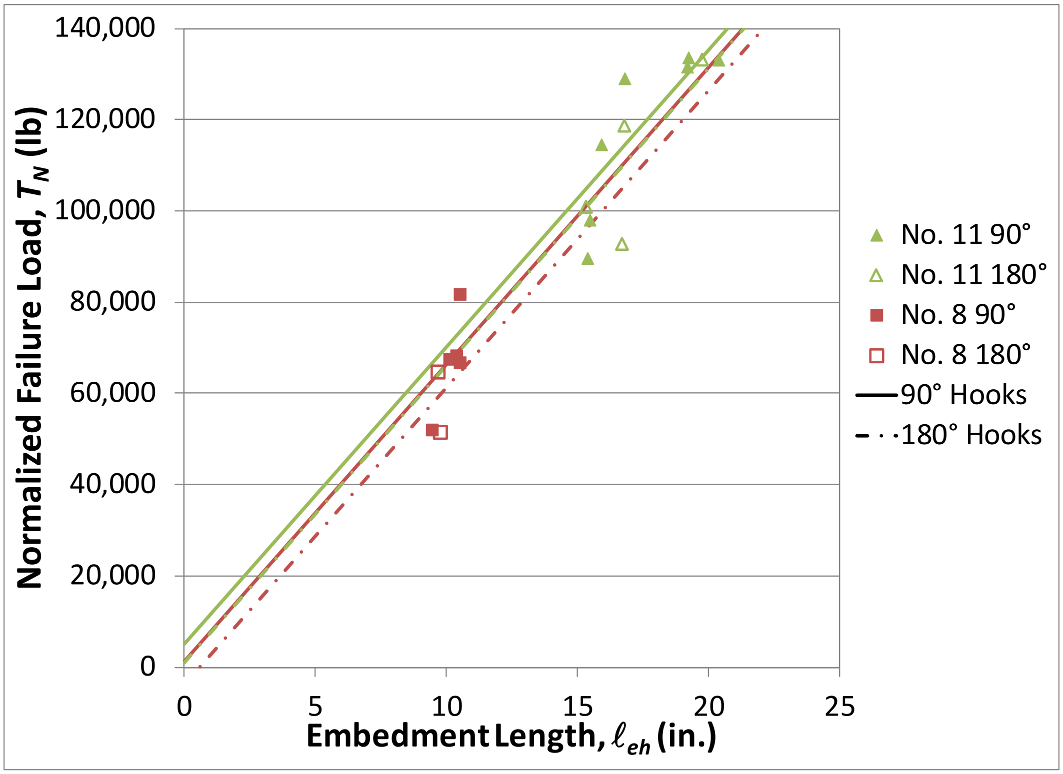


Figure 4.6 Bar force at failure normalized to 5,000 psi concrete versus embedment length for hooked bars with confining reinforcement conforming to Section 25.4.3.2 of ACI 318-14

Overall, although there were minor differences between the anchorage strengths of 90° and 180° hooked bars, none of the differences are statistically significant, and for all other parameters the same, hooked bars with either bend angle should be treated as having the same anchorage strength, as reflected in the ACI Code (ACI 318-14).

4.4.2 Effect of Side Cover

This section describes the effect of side clear cover on the anchorage strength of hooked bars. The results for No. 5, No. 8, and No. 11 (No. 16, No. 25, and No. 36) hooked bars tested in this study are discussed in turn.

Figure 4.7 shows the test results from this study for 39 beam-column joint specimens containing No. 5 (No. 16) hooked bars. The nominal side covers were 2.5 in. (64 mm) (solid lines) and 3.5 in. (89 mm) (broken lines). Three different quantities of confining transverse reinforcement were investigated: no confining transverse reinforcement; two No. 3 (No. 10) ties within the joint region; and No. 3 (No. 10) ties spaced at $3d_b$ (satisfying the requirements for the 0.8 development length reduction factor in ACI 318-14 Section 25.4.3.2). The embedment lengths ℓ_{eh} ranged from 3.75 in. to 10.5 in. (95 to 267 mm). The average bar forces at failure normalized to a concrete compressive strength of 5,000 psi (34.5 MPa) T_N ranged from 14,000 to 41,500 lb (62 to 185 kN), and the concrete compressive strengths ranged from 5,190 to 15,800 psi (36 to 109 MPa). Figure 4.7 shows that, as expected, anchorage strength increased with increasing embedment length and amount of confining transverse reinforcement. Regardless of the amount of confining transverse reinforcement, the results indicate that there was a *decrease* in strength as the side cover increased from 2.5 in. to 3.5 in. (64 to 89 mm). Student's t-test, however, shows that this decrease is not statistically significant either for specimens without confining transverse reinforcement or for specimens with No. 3 (No. 10) ties spaced at $3d_b$ (α = 0.72 and 0.30, respectively). The value of α for specimens with two No. 3 (No. 10) ties is 0.08, just above the threshold value of 0.05 that indicates statistical significance.

The results for 78 No. 8 (No. 25) hooked bar beam-column joint specimens from this study are shown in Figure 4.8. The average embedment lengths ℓ_{eh} ranged from 6.1 to 18.7 in. (155 to 475 mm), the concrete compressive strengths ranged from 4,300 to 16,510 psi (29.6 to 114 MPa), and the normalized average bar forces at failure T_N ranged from 28,200 to 93,600 lb (125 to 417 kN). Anchorage strength increases with increasing embedment length and amount of transverse

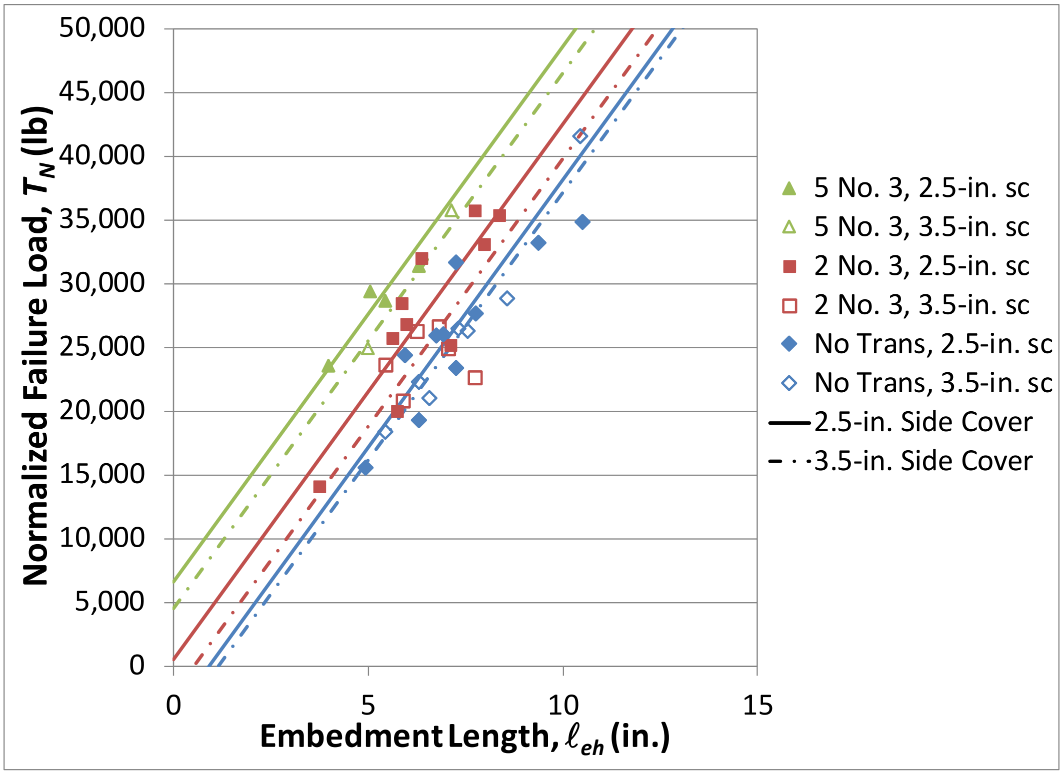


Figure 4.7 Bar force at failure normalized to 5,000 psi concrete versus embedment length for No. 5 (No. 16) hooked bars with different amounts of confining reinforcement and side cover

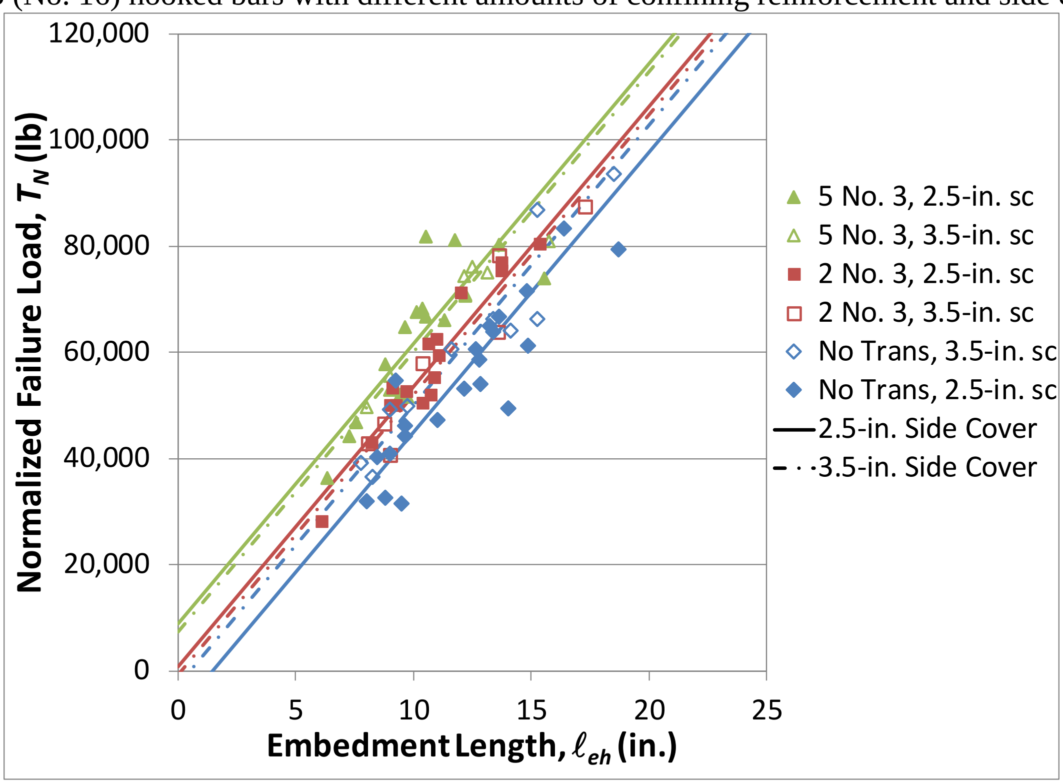


Figure 4.8 Bar force at failure normalized to 5,000 psi concrete versus embedment length for No. 8 (No. 25) hooked bars with different amounts of confining reinforcement and side cover

reinforcement. For No. 8 (No. 25) bars, increasing side cover from 2.5 in. to 3.5 in. (64 to 89 mm) led to increases in anchorage strength for specimens without confining transverse reinforcement. For specimens with two No. 3 (No. 10) ties and No. 3 (No. 10) ties spaced at $3d_b$ in the joint region, the specimens with 3.5-in. (89-mm) side cover had anchorage strengths that were slightly lower than those of specimens with 2.5-in. (64-mm) side cover. Student's t-test shows that the differences in anchorage strength associated with changes in cover for specimens with two No. 3 (No. 10) ties and No. 3 (No. 10) ties spaced at $3d_b$ are not statistically significant, with α equal to 0.32 and 0.47, respectively. The difference in capacity between hooked bars with 2.5 and 3.5-in. (64 and 89-mm) side cover, however, is statistically significant (α = 0.03) for specimens without confining transverse reinforcement.

Figure 4.9 shows the results for 43 No. 11 (No. 36) hooked bar beam-column joint specimens. The average embedment lengths ℓ_{eh} ranged from 9.5 to 26.0 in. (241 to 660 mm), the concrete compressive strength ranged from 4,910 to 16,180 psi (33.9 to 114 MPa), and the normalized average bar forces at failure T_N ranged from 39,800 to 174,400 lb (177 to 776 kN). As for the No. 5 (No. 16) and No. 8 (No. 25) hooked bars, anchorage strength increases with embedment length and the amount of transverse reinforcement. For specimens without confining transverse reinforcement and specimens with two No. 3 (No. 10) ties, there is little difference in anchorage strength as side cover increases from 2.5 to 3.5 in. (64 to 89 mm). For specimens with No. 3 (No. 10) ties spaced at $3d_b$, there is a slight decrease in anchorage strength as side cover increases from 2.5 to 3.5 in. (64 to 89 mm). Student's t-test indicates that the differences in anchorage strength associated with the changes in side cover for specimens without confining transverse reinforcement and specimens with two No. 3 (No. 10) ties are not statistically significant (α = 0.56 and 0.82, respectively). Student's t-test cannot be performed for the specimens with No. 3 (No. 10) ties spaced at $3d_b$ because there was only one specimen with 3.5-in. (89-mm) side cover.

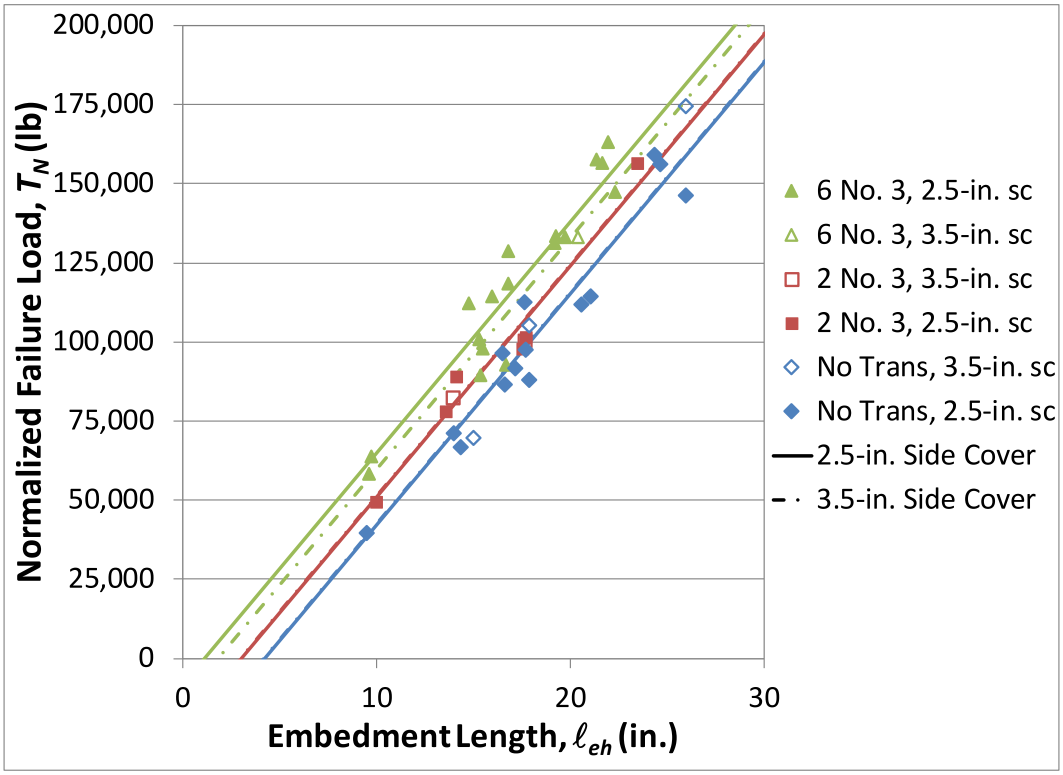


Figure 4.9 Bar force at failure normalized to 5,000 psi concrete versus embedment length for No. 11 (No. 36) hooked bars with different amounts of confining reinforcement and side cover

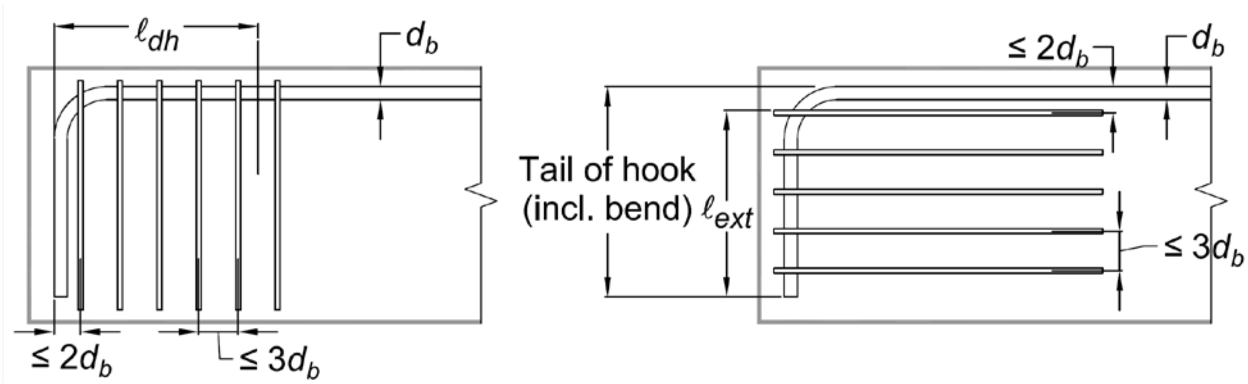
For the No. 5 and No. 8 (No. 16 and No. 25) hooked bar specimens, there was only one instance in each case in which the value of α was indicative of a statistically significant difference between the anchorage strength of specimens with 2.5-in. (64-mm) side cover and specimens with 3.5-in. (89-mm) side cover. These two instances were No. 5 (No. 16) hooked bars confined by two No. 3 (No. 10) ties and No. 8 (No. 25) hooked bars without confining transverse reinforcement. Of these two comparisons, the comparison for the No. 5 (No. 16) bars suggests that a hook with 3.5-in. (89-mm) side cover will have *less* capacity than a hook with 2.5-in. (64-mm) side cover (α = 0.08), while the No. 8 (No. 25) specimens suggest that a hook with 3.5-in. (89-mm) side cover will have a greater anchorage capacity than a hook with 2.5-in. (64-mm) side cover (α = 0.03).

These contradictory findings suggest that these differences carry little weight when considered in the context of the total population and may be the result of the relatively small population sizes for these two subsets of data. Overall, the results indicate that, in the current study, anchorage strength was not affected by differences in side cover in the range of 2.5 to 3.5 in. (64 and 89 mm).

4.4.3 Effect of Orientation of Transverse Reinforcement

To take advantage of the 0.8 reduction factor for development length with 90° hooked bars, 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 as illustrated for a cantilever in Figure 4.10, while for 180° hooked bars the reduction factor can only be applied for reinforcement oriented perpendicular (Figure 4.10a) to the straight portion of the bar being developed. Because confining reinforcement parallel to hooked bars is more convenient in beam-column joints, it is important to determine if a parallel orientation yields comparable increases in anchorage strength to those provided by a perpendicular orientation for 180° hooks. This section evaluates the strength of both 90° and 180° hooked bars within simulated beam-column joints confined by ties oriented vertically and horizontally with respect to the straight portion of the hooked bars. The term "ties" is used to describe confining reinforcement oriented in either direction.

Test results for twelve beam-column joint specimens with 90° and 180° No. 8 (No. 25) hooked bars that were cast in the same batch are compared. The respective cross-section dimensions for the specimens with 10, 11, and 12.5-in. (254, 279, and 318-mm) embedment lengths were 17×12 in., 17×13 in., and 17×14.5 in. (432×305 mm, 432×330 mm, 432×368 mm).



(a) (b)

Figure 4.10 Ties placed (a) perpendicular to the bar being developed and (b) parallel to the bar being developed in a cantilever beam (as shown for 90° hooks) (after ACI 318-14)

The compressive strengths for the specimens in this test series ranged from 11,800 to 12,010 psi (81.4 to 82.8 MPa). The average embedment lengths ranged from 9.4 to 12.8 in. (234 to 325 mm), and the average failure loads ranged from 60,200 to 75,200 lb (268 to 335 kN). Of the twelve specimens, six contained hooks with a 90° bend angle and six contained hooks with a 180° bend angle. For both sets of six, one specimen contained no confining transverse reinforcement, one contained two No. 3 (No. 10) ties placed horizontally (parallel to bar being developed), one contained two No. 3 (No. 10) ties placed vertically (perpendicular to bar being developed), one contained No. 3 (No. 10) ties spaced at $3d_b$ placed horizontally, and two contained No. 3 (No. 10) ties spaced at less than $3d_b$ placed vertically.

To take advantage of the 0.8 development length reduction factor in Section 25.4.3.2 of ACI 318-14, the maximum spacing for transverse reinforcement is $3d_b$, regardless of whether they are placed horizontally or vertically (that is, parallel or perpendicular to the straight portion of the bar). In the specimens with ties placed horizontally along the tail of the hook, a minimum of five ties were needed to meet the $3d_b$ spacing requirement. Given the configuration of the specimens and the depth of the joint, only four ties were required to meet the $3d_b$ spacing requirement when the ties were placed vertically. To obtain an objective comparison between the effect of horizontal and vertical tie placement, two different configurations were used for specimens with vertical ties satisfying $3d_b$ maximum spacing requirement—one with four No. 3 (No. 10) ties to meet the $3d_b$ maximum spacing requirement for vertical ties and one with five No. 3 (No. 10) ties to match the area of transverse reinforcement used in the specimens with ties placed in the horizontal direction. The difference between the two configurations is shown in Figure 4.11. For specimens with 180° hook bend angles, the horizontal ties were placed throughout the hook region as defined by the bend and tail of a 90° hooked bar, as shown in Figure 4.1.

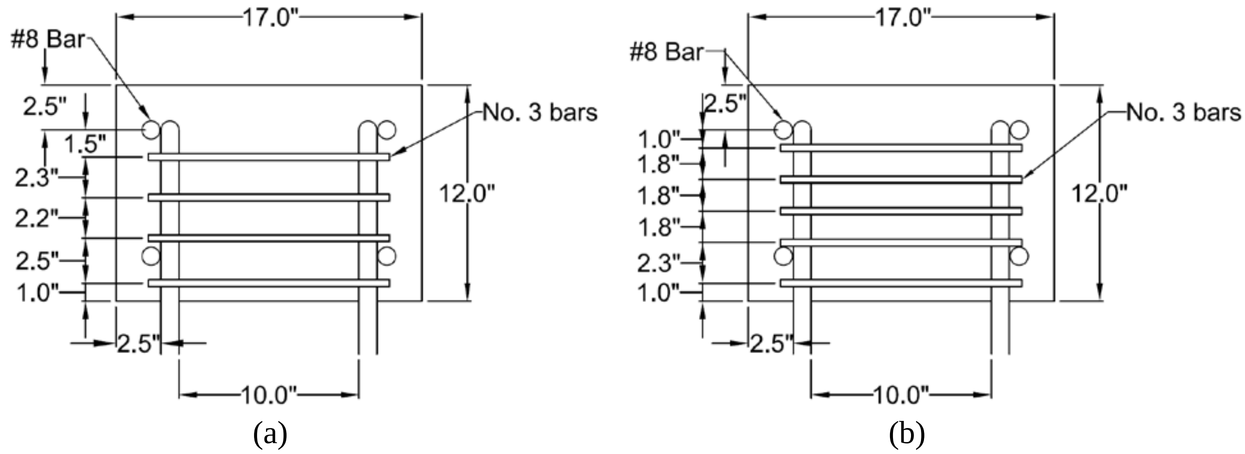
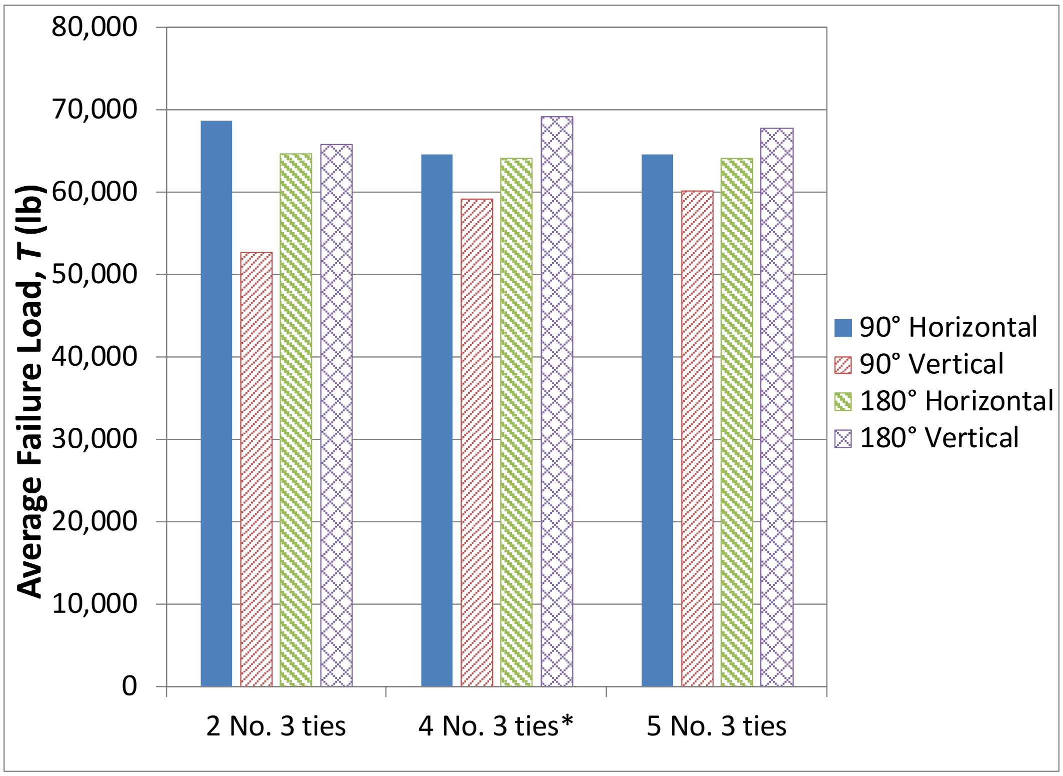


Figure 4.11 Plan view of hooked bars with vertical ties satisfying maximum spacing requirement in ACI 318-14 Section 25.4.3.2: (a) four No. 3 (No. 10) ties and (b) five No. 3 (No. 10) ties

The test results for specimens with two No. 3 (No. 10) ties and specimens with No. 3 (No. 10) ties spaced at $\leq 3d_b$ are shown in the bar graph in Figure 4.12. Each bar in the figure represents the average force in an individual hooked bar in a single specimen at the peak load sustained by the specimen. The first set of four bars shows the average failure loads of the 90° and 180° hooked bars confined by two No. 3 (No. 10) horizontal or vertical ties. As shown for these four specimens, the 90° hooks confined by horizontal ties performed better than the 90° hooks with the vertical ties—the average failure load for the hooked bars with horizontal ties was approximately 1.3 times the average failure load for the hooked bars with vertical ties. For the specimens with a 180° bend angle, configurations with vertical and horizontal ties had comparable strengths—the average failure load for the hooked bars with the vertical ties was 1.02 times the average failure load of the hooked bars with the horizontal ties.

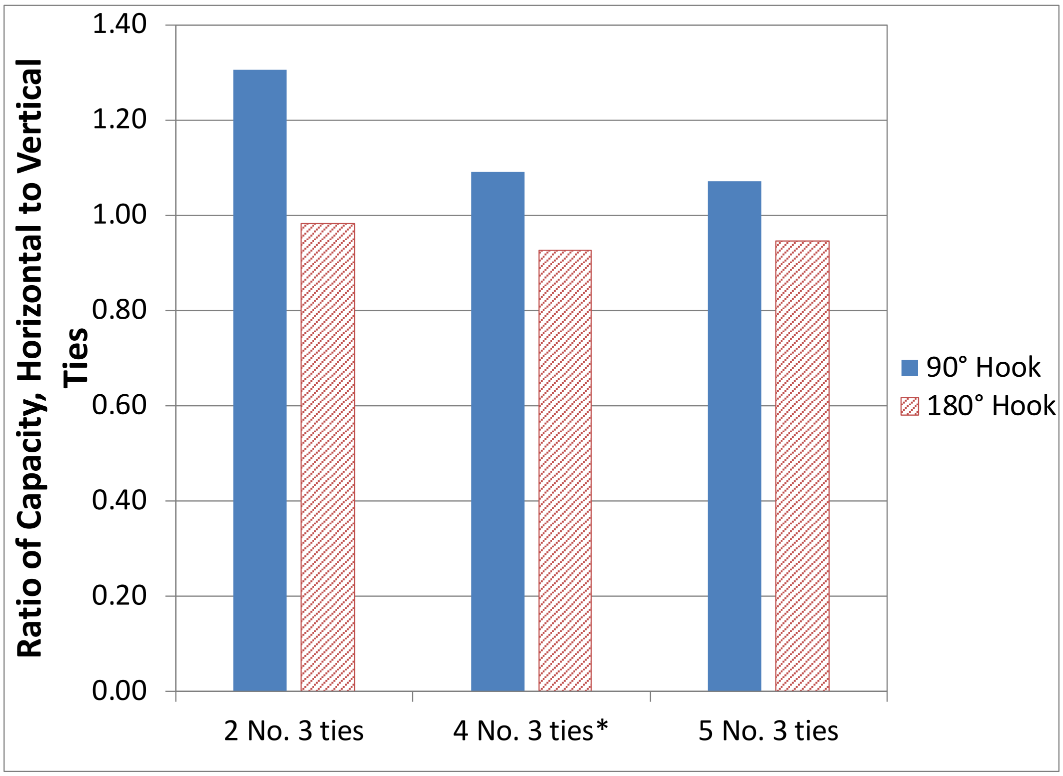


*Specimens with horizontal confining reinforcement had 5 No. 3 ties

Figure 4.12 Failure load for specimens containing No. 8 (No. 25) hooked bars with horizontal and vertical confining reinforcement and 90° and 180° bend angles

The second and third sets of four bars in Figure 4.12 show the results for specimens with ties spaced ≤ $3d_b$. Only two specimens were cast containing horizontal ties spaced ≤ $3d_b$. For ease of comparison, the first and third bars in these sets are duplicates and represent the same two specimens. Trends for specimens with ties spaced ≤ $3d_b$ are similar to those observed for specimens with two No. 3 (No. 10) ties. The 90° hooks with vertical ties failed at a lower load than those with horizontal ties, although the difference is significantly smaller than that observed for the specimens with two No. 3 (No. 10) ties. The failure load of the specimen with five No. 3 (No. 10) horizontal ties was, respectively, 1.09 and 1.07 times the failure loads of the specimens with four No. 3 (No. 10) vertical ties and five No. 3 (No. 10) vertical ties. For the 180° hook specimens, the opposite was true. Specimens with vertical ties failed at a higher load than the companion specimens with horizontal ties. The failure loads of the 180° hook specimens with four No. 3 (No. 10) vertical ties and five No. 3 (No. 10) vertical ties were, respectively, 1.08 and 1.06 times the failure load of the companion specimen with horizontal ties. The 180° hook specimen with five No. 3 (No. 10) horizontal ties had nearly identical strengths to the 90° hook specimen with horizontal ties and higher strengths than the 90° hook specimens with vertical ties, although current design provisions for hooked bars do not allow the use of the 0.8 reduction factor for development length for 180° hooks with horizontal ties.

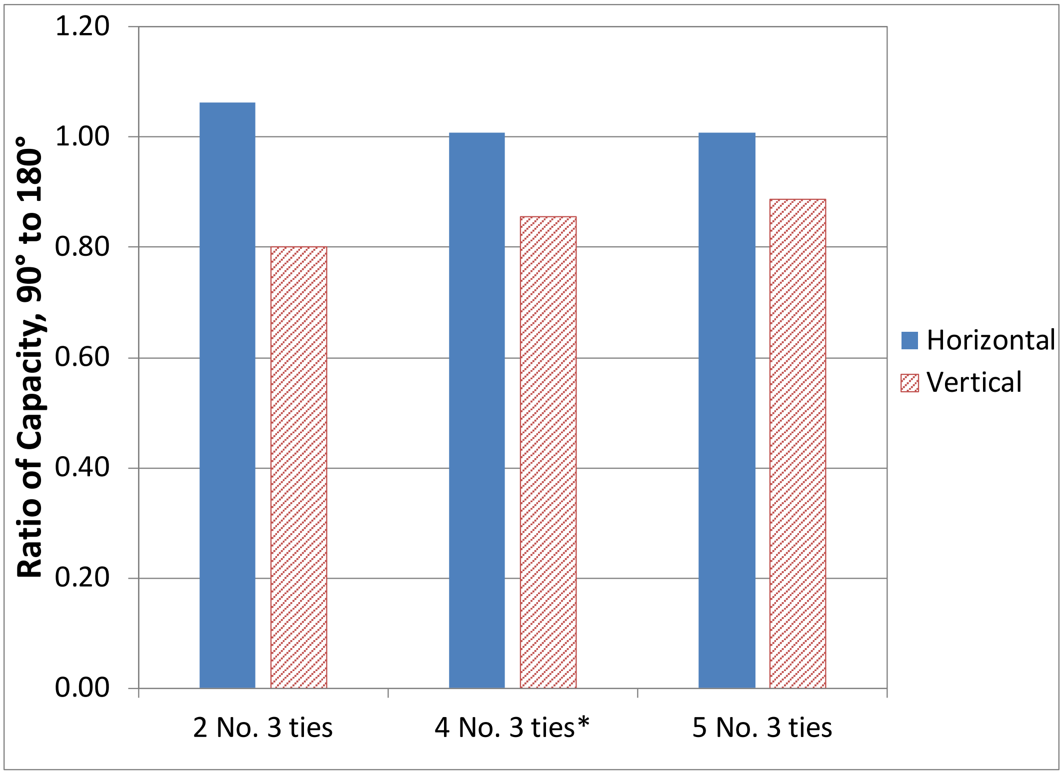
Figure 4.13 shows the ratio of the anchorage capacity of the hooked bars confined by horizontal ties to the anchorage capacity of hooked bars confined by vertical ties. This figure indicates that for 90° hooked bars, horizontal ties had a greater effect on anchorage strength than vertical ties, while for 180° hooked bars the opposite was true. The behavior of the 90° hooked bars may result because horizontal ties act similar to anchor reinforcement for the hooked bars and keep the concrete cone intact by carrying a direct tensile force, while vertical ties, whose orientation does not allow a direct tensile force to develop, may not be as efficient as horizontal ties in acting as anchor reinforcement. Vertical ties, 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° hooked bars than for 90° hooked bars. Greater slip was observed for 180° hooked bars by Marques and Jirsa (1975) and Hamad et al. (1993). Splitting stresses are also key in straight bar development, where the resistance to the wedging action of the bar due to slip is a function of the amount of confining transverse reinforcement oriented perpendicular to the bar and the concrete compressive strength. This suggests that the confinement provided by reinforcement oriented perpendicular to the straight portion of a hooked bar may be similar to that of the confinement provided by reinforcement perpendicular to straight bars (Darwin et al. 1996, Zuo and Darwin 2000, ACI Committee 408R-03).



*Specimens with horizontal confining reinforcement had 5 No. 3 ties

Figure 4.13 Ratio of anchorage strengths for No. 8 (No. 25) hooked bars with horizontal ties to No. 8 (No. 25) hooked bars with vertical ties

Figure 4.14 shows the ratio of anchorage strength of hooked bars with a 90° bend angle to that of hooked bars with a 180° bend angle with both tie orientations. The ratio for specimens with horizontal ties ranges from 1.01 to 1.06, while the ratio for specimens with vertical ties ranges from 0.80 to 0.89. For specimens with horizontal ties, the ratio of anchorage strengths is very close to 1.0, indicating that regardless of the number of ties in the specimens, placing the ties in the horizontal direction provided similar capacity for hooked bars with 90° and 180° bend angles. For specimens with vertical ties, the average anchorage strength ratio is approximately 0.85, showing that when vertical ties are used, the anchorage capacity attained with 90° hooks is lower than that attained with 180° hooks.



*Specimens with horizontal confining reinforcement had 5 No. 3 ties

Figure 4.14 Ratio of anchorage strengths, No. 8 (No. 25) hooked bars with 90° bend angle to No. 8 (No. 25) hooked bars with 180° bend angle

Based on the observed failure modes, it appears that horizontal ties act to keep the concrete intact, serving to keep the concrete from being pulled out the front of the column, similar to anchor reinforcement. The force in the hooked bars tends to pull a section of concrete out the front of the column as shown in Figure 4.15, but the ties act in direct opposition to that force. When vertical ties are used to confine 90° hooked bars, they help keep the concrete intact but no longer act as anchor reinforcement and, thus, are pulled through the front of the column with the cone of concrete, as shown in Figure 4.16.

Based on the results above, it can be concluded that the anchorage strength of 180° hooks with either tie orientation is similar to that of 90° hooks with horizontal ties. Vertical ties are not as effective for 90° hooks. Considering that this study is the first to address the effect on anchorage capacity of transverse reinforcement perpendicular to the straight portion of a hooked bar, more research on the effect of transverse reinforcement with this orientation is needed.

Figure 4.15 Horizontal ties pinning back concrete cone (Specimens 8-12-90-5#3-i-2.5-2-10 after failure)

Figure 4.16 Vertical tie being pulled from the front of the column (Specimen 8-12-90-5#3vr-i-2.5-2-10 after failure)

4.5 SUMMARY AND CONCLUSIONS

In this study, the 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 transverse reinforcement orientation on the anchorage of hooked bars. No. 5, No. 8, and No. 11 (No. 16, 25, and 36) hooked bars were tested with both 90° and 180° bend angles. The clear concrete side cover ranged from 2.5 in. to 3.5 in. (64 to 89 mm). The specimens were cast with normalweight concrete with compressive strengths ranging from 4,300 to 16,510 psi (29.6 to 133.8 MPa). Bar stresses at failure ranged from 33,000 to 137,400 psi (228 to 947 MPa). To determine the effect of orientation of transverse reinforcement on joint capacity, a set of specimens contained either vertical or horizontal ties in the joint region as all other parameters were held constant. Data from prior studies were included in the analysis when applicable.

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

1. Hooked bars with 90° and 180° bend angles produce similar anchorage capacities. This includes hooked bars with a 180° bend angle confined by transverse reinforcement parallel to the straight portion of the bar spaced over the region required in Section 25.4.3.2 of ACI 318-14 to allow use of the 0.8 development length reduction factor for 90° hooks.
2. Increasing concrete side cover from 2.5 to 3.5 in. (64 to 89 mm) does not increase the anchorage capacity of hooked bars.
3. For hooked bars with a 90° bend angle, confining transverse reinforcement placed perpendicular to the straight portion of the bars results in lower anchorage capacity than confining transverse reinforcement with a similar spacing placed parallel to the straight portion of the bars.

4.6 NOTATION

d_b Nominal bar diameter of the hooked bar

f'_c Specified concrete compressive strength

f_{cm} Measured average concrete compressive strength

h_c Width of bearing member flange

h_{cl} Height measured from the center of the hook to the top of the bearing member flange

h_{cu} Height measured from the center of the hook to the bottom of the upper compression member

ℓ_{dh} Development length in tension of deformed bar with a standard hook, measured from the outside end of hook, point of tangency, toward critical section

ℓ_{eh} Embedment length measured from the back of the hook to the front of the column

T Average peak load on hooked bars

T_N Hooked bar anchorage capacity normalized to 5,000 psi concrete compressive strength

α Student's t-test significance

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CHAPTER 5: RELIABILITY-BASED STRENGTH REDUCTION FACTOR FOR HOOKED BAR ANCHORAGE

5.1 INTRODUCTION

Hooked bars are commonly used in reinforced concrete construction, but the anchorage strength of hooked bars has not been studied as extensively as other aspects of reinforced concrete design. Furthermore, very little research has been performed to determine the capacity of hooked high-strength bars or hooked bars in high-strength concrete. Current design provisions for reinforced concrete including the ACI 318 Building Code Requirements for Structural Concrete, ACI 349 Code Requirements for Nuclear Safety-Related Concrete Structures, and the AASHTO LRFD Bridge Design Specifications have requirements for the development of bars with standard hooks that are based on tests conducted by Minor and Jirsa (1975), Marques and Jirsa (1975), and Pinc et al. (1977). These experimental studies included only a small number of specimens that contained standard hooks; in addition, the range of material properties used in the specimens was very limited and did not include high-strength steel bars or high-strength concrete.

Chapter 2 and recent work by Sperry et al. (2015) has shown that the current provisions for hooked bar development length overpredict the anchorage strength of larger hooked bars, the effect of concrete compressive strength, and the effect of confining transverse reinforcement on the anchorage capacity of hooked bars in tension. It was also observed that the factors applied in Section 25.4.3.2 of ACI 318-14 for minimum values of concrete cover and confining transverse reinforcement (0.7 and 0.8, respectively) are unconservative. In Chapter 3 equations were developed to characterize the behavior of hooked bars both without and with confining reinforcement based on tests with bar stresses at failure up to 137 ksi (945 MPa) and concrete compressive strengths up to 16 ksi (110 MPa). The characterizing equations were developed for two hooked bars in a single plane cast inside the column longitudinal bars and in normalweight concrete. Modification factors to account for more than two hooked bars and hooked bars cast outside the column longitudinal bars were developed by Sperry et al. (2015) and will be addressed in a follow-on paper.

The characterizing equations, however, are not safe for design in that they do not account for the uncertainty in loading or material properties as well as the uncertainty in the equations themselves. If these equations were used to calculate the development length of hooked bars, the resulting designs would overpredict the strength of the hooked bars in approximately 50% of the cases. This leads to the need for a strength-reduction factor that will provide a safety margin against failure. It is desirable to determine the strength-reduction factor on a probabilistic basis, ensuring not only that the resulting equation is safe, but also that the sudden nature of bond failure is precluded. Such an approach was taken by Darwin et al. (1998) in the development of a design equation for development length of straight bars; a similar approach will be applied in this paper for hooked bars.

The purpose of this paper is to develop a strength-reduction factor for a design equation derived from the characterizing equations developed in Chapter 3. A reliability analysis is conducted accounting for the uncertainty in loading, member dimensions, material properties, and the characterizing equations themselves. A similar analysis is conducted for the current ACI 318 (2014) design equation for hooked bars to compare the relative reliability of the current equation with the proposed equation.

5.2 RESEARCH SIGNIFICANCE

The current development length equation for hooked bars in tension is based on a relatively small data set that does not include high strength materials. Recent work on the development length of hooked bars including bar stresses up to 137 ksi (945 MPa) and concrete compressive strength up to 16 ksi (110 MPa) produced expressions aimed to characterize the behavior of these members. These characterizing equations are not suitable for use in design, leading to the need for probability-based strength-reduction factors to provide a safe design equation.

5.3 HOOKED BAR ANCHORAGE EQUATIONS

Based on the analysis in Chapter 3, the best-fit equation for the anchorage strength of a single hook in tension not confined by transverse reinforcement is

$$T_c = A_b f_s = 332 f_{cm}^{0.29} \ell_{eh}^{1.06} d_b^{0.54} \tag{5.1}$$

where A_b is the area of the hooked bar, f_s is the stress in the hooked bar, f_{cm} is the measured concrete compressive strength, ℓ_{eh} is the embedded length of the hooked bar measured to the back of the tail of the hook, and d_b is the diameter of the hooked bar.

Equation (5.1) is based on the analysis of 99 beam-column joint specimens containing two hooked bars without confining transverse reinforcement from studies by Marques and Jirsa (1975), Pinc et al. (1977), Hamad et al. (1993), Ramirez and Russell (2008), Lee and Park (2010), and the tests reported in Chapter 2. The bar forces at failure T for this dataset ranged from 19,200 to 213,300 lb (85 to 949 kN) corresponding to a range in stress from 30,800 to 136,700 psi (212 to 943 MPa), the embedment lengths ℓ_{eh} ranged from 3.75 to 26.0 in. (95 to 660 mm), the hooked bar size ranged from No. 5 to No. 11 (No. 16 to No. 36), and the concrete compressive strengths ranged from 2,570 to 16,510 psi (17.7 to 114 MPa). The average test-to-calculated ratio based on Eq. (5.1) is 1.0 with a coefficient of variation $V_{T/C}$ of 0.119.

For hooked bars confined by transverse reinforcement parallel to the straight portion of the hooked bar, the best-fit equation for the anchorage strength of a single hook in tension is

$$T_h = A_b f_s = 332 f_{cm}^{0.29} \ell_{eh}^{1.06} d_b^{0.54} + 54,250 \left(\frac{NA_{tr}}{n} \right)^{1.06} d_b^{0.59} \tag{5.2}$$

For hooked bars confined by transverse reinforcement perpendicular to the straight portion of the hooked bar, the best-fit equation for the anchorage strength of a single hook in tension is

$$T_h = A_b f_s = 332 f_{cm}^{0.29} \ell_{eh}^{1.06} d_b^{0.54} + 983 \left(\frac{NA_{tr}}{n} \right)^{1.06} d_b^{0.59} f_{cm}^{0.29} \tag{5.3}$$

The amount of transverse reinforcement per hooked bar is NA_{tr}/n, where N is the number of legs parallel to the straight length of the hooked bar within $8d_b$ from the top of the bar for No. 3 through No. 8 (No. 10 through No. 25) bars or $10d_b$ from the top of the bar for No. 9 through No. 11 (No. 29 through No. 36) bars (the out-to-out dimension of a 180° hooked bar) or the number of legs perpendicular to the bar over the length being developed, A_{tr} is the area of one leg of transverse reinforcement, and n is the number of hooked bars being developed. One major advantage to this new definition of the contribution of confining transverse reinforcement is that the designer can take advantage of smaller amounts of confining transverse reinforcement in the joint region without being obligated to provide reinforcement spaced at $3d_b$, as is currently required to use the 0.8 reduction factor for development length specified in ACI 318-14 Section 25.4.3.2. This can lead to lower congestion in the joint region, especially when using smaller diameter bars.

Equations (5.2) and (5.3) are based on the analysis of 146 beam-column joint specimens containing two hooked bars tested by Sperry et al. (2015) and presented in Chapter 2 with various amounts of confining transverse reinforcement. The bar forces at failure for the 146 specimens ranged from 18,700 to 209,600 lb (83 to 93 kN) corresponding to a range in stress from 41,000 to 137,400 psi (283 to 947 MPa), the average embedment lengths ranged from 3.75 to 23.5 in. (95 to 597 mm), the hooked bar size ranged from No. 5 to No. 11 (No. 16 to No. 36), and concrete compressive strengths ranged from 4,300 to 16,180 psi (229.6 to 112 MPa). The mean test-to-calculated strength ratio for Eq. (5.2) is 1.0, and the coefficient of variation $V_{T/C}$ is 0.113. The mean test-to-calculated strength ratio for Eq. (5.3) is 0.94. A ratio of 1.0 was deemed inappropriate because only six specimens from a single batch of 14 specimens were cast with vertical stirrups, with the balance containing horizontal ties or no confining reinforcement; in general, the specimens in this batch were among the weakest of all the specimens tested in the study. Specimens from this batch with horizontal ties had an average test-to-calculated ratio of 0.94; thus, to be fair, the equation for vertical ties was targeted to the same ratio. Since the equation for vertical ties was based on such a small sample, the coefficient of variation $V_{T/C}$ for Eq. (5.2) was used in the Monte Carlo analysis.

Equations (5.1) through (5.3) are best-fit functions for the dataset used to develop the equations. These equations do not address the effects of more than two hooked bars in a member or closely-spaced hooked bars. Based on the observed failure modes [discussed in Chapter 2 and by Sperry et al. (2015)], it can be assumed that placing additional hooked bars in a member or having closely-spaced hooked bars will lead to a decrease in failure load per hooked bar. Members with more than two hooked bars and members with closely-spaced hooked bars are under study and will be addressed in a subsequent paper.

For use in design, several steps were taken to simplify the characterizing equations.

1. The power of ℓ_{eh} in Eq. (5.1) through (5.3) is 1.06, indicating that the effect of ℓ_{eh} on the anchorage capacity of hooked bars does not deviate substantially from a linear relationship. Consequently, the anchorage capacity of a hooked bar is assumed to be proportional to the embedment length ℓ_{eh}.

2. The power of the concrete compressive strength is assumed to be 0.25. This value is reasonably close to the value of 0.29 in the equations. This value also matches the power of concrete compressive strength used in the descriptive equations for straight development and lap splices (Darwin et al. 1996, Darwin et al. 1998, Zuo and Darwin 2000, ACI 408R-03).

3. The power for d_b is assumed to be 0.5 as a reasonable representative value of the empirically derived powers of 0.54 and 0.59 that appear in Eq. (5.1) through (5.3).

4. The power for the term NA_{tr}/n is assumed to be 1.0, because the power of 1.06 that appears in Eq. (5.2) and (5.3) indicates that the relationship is close to linear.

With these assumptions, the best-fit equation for hooked bars in tension with transverse reinforcement parallel to the straight portion of the bar becomes

$$T_h = A_b f_s = 545 f_{cm}^{0.25} \ell_{eh} d_b^{0.5} + 48{,}000 \frac{NA_{tr}}{n} d_b^{0.5} \tag{5.4}$$

For hooked bars with transverse reinforcement oriented perpendicular to the bar, the equation becomes

$$T_h = A_b f_s = 545 f_{cm}^{0.25} \ell_{eh} d_b^{0.5} + 1{,}290 \frac{NA_{tr}}{n} d_b^{0.5} f_{cm}^{0.25} \tag{5.5}$$

Equations (5.4) and (5.5) give the same result for cases without transverse reinforcement, as $NA_{tr}/n = 0$.

Equation (5.4) provides a mean test-to-calculated ratio of 1.0 for specimens both without and with confining transverse reinforcement. The coefficient of variation $V_{T/C}$ for specimens without confining reinforcement is 0.124 and for specimens with confining reinforcement is 0.122.

Equation (5.4) can be used to calculate the embedment length necessary to develop a stress f_s in the bar.

$$\ell_{eh} = 0.00144 \frac{f_s d_b^{\ 1.5}}{f_{cm}^{0.25}} - 88 \frac{NA_{tr}}{n f_{cm}^{0.25}} \tag{5.6}$$

For hooked bars with transverse reinforcement oriented perpendicular to the bar, Eq. (5.5) becomes:

$$\ell_{eh} = 0.00144 \frac{f_s d_b^{\ 1.5}}{f_{cm}^{0.25}} - 2.4 \frac{NA_{tr}}{n} \tag{5.7}$$

Alternatively, Eq. (5.6) and (5.7) can be expressed as

$$\ell_{eh} = \left(0.00144 \frac{f_s \psi_r}{f_{cm}^{0.25}} \right) d_b^{1.5} \tag{5.8}$$

where for hooked bars confined by transverse reinforcement parallel to the bar,

$$\psi_r = \frac{f_s d_b^{1.5} - 61{,}100\, NA_{tr} / n}{f_s d_b^{1.5}} \leq 1.0 \tag{5.9a}$$

and for hooked bars confined by transverse reinforcement perpendicular to the bar,

$$\psi_r = 1 - \frac{1{,}670\, f_{cm}^{0.25} NA_{tr}}{n f_s d_b^{1.5}} \tag{5.9b}$$

5.4 CALCULATION OF STRENGTH REDUCTION FACTORS

5.4.1 Overall approach

The overall approach for the development of a strength reduction factor is similar to that used by Darwin et al. (1998). The development of a design equation requires the application of a strength reduction factor to Eq. (5.4) and (5.5) to ensure a sufficiently low probability of failure. Hooked bar anchorage failures are brittle and sudden, thus, it is desirable that the probability of anchorage failure of the beam reinforcement be less than that of flexural failure of the beam. The concepts of structural reliability are applied to ensure this safe behavior is incorporated into the eventual anchorage design equation.

For a given load *Q* and resistance *R*, failure will not occur as long as the ratio $R/Q \geq 1$. Reliability-based design uses the concepts of probability to design a system or element to have a target reliability that takes into account the various sources of uncertainty in *R* and *Q*. Load and strength reduction factors (ϕ-factors) are used to provide the target reliability. These factors account for the inherent variability in expected loads and predicted strength of structural members and work in concert to increase the predicted loads and reduce the predicted strength of elements. The reliability of the structure can be represented by the reliability index β, which equals the number of standard deviations separating the mean from the value representing failure. In general, the higher the value of the reliability index, the greater the reliability of the member. Assuming that *R* and *Q* have lognormal distributions (Fig. 1) and using small-variance approximations (Ellingwood et al. 1980), $\overline{\ln(R/Q)} \approx \ln(\bar{R}/\bar{Q})$ and $\sigma_{\ln(R/Q)} \approx \sqrt{V_R^2 + V_Q^2}$, where the overbar indicates the average, σ is the standard deviation, and *V* is the coefficient of variation,

$$\beta = \frac{\overline{\ln(R/Q)}}{\sigma_{\ln(R/Q)}} \approx \frac{\ln(\bar{R}/\bar{Q})}{\sqrt{V_R^2 + V_Q^2}} \tag{5.10}$$

Figure 5.1 illustrates the relationship between the reliability index and the probability of failure.

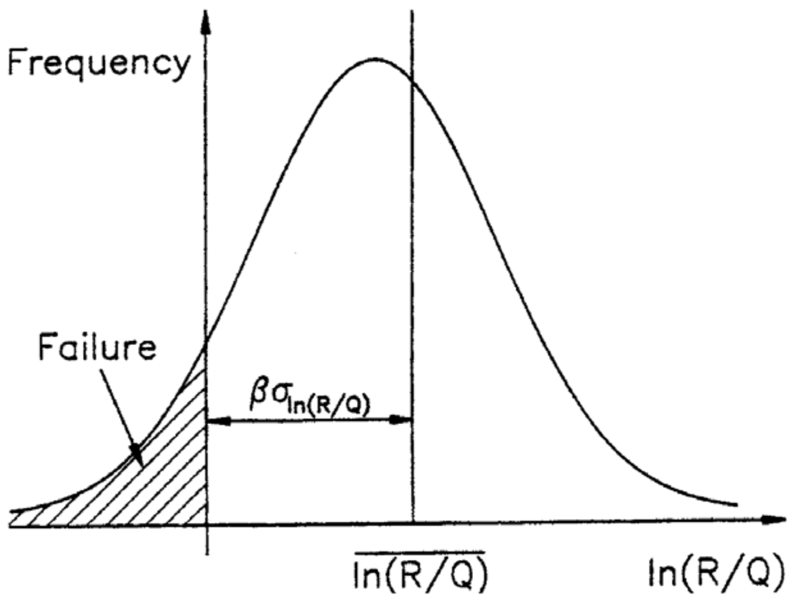

Figure 5.1 Illustration of reliability index (taken from Darwin et al. 1998): β = number of standard deviations between $\ln(R/Q) = \overline{\ln(R/Q)}$ and $\ln(R/Q) = 0$

For reinforced concrete beams and columns with typical loading, β ≈ 3.0 (Ellingwood et al. 1980). As discussed earlier, it is desirable to have a lower probability of anchorage failure than flexural failure; thus, the value of β must be greater than the typical value of 3.0. Assuming β = 3.5 for anchorage failures gives a probability of failure about one-fifth of that of a flexural failure (for which β = 3.0), based on the assumed form of the distributions (Ellingwood et al. 1980). This increased reliability is deemed sufficient by the authors and will be used in development of a strength reduction factor for anchorage.

The reliability index can be used to calculate the appropriate strength-reduction factor for hooked bar anchorage capacity. It must first be realized, however, that the bar force $T_h = A_b f_s$ that appears on the left side of Eq. (5.4) or (5.5) has already been increased by a factor of 1/ϕ, where ϕ is the strength reduction factor for the main loading (this would be flexure for anchorage of tensile steel in a beam). This increase occurs before the development length for the hooked bar is calculated. Following the requirements of ACI 318-14, $\phi M_n \geq M_u$. The limiting case is $\phi M_n = M_u$ or $\phi A_b f_s(d - a/2) = M_u$. Then $A_b f_s = M_u / \phi(d - a/2)$ (where M_n and M_u are the nominal and factored moments, respectively, ϕ is the strength reduction factor for bending, d is the effective depth, and a is the depth of the stress block). This demonstrates that $A_b f_s$ is greater by a factor of $1/\phi$ than that corresponding to the value of the factored moment M_u. For hooked bar development, the right side of Eq. (5.4) or (5.5) times ϕ_b will also equal $M_u /(d - a/2)$. Setting the two design forces equal gives

$$A_b f_s = \phi_b \left[\text{Right side of Eq. (5.4) or (5.5)}\right] \tag{5.11}$$

In most designs, the force provided by the tensile steel in a beam, $A_b f_s$, depends on the flexural demand (as opposed to anchorage requirements). Therefore, the effective strength reduction factor for hooked bar development length is $\phi_d = \phi_b / \phi$. Thus,

$$\phi A_b f_s = \phi_d \left[\text{Right side of Eq. (5.4) or (5.5)}\right] \tag{5.12}$$

The strength reduction factor against hooked bar failure ϕ_b can be calculated using Eq. (5.10), but the random and uncertain nature of R and Q must first be characterized. To do so, data collected by the authors and other researchers on the mean and variation of critical parameters is applied using Monte Carlo analysis. The following derivations follow the procedure used by Darwin et al. (1998) and Zuo and Darwin (1998).

Resistance and loading random variables—Determining ϕ_b requires several substitutions to introduce ϕ into Eq. (5.10). These steps are outlined in Eq. (5.13) through (5.25).

The random variable for resistance R is given as

$$R = X_1 R_p \tag{5.13}$$

where X_1 = test-to-calculated load capacity random variable and R_p = predicted capacity random variable, dependent on material and geometric properties of member, which are also random variables.

The random variable for dead load and live load Q is

$$Q = Q_D + Q_L \text{, or} \tag{5.14}$$

$$Q = \left(\frac{Q_D}{Q_{Dn}} + \frac{Q_L}{Q_{Dn}} \right) Q_{Dn} \tag{5.15}$$

Where Q_D = random variable representing dead load effects, Q_L = random variable representing live load effects, and Q_{Dn} = nominal dead load.

The ratios of Q_D / Q_{Dn} and Q_L / Q_{Dn} in Eq. (5.15) can be written as

$$\frac{Q_D}{Q_{Dn}} = X_2 \tag{5.16}$$

$$\frac{Q_L}{Q_{Dn}} = \frac{Q_L}{Q_{Ln}} \frac{Q_{Ln}}{Q_{Dn}} = X_3 \left(\frac{Q_L}{Q_D} \right)_n \tag{5.17}$$

where

Q_{Ln} = nominal live load

X_2, X_3 = actual-to-nominal dead and live load random variables

$\left(\frac{Q_L}{Q_D} \right)_n$ = nominal ratio of live load to dead load

Expression for strength reduction factor—In design, the strength reduction factor times the nominal capacity should equal or exceed the factored load, as shown in Eq. (5.18).

$$\phi_c R_n \geq \gamma_D Q_{Dn} + \gamma_L Q_{Ln} \tag{5.18a}$$

In the limiting case,

$$\phi_c R_n = \gamma_D Q_{Dn} + \gamma_L Q_{Ln} \tag{5.18b}$$

where ϕ_c = strength reduction factor for the loading under consideration (in this case, $\phi_c = \phi_b$), R_n = nominal resistance, and γ_D, γ_L = load factors for dead and live loads.

Factoring out Q_{Dn} on the right side of Eq. (5.18) and setting $Q_{Ln} / Q_{Dn} = (Q_L / Q_D)_n$ gives

$$\phi_c R_n = Q_{Dn}\left[\gamma_D + \gamma_L\left(\frac{Q_L}{Q_D}\right)_n\right] \tag{5.19}$$

Solving Eq. (5.19) for Q_{Dn},

$$Q_{Dn} = \frac{\phi_c R_n}{\gamma_D + \gamma_L\left(\frac{Q_L}{Q_D}\right)_n} \tag{5.20}$$

Eq. (5.16), (5.17), and (5.20) can be substituted into Eq. (5.15) to find the total load, Q:

$$Q = \frac{\phi_c\left[X_2 + X_3\left(\frac{Q_L}{Q_D}\right)_n\right]R_n}{\gamma_D + \gamma_L\left(\frac{Q_L}{Q_D}\right)_n} = \phi_c q R_n \tag{5.21}$$

where

$$q = \frac{\left[X_2 + X_3\left(\frac{Q_L}{Q_D}\right)_n\right]}{\gamma_D + \gamma_L\left(\frac{Q_L}{Q_D}\right)_n}$$

Let r be the ratio of random member resistance to nominal resistance:

$$r = \frac{R}{R_n} = \frac{X_1 R_p}{R_n} \tag{5.22}$$

Solving Eq. (5.22) for R:

$$R = X_1 R_p = r R_n \tag{5.23}$$

Substituting expressions for R [Eq. (5.23)] and Q [Eq. (5.21)] into Eq. (5.10) introduces ϕ_c into the expression:

$$\beta = \frac{\overline{\ln(R/Q)}}{\sigma_{\ln(R/Q)}} = \frac{\overline{\ln(rR_n/\phi_c qR_n)}}{\sigma_{\ln(rR_n/\phi_c qR_n)}} = \frac{\overline{\ln(r/\phi_c q)}}{\sigma_{\ln(rR/\phi_c q)}} \approx \frac{\ln(\overline{r}/\phi_c \overline{q})}{\sqrt{V_r^2 + V_{\phi q}^2}} \tag{5.24}$$

where

$$\overline{r} = \overline{\left(\frac{X_1 R_p}{R_n}\right)}$$

$$V_r = \frac{\sigma_r}{\overline{r}}$$

$$\overline{q} = \frac{\overline{\left[X_2 + X_3\left(\frac{Q_L}{Q_D}\right)_n\right]}}{\gamma_D + \gamma_L\left(\frac{Q_L}{Q_D}\right)_n}$$

$$V_{\phi q} = \frac{\phi_c \sigma_q}{\phi_c \overline{q}} = \frac{\sigma_q}{\overline{q}} = \frac{\left\{\left[\overline{X_2} V_{Q_D}\right]^2 + \left[\overline{X_3}\left(\frac{Q_L}{Q_D}\right)_n V_{Q_L}\right]^2\right\}^{1/2}}{\overline{X_2} + \overline{X_3}\left(\frac{Q_L}{Q_D}\right)_n}$$

Solving Eq. (5.24) for ϕ_c (and remembering that in this case $\phi_c = \phi_b$) gives

$$\phi_c = \phi_b = \frac{\overline{r}}{\overline{q}} e^{-\beta\sqrt{V_r^2 + V_{\phi q}^2}} \tag{5.25}$$

The solution of Eq. (5.25) requires knowledge of $\overline{r}$ and $\overline{q}$ and the coefficients of variation V_r and $V_{\phi q}$. This is discussed next.

5.4.2 Random Variables

In this section, the values of $\overline{r}$, V_r, $\overline{q}$, and $V_{\phi q}$ are obtained. The discussion up to this point [Eq. (5.25)] can be applied to any design problem (Darwin et al. 1998); however, proceeding further requires the discussion to become specific to hooked bar development.

Resistance random variable

The ratio of random to nominal resistance r is determined by using Eq. (5.22), which requires the knowledge of the test-to-calculated random variable X_1 and the predicted capacity random variable R_p.

Test-to-calculated random variable, X_1—The test-to-calculated load random variable X_1 is based on the actual variability of the hooked bar characterizing equation, Eq. (5.1) through (5.3). X_1 is assumed to be a random variable with a normal distribution and a mean of 1.0 [the mean test-to-calculated ratio of Eq. (5.1) and (5.2)]. The coefficient of variation V_{X_1} is equal to the coefficient of variation of the characterizing equations V_m. In addition to the variation in the characterizing equations, the total variation in the test-to-calculated ratio $V_{T/C}$ is also influenced by variations in test parameters such as member geometry, material properties, and measured load; variation from these sources is represented by V_{ts} (Grant et al. 1978). Thus,

$$V_{T/C} = \left(V_m^2 + V_{ts}^2\right)^{1/2} \tag{5.26}$$

Solving for V_m gives,

$$V_m = \left(V_{T/C}^2 - V_{ts}^2\right)^{1/2} \tag{5.27}$$

Prior research (Grant et al. 1978) has found $V_{ts} \approx 0.07$ for reinforced concrete structures. Thus, for hooked bars not confined by transverse reinforcement, $V_m = \left(V_{T/C}^2 - V_{ts}^2\right)^{1/2} = \left(0.119^2 - 0.07^2\right)^{1/2} = 0.096,$ and for hooked bars confined by transverse reinforcement, $V_m = \left(V_{T/C}^2 - V_{ts}^2\right)^{1/2} = \left(0.113^2 - 0.07^2\right)^{1/2} = 0.089.$

Predicted capacity random variable, R_p—The predicted capacity random variable R_p is itself a function of other random variables. Thus, the individual values of the predicted capacity random variable are obtained for hypothetical beam-column joints using Monte Carlo analysis.

The random variables that affect the value of R_p are the concrete compressive strength f'_c (which must be adjusted for loading rate) and the development length of the hooked bar ℓ_{dh}. Other aspects of the member geometry, such as more than two hooked bars in a member and closely-spaced hooked bars, may alter the capacity random variable if it is found that these factors affect the capacity of the hooked bars. The predicted capacity R_p is calculated using Eq. (5.1) for hooked bars not confined by transverse reinforcement or Eq. (5.2) or (5.3) for hooked bars confined by transverse reinforcement. The individual values for R_p are calculated by substituting values for each of the random variables based on the nominal value (the value assumed in design) and statistical properties associated with that variable.

Concrete compressive strength random variable, X_4—In addition to the mean strength and variation in strength for a given specified compressive strength, the random variable for concrete compressive strength X_4 must consider the effect of the loading rate in the structure, as opposed to the standard loading rate used in compression tests (35 psi/sec [0.24 MPa/sec]) (ASTM C39-15).

Using the relation proposed by Jones and Richart (1936), the concrete compressive strength at a loading rate $\dot{f}$ can be obtained with Eq. (5.28):

$$f'_{c\dot{f}} = 0.89 f'_{c35}\left(1 + 0.08 \log \dot{f}\right) \tag{5.28}$$

where 0.1 psi/sec $\leq \dot{f} \leq$ 10,000 psi/sec, $f'_{c\dot{f}}$ = compressive strength of concrete at stress rate $\dot{f}$, and f'_{c35} = compressive strength of concrete at $\dot{f}$ = 35 psi/sec (0.24 MPa/sec).

It is assumed that failures in practice will rarely be the result of rapid loading; typical failures are likely to be gradual. In this analysis, the loading rate is set equivalent to that which would cause failure in one hour [Eq. (5.29)].

$$\dot{f} = \frac{f'_{c\dot{f}}}{3600} \tag{5.29}$$

The values of $\dot{f}$ and $f'_{c\dot{f}}$ are calculated iteratively by using Eq. (5.28) and (5.29), and provide a lower compressive strength than indicated from a standard cylinder test. For example, for concrete with f'_{c35} = 5,000 psi, the effective loading rate and compressive strength after iteration are 1.25 psi/sec (8.6 kPa/sec) and 4,480 psi (30.9 MPa), respectively.

The value of f'_{c35} should be representative of in-situ concrete strength. True in-situ strength is rarely obtained; field-cured cylinders provide a close, but still differing, approximation to the strength in the member. Field-cured cylinders typically exhibit somewhat lower strength than laboratory-cured cylinders, meaning the standard laboratory-cured cylinder test overestimates compressive strength in the structure. However, when designing concrete mixtures for use in a structure, engineers target a higher compressive strength than that used in design to ensure that a sufficiently low percentage of batches produce strengths lower than the specified value. For simplicity, these two effects are assumed to cancel each other out; therefore, the specified value of f'_c is substituted into Eq. (5.28) for f'_{c35}.

In Eq. (5.1) through (5.3), f'_c is replaced by the normally distributed random variable X_4 with a mean value of $f'_{c\dot{f}}$. The standard deviation $\sigma_{X_4} = V_c f'_{c\dot{f}}$ is based on the list of standard deviations for laboratory cured cylinders given in Table 5.1 (Nowak et al. 2012), and an assumed variability for in-situ concrete (Mirza et al. 1979):

$$V_c = \sqrt{V_{ccyl}^2 + 0.0084} \tag{5.30}$$

where V_{ccyl} = the coefficient of variation for laboratory cured cylinders (Table 5.1).

The values in Table 5.1 for V_{ccyl} are taken from a study by Nowak et al. (2012). For f'_c = 4,000 psi (28 MPa), V_c = 0.176 and σ_{X_4} = 626 psi (4.32 MPa).

Table 5.1 Statistical Parameters for Concrete Compressive Strength

f'_c (psi)	V_{ccyl}*	V_c	f'_{cf} (psi)	σ_{X_4} (psi)
4,000	0.150	0.176	3,559	626
6,000	0.125	0.155	5,416	839
8,000	0.110	0.143	7,295	1,044
10,000	0.110	0.143	9,190	1,316
12,000	0.110	0.143	11,098	1,589
15,000	0.110	0.143	13,979	2,002

* Data from Nowak et al. (2012)
1 psi = 6.89 kPa

Geometric properties—the variability of the geometric properties of the member are based on the tolerances for construction specified in ACI 117-14. A normal distribution is assumed to represent the variability of the geometric properties of the concrete sections.

The development length of the hooked bar is represented by the random variable X_5, with a mean value equal to the nominal value of ℓ_{dh}. The tolerance for the embedded length of bars in ACI 117-14 is –1 in. (25 mm) for No. 3 (No. 10) through No. 11 (No. 36) bars. With a lack of more detailed information, it was assumed that 5 percent of bars will have a development length shorter than (ℓ_{dh} – 1) in. [(ℓ_{dh} – 25) mm]. For this assumption and if a normal distribution is assumed for embedment length, then the value (ℓ_{dh} – 1) in. [(ℓ_{dh} – 25) mm] will be 1.645 standard deviations from the mean ℓ_{dh}. Thus, the random variable X_5 has a standard deviation that is defined by $1.645\sigma_{X_5} = 1$ in. (25 mm), or $\sigma_{X_5} = 0.61$ in. (16 mm).

Nominal Strength, R_n—The nominal strength, R_n, is calculated using Eq. (5.4) or (5.5) using the nominal dimensions of the member and the specified concrete compressive strength.

Monte Carlo simulation—The values of $\overline{r}$ and V_r are obtained using Monte Carlo simulations of a selected set of hypothetical beams. The concrete compressive strength and bar size were chosen to be representative of those typically used in practice. Additional considerations, such as number of hooked bars and spacing, will be addressed in a subsequent paper. These beams have concrete compressive strength ranging from 4,000 psi to 15,000 psi (27.6 MPa to 103 MPa) and Grade 60 to Grade 120 (Grade 420 to Grade 830) reinforcing steel.

For each beam and simulation, specific values are probabilistically chosen for X_1 and X_4 through X_7 using the mean and variation for each. To accomplish this, a random number generator is used to produce a number between 0 and 1 for each variable; this random number is treated as a probability in the cumulative distribution function, which, in turn, is used to determine the standard normal random variable z ($-\infty < z < \infty$). This value of z is used to determine the variation of X_i from the mean. For the variable i, $X_i = \overline{X_i} + z\sigma_{X_i}$. These values of X_i are used to calculate r [Eq. (5.22)] for the simulation. Each beam is simulated 10,000 times, resulting in an individual $\overline{r}$ and V_r for each beam. The individual $\overline{r}$ and V_r are then combined to get a cumulative $\overline{r}$ and V_r for the population.

Loading random variable

The term q is a function of the random variables X_2 and X_3, ratios of actual-to-nominal dead and live load, respectively, the nominal live-to-dead load ratio $(Q_L/Q_D)_n$, and the dead and live load factors γ_D and γ_L, respectively equal to 1.2 and 1.6. The values of $(Q_L/Q_D)_n$ selected are 0.5, 1.0, and 1.5. These values are typically used when evaluating the reliability of reinforced concrete structures, with a nominal live-to-dead load ratio of 1.0 being the standard for calculating ϕ-factors or determining the reliability index β.

For reinforced concrete structures, $\overline{X_2} = \overline{Q_D}/Q_{Dn} = 1.03$ and V_{Q_D} = 0.093 (Ellingwood et al. 1980). The value of $\overline{X_3} = \overline{Q_L}/Q_{Ln}$ is dependent on the value of mean and nominal live loads. The fifty year mean live load can be represented by Eq. (5.31) (Ellingwood et al. 1980).

$$\overline{Q_L} = \left(0.25 + \frac{15}{\sqrt{A_I}}\right) L_o \tag{5.31}$$

where A_I = influence area, ft^2 and L_o = basic unreduced live load, psf.

The nominal live load Q_{Ln} is represented, according to ASCE 7-10, as

$$Q_{Ln} = \left(0.25 + \frac{15}{\sqrt{K_{LL} A_T}}\right) L_o \tag{5.32}$$

where K_{LL} = live load element factor (For interior beams K_{LL} = 2) and A_T = tributary area, ft^2.

For typical values of A_T and A_I of 400 ft^2 and 800 ft^2, respectively, the value of $\overline{X_3}$ becomes 1.0. V_{Q_L} = 0.25 (Ellingwood et al. 1980).

5.5 STRENGTH REDUCTION FACTORS

Strength reduction (ϕ) factors are calculated for Eq. (5.4) and (5.5) for members without and with confining transverse reinforcement using nominal live-to-dead load ratios of 0.5, 1.0, and 1.5. The members used in the calculations include 96 beams with hooked bars not confined by transverse reinforcement and 384 beams (in four groups of 96) with hooked bars confined by transverse reinforcement. Concrete compressive strength is either 4,000, 6,000, 8,000, 10,000, 12,000, or 15,000 psi (27.6, 41.4, 55.2, 68.9, 82.7, and 103 MPa). Hooked bars are either Grade 60, 80, 100, or 120 (Grade 420, 550, 690, or 830). No. 6, No. 8, No. 9, and No. 11 hooked bars (No. 19, No. 25, No. 29, and No. 36) are used. For hooked bars confined by transverse reinforcement, No. 3 (No. 10) ties are used with either 1 tie, 2 ties, or ties spaced at 3d_b. For ties spaced at 3d_b, the ties are oriented both parallel and perpendicular to the straight portion of the hooked bars. For ties oriented parallel to the straight portion of the hooked bar, following the maximum spacing allowed in ACI 318-14 Section 25.4.3.2, only three ties fall within the distance $8d_b$ for No. 3 through No. 8 (No. 10 through No. 25) or $10d_b$ for No. 9 through No. 11 (No. 29 through No. 36) hooked bars. For ties oriented perpendicular to the straight portion of the hooked bar, however, the number of ties spaced at $3d_b$ is dependent on the embedded length of the bar. Thus, the orientation of the ties can lead to different amounts of confining reinforcement and hooked bar anchorage capacity for a given embedded length. A summary of the beams used for the analysis is presented in Appendix C.

Ten thousand Monte Carlo simulations are performed for each beam. In each simulation, the predicted strength of the beam is calculated using Eq. (5.1), (5.2), or (5.3) as appropriate, based on the amount and orientation of confining transverse reinforcement. The material and geometric random variables described earlier are incorporated into the calculations. The results of the Monte Carlo simulation (the strengths of each beam) are used to calculate the cumulative $\overline{r}$ and V_r. The load factors and live-to-dead load ratios are used to calculate $\overline{q}$ and $V_{\phi q}$. The value of $\phi_c = \phi_b$ is then calculated from Eq. (5.25) using $\beta = 3.5$. Finally, the value of $\phi_d = \phi_b/\phi$ is determined. The results of the Monte Carlo simulations are presented in Table 5.2.

Using a live-to-dead load ratio of 1.0, ϕ_d equals 0.810 for hooked bars without confining transverse reinforcement, 0.820 for hooked bars confined by 1 No. 3 (No. 10) tie, 0.827 for hooked bars confined by 2 No. 3 (No. 10) ties, 0.838 for hooked bars with ties spaced at $3d_b$ oriented parallel to the hooked bar, and 0.818 for hooked bars with ties spaced at $3d_b$ oriented perpendicular to the hooked bar. Selecting a value of $\phi_d = 0.81$ will, thus, be slightly conservative for hooked bars both with and without confining transverse reinforcement.

Table 5.2 Strength reduction factors using Eq. (5.4) and (5.5)

	Without Trans			1 No. 3 Parallel			2 No. 3 Parallel		
$\overline{r}$	1.00			0.99			1.00		
V_r	0.125			0.118			0.116		
$(Q_L/Q_D)_n$	0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5
$\overline{q}$	0.765	0.725	0.703	0.765	0.725	0.703	0.765	0.725	0.703
$V_{\phi q}$	0.103	0.132	0.153	0.103	0.132	0.153	0.103	0.132	0.153
ϕ_b	0.740	0.729	0.711	0.751	0.738	0.719	0.758	0.744	0.725
ϕ_d	0.823	0.810	0.790	0.834	0.820	0.799	0.842	0.827	0.805

Table 5.2 Cont. Strength reduction factors using Eq. (5.4) and (5.5)

	Spaced at $3d_b$ Parallel			Spaced at $3d_b$ Perpendicular		
$\overline{r}$	1.00			0.99		
V_r	0.113			0.120		
$(Q_L/Q_D)_n$	0.5	1.0	1.5	0.5	1.0	1.5
$\overline{q}$	0.765	0.725	0.703	0.765	0.725	0.703
$V_{\phi q}$	0.103	0.132	0.153	0.103	0.132	0.153
ϕ_b	0.769	0.754	0.734	0.748	0.736	0.717
ϕ_d	0.854	0.838	0.816	0.832	0.818	0.797

As demonstrated in Table 5.2, the values of ϕ_d decrease as the live-to-dead load ratio increases. This is the result of the increased variability that results from uncertainty in the live load.

Design expression—For ease in application, ϕ_d can be incorporated directly into the design expression. Multiplying the right side of Eq. (5.4) by ϕ_d = 0.81, setting $f_s = f_y$, $f_{cm} = f'_c$, and $\ell_{eh} = \ell_{dh}$, and solving for ℓ_{dh} gives

$$\ell_{dh} = 0.0018\frac{f_y d_b^{1.5}}{f_c'^{\,0.25}} - 88\frac{NA_{tr}}{nf_c'^{\,0.25}} \tag{5.33}$$

Multiplying the right side of Eq. (5.5) by ϕ_d = 0.81 and solving for ℓ_{dh},

$$\ell_{dh} = 0.0018\frac{f_y d_b^{1.5}}{f_c'^{\,0.25}} - 2.4\frac{NA_{tr}}{n} \tag{5.34}$$

Taking the alternate form of the equation [Eq. (5.8)],

$$\ell_{dh} = \left(0.0018\frac{f_y \psi_r}{f_c'^{0.25}}\right) d_b^{1.5} \tag{5.35}$$

where, for hooked bars confined by confining reinforcement oriented parallel to the bar

$$\psi_r = \frac{f_s d_b^{1.5} - 49{,}500\, NA_{tr}/n}{f_s d_b^{1.5}} \le 1.0 \tag{5.36a}$$

for hooked bars confined by confining reinforcement oriented perpendicular to the bar

$$\psi_r = 1 - \frac{1{,}300\, f_{cm}^{0.25} NA_{tr}}{n f_s d_b^{1.5}} \tag{5.36b}$$

The development length of hooked bars obtained using Eq. (5.36) is compared with that obtained using the provisions of ACI 318-14 in a companion paper.

For purposes of comparison, a similar analysis was performed using the current equation for hooked bar development in ACI 318-14. Strength-reduction factors for one and two No. 3 (No. 10) ties and No. 3 (No. 10) ties spaced at $3d_b$ were calculated. ACI 318-14, however, only considers transverse reinforcement spaced $\le 3d_b$ as contributing to the anchorage capacity. As a result, any benefits from lesser amounts of confining reinforcement are not accounted for by the Code, resulting in the same development length as hooked bars without confining reinforcement. The results, presented in Table 5.3, show that the calculated strength-reduction factors ϕ_d associated with the ACI equation range between 0.61 and 0.86. The ϕ-factors associated with 1 No. 3 (No. 10) or 2 No. 3 (No. 10) ties are the highest, showing that as confining reinforcement is added, the relative safety of the Code provisions increases. When the 0.8 reduction factor for ties spaced $\le 3d_b$ is applied, however, the ϕ-factor drops below that for hooked bars without confining reinforcement, thus showing once again that the reduction factor for confining reinforcement is unconservative. Table 5.3 also shows that the Code provisions are sensitive to the orientation of the confining reinforcement; ties spaced at $3d_b$ oriented perpendicular to the bar had the lowest ϕ-factor. Thus, a reasonable strength-reduction factor for use with the provisions in ACI 318-14 would be 0.61 when the hooked bars are confined by reinforcement spaced ≤ $3d_b$ or 0.76 when the hooked bars are not confined. It should also be noted that all ϕ-factors are below 1.0, indicating that the Code provisions are unconservative.

Table 5.3 Strength reduction factors using provisions of ACI 318-14

	Without Trans			1 No. 3 Parallel			2 No. 3 Parallel		
$\overline{r}$	1.05			1.13			1.22		
V_r	0.168			0.170			0.180		
$(Q_L/Q_D)_n$	0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5
$\overline{q}$	0.765	0.725	0.703	0.765	0.725	0.703	0.765	0.725	0.703
$V_{\phi q}$	0.103	0.132	0.153	0.103	0.132	0.153	0.103	0.132	0.153
ϕ_b	0.687	0.684	0.672	0.737	0.734	0.722	0.772	0.771	0.759
ϕ_d	0.763	0.760	0.747	0.819	0.815	0.802	0.858	0.856	0.844

Table 5.3 Cont. Strength reduction factors using provisions of ACI 318-14

	Spaced at $3d_b$ Parallel			Spaced at $3d_b$ Perpendicular		
$\overline{r}$	1.09			0.86		
V_r	0.203			0.174		
$(Q_L/Q_D)_n$	0.5	1.0	1.5	0.5	1.0	1.5
$\overline{q}$	0.765	0.725	0.703	0.765	0.725	0.703
$V_{\phi q}$	0.103	0.132	0.153	0.103	0.132	0.153
ϕ_b	0.644	0.645	0.638	0.555	0.553	0.544
ϕ_d	0.715	0.717	0.709	0.616	0.614	0.605

5.6 SUMMARY AND CONCLUSIONS

This paper describes the development of a reliability-based strength reduction (ϕ) factor for the development length of hooked bars. The analysis incorporates existing and new data on hooked bar anchorage in conventional and high-strength concrete and with conventional and high-strength steel, and considers bar stresses between 60 and 120 ksi (414 and 827 MPa) and concrete compressive strengths between 3,000 and 16,000 psi (21 and 110 MPa). The ϕ-factor is calculated for a representative series of beam-column joints using statistically-based expressions for hooked bar anchorage strength and Monte Carlo simulations, following the procedures used by Darwin et al. (1998) for spliced bars. The overall approach to calculating the ϕ-factor is applicable to all types of loading on reinforced concrete structures. This analysis did not consider factors such as more than two hooked bars in a member, hooked bar spacing, or hooked bars cast outside the column longitudinal bars. Such factors should be considered and will be addressed in a subsequent paper.

The analysis determined that a strength reduction factor of 0.81 would provide a reasonable measure of safety against an anchorage failure (about one-fifth the probability of failure in bending) when applied to Eq. (5.4) and (5.5). This reduction factor is incorporated into a design equation for hooked bar development length. A similar analysis was performed using the provisions of ACI 318-14. The strength-reduction factor for this analysis was found to be 0.61 for hooked bars with confining reinforcement spaced $\leq 3d_b$ or 0.76 for hooked bars without confining reinforcement.

5.7 NOTATION

A_b = bar area, in.^{2}

A_I = influence area, ft.^{2}

A_T = tributary area, ft.^{2}

A_{tr} = area of a single leg of confining steel inside hook region, in.^{2}

b = beam width, in.

c_{so} = side cover of hooked bar, in.

d_b = nominal bar diameter, in.[2]

$\dot{f}$ = stress rate, psi/sec

f'_c = specified concrete compressive strength, psi

f'_{c35} = concrete compressive strength at $\dot{f}$ = 35 psi/sec, psi

$f'_{c\dot{f}}$ = concrete compressive strength at stress rate $\dot{f}$, psi

f_{cm} = measured average concrete compressive strength, psi

f_s = steel stress at failure, psi

f_y = yield strength of bars being developed, psi

h = beam depth, in.

ℓ_{dh} = development length of hooked bar, in.

ℓ_{eh} = embedment length of hooked bar, in.

L_o = basic (unreduced) live load

n = number of hooked bars confined by N legs

N = number of legs of confining reinforcement parallel to the straight length of the hooked bar within $8d_b$ from the top of the bar for No. 3 through No. 8 (No. 10 through No. 25) bars or $10d_b$ from the top of the bar for No. 9 through No. 11 (No. 29 through No. 36) bars or the number of legs perpendicular to the bar over the length being developed

Q = total load

Q_D = random variable representing dead load effects

Q_{Dn} = nominal dead load

Q_L = random variable representing live load effects

Q_{Ln} = nominal live load

$(Q_L/Q_D)_n$ = nominal ratio of live to dead load

q = random loading

R = random variable for resistance

R_n = nominal resistance

R_p = predicted capacity random variable

$r = R/R_n = X_1R_p/R_n$

s = center-to-center spacing of hooked bars, in.

T_c = total force in hooked bars without confining transverse reinforcement at failure, lb

T_h = total force in hooked bars with confining transverse reinforcement at failure, lb

V = coefficient of variation

V_R = coefficient of variation for random variable for resistance

V_Q = coefficient of variation for random variable for total load

$V_c = \left(V_{ccyl}^2 + 0.0084\right)^{1/2}$, assumed coefficient of variation for in-place concrete

V_{ccyl} = coefficient of variation for laboratory cured concrete cylinder

V_m = coefficient of variation associated with the predictive equation (or model) itself

V_{Q_D} = coefficient of variation of random variable representing dead load effects

V_{Q_L} = coefficient of variation of random variable representing live load effects

V_r = coefficient of variation of resistance random variable r

$V_{T/C}$ = coefficient of variation of test-to-calculated ratio

V_{ts} = coefficient of variation of the predictive equation caused by uncertainties in the measured loads and differences in the actual material and geometric properties of the specimens from values used to calculate the predicted strength

V_{Xi} = coefficient of variation of random variable X_i

$V_{\phi q}$ = coefficient of variation of loading random variable q

X_1 = test-to-calculated load capacity random variable

X_2 = actual-to-nominal dead load random variable

X_3 = actual-to-nominal live load random variable

X_4 = concrete strength f_c' random variable

X_5 = development length ℓ_{dh} random variable

X_6 = beam width b random variable

X_7 = concrete side cover c_{so} random variable

β = reliability index

ϕ = strength reduction factor for the main loading

ϕ_b = overall strength reduction factor against hooked bar anchorage failure

ϕ_c = strength reduction factor for the loading under consideration

$\phi_d = \phi_b/\phi$, effective strength reduction factor for use in calculating hooked bar development length

γ_D = load factor for dead loads

γ_L = load factor for live loads

ψ_m = correction factor for closely spaced hooked bars

σ = standard deviation

σ_{ccyl} = standard deviation for standard laboratory cylinders

Overbar represents average value of the variable

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CHAPTER 6: SUMMARY AND CONCLUSIONS

6.1 SUMMARY

A total of 337 simulated exterior beam-column joints were tested to investigate the anchorage capacity of hooked bars. Of the 337 beam-column joints, 276 contained two hooked bars, and 61 contained more than two hooked bars. The simulated beam-column joints were cast as reinforced concrete columns without the beam. The longitudinal beam reinforcing bars protruded from the face of the column, and the compression region of the beam was simulated using the testing frame. No. 5, No. 8, and No. 11 hooked bars were tested with both 90° and 180° bend angles. The clear concrete side cover ranged from 1.5 in. to 4 in., with most values between 2.5 and 3.5 in., and the center-to-center spacing of the hooked bars ranged from $3d_b$ to $11d_b$. The specimens were cast with normalweight concrete with compressive strengths ranging from 4,300 to 16,510 psi. The hooked bars were located both inside and outside the column core (defined as the area of concrete inside the column longitudinal reinforcement). Most hooked bars were anchored on the far side of the column, but some tests included hooks that were extended only to the middle of the column. Bar stresses at failure ranged from 22,800 to 141,600 psi. To determine the effect of transverse reinforcement on joint capacity, specimens were constructed with either no transverse reinforcement, 1 No. 3 tie, 2 No. 3 ties, 1 No. 4 tie, 2 No. 4 ties, 4 No. 3 ties, No. 3 ties spaced at $3d_b$ (which qualify for a 0.8 reduction in development length in accordance with ACI 318-14 Section 25.4.3.2), or transverse reinforcement placed in accordance with ACI 318-14 Section 18.8.3 for joints in special moment frames. Test results available in the literature were included in the study.

Using a subset of 214 simulated exterior beam-column joints, expressions were developed to characterize the anchorage capacity of hooked bars as a function of embedment length, concrete compressive strength, bar diameter, and amount and orientation of confining reinforcement. These expressions were used, in turn, to develop design equations for hooked bar development length using reliability-based techniques. The effects of casting position (inside or outside the column core and within the depth of the column), spacing of hooked bars, and more than two hooked bars in a member will be addressed elsewhere.

6.2 CONCLUSIONS

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

1. Both a front and side failure were involved for the majority of hooked bars, with front failure being the dominant failure mode in a greater percentage of the tests.
2. Of hooked bars exhibiting only one failure mode, a greater number exhibited front failure than side failure.
3. Front failure plays an important role in the behavior of hooked bars, which is in contrast to findings of previous studies.
4. As the bar size increases, the percentage of hooked bars exhibiting side failure as the primary failure mode increases.
5. The provisions of ACI 318-14 overpredict the anchorage strength of larger hooked bars, the effect of concrete compressive strength, and the effect of confining reinforcement on the anchorage capacity of hooked bars in tension.
6. The reduction factors as applied in Section 25.4.3.2 of ACI 318-14 for concrete cover and confining reinforcement are unconservative.

7. The contribution of concrete to the anchorage capacity of hooked bars can be represented by the concrete compressive strength to the 0.29 power.
8. Confining reinforcement, expressed as the area of confining reinforcement per confined hooked bar, provides in an incremental rather than percentage increase in the anchorage capacity of hooked bars.
9. When ties are oriented parallel to the hooked bar, ties that are placed within approximately $8d_b$ of the top of the hooked bar for No. 3 through No. 8 (No. 10 through No. 25) hooked bars or within approximately $10d_b$ of the top of the hooked bar for No. 9 through No. 11 (No. 29 through No. 36) hooked bars are effective in resisting the pullout force of the hooked bar. Ties located further away are largely ineffective.
10. For a given embedment length, the anchorage capacity of hooked bars without and with confining reinforcement increases as the bar diameter increases.
11. For hooked bars with a 90° bend angle, confining reinforcement placed perpendicular to the straight portion of the bars results in lower anchorage capacity than confining reinforcement with a similar spacing placed parallel to the straight portion of the bars.
12. The contribution of confining reinforcement oriented perpendicular to the straight portion of the hooked bar differs from that of confining reinforcement parallel to the straight portion of the hooked bar and may be similar to the contribution of confining reinforcement to the development and splice strength of straight bars. More research is needed to fully understand the effect of the orientation of confining reinforcement on the behavior of hooked bars.

13. Hooked bars with 90° and 180° bend angles produce similar anchorage capacities and can be used interchangeably. This includes hooked bars with a 180° bend angle confined by transverse reinforcement parallel to the straight portion of the bar spaced over the region required in Section 25.4.3.2 of ACI 318-14 to allow use of the 0.8 development length reduction factor for 90° hooks.
14. Increasing concrete side cover from 2.5 to 3.5 in. (64 to 89 mm) does not increase the anchorage capacity of hooked bars.
15. When applied to Eq. (5.4) and (5.5), a strength reduction factor of 0.81 will provide a probability of an anchorage failure equal to approximately one-fifth of the probability of a flexural failure for members designed in accordance with ACI 318-14.
16. When applied to the current hooked bar provisions in ACI 318-14, a strength reduction factor of 0.61 for hooked bars with confining reinforcement spaced $\leq 3d_b$ or 0.76 for hooked bars without confining reinforcement will provide a probability of anchorage failure equal to approximately one-fifth of the probability of a flexural failure for members designed in accordance with ACI 318-14.

6.3 FUTURE WORK

In addition to the factors influencing the anchorage strength of hooked bars addressed in this report, other variables were investigated as part of this research study. These variables include the spacing between hooked bars, use of more than two hooked bars in a joint, location of hooked bars (inside or outside the column longitudinal reinforcement or within the depth of the column), column longitudinal reinforcement ratio, the use of staggered hooked bars (multiple rows), and the use of shallow embedment (such as hooked bars anchored in walls). The effects of these factors on hooked bar anchorage strength will be addressed in subsequent reports. In addition, the findings of this study suggest that more research is needed to determine the effect of confining reinforcement oriented perpendicular to the straight portion of the bar on the anchorage strength of hooked bars.

APPENDIX A: NOTATION AND DATA TABLES

A_h Bar area of hook
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
α Student's t-test significance
ψ_e Epoxy coating factor as defined in ACI 318-14 Section 25.4.3.2

ψ_c Factor for cover as defined in ACI 318-14 Section 25.4.3.2
ψ_r Factor for transverse reinforcement in the hook region
ψ_o Factor for hooked bar location
ψ_m Hooked bar spacing factor

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

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

Table A.1 Comprehensive test results and data for No. 5 specimens with two hooks

	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.
1	5-5-90-0-o-1.5-2-5†	A B	90°	Horizontal	A615	5.0 5.0	5.0	4930	4	0.625	0.077	11	5.25	8.375
2	5-5-90-0-o-1.5-2-6.5†	A B	90°	Horizontal	A1035	6.5 5.9	6.2	5650	6	0.625	0.073	11	5.25	8.375
3	5-5-90-0-o-1.5-2-8†	B A	90°	Horizontal	A1035	7.9 4.8	7.9	5650	6	0.625	0.073	11	5.25	8.375
4	5-5-90-0-o-2.5-2-5	B A	90°	Horizontal	A615	4.8 9.0	4.8	4930	4	0.625	0.077	13	5.25	8.375
5	5-5-180-0-o-1.5-2-9.5†	A B	180°	Horizontal	A1035	9.6 9.3	9.4	4420	7	0.625	0.077	11	5.25	8.375
6	5-5-180-0-o-1.5-2-11.25†	A	180°	Horizontal	A1035	11.3	11.3	4520	8	0.625	0.077	11	5.25	8.375
7	5-5-180-0-o-2.5-2-9.5†	A B	180°	Horizontal	A1035	9.5 9.5	9.5	4520	8	0.625	0.077	13	5.25	8.375
8	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
9	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
10	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
11	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
12	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
13	(2@4) 5-8-90-0-i-2.5-2-6	A B	90°	Horizontal	A1035	5.8 6.0	5.9	6950	18	0.625	0.073	8	5.25	8.375
14	(2@6) 5-8-90-0-i-2.5-2-6	A B	90°	Horizontal	A1035	6.0 6.0	6.0	6950	18	0.625	0.073	9	5.25	8.375
15	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
16	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
17	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
18	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
19	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
20	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
21	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
22	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
23	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
24	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
25	5-12-90-0-i-3.5-2-10	A B	90°	Horizontal	A1035	10.1 10.0	10.1	11600	84	0.625	0.073	15	5.25	8.375

*No failure of hook; equipment malfunction
† Specimens had constant 80 kip axial load
[1]Specimen had full stirrups around the longitudinal bars in the hook region but not around the hooked bars

Table A.1 Cont. Comprehensive test results and data for No. 5 specimens with two hooks

	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	$f_{su,\ ind}$ ksi	f_{su} ksi	Slip at Failure in.	Failure Type
1	5-5-90-0-o-1.5-2-5†	A B	1.5 1.8	1.6	2.0 2.0	6.8	2	14100 19600	28140	14070	45500 63200	45400	- -	FP/SB FP/SB
2	5-5-90-0-o-1.5-2-6.5†	A B	1.5 1.6	1.6	2.0 2.8	6.6	2	20800 18200	35630	17815	67100 58700	57500	- -	FP FP/SB
3	5-5-90-0-o-1.5-2-8†	B A	1.5 2.5	1.5	2.1 2.1	6.6	2	23500 19500	23500	23500	75800 62900	75800	- -	SB FP/SB
4	5-5-90-0-o-2.5-2-5	B A	2.5 2.6	2.5	2.1 1.5	6.4	2	24000 30300	38570	19285	77400 97700	62200	- -	FP/SB SB
5	5-5-180-0-o-1.5-2-9.5†	A B	1.6 1.6	1.6	2.1 2.1	6.4	2	35200 30400	58970	29485	113500 98100	95100	- -	FP FP/SB
6	5-5-180-0-o-1.5-2-11.25†	A	1.8	1.8	2.3	6.6	2	32400	32400	32400	104500	104500	-	FP/SB
7	5-5-180-0-o-2.5-2-9.5†	A B	2.5 2.5	2.5	1.9 1.8	6.6	2	40400 24660	60260	30130	130300 79500	97200	- -	FP FP
8	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
9	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
10	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
11	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 .330(.030)	FP FP
12	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
13	(2@4) 5-8-90-0-i-2.5-2-6	A B	2.7 3.7	3.2	2.3 2.0	1.9	2 2	23200 21700	44700	22400	74800 73200	72300	- -	FP FP
14	(2@6) 5-8-90-0-i-2.5-2-6	A B	2.6 2.7	2.6	2.0 2.0	3.1	2 2	127060 147900	47900	24000	82300 77400	77400	- -	FP/SS FP/SS
15	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
16	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
17	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
18	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 *
19	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
20	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
21	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
22	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 .178(.150)	FP/SS FP/SS
23	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
24	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
25	5-12-90-0-i-3.5-2-10	A B	3.5 3.5	3.5	2.5 1.5	6.8	2	46000 46000	46000	46000	148400 148400	148400	- -	BY BY

*No failure of hook; equipment malfunction

† Specimens had constant 80 kip axial load

[1] Specimen had full stirrups around the longitudinal bars in the hook region but not around the hooked bars

Table A.1 Cont. Comprehensive test results and data for No. 5 specimens with two hooks

	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
1	5-5-90-0-o-1.5-2-5†	A B	60	-	-	-	-	0.88	4[1]	2.5	0.375	2.50	-	-	1.27	60
2	5-5-90-0-o-1.5-2-6.5†	A B	60	-	-	-	-	0.88	4[1]	2.5	0.375	2.50	-	-	1.89	60
3	5-5-90-0-o-1.5-2-8†	B A	60	-	-	-	-	0.88	4[1]	2.5	0.375	2.50	-	-	1.27	60
4	5-5-90-0-o-2.5-2-5	B A	60	-	-	-	-	0.88	4[1]	2.5	0.375	2.50	-	-	1.27	60
5	5-5-180-0-o-1.5-2-9.5†	A B	60	-	-	-	-	0.22	1[1]	4.0	0.375	4.00	-	-	1.27	60
6	5-5-180-0-o-1.5-2-11.25†	A	60	-	-	-	-	0.22	1[1]	4.0	0.375	4.0	-	-	1.27	60
7	5-5-180-0-o-2.5-2-9.5†	A B	60	-	-	-	-	0.22	1[1]	4.0	0.375	4.00	-	-	1.89	60
8	5-5-90-0-i-2.5-2-10	A B	60	-	-	-	-	0.33	3	3.0	0.375	3.00	-	-	1.89	60
9	5-5-90-0-i-2.5-2-7	A B	60	-	-	-	-	0.80	4	2.5	0.500	3.50	-	-	1.27	60
10	5-8-90-0-i-2.5-2-6†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
11	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
12	5-8-90-0-i-2.5-2-8†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
13	(2@4) 5-8-90-0-i-2.5-2-6	A B	60	-	-	-	-	-	-	-	0.375	3.00	-	-	3.16	60
14	(2@6) 5-8-90-0-i-2.5-2-6	A B	60	-	-	-	-	-	-	-	0.375	3.00	-	-	3.16	60
15	5-12-90-0-i-2.5-2-10	A B	60	-	-	-	-	0.11	1	7.0	0.375	5.00	-	-	1.89	60
16	5-12-90-0-i-2.5-2-5	A B	60	-	-	-	-	0.66	6	2.5	0.500	3.00	-	-	1.27	60
17	5-15-90-0-i-2.5-2-5.5	A B	60	-	-	-	-	-	-	-	0.375	2.50	-	-	1.27	60
18	5-15-90-0-i-2.5-2-7.5	A B	60	-	-	-	-	-	-	-	0.375	3.50	-	-	3.16	60
19	5-5-90-0-i-3.5-2-10	A B	60	-	-	-	-	0.33	3	3.0	0.375	3.00	-	-	1.89	60
20	5-5-90-0-i-3.5-2-7	A B	60	-	-	-	-	0.80	4	2.5	0.375	3.50	-	-	1.27	60
21	5-8-90-0-i-3.5-2-6†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
22	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
23	5-8-90-0-i-3.5-2-8†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
24	5-12-90-0-i-3.5-2-5	A B	60	-	-	-	-	0.66	6	2.5	0.500	3.00	-	-	1.27	60
25	5-12-90-0-i-3.5-2-10	A B	60	-	-	-	-	0.11	1	7.0	0.375	5.00	-	-	1.89	60

*No failure of hook; equipment malfunction

† Specimens had constant 80 kip axial load

[1]Specimen had full stirrups around the longitudinal bars in the hook region but not around the hooked bars

Table A.1 Cont. Comprehensive test results and data for No. 5 specimens with two hooks

	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.
26	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
27	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
28	5-5-90-1#3-i-2.5-2-8†	A B	90°	Horizontal	A1035	8.0 7.6	7.8	5310	6	0.625	0.073	13	5.25	8.375
29	5-5-90-1#3-i-2.5-2-6†	A B	90°	Horizontal	A615	4.8 5.5	5.1	5800	9	0.625	0.060	13	5.25	8.375
30	5-8-90-1#3-i-2.5-2-6†	A B	90°	Horizontal	A615	6.0 6.3	6.1	8450	14	0.625	0.060	13	5.25	8.375
31	5-8-90-1#3-i-2.5-2-6(1)	A B	90°	Horizontal	A1035	6.1 5.6	5.9	9300	13	0.625	0.073	13	5.25	8.375
32	5-8-90-1#3-i-3.5-2-6†	A B	90°	Horizontal	A1035	6.0 6.0	6.0	8710	16	0.625	0.060	15	5.25	8.375
33	5-8-90-1#3-i-3.5-2-6(1)	A B	90°	Horizontal	A1035	6.3 6.3	6.3	9190	12	0.625	0.073	15	5.25	8.375
34	5-5-180-1#3-i-2.5-2-8†	A B	180°	Horizontal	A1035	8.0 7.8	7.9	5670	7	0.625	0.073	13	5.25	8.375
35	5-5-180-1#3-i-2.5-2-6†	A B	180°	Horizontal	A615	6.0 6.0	6.0	5800	9	0.625	0.060	13	5.25	8.375
36	5-8-180-1#3-i-2.5-2-7	A B	180°	Horizontal	A1035	7.1 7.3	7.2	9300	13	0.625	0.073	13	5.25	8.375
37	5-8-180-1#3-i-3.5-2-7	A B	180°	Horizontal	A1035	7.1 6.8	6.9	9190	12	0.625	0.073	15	5.25	8.375
38	5-5-90-1#4-i-2.5-2-8†	A B	90°	Horizontal	A1035	7.4 7.8	7.6	5310	6	0.625	0.073	13	9.25	8.375
39	5-5-90-1#4-i-2.5-2-6†	A B	90°	Horizontal	A615	5.3 5.8	5.5	5860	8	0.625	0.060	13	5.25	8.375
40	5-8-90-1#4-i-2.5-2-6	A B	90°	Horizontal	A1035	5.9 6.0	6.0	9300	13	0.625	0.073	13	5.25	8.375
41	5-8-90-1#4-i-3.5-2-6	A B	90°	Horizontal	A1035	6.0 7.0	6.5	9190	12	0.625	0.073	15	5.25	8.375
42	5-5-180-1#4-i-2.5-2-8†	A B	180°	Horizontal	A1035	8.0 8.0	8.0	5310	6	0.625	0.073	13	5.25	8.375
43	5-5-180-1#4-i-2.5-2-6†	A B	180°	Horizontal	A615	6.5 6.0	6.3	5670	7	0.625	0.060	13	5.25	8.375
44	5-5-180-2#3-o-1.5-2-11.25†	A B	180°	Horizontal	A1035	11.6 11.5	11.6	4420	7	0.625	0.077	11	5.25	8.375
45	5-5-180-2#3-o-1.5-2-9.5†	B	180°	Horizontal	A1035	8.8	8.8	4520	8	0.625	0.08	11	5.25	8.375
46	5-5-180-2#3-o-2.5-2-9.5†	A B	180°	Horizontal	A1035	9.1 9.3	9.2	4420	7	0.625	0.077	13	5.25	8.375
47	5-5-180-2#3-o-2.5-2-11.25†	A B	180°	Horizontal	A1035	11.1 11.4	11.3	4520	8	0.625	0.077	13	5.25	8.375
48	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
49	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
50	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
51	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

*No failure of hook; equipment malfunction

† Specimens had constant 80 kip axial load

[1]Specimen had full stirrups around the longitudinal bars in the hook region but not around the hooked bars

Table A.1 Cont. Comprehensive test results and data for No. 5 specimens with two hooks

	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	$f_{su,\,ind}$ ksi	f_{su} ksi	Slip at Failure in.	Failure Type
26	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 .146(.016)	FP/SS SB/FP
27	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 .237(.021)	SS/FP FP/SS
28	5-5-90-1#3-i-2.5-2-8[†]	A B	2.5 2.5	2.5	2.4 2.8	6.9	2	32900 37400	66270	33135	106100 120600	106900	- -	FP SB/FB
29	5-5-90-1#3-i-2.5-2-6[†]	A B	2.5 2.5	2.5	3.3 2.5	6.9	2	20000 29300	39830	19915	64500 94500	64200	- -	SS SS/FP
30	5-8-90-1#3-i-2.5-2-6[†]	A B	2.5 2.5	2.5	2.0 1.8	6.6	2	26200 27900	53150	26575	84500 90000	85700	- -	FP SS
31	5-8-90-1#3-i-2.5-2-6(1)	A B	2.6 2.8	2.7	2.1 2.6	6.5	2	29300 25400	50800	25400	94500 81900	81900	- -	FP/SS FP/SS
32	5-8-90-1#3-i-3.5-2-6[†]	A B	3.6 3.6	3.6	2.0 2.0	6.8	2	41400 31200	60170	30085	133500 100600	97000	- -	FP/SS FP/SS
33	5-8-90-1#3-i-3.5-2-6(1)	A B	3.8 3.5	3.6	2.4 2.4	6.8	2	29000 26300	51810	25905	93500 84800	83600	0.239 0.158	FP/SS FP/SS
34	5-5-180-1#3-i-2.5-2-8[†]	A B	2.6 2.5	2.6	2.3 2.5	6.6	2	36600 39900	72900	36450	118100 128700	117600	- -	SS SS/FP
35	5-5-180-1#3-i-2.5-2-6[†]	A B	2.6 2.6	2.6	2.0 2.0	6.6	2	29100 24300	47830	23915	93900 78400	77100	- -	SS/FP FP/SS
36	5-8-180-1#3-i-2.5-2-7	A B	2.5 2.5	2.5	2.4 2.3	6.5	2	34200 35400	65820	32910	110300 114200	106200	0.373 .261(.035)	FP/SS FP/SS
37	5-8-180-1#3-i-3.5-2-7	A B	3.5 3.5	3.5	2.1 2.5	7.0	2	35800 28900	61000	30500	115500 93200	98400	0.205 0.238	FP FP
38	5-5-90-1#4-i-2.5-2-8[†]	A B	2.5 2.5	2.5	2.8 2.4	6.9	2	35700 27500	55070	27535	115200 88700	88800	- -	FP/SS SB
39	5-5-90-1#4-i-2.5-2-6[†]	A B	2.5 2.5	2.5	2.8 2.3	6.6	2	21600 26800	42910	21455	69700 86500	69200	- -	SS SS
40	5-8-90-1#4-i-2.5-2-6	A B	2.5 2.8	2.6	2.8 2.8	6.4	2	23900 27900	48580	24290	77100 90000	78400	0.25 0.22	FP FP/SS
41	5-8-90-1#4-i-3.5-2-6	A B	3.6 3.5	3.6	3.0 2.0	6.8	2	25300 25200	50480	25240	81600 81300	81400	- -	FP/SS FP/SS
42	5-5-180-1#4-i-2.5-2-8[†]	A B	2.5 2.5	2.5	2.0 2.0	6.6	2	43100 38400	76840	38420	139000 123900	123900	- -	FP/SS FP
43	5-5-180-1#4-i-2.5-2-6[†]	A B	2.5 2.6	2.6	2.0 2.5	6.6	2	25300 22900	45950	22975	81600 73900	74100	- -	FP/SS FP
44	5-5-180-2#3-o-1.5-2-11.25[†]	A B	1.6 1.5	1.6	1.9 1.9	6.6	2	48300 43000	86100	43050	155800 138700	138900	- -	FP/SB FP/SB
45	5-5-180-2#3-o-1.5-2-9.5[†]	B	1.6	1.6	2.4	6.6	2	20300	20300	20300	65500	65500	-	FP/SB
46	5-5-180-2#3-o-2.5-2-9.5[†]	A B	2.5 2.5	2.5	2.1 2.0	6.6	2	35500 43900	87800	43900	114500 141600	141600	- -	FP/SB FP
47	5-5-180-2#3-o-2.5-2-11.25[†]	A B	2.5 2.8	2.6	2.5 2.1	6.6	2	43600 42500	84650	42325	140600 137100	136500	- -	FP FP/SB
48	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
49	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
50	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
51	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

*No failure of hook; equipment malfunction

[†] Specimens had constant 80 kip axial load

[1]Specimen had full stirrups around the longitudinal bars in the hook region but not around the hooked bars

Table A.1 Cont. Comprehensive test results and data for No. 5 specimens with two hooks

	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
26	5-8-180-0-i-2.5-2-7	A B	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60
27	5-8-180-0-i-3.5-2-7	A B	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60
28	5-5-90-1#3-i-2.5-2-8†	A B	60	0.38	0.1	1	5.00	0.44	4	6.0	0.375	4.00	-	-	1.27	60
29	5-5-90-1#3-i-2.5-2-6†	A B	60	0.38	0.1	1	5.00	0.44	4	6.0	0.375	4.00	-	-	1.27	60
30	5-8-90-1#3-i-2.5-2-6†	A B	60	0.38	0.1	1	5.00	0.80	4	6.0	0.500	4.00	-	-	1.27	60
31	5-8-90-1#3-i-2.5-2-6(1)	A B	60	0.38	0.1	1	6.00	0.66	6	3.0	0.500	3.00	-	-	1.27	60
32	5-8-90-1#3-i-3.5-2-6†	A B	60	0.38	0.1	1	5.00	0.80	4	6.0	0.500	4.00	-	-	1.27	60
33	5-8-90-1#3-i-3.5-2-6(1)	A B	60	0.38	0.1	1	6.00	0.66	6	3.0	0.500	3.00	-	-	1.27	60
34	5-5-180-1#3-i-2.5-2-8†	A B	60	0.38	0.1	1	4.00	-	-	-	0.375	4.00	-	-	1.27	60
35	5-5-180-1#3-i-2.5-2-6†	A B	60	0.38	0.1	1	4.00	-	-	-	0.375	4.00	-	-	1.27	60
36	5-8-180-1#3-i-2.5-2-7	A B	60	0.38	0.1	1	3.00	-	-	-	0.375	3.00	-	-	1.27	60
37	5-8-180-1#3-i-3.5-2-7	A B	60	0.38	0.1	1	3.00	-	-	-	0.375	3.00	-	-	1.27	60
38	5-5-90-1#4-i-2.5-2-8†	A B	60	0.5	0.2	1	5.00	0.44	4	6.0	0.375	4.00	-	-	1.27	60
39	5-5-90-1#4-i-2.5-2-6†	A B	60	0.5	0.2	1	5.00	0.44	4	6.0	0.375	4.00	-	-	1.27	60
40	5-8-90-1#4-i-2.5-2-6	A B	60	0.5	0.2	1	6.00	0.44	4	6.0	0.500	3.00	-	-	1.27	60
41	5-8-90-1#4-i-3.5-2-6	A B	60	0.5	0.2	1	6.00	0.44	4	6.0	0.500	3.00	-	-	1.27	60
42	5-5-180-1#4-i-2.5-2-8†	A B	60	0.5	0.2	1	4.00	-	-	-	0.375	4.00	-	-	1.27	60
43	5-5-180-1#4-i-2.5-2-6†	A B	60	0.5	0.2	1	4.00	-	-	-	0.375	4.00	-	-	1.27	60
44	5-5-180-2#3-o-1.5-2-11.25†	A B	60	0.38	0.2	2	2.00	-	-	-	0.375	4.00	-	-	1.89	60
45	5-5-180-2#3-o-1.5-2-9.5†	B	60	0.375	0.22	2	2.0	-	-	-	0.375	4.0	-	-	1.27	60
46	5-5-180-2#3-o-2.5-2-9.5†	A B	60	0.38	0.2	2	2.00	-	-	-	0.375	4.00	-	-	1.89	60
47	5-5-180-2#3-o-2.5-2-11.25†	A B	60	0.38	0.2	2	2.00	-	-	-	0.375	4.50	-	-	1.89	60
48	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
49	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
50	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
51	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

*No failure of hook; equipment malfunction

† Specimens had constant 80 kip axial load

[1]Specimen had full stirrups around the longitudinal bars in the hook region but not around the hooked bars

Table A.1 Cont. Comprehensive test results and data for No. 5 specimens with two hooks

	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.
52	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
53	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
54	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
55	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
56	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
57	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
58	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
59	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
60	5-12-90-2#3-i-3.5-2-10	A B	90°	Horizontal	A1035	10.8 10.6	10.7	11090	83	0.625	0.073	15	5.25	8.375
61	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
62	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
63	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
64	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
65	5-8-90-4#3-i-2.5-2-8†	A B	90°	Horizontal	A1035	7.9 7.5	7.7	8380	13	0.625	0.060	13	5.25	8.375
66	5-8-90-4#3-i-3.5-2-8†	A B	90°	Horizontal	A1035	8.6 8.3	8.4	8380	13	0.625	0.060	15	5.25	8.375
67	5-5-90-5#3-o-1.5-2-5†	B	90°	Horizontal	A615	5.0	5.0	5205	5	0.625	0.077	11	5.25	8.375
68	5-5-90-5#3-o-1.5-2-8†	A B	90°	Horizontal	A1035	8.0 7.8	7.9	5650	6	0.625	0.077	11	5.25	8.375
69	5-5-90-5#3-o-1.5-2-6.5†	A B	90°	Horizontal	A1035	6.5 6.5	6.5	5780	7	0.625	0.073	11	5.25	8.375
70	5-5-90-5#3-o-2.5-2-5†	A B	90°	Horizontal	A615	5.2 5.1	5.2	4903	4	0.625	0.077	13	5.38	8.375
71	5-5-90-5#3-o-2.5-2-8†	A	90°	Horizontal	A1035	7.5	7.5	5650	6	0.625	0.077	13	5.25	8.375
72	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
73	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
74	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
75	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
76	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
77	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
78	5-12-90-5#3-i-3.5-2-10	A B	90°	Horizontal	A1035	11.0 11.3	11.1	11090	83	0.625	0.073	15	5.25	8.375

*No failure of hook; equipment malfunction

† Specimens had constant 80 kip axial load

[1]Specimen had full stirrups around the longitudinal bars in the hook region but not around the hooked bars

Table A.1 Cont. Comprehensive test results and data for No. 5 specimens with two hooks

	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	$f_{su,\ ind}$ ksi	f_{su} ksi	Slip at Failure in.	Failure Type
52	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
53	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
54	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
55	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
56	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
57	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
58	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
59	5-12-90-2#3-i-3.5-2-5	A B	3.8 3.5	3.6	1.8 2.2	6.6	2	27900 28900	56730	28365	90000 93200	91500	- 0.349	FP FP
60	5-12-90-2#3-i-3.5-2-10	A B	3.5 3.6	3.6	2.3 2.4	6.8	2	46000 46000	92000	46000	148400 148400	148400	- -	BY BY
61	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
62	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
63	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	- .369(.081)	FP/SS FP/SS
64	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	- .329(.028)	FP/SS FP
65	5-8-90-4#3-i-2.5-2-8†	A B	2.5 2.5	2.5	2.1 2.5	6.4	2	33400 27000	52820	26410	107700 87100	85200	- -	FP/SS FP/SS
66	5-8-90-4#3-i-3.5-2-8†	A B	3.5 3.5	3.5	1.4 1.8	6.9	2	42500 39300	76960	38480	137100 126800	124100	- -	FP SS/FP
67	5-5-90-5#3-o-1.5-2-5†	B	1.5	1.5	2.0	6.5	2	22000	22000	22000	71000	71000	-	FP/SB
68	5-5-90-5#3-o-1.5-2-8†	A B	1.6 1.5	1.5	2.3 2.6	6.4	2	25200 30400	50220	25110	81300 98100	81000	- -	FP/SB FP/SB
69	5-5-90-5#3-o-1.5-2-6.5†	A B	1.6 1.6	1.6	2.0 2.0	6.5	2	26200 20900	43420	21710	84500 67400	70000	- -	FP/SB FP/SB
70	5-5-90-5#3-o-2.5-2-5†	A B	2.6 2.6	2.6	1.9 1.9	6.6	2	22300 29500	45060	22530	71900 95200	72700	- -	FP/SB FP/SB
71	5-5-90-5#3-o-2.5-2-8†	A	2.6	2.6	2.1	6.5	2	28400	28400	28400	91600	91600	-	FP
72	5-5-90-5#3-i-2.5-2-7	A B	2.8 2.8	2.8	3.6 2.3	6.5	2	32100 31300	63390	31695	103500 101000	102200	- -	FP FP/SS
73	5-12-90-5#3-i-2.5-2-5	A B	2.6 2.6	2.6	2.1 1.5	6.5	2	33900 34900	68840	34420	109400 112600	111000	0.292 0.295	FP/SS SS/FP
74	5-15-90-5#3-i-2.5-2-4	A B	2.4 2.5	2.4	2.2 1.9	6.6	2	31300 31300	62600	31360	101000 101000	101200	0.603 0.378	FP FP
75	5-15-90-5#3-i-2.5-2-5	A B	2.4 2.3	2.4	2.1 1.9	6.8	2	38600 46200	78300	39200	124500 149000	126500	- -	FP BY
76	5-5-90-5#3-i-3.5-2-7	A B	3.4 3.5	3.4	2.0 2.8	7.0	2	44300 35200	72050	36025	142900 113500	116200	- -	FP FP
77	5-12-90-5#3-i-3.5-2-5	A B	3.3 3.3	3.3	2.5 1.5	6.6	2	31500 31300	60880	30440	101600 101000	98200	- -	FP FP
78	5-12-90-5#3-i-3.5-2-10	A B	3.5 3.5	3.5	2.0 1.8	6.9	2	46000 46000	46000	46000	148400 148400	148400	- -	BY BY

*No failure of hook; equipment malfunction
† Specimens had constant 80 kip axial load
[1]Specimen had full stirrups around the longitudinal bars in the hook region but not around the hooked bars

Table A.1 Cont. Comprehensive test results and data for No. 5 specimens with two hooks

	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
52	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
53	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
54	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
55	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
56	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
57	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
58	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
59	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
60	5-12-90-2#3-i-3.5-2-10	A B	60	0.38	0.2	2	3.30	-	-	-	0.375	5.00	-	-	1.89	60
61	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
62	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
63	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
64	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
65	5-8-90-4#3-i-2.5-2-8†	A B	60	0.38	0.4	4	2.00	-	-	-	0.500	4.00	-	-	1.67	60
66	5-8-90-4#3-i-3.5-2-8†	A B	60	0.38	0.4	4	2.00	-	-	-	0.500	4.00	-	-	1.67	60
67	5-5-90-5#3-o-1.5-2-5†	B	60	0.375	0.55	5	2.00	-	-	-	0.375	2.50	-	-	1.27	60
68	5-5-90-5#3-o-1.5-2-8†	A B	60	0.38	0.6	5	2.50	-	-	-	0.375	2.50	-	-	1.27	60
69	5-5-90-5#3-o-1.5-2-6.5†	A B	60	0.38	0.6	5	2.50	-	-	-	0.375	2.50	-	-	1.89	60
70	5-5-90-5#3-o-2.5-2-5†	A B	60	0.38	0.6	5	2.00	-	-	-	0.375	2.50	-	-	1.27	60
71	5-5-90-5#3-o-2.5-2-8†	A	60	0.375	0.55	5	2.50	-	-	-	0.375	2.50	-	-	1.27	60
72	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
73	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
74	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
75	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
76	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
77	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
78	5-12-90-5#3-i-3.5-2-10	A B	60	0.38	0.6	5	1.70	-	-	-	0.375	5.00	-	-	1.89	60

*No failure of hook; equipment malfunction

† Specimens had constant 80 kip axial load

[1]Specimen had full stirrups around the longitudinal bars in the hook region but not around the hooked bars

Table A.2 Comprehensive test results and data for No. 8 specimens with two hooks

	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.
79	8-5-90-0-o-2.5-2-10a†	A B	90°	Horizontal	A1035[a]	10.3 10.5	10.4	5270	7	1	0.084	17	10.5	8.375
80	8-5-90-0-o-2.5-2-10b†	A B	90°	Horizontal	A1035[a]	9.3 10.3	9.8	5440	8	1	0.084	17	10.5	8.375
81	8-5-90-0-o-2.5-2-10c†	A B	90°	Horizontal	A1035[a]	10.8 10.5	10.6	5650	9	1	0.084	17	10.5	8.375
82	8-8-90-0-o-2.5-2-8	A B	90°	Horizontal	A1035[b]	8.6 8.3	8.4	8740	12	1	0.078	17	10.5	8.375
83	8-8-90-0-o-3.5-2-8	A B	90°	Horizontal	A1035[b]	7.6 8.0	7.8	8810	14	1	0.078	19	10.5	8.375
84	8-8-90-0-o-4-2-8	A B	90°	Horizontal	A1035[b]	8.1 8.3	8.2	8630	11	1	0.078	20	10.5	8.375
85	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
86	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
87	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
88	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
89	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
90	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
91	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
92	(2@3) 8-5-90-0-i-2.5-2-10‡	A B	90°	Horizontal	A615	10.4 10.6	10.5	4490	10	1	0.073	9	10.5	8.375
93	(2@5) 8-5-90-0-i-2.5-2-10‡	A B	90°	Horizontal	A615	10.1 10.1	10.1	4490	10	1	0.073	11	10.5	8.375
94	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
95	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
96	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
97	8-8-90-0-i-2.5sc-2tc-9‡	A B	90°	Horizontal	A615	9.5 9.5	9.5	7710	25	1	0.073	17	10.5	8.375
98	8-8-90-0-i-2.5sc-9tc-9	A B	90°	Horizontal	A615	9.3 9.0	9.1	7710	25	1	0.073	17	10.5	8.375
99	(2@3) 8-8-90-0-i-2.5-9-9	A B	90°	Horizontal	A615	9.3 9.0	9.1	7510	21	1	0.073	9	10.5	8.375
100	(2@4) 8-8-90-0-i-2.5-9-9	A B	90°	Horizontal	A615	9.9 10.0	9.9	7510	21	1	0.073	10	10.5	8.375
101	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
102	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
103	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
104	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

† 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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	$f_{su,\,ind}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
79	8-5-90-0-o-2.5-2-10a†	A B	2.5 2.6	2.6	2.0 1.8	10.0	2	40600 46600	84630	42315	51400 59000	53600	- 0.186	FP/SS SS/FP
80	8-5-90-0-o-2.5-2-10b†	A B	2.5 2.5	2.5	3.3 2.3	10.0	2	47900 30600	67300	33650	60600 38700	42600	- -	FP/SS SS/FP
81	8-5-90-0-o-2.5-2-10c†	A B	2.5 2.5	2.5	1.5 1.8	10.0	2	62700 54600	111950	55975	79400 69100	70900	- 0.132	FP/SS SS/FP/TK
82	8-8-90-0-o-2.5-2-8	A B	2.8 2.5	2.6	1.8 2.1	9.0	2	44400 33200	66030	33015	56200 42000	41800	0.153 0.113	SB/TK SB/TK
83	8-8-90-0-o-3.5-2-8	A B	3.5 3.6	3.6	2.4 2.0	9.8	2	35600 44500	71740	35870	45100 56300	45400	- -	FP/SS SS/FP
84	8-8-90-0-o-4-2-8	A B	4.5 3.8	4.1	2.5 2.4	9.8	2	37100 39200	75020	37510	47000 49600	47500	0.362 .(0.017)	SS/FP SS
85	8-5-90-0-i-2.5-2-16†	A B	2.8 2.8	2.8	1.8 1.4	9.5	2	83300 86100	166480	83240	105400 109000	105400	- -	FP/SB FB/TK
86	8-5-90-0-i-2.5-2-9.5†	A B	2.8 2.5	2.6	3.0 1.8	9.5	2	44600 65800	88970	44485	56500 83300	56300	- -	FP SS
87	8-5-90-0-i-2.5-2-12.5†	A B	2.8 2.8	2.8	1.3 1.3	9.8	2	65300 69900	131640	65820	82700 88500	83300	- -	SS/B SS
88	8-5-90-0-i-2.5-2-18	A B	2.5 2.5	2.5	0.8 2.4	10.5	2	100200 79800	161760	80880	126800 101000	102400	- 0.153	FB/SS/TK FB/SS/TK
89	8-5-90-0-i-2.5-2-13	A B	2.5 2.5	2.5	2.0 1.8	9.8	2	73100 65200	131080	65540	92500 82500	83000	- -	SS FP/SS
90	8-5-90-0-i-2.5-2-15(1)	A B	2.5 2.6	2.5	2.8 2.0	9.6	2	64500 87300	127530	63765	81600 110500	80700	- -	FB/SB SB
91	8-5-90-0-i-2.5-2-15	A B	2.5 2.6	2.6	2.0 2.9	9.5	2	76300 80700	150960	75480	96600 102200	95500		SS/FP SB/FP
92	(2@3) 8-5-90-0-i-2.5-2-10‡	A B	2.5 2.5	2.5	1.6 1.4	2.0	2	38900 41700	80600	40300	49241 52785	51013	0.2 -	FP FP
93	(2@5) 8-5-90-0-i-2.5-2-10‡	A B	2.5 2.3	2.4	1.9 1.9	4.1	2	41900 38300	80100	40100	53038 48481	50759	0.33 0	FP FB/SS
94	8-8-90-0-i-2.5-2-8	A B	2.8 2.9	2.8	1.1 2.0	8.6	2	54700 45200	90490	45245	69200 57200	57300	- -	FP/TK FP/SS
95	8-8-90-0-i-2.5-2-10	A B	2.8 2.9	2.8	2.3 2.5	9.0	2	50000 52900	102910	51455	63300 67000	65100	0.195 0.185	FP FP
96	8-8-90-0-i-2.5-2-8(1)	A B	2.8 2.8	2.8	2.8 2.8	9.5	2	38000 37700	73640	36820	48100 47700	46600	0.387 0.229	FP/SS FP/SS
97	8-8-90-0-i-2.5sc-2tc-9‡	A B	2.5 2.8	2.6	1.5 1.5	10.0	2	35500 34700	70	35100	44937 43924	44430	0.104 0	FB FB
98	8-8-90-0-i-2.5sc-9tc-9	A B	2.8 2.8	2.8	8.8 9.0	10.0	2	38500 36800	75	37700	48734 46582	47722	0.12 0.29	FB FB
99	(2@3) 8-8-90-0-i-2.5-9-9	A B	2.5 2.6	2.6	8.8 9.0	2.0	2	34000 27600	61300	30700	43038 34937	38861	 -	FP FP
100	(2@4) 8-8-90-0-i-2.5-9-9	A B	2.6 2.5	2.5	8.1 8.0	3.1	2	32900 35500	68400	34200	41646 44937	43291	0.018 0	FP FP
101	8-12-90-0-i-2.5-2-9	A B	2.8 2.6	2.7	2.4 2.4	9.6	2	50800 54800	99850	49925	64300 69400	63200	0.219	FP/SS SS/FP
102	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
103	8-12-90-0-i-2.5-2-12	A B	2.5 2.4	2.5	1.9 1.9	9.8	2	70700 65800	131800	65900	89500 83300	83400	- 0.0119	SB/FP FB/SS
104	8-15-90-0-i-2.5-2-8.5	A B	2.5 2.5	2.5	2.0 1.9	10.0	2	43100 44100	87200	43600	54600 55800	55200	- -	FP FP

† 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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
79	8-5-90-0-o-2.5-2-10a[†]	A B	60	-	-	-	-	3.10	5	3.5	0.63	3.50	-	-	3.16	60
80	8-5-90-0-o-2.5-2-10b[†]	A B	60	-	-	-	-	3.10	5	3.5	0.63	3.50	-	-	3.16	60
81	8-5-90-0-o-2.5-2-10c[†]	A B	60	-	-	-	-	3.10	5	3.5	0.63	3.50	-	-	3.16	60
82	8-8-90-0-o-2.5-2-8	A B	60	-	-	-	-	2.00	10	3.0	0.50	1.75	-	-	3.16	60
83	8-8-90-0-o-3.5-2-8	A B	60	-	-	-	-	2.00	10	3.0	0.50	1.75	-	-	3.16	60
84	8-8-90-0-o-4-2-8	A B	60	-	-	-	-	2.00	10	3.0	0.50	1.75	-	-	3.16	60
85	8-5-90-0-i-2.5-2-16[†]	A B	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60
86	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
87	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
88	8-5-90-0-i-2.5-2-18	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	1	3.78	60
89	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
90	8-5-90-0-i-2.5-2-15(1)	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60
91	8-5-90-0-i-2.5-2-15	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60
92	(2@3) 8-5-90-0-i-2.5-2-10[‡]	A B	60	-	-	-	-	-	-	-	0.38	5.00	-	-	3.16	120
93	(2@5) 8-5-90-0-i-2.5-2-10[‡]	A B	60	-	-	-	-	-	-	-	0.38	5.00	-	-	3.16	120
94	8-8-90-0-i-2.5-2-8	A B	60	-	-	-	-	1.60	8	4.0	0.50	1.75	-	-	3.16	60
95	8-8-90-0-i-2.5-2-10	A B	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60
96	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
97	8-8-90-0-i-2.5sc-2tc-9[‡]	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.16	60
98	8-8-90-0-i-2.5sc-9tc-9	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	4.74	60
99	(2@3) 8-8-90-0-i-2.5-9-9	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	4.74	60
100	(2@4) 8-8-90-0-i-2.5-9-9	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	4.74	60
101	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
102	8-12-90-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60
103	8-12-90-0-i-2.5-2-12	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.16	60
104	8-15-90-0-i-2.5-2-8.5	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.78	60

[†] 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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.
105	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
106	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
107	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
108	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
109	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
110	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
111	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
112	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
113	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
114	8-8-90-0-i-4-2-8	A B	90°	Horizontal	A1035[b]	7.6 8.0	7.8	8740	12	1	0.078	20	10.5	8.375
115	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
116	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
117	(2@3) 8-5-180-0-i-2.5-2-10‡	A B	180°	Horizontal	A615	10.3 10.0	10.2	5260	15	1	0.073	9	10.5	8.375
118	(2@5)8-5-180-0-i-2.5-2-10‡	A B	180°	Horizontal	A615	10.0 10.0	10.0	5260	15	1	0.073	11	10.5	8.375
119	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
120	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
121	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
122	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
123	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
124	8-5-90-1#3-i-2.5-2-16†	A B	90°	Horizontal	A1035[b]	15.6 15.6	15.6	4810	6	1	0.078	17	10.5	8.375
125	8-5-90-1#3-i-2.5-2-12.5†	A B	90°	Horizontal	A1035[b]	12.5 12.5	12.5	5140	8	1	0.078	17	10.5	8.375
126	8-5-90-1#3-i-2.5-2-9.5†	A B	90°	Horizontal	A615	9.0 9.0	9.0	5240	9	1	0.078	17	10.5	8.375
127	8-5-180-1#3-i-2.5-2-11†	A B	180°	Horizontal	A615	11.5 11.5	11.5	4300	6	1	0.078	15	10.5	8.375
128	8-5-180-1#3-i-2.5-2-14†	A B	180°	Horizontal	A1035[b]	14.8 15.0	14.9	4870	9	1	0.078	15	10.5	8.375
129	8-5-180-1#3-i-3.5-2-11†	A B	180°	Horizontal	A615	11.6 10.6	11.1	4550	7	1	0.078	17	10.5	8.375
130	8-5-180-1#3-i-3.5-2-14†	A B	180°	Horizontal	A1035[b]	15.6 14.5	15.1	4840	8	1	0.078	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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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	$f_{su,\ ind}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
105	8-15-90-0-i-2.5-2-13	A B	2.4 2.5	2.4	2.1 2.0	9.9	2	77200 79000	156200	78100	97700 100000	98900	- -	FB/SB FB
106	8-5-90-0-i-3.5-2-18	A B	3.8 3.4	3.6	1.4 2.4	9.4	2	96000 105100	190740	95370	121500 133000	120700	0.181 -	FP/SS/TK FB/SS
107	8-5-90-0-i-3.5-2-13	A B	3.6 3.4	3.5	1.9 1.9	9.4	2	69400 68300	136200	68100	87800 86500	86200	- -	FP/SS SS/FP
108	8-5-90-0-i-3.5-2-15(2)	A B	3.5 3.5	3.5	1.6 2.4	9.5	2	106200 85500	175420	87710	134400 108200	111000	- -	SS SS/FP
109	8-5-90-0-i-3.5-2-15(1)	A B	3.3 3.4	3.3	1.8 2.0	10.1	2	71200 79400	141300	70650	90100 100500	89400		SS/FP SB
110	8-8-90-0-i-3.5-2-8(1)	A B	3.5 3.8	3.6	2.3 2.3	9.0	2	43700 44000	87690	43845	55300 55700	55500	0.144 0.156	SS/FP SS/FP
111	8-8-90-0-i-3.5-2-10	A B	3.8 3.8	3.8	3.3 1.3	9.0	2	55200 71900	111130	55565	69900 91000	70300	0.195 0.242	FP/SS SS/FP
112	8-8-90-0-i-3.5-2-8(2)	A B	3.6 3.8	3.7	2.1 2.6	10.0	2	41200 42900	84070	42035	52200 54300	53200	0.133 0.201	FP FP
113	8-12-90-0-i-3.5-2-9	A B	3.5 3.8	3.6	2.4 2.1	9.8	2	61400 68500	120480	60240	77700 86700	76300	 0.434	FP FP/SS
114	8-8-90-0-i-4-2-8	A B	4.5 3.9	4.2	2.9 2.5	9.5	2	37600 48700	74860	37430	47600 61600	47400	- -	FP/SS FP
115	8-5-180-0-i-2.5-2-11†	A B	3.0 2.8	2.9	2.0 2.0	9.8	2	45600 50500	92290	46145	57700 63900	58400	0.275 -	SS/FP SS
116	8-5-180-0-i-2.5-2-14†	A B	2.8 2.6	2.7	2.0 2.0	9.8	2	49400 69400	98300	49150	62500 87800	62200	0.088 0.096	SS SS
117	(2@3) 8-5-180-0-i-2.5-2-10‡	A B	2.5 2.4	2.4	1.7 2.0	2.0	2	47600 56100	103700	51800	60253 71013	65570	0 0.9	FP FP
118	(2@5)8-5-180-0-i-2.5-2-10‡	A B	2.4 2.5	2.4	2.0 2.0	4.1	2	52300 54000	106300	53200	66203 68354	67342		FP FP
119	8-8-180-0-i-2.5-2-11.5	A B	3.0 3.0	3.0	4.5 4.5	9.5	2	62800 80200	125600	62800	79500 101500	79500	- -	FP/SB FP/SS
120	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
121	8-5-180-0-i-3.5-2-11†	A B	3.8 3.8	3.8	1.4 1.4	10.0	2	58600 60500	118580	59290	74200 76600	75100	0.372 0.239	FP/SS SS
122	8-5-180-0-i-3.5-2-14†	A B	3.9 3.8	3.8	1.6 2.1	9.8	2	63700 78000	127010	63505	80600 98700	80400	- -	SS FB/SS
123	8-15-180-0-i-2.5-2-13.5	A B	2.5 2.5	2.5	2.0 2.3	10.0	2	90700 89100	179800	89900	114800 112800	113800	- -	- FB/SB
124	8-5-90-1#3-i-2.5-2-16†	A B	2.8 3.0	2.9	2.3 2.3	9.5	2	94600 73900	149620	74810	119700 93500	94700	- -	FP/SS FP/SS
125	8-5-90-1#3-i-2.5-2-12.5†	A B	2.6 2.8	2.7	2.1 2.1	9.8	2	73900 64800	129670	64835	93500 82000	82100	- -	FP/SS SS/FP
126	8-5-90-1#3-i-2.5-2-9.5†	A B	2.6 2.8	2.7	2.5 2.5	9.8	2	62000 55000	98070	49035	78500 69600	62100	- -	SB FP/SS
127	8-5-180-1#3-i-2.5-2-11†	A B	2.5 2.5	2.5	1.5 1.5	10.0	2	57300 69000	99460	49730	72500 87300	62900	0.088 0.341	SS/FP SS/FP
128	8-5-180-1#3-i-2.5-2-14†	A B	2.8 2.9	2.8	1.3 1.0	9.9	2	67300 70900	138040	69020	85200 89700	87400	- 0.123	SS/FP FP/SS
129	8-5-180-1#3-i-3.5-2-11†	A B	3.8 3.5	3.6	1.4 2.4	10.0	2	62900 56200	110780	55390	79600 71100	70100	0.434 0.216	SS SS
130	8-5-180-1#3-i-3.5-2-14†	A B	3.6 3.6	3.6	0.9 2.0	10.0	2	78700 76900	151990	75995	99600 97300	96200	0.232 0.227	SS/FP SS/FP

† 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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
105	8-15-90-0-i-2.5-2-13	A B	60	-	-	-	-	-	-	-	0.38	5.00	-	-	4.74	60
106	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
107	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
108	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
109	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
110	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
111	8-8-90-0-i-3.5-2-10	A B	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60
112	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
113	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
114	8-8-90-0-i-4-2-8	A B	60	-	-	-	-	1.60	8	4.0	0.50	1.75	-	-	3.16	60
115	8-5-180-0-i-2.5-2-11†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
116	8-5-180-0-i-2.5-2-14†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
117	(2@3) 8-5-180-0-i-2.5-2-10‡	A B	60	-	-	-	-	-	-	-	0.50	4.00	-	-	6.32	120
118	(2@5)8-5-180-0-i-2.5-2-10‡	A B	60	-	-	-	-	-	-	-	0.50	4.00	-	-	6.32	120
119	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
120	8-12-180-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60
121	8-5-180-0-i-3.5-2-11†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
122	8-5-180-0-i-3.5-2-14†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
123	8-15-180-0-i-2.5-2-13.5	A B	60	-	-	-	-	-	-	-	0.50	4.00	-	-	4.74	60
124	8-5-90-1#3-i-2.5-2-16†	A B	60	0.38	0.1	1	9.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
125	8-5-90-1#3-i-2.5-2-12.5†	A B	60	0.38	0.1	1	9.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
126	8-5-90-1#3-i-2.5-2-9.5†	A B	60	0.38	0.1	1	9.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
127	8-5-180-1#3-i-2.5-2-11†	A B	60	0.38	0.1	1	3.50	0.44	4	4.5	0.50	3.50	-	-	3.16	60
128	8-5-180-1#3-i-2.5-2-14†	A B	60	0.38	0.1	1	3.50	0.44	4	4.5	0.50	3.50	-	-	3.16	60
129	8-5-180-1#3-i-3.5-2-11†	A B	60	0.38	0.1	1	3.50	0.44	4	4.5	0.50	3.50	-	-	3.16	60
130	8-5-180-1#3-i-3.5-2-14†	A B	60	0.38	0.1	1	3.50	0.44	4	4.5	0.50	3.50	-	-	3.16	60

† 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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.
131	8-8-180-1#4-i-2.5-2-11.5	A B	180°	Horizontal	A1035[b]	12.0 12.3	12.1	8740	12	1	0.078	17	10.5	8.375
132	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
133	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
134	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
135	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
136	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
137	(2@3) 8-5-90-2#3-i-2.5-2-10[‡]	A B	90°	Horizontal	A615	10.0 10.5	10.3	4760	11	1	0.073	9	10.5	8.375
138	(2@5) 8-5-90-2#3-i-2.5-2-10[‡]	A B	90°	Horizontal	A615	9.6 10.0	9.8	4760	11	1	0.073	11	10.5	8.375
139	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
140	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
141	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
142	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
143	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
144	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
145	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
146	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
147	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
148	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
149	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
150	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
151	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
152	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
153	(2@3) 8-5-180-2#3-i-2.5-2-10[‡]	A B	180°	Horizontal	A615	10.3 10.3	10.3	5400	16	1	0.073	9	10.5	8.375
154	(2@5) 8-5-180-2#3-i-2.5-2-10[‡]	A B	180°	Horizontal	A615	10.3 9.8	10.0	5400	16	1	0.073	11	10.5	8.375
155	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

[†] 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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	$f_{su,\,ind}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
131	8-8-180-1#4-i-2.5-2-11.5	A B	2.9 2.8	2.8	2.0 1.8	9.5	2	72000 72500	144460	72230	91100 91800	91400	- .(0.013)	FP/SS FP/SS
132	8-5-90-2#3-i-2.5-2-16†	A B	2.8 2.9	2.8	2.9 2.1	9.5	2	80000 92800	159260	79630	101300 117500	100800	- -	SS/FP FP
133	8-5-90-2#3-i-2.5-2-9.5†	A B	2.5 2.5	2.5	2.6 2.3	10.0	2	54900 53600	107240	53620	69500 67800	67900	- -	FP FP
134	8-5-90-2#3-i-2.5-2-12.5†	A B	2.8 2.8	2.8	2.6 2.6	9.5	2	74100 76300	144130	72065	93800 96600	91200	- -	FP FP/SS
135	8-5-90-2#3-i-2.5-2-8.5	A B	3.0 3.0	3.0	1.8 1.1	9.1	2	52900 48400	101100	50550	67000 61300	64000		FP/SS SS
136	8-5-90-2#3-i-2.5-2-14	A B	2.8 3.0	2.9	2.6 2.1	9.3	2	77000 77500	153930	76965	97500 98100	97400		SS/FP FP/SS
137	(2@3) 8-5-90-2#3-i-2.5-2-10‡	A B	2.5 2.5	2.5	2.0 1.5	2.3	2	58000 46000	104000	46800	73418 58228	59241	0.21 -	FP FP
138	(2@5) 8-5-90-2#3-i-2.5-2-10‡	A B	2.5 2.5	2.5	2.4 2.0	3.9	2	48400 48600	97000	48500	61266 61519	61392	0.23 0.108	FB FB
139	8-8-90-2#3-i-2.5-2-8	A B	3.0 2.9	2.9	2.0 1.5	9.0	2	46200 55400	95750	47875	58500 70100	60600	- -	FP/SS FP/SS
140	8-8-90-2#3-i-2.5-2-10	A B	2.8 2.8	2.8	2.1 2.5	8.5	2	60700 67000	122050	61025	76800 84800	77200	0.186 0.152	FP FB
141	8-12-90-2#3-i-2.5-2-9	A B	2.9 2.6	2.8	2.3 2.3	9.5	2	61800 60300	122030	61015	78200 76300	77200	0.345 0.361	FP/SS SS/FP
142	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
143	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	- 0.13	FP/SS FP
144	8-15-90-2#3-i-2.5-2-6	A B	2.5 2.4	2.4	2.3 1.8	9.9	2	37400 37700	75100	37600	47300 47700	47600	- -	FP FP
145	8-15-90-2#3-i-2.5-2-11	A B	2.5 2.5	2.5	1.9 2.4	10.0	2	99000 83600	166600	83300	125300 105800	105400	- 0.123	FB FB
146	8-5-90-2#3-i-3.5-2-17	A B	3.3 3.5	3.4	1.8 2.3	10.1	2	102600 88600	179830	89915	129900 112200	113800	- -	SS SS/FP
147	8-5-90-2#3-i-3.5-2-13	A B	3.1 3.6	3.4	1.5 1.8	10.3	2	81200 86900	160720	80360	102800 110000	101700	- -	SS/FP SS/FP
148	8-8-90-2#3-i-3.5-2-8	A B	3.6 3.8	3.7	2.0 1.9	8.5	2	48300 49300	97550	48775	61100 62400	61700	0.31 .340(.147)	FP FP
149	8-8-90-2#3-i-3.5-2-10	A B	3.6 3.8	3.7	3.3 3.3	8.5	2	54000 53800	107770	53885	68400 68100	68200	- -	SS FP
150	8-12-90-2#3-i-3.5-2-9	A B	3.6 4.0	3.8	2.3 2.4	9.6	2	50300 49300	99550	49775	63700 62400	63000	0.15	FP/SS FP/SS
151	8-5-180-2#3-i-2.5-2-11†	A B	2.8 2.5	2.6	2.3 2.5	9.5	2	64200 61900	120470	60235	81300 78400	76200	0.26 0.087	SS/FP SS/FP
152	8-5-180-2#3-i-2.5-2-14†	A B	2.8 2.8	2.8	2.5 2.0	9.8	2	87100 76900	152560	76280	110300 97300	96600	0.774 0.199	FP FP/SS
153	(2@3) 8-5-180-2#3-i-2.5-2-10‡	A B	2.5 2.5	2.5	1.8 1.8	2.0	2	57500 58800	115300	57700	72785 74430	73038	 0.288	FP FP
154	(2@5) 8-5-180-2#3-i-2.5-2-10‡	A B	2.5 2.5	2.5	1.8 2.3	4.0	2	63700 60100	123800	61900	80633 76076	78354	 0.263	FB FB
155	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 .25(.027)	FB/SS FP/SS

† 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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
131	8-8-180-1#4-i-2.5-2-11.5	A B	60	0.5	0.2	1	3.00	0.44	4	3.0	0.50	3.00	-	-	3.16	60
132	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
133	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
134	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
135	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
136	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
137	(2@3) 8-5-90-2#3-i-2.5-2-10[‡]	A B	60	0.38	0.2	2	3.00	-	-	-	0.38	4.00	-	-	3.16	120
138	(2@5) 8-5-90-2#3-i-2.5-2-10[‡]	A B	60	0.38	0.2	2	3.00	-	-	-	0.38	5.00	-	-	3.16	120
139	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
140	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
141	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
142	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
143	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
144	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
145	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
146	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
147	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
148	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
149	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
150	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
151	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
152	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
153	(2@3) 8-5-180-2#3-i-2.5-2-10[‡]	A B	60	0.38	0.2	2	3.00	-	-	-	0.50	4.00	-	-	6.32	120
154	(2@5) 8-5-180-2#3-i-2.5-2-10[‡]	A B	60	0.38	0.2	2	3.00	-	-	-	0.50	4.00	-	-	6.32	120
155	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

[†] 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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.
156	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
157	8-12-180-2#3vr-i-2.5-2-11	A B	180°	Vertical	A1035[b]	10.9 10.9	10.9	12010	42	1	0.073	17	10.5	8.375
158	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
159	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
160	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
161	8-8-90-2#4-i-2.5-2-10	A B	90°	Horizontal	A1035[b]	8.5 9.3	8.9	8290	16	1	0.078	17	10.5	8.375
162	8-8-90-2#4-i-3.5-2-10	A B	90°	Horizontal	A1035[b]	9.0 9.8	9.4	8290	16	1	0.078	19	10.5	8.375
163	8-5-90-4#3-i-2.5-2-16†	B A	90°	Horizontal	A1035[b]	16.0 16.3	16.1	4810	6	1	0.078	17	10.5	8.375
164	8-5-90-4#3-i-2.5-2-12.5†	A B	90°	Horizontal	A1035[b]	11.9 11.9	11.9	4980	7	1	0.078	17	10.5	8.375
165	8-5-90-4#3-i-2.5-2-9.5†	A B	90°	Horizontal	A615	9.5 9.5	9.5	5140	8	1	0.078	17	10.5	8.375
166	8-5-90-5#3-o-2.5-2-10a†	A B	90°	Horizontal	A1035[a]	10.3 10.5	10.4	5270	7	1	0.084	17	10.5	8.375
167	8-5-90-5#3-o-2.5-2-10b†	A B	90°	Horizontal	A1035[a]	10.5 10.5	10.5	5440	8	1	0.084	17	10.5	8.375
168	8-5-90-5#3-o-2.5-2-10c†	A B	90°	Horizontal	A1035[a]	11.3 10.5	10.9	5650	9	1	0.084	17	10.5	8.375
169	8-8-90-5#3-o-2.5-2-8	A B	90°	Horizontal	A1035[b]	8.3 8.8	8.5	8630	11	1	0.078	17	10.5	8.375
170	8-8-90-5#3-o-3.5-2-8	A B	90°	Horizontal	A1035[b]	7.8 8.0	7.9	8810	14	1	0.078	19	10.5	8.375
171	8-8-90-5#3-o-4-2-8	A B	90°	Horizontal	A1035[b]	8.5 8.0	8.3	8740	12	1	0.078	20	10.5	8.375
172	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
173	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
174	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
175	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
176	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
177	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
178	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
179	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
180	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
181	(2@3) 8-5-90-5#3-i-2.5-2-10‡	A B	90°	Horizontal	A615	10.0 10.5	10.3	4805	12	1	0.073	9	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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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	$f_{su,\ ind}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
156	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
157	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
158	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
159	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
160	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
161	8-8-90-2#4-i-2.5-2-10	A B	3.0 3.0	3.0	3.5 2.8	9.3	2	61400 71300	122720	61360	77700 90300	77700	0.171 .285(.129)	FP/SS FP/SS
162	8-8-90-2#4-i-3.5-2-10	A B	3.8 3.9	3.8	3.0 2.3	9.1	2	69500 69500	138930	69465	88000 88000	87900	0.26 .181(.104)	SS/FP FP/SS
163	8-5-90-4#3-i-2.5-2-16†	B A	2.8 3.0	2.9	1.9 1.6	9.5	2	91800 97200	180860	90430	116200 123000	114500	- -	FP/SS FP/SS
164	8-5-90-4#3-i-2.5-2-12.5†	A B	2.5 2.5	2.5	2.0 2.0	10.0	2	83100 68600	137170	68585	105200 86800	86800	- -	FP FP
165	8-5-90-4#3-i-2.5-2-9.5†	A B	2.8 2.9	2.8	2.0 2.0	9.5	2	63300 54800	109830	54915	80100 69400	69500	- -	FP FP/SS
166	8-5-90-5#3-o-2.5-2-10a†	A B	2.6 2.6	2.6	1.8 2.0	9.9	2	55700 55800	108510	54255	70500 70600	68700	- 0.213	SS SB
167	8-5-90-5#3-o-2.5-2-10b†	A B	2.5 2.6	2.6	2.0 2.0	9.9	2	66400 69500	131180	65590	84100 88000	83000	0.203 0.235	FP/SB SB/FP
168	8-5-90-5#3-o-2.5-2-10c†	A B	2.6 2.5	2.6	1.3 2.0	9.9	2	80600 57700	115400	57700	102000 73000	73000	- -	SS/FP SS/FP
169	8-8-90-5#3-o-2.5-2-8	A B	2.8 2.8	2.8	1.8 1.3	9.3	2	56100 66800	115960	57980	71000 84600	73400	0.253 .237(.033)	FP/SS FB/SS
170	8-8-90-5#3-o-3.5-2-8	A B	3.5 3.5	3.5	2.3 2.0	9.5	2	53900 56100	109910	54955	68200 71000	69600	- .251(.249)	FP FP/SS
171	8-8-90-5#3-o-4-2-8	A B	3.9 4.5	4.2	1.5 2.0	10.0	2	39600 41500	78140	39070	50100 52500	49500	0.388 0.754	SS/FP FP
172	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
173	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
174	8-5-90-5#3-i-2.5-2-15	A B	2.8 2.5	2.6	1.9 1.4	9.9	2	77100 72600	146750	73375	97600 91900	92900	0.196 -	FP/SS FP/SS
175	8-5-90-5#3-i-2.5-2-13	A B	2.5 2.4	2.4	1.5 1.8	10.3	2	93100 81300	164750	82375	117800 102900	104300	- -	SS/FP FP/SS
176	8-5-90-5#3-i-2.5-2-12(1)	A B	2.5 2.5	2.5	2.6 3.0	9.8	2	66700 75900	132730	66365	84400 96100	84000	- -	SS/FP SS/FP
177	8-5-90-5#3-i-2.5-2-12	A B	2.5 2.4	2.4	3.0 2.0	9.8	2	84900 72000	156900	84900	107500 91100	107500		SS SS
178	8-5-90-5#3-i-2.5-2-12(2)	A B	2.5 2.6	2.6	1.8 2.1	9.0	2	72400 77400	142940	71470	91600 98000	90500		FP/SS FP/SS
179	8-5-90-5#3-i-2.5-2-8	A B	2.8 2.9	2.8	2.6 2.9	9.0	2	48000 47000	94960	47480	60800 59500	60100	 0.321	FP FP
180	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
181	(2@3) 8-5-90-5#3-i-2.5-2-10‡	A B	2.4 2.8	2.6	2.0 1.5	2.0	2	61500 58200	119700	57900	77848 73671	73291	0.05 0.37	FB/SS FB/SS

† 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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
156	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
157	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
158	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
159	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
160	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
161	8-8-90-2#4-i-2.5-2-10	A B	60	0.5	0.4	2	7.13	1.20	6	4.0	0.50	2.00	-	-	3.16	60
162	8-8-90-2#4-i-3.5-2-10	A B	60	0.5	0.4	2	7.13	1.20	6	4.0	0.50	2.00	-	-	3.16	60
163	8-5-90-4#3-i-2.5-2-16†	B A	60	0.38	0.4	4	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
164	8-5-90-4#3-i-2.5-2-12.5†	A B	60	0.38	0.4	4	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
165	8-5-90-4#3-i-2.5-2-9.5†	A B	60	0.38	0.4	4	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
166	8-5-90-5#3-o-2.5-2-10a†	A B	60	0.38	0.6	5	3.00	1.10	10	3.0	0.63	5.00	-	-	3.16	60
167	8-5-90-5#3-o-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
168	8-5-90-5#3-o-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
169	8-8-90-5#3-o-2.5-2-8	A B	60	0.38	0.6	5	3.00	2.00	10	3.0	0.50	1.75	-	-	3.16	60
170	8-8-90-5#3-o-3.5-2-8	A B	60	0.38	0.6	5	3.00	2.00	10	3.0	0.50	1.75	-	-	3.16	60
171	8-8-90-5#3-o-4-2-8	A B	60	0.38	0.6	5	3.00	2.00	10	3.0	0.50	1.75	-	-	3.16	60
172	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
173	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
174	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
175	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
176	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
177	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
178	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
179	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
180	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
181	(2@3) 8-5-90-5#3-i-2.5-2-10‡	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	3.16	120

† 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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.
182	(2@5) 8-5-90-5#3-i-2.5-2-10‡	A B	90°	Horizontal	A615	9.9 9.5	9.7	4805	12	1	0.073	11	10.5	8.375
183	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
184	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
185	8-8-90-5#3-i-2.5-9-9‡	A B	90°	Horizontal	A615	9.0 9.3	9.1	7710	25	1	0.073	17	10.5	8.375
186	(2@3) 8-8-90-5#3-i-2.5-9-9	A B	90°	Horizontal	A615	9.3 9.5	9.4	7440	22	1	0.073	9	10.5	8.375
187	(2@4) 8-8-90-5#3-i-2.5-9-9	A B	90°	Horizontal	A615	8.9 9.1	9.0	7440	22	1	0.073	10	10.5	8.375
188	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
189	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
190	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
191	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
192	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
193	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
194	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
195	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
196	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
197	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
198	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
199	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
200	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
201	(2@5) 8-5-180-5#3-i-2.5-2-10‡	A B	180°	Horizontal	A615	10.0 10.3	10.1	5540	17	1	0.073	11	10.5	8.375
202	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
203	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
204	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
205	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
206	8-5-90-4#4s-i-2.5-2-15	A B	90°	Horizontal	A1035[b]	15.6 15.6	15.6	4810	6	1	0.078	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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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	$f_{su,\,ind}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
182	(2@5) 8-5-90-5#3-i-2.5-2-10‡	A B	2.3 2.4	2.3	2.1 2.5	4.3	2	59700 52700	112400	56000	75570 66709	70886	0.12 0.29	FB FB
183	8-8-90-5#3-i-2.5-2-8	A B	2.9 2.8	2.8	2.8 2.8	8.5	2	56000 51200	100530	50265	70900 64800	63600	0.3 0.375 (.092)	FP FP
184	8-8-90-5#3-i-2.5-2-9‡	A B	2.8 3.3	3.0	2.4 2.0	9.8	2	64800 64800	129	64390	82025 82025	81506	0.047 0	FB FB
185	8-8-90-5#3-i-2.5-9-9‡	A B	2.5 2.8	2.6	9.0 8.8	10.0	2	62000 65200	127	63290	78481 82532	80114	0.05 0	FB FB
186	(2@3) 8-8-90-5#3-i-2.5-9-9	A B	2.5 2.5	2.5	8.8 8.5	2.0	2	56500 61200	117600	58790	71519 77468	74418	0.082 -	FP FP
187	(2@4) 8-8-90-5#3-i-2.5-9-9	A B	2.5 2.5	2.5	9.1 8.9	3.3	2	55700 59300	114900	57450	70506 75063	72722	0.117 0	FB FB
188	8-12-90-5#3-i-2.5-2-9	A B	2.5 2.6	2.6	2.5 2.5	9.5	2	66500 63100	129510	64755	84200 79900	82000	0.224 0.252	FP/SS FP/SS
189	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	0.44 0.547	FB/SS SS/FP
190	8-12-90-5#3-i-2.5-2-12‡	A B	2.4 2.5	2.4	2.0 1.9	10.0	2	90500 86500	175400	87700	114600 109500	111000	- -	FB/SS SS/FP
191	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
192	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
193	8-15-90-5#3-i-2.5-2-6	A B	2.6 2.6	2.6	1.8 2.2	9.8	2	48300 48700	97000	48500	61100 61600	61400	- -	FP FP
194	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
195	8-5-90-5#3-i-3.5-2-15	A B	3.6 3.5	3.5	1.3 1.3	10.3	2	81200 87100	160680	80340	102800 110300	101700	.214(.026) -	SS/FP SS/FP
196	8-5-90-5#3-i-3.5-2-13	A B	3.4 3.5	3.4	2.1 2.4	10.4	2	89600 76000	154140	77070	113400 96200	97600	- -	SS SS/FP
197	8-5-90-5#3-i-3.5-2-12(1)	A B	3.5 3.4	3.5	1.6 2.1	9.8	2	78900 75900	152860	76430	99900 96100	96700	- -	SS/FP SS
198	8-5-90-5#3-i-3.5-2-12	A B	3.4 3.5	3.4	1.7 2.4	9.8	2	79200 79300	158300	79150	100300 100400	100200	 0.162	FP FP/SS
199	8-8-90-5#3-i-3.5-2-8	A B	3.5 3.6	3.6	2.0 2.0	8.9	2	55400 56200	111620	55810	70100 71100	70600	- -	FP FP
200	8-12-90-5#3-i-3.5-2-9*	A B	3.3 3.4	3.3	2.5 2.5	9.5	2	68800 82200	135660	67830	87100 104100	85900	 0.415	FP/SS FP/SS
201	(2@5) 8-5-180-5#3-i-2.5-2-10‡	A B	2.5 2.5	2.5	2.0 1.8	4.0	2	58100 72200	133300	66640	73544 91392	84354	 0.111	FB FB
202	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
203	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
204	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
205	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
206	8-5-90-4#4s-i-2.5-2-15	A B	3.0 2.9	2.9	1.6 1.6	9.1	2	93300 107700	187310	93655	118100 136300	118600	0.21 -	SS/FP FP/SS

† 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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
182	(2@5) 8-5-90-5#3-i-2.5-2-10‡	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	3.16	120
183	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
184	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
185	8-8-90-5#3-i-2.5-9-9‡	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	4.74	120
186	(2@3) 8-8-90-5#3-i-2.5-9-9	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	4.74	60
187	(2@4) 8-8-90-5#3-i-2.5-9-9	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	4.74	60
188	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
189	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
190	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
191	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
192	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
193	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
194	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
195	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
196	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
197	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
198	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
199	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
200	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
201	(2@5) 8-5-180-5#3-i-2.5-2-10‡	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	4.00	-	-	6.32	120
202	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
203	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
204	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
205	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
206	8-5-90-4#4s-i-2.5-2-15	A B	60	0.5	0.8	4	4.00	0.88	8	4.0	0.38	3.50	0.375	2	3.16	60

† 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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.
207	8-5-90-4#4s-i-2.5-2-12(1)	A B	90°	Horizontal	A1035[c]	12.3 12.5	12.4	5180	8	1	0.073	17	10.5	8.375
208	8-5-90-4#4s-i-2.5-2-12	A B	90°	Horizontal	A1035[c]	12.0 12.6	12.3	6210	8	1	0.073	17	10.5	8.375
209	8-5-90-4#4s-i-3.5-2-15	A B	90°	Horizontal	A1035[b]	15.5 15.1	15.3	4810	6	1	0.078	19	10.5	8.375
210	8-5-90-4#4s-i-3.5-2-12(1)	A B	90°	Horizontal	A1035[c]	12.0 11.9	11.9	5910	14	1	0.073	19	10.5	8.375
211	8-5-90-4#4s-i-3.5-2-12	A B	90°	Horizontal	A1035[c]	12.0 12.5	12.3	5960	7	1	0.073	19	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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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	$f_{su,\text{ ind}}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
207	8-5-90-4#4s-i-2.5-2-12(1)	A B	2.5 2.6	2.6	2.1 1.9	10.0	2	100200 90100	181630	90815	126800 114100	115000	- -	FP/SS FP/SS
208	8-5-90-4#4s-i-2.5-2-12	A B	2.6 2.5	2.6	2.3 1.6	9.5	2	116400 99700	199510	99755	147300 126200	126300		FP/SS SS/FP
209	8-5-90-4#4s-i-3.5-2-15	A B	4.1 4.0	4.1	1.8 2.1	9.5	2	106000 90200	181730	90865	134200 114200	115000	- -	FP/SS SS/FP
210	8-5-90-4#4s-i-3.5-2-12(1)	A B	3.8 3.5	3.6	2.3 2.4	9.8	2	115200 97400	190910	95455	145800 123300	120800	- -	SS FP/SS
211	8-5-90-4#4s-i-3.5-2-12	A B	3.8 3.5	3.6	2.4 1.9	9.0	2	103900 96900	196310	98155	131500 122700	124200		SS/FP FP/SS

† 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 2.3

Table A.2 Cont. Comprehensive test results and data for No. 8 specimens with two hooks

	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
207	8-5-90-4#4s-i-2.5-2-12(1)	A B	60	0.5	0.8	4	4.00	1.60	8	4.0	0.50	3.50	0.5	1	3.16	60
208	8-5-90-4#4s-i-2.5-2-12	A B	60	0.5	0.8	4	4.00	1.60	8	4.0	0.50	3.50	0.5	1	3.16	60
209	8-5-90-4#4s-i-3.5-2-15	A B	60	0.5	0.8	4	4.00	0.88	8	4.0	0.38	3.50	0.375	2	3.16	60
210	8-5-90-4#4s-i-3.5-2-12(1)	A B	60	0.5	0.8	4	4.00	1.60	8	4.0	0.50	3.50	0.5	1	3.16	60
211	8-5-90-4#4s-i-3.5-2-12	A B	60	0.5	0.8	4	4.00	1.60	8	4.0	0.50	3.50	0.5	1	3.16	60

† 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 2.3

Table A.3 Comprehensive test results and data for No. 11 specimens with two hooks

	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.
212	11-8-90-0-o-2.5-2-25	A B	90°	Horizontal	A1035	25.3 25.1	25.2	9460	9	1.41	0.085	21.5	19.5	8.375
213	11-8-90-0-o-2.5-2-17	A B	90°	Horizontal	A1035	16.8 16.4	16.6	9460	9	1.41	0.085	21.5	19.5	8.375
214	11-12-90-0-o-2.5-2-17	A B	90°	Horizontal	A1035	17.1 16.6	16.9	11800	36	1.41	0.085	21.5	19.5	8.375
215	11-12-180-0-o-2.5-2-17	A B	180°	Horizontal	A1035	16.9 17.3	17.1	11800	36	1.41	0.085	21.5	19.5	8.375
216	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
217	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
218	(2@5.35) 11-5-90-0-i-2.5-13-13	A B	90°	Horizontal	A615	14.0 13.9	13.9	5330	11	1.41	0.085	14	19.5	8.375
219	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
220	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
221	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
222	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
223	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
224	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
225	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
226	11-15-90-0-i-2.5-2-11	A B	90°	Horizontal	A1035	12.1 11.5	11.8	16180	63	1.41	0.085	21.5	19.5	8.375
227	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
228	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
229	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
230	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
231	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
232	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
233	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
234	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
235	11-5-90-1#4-i-2.5-2-17	A B	90°	Horizontal	A1035	17.8 17.6	17.7	5790	25	1.41	0.085	21.5	19.5	8.375
236	11-5-90-1#4-i-3.5-2-17	A B	90°	Horizontal	A1035	17.8 17.8	17.8	5790	25	1.41	0.085	23.5	19.5	8.375
237	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

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
*No failure; load reached maximum capacity of jacks

Table A.3 Cont. Comprehensive test results and data for No. 11 specimens with two hooks

	Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T lb	T_{Total} lb	T_{avg} lb	f_{su} psi	$f_{su,avg}$ psi	Slip at Failure in.	Failure Type
212	11-8-90-0-o-2.5-2-25	A B	2.6 2.9	2.8	2.2 2.3	13.6	2	194500 170700	349400	174700	124700 109400	112000	- -	SB SB
213	11-8-90-0-o-2.5-2-17	A B	2.5 2.4	2.4	2.6 2.9	13.8	2	121400 105700	214400	107200	77800 67800	68700	- -	SB/FB SB/TK
214	11-12-90-0-o-2.5-2-17	A B	2.5 2.5	2.5	2.2 2.7	13.8	2	123700 105800	210800	105400	79300 67800	67600	0.143 -	FB/TK FP/TK
215	11-12-180-0-o-2.5-2-17	A B	2.5 2.6	2.5	2.3 1.9	13.4	2	83300 90100	167000	83500	53400 57800	53500	- -	SS/FP SB
216	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
217	11-5-90-0-i-2.5-2-26	A B	2.5 2.9	2.7	2.1 2.1	13.3	2	165700 146800	297450	148725	106200 94100	95300	- -	FB/SS FB/SS/TK
218	(2@5.35) 11-5-90-0-i-2.5-13-13	A B	2.6 2.6	2.6	12.0 12.1	6.2	2	58200 63000	121200	60600	37308 40385	38846	0.2 -	FP FP
219	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
220	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
221	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
222	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
223	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	- 0.25	SS/TK SS
224	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
225	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
226	11-15-90-0-i-2.5-2-11	A B	2.4 2.8	2.6	1.0 1.6	13.0	2	48600 47700	96300	48100	31200 30600	30800	- 0.252	FP/TK FP
227	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
228	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
229	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
230	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
231	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
232	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
233	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
234	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
235	11-5-90-1#4-i-2.5-2-17	A B	2.8 2.8	2.8	1.8 2.0	13.1	2	99400 119700	203000	101500	63700 76700	65100	- -	SS/FP FP/SS
236	11-5-90-1#4-i-3.5-2-17	A B	3.8 3.9	3.8	1.8 1.8	13.1	2	105700 108800	212540	106270	67800 69700	68100	- -	SS SS/FP/TK
237	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

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
*No failure; load reached maximum capacity of jacks

Table A.3 Cont. Comprehensive test results and data for No. 11 specimens with two hooks

	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
212	11-8-90-0-o-2.5-2-25	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.48	60
213	11-8-90-0-o-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.48	60
214	11-12-90-0-o-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	3.5	-	-	4.74	60
215	11-12-180-0-o-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	3.5	-	-	4.74	60
216	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
217	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
218	(2@5.35) 11-5-90-0-i-2.5-13-13	A B	60	-	-	-	-	-	-	-	0.50	7.0	-	-	7.90	60
219	11-8-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.48	60
220	11-8-90-0-i-2.5-2-21	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
221	11-8-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60
222	11-12-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
223	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
224	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
225	11-15-90-0-i-2.5-2-24	A B	60	-	-	-	-	-	-	-	0.50	3.5	-	-	6.32	60
226	11-15-90-0-i-2.5-2-11	A B	60	-	-	-	-	-	-	-	0.50	3.0	-	-	3.16	60
227	11-15-90-0-i-2.5-2-10‡	A B	60	-	-	-	-	-	-	-	0.50	4.5	-	-	6.94	120
228	11-15-90-0-i-2.5-2-15‡	A B	60	-	-	-	-	-	-	-	0.50	4.5	-	-	6.94	120
229	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
230	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
231	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
232	11-8-180-0-i-2.5-2-21	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
233	11-8-180-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60
234	11-12-180-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
235	11-5-90-1#4-i-2.5-2-17	A B	60	0.5	0.2	1	8.75	2.2	11	4.0	0.50	4.0	0.375	2	4.74	60
236	11-5-90-1#4-i-3.5-2-17	A B	60	0.5	0.2	1	8.75	2.2	11	4.0	0.50	4.0	0.375	2	4.74	60
237	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

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
*No failure; load reached maximum capacity of jacks

Table A.3 Cont. Comprehensive test results and data for No. 11 specimens with two hooks

	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.
238	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
239	(2@5.35) 11-5-90-2#3-i-2.5-13-13	A B	90°	Horizontal	A615	13.9 13.8	13.8	5330	11	1.41	0.085	14	19.5	8.375
240	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
241	11-12-90-2#3-i-2.5-2-25	A B	90°	Horizontal	A1035	25.0 24.5	24.8	13710	30	1.41	0.085	21.5	19.5	8.375
242	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
243	11-15-90-2#3-i-2.5-2-10.5	A B	90°	Horizontal	A1035	11.8 10.5	11.1	16180	63	1.41	0.085	21.5	19.5	8.375
244	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
245	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
246	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
247	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
248	11-5-90-5#3-i-2.5-2-14	A B	90°	Horizontal	A615	14.3 13.5	13.9	4910	12	1.41	0.069	21.5	19.5	8.375
249	11-5-90-5#3-i-3.5-2-14	A B	90°	Horizontal	A615	14.6 14.5	14.6	4910	14	1.41	0.069	23.5	19.5	8.375
250	11-8-90-6#3-o-2.5-2-16	A B	90°	Horizontal	A1035	15.9 16.5	16.2	9420	8	1.41	0.085	21.5	19.5	8.375
251	11-8-90-6#3-o-2.5-2-22	A B	90°	Horizontal	A1035	21.5 22.3	21.9	9120	7	1.41	0.085	21.5	19.5	8.375
252	11-12-90-6#3-o-2.5-2-17	A B	90°	Horizontal	A1035	15.6 17.3	16.4	11800	36	1.41	0.085	21.5	19.5	8.375
253	11-12-180-6#3-o-2.5-2-17	A B	180°	Horizontal	A1035	16.6 16.4	16.5	11800	36	1.41	0.085	21.5	19.5	8.375
254	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
255	(2@5.35) 11-5-90-6#3-i-2.5-13-13	A B	90°	Horizontal	A615	14.0 13.8	13.9	5280	12	1.41	0.085	14	19.5	8.375
256	(2@5.35) 11-5-90-6#3-i-2.5-18-18	A B	90°	Horizontal	A1035	19.3 19.5	19.4	5280	12	1.41	0.085	14	19.5	8.375
257	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
258	11-8-90-6#3-i-2.5-2-22	A B	90°	Horizontal	A1035	21.3 21.5	21.4	9420	8	1.41	0.085	21.5	19.5	8.375
259	11-8-90-6#3-i-2.5-2-22	A B	90°	Horizontal	A1035	21.9 22.0	21.9	9420	8	1.41	0.085	21.5	19.5	8.375
260	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
261	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
262	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
263	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

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
*No failure; load reached maximum capacity of jacks

Table A.3 Cont. Comprehensive test results and data for No. 11 specimens with two hooks

	Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T lb	T_{Total} lb	T_{avg} lb	f_{su} psi	$f_{su,avg}$ psi	Slip at Failure in.	Failure Type
238	11-5-90-2#3-i-2.5-2-14	A	2.8	2.8	2.5	13.3	2	77700	154840	77420	49800	49600	0.206	FP/SS
		B	2.9		2.3			77200			49500		-	SS
239	(2@5.35) 11-5-90-2#3-i-2.5-13-13	A	2.7	2.6	12.1	6.2	2	68300	138200	69100	43782	44295	-	FP
		B	2.6		12.3			70100			44936			FP
240	11-12-90-2#3-i-2.5-2-17.5	A	2.5	2.5	1.5	13.3	2	133200	260780	130390	85400	83600	-	SS
		B	2.5		2.0			129900			83300		-	SS
241	11-12-90-2#3-i-2.5-2-25	A	2.6	2.8	2.3	13.0	2	211000	422000	211000	135300	135300	-	BY
		B	3.0		2.8			211000			135300		-	BY
242	11-15-90-2#3-i-2.5-2-23	A	2.8	2.8	1.5	13.0	2	232100	419200	209600	148800	134400	-	SB
		B	2.8		1.5			206900			132600		-	SB/FB
243	11-15-90-2#3-i-2.5-2-10.5	A	2.5	2.6	1.0	13.8	2	50600	100100	50100	32400	32100	0.249	FP
		B	2.8		2.3			49600			31800		-	FP/SS
244	11-15-90-2#3-i-2.5-2-10‡	A	2.8	2.9	2.0	13.4	2	64300	128	63900	41218	40962	-	FP
		B	3.0		2.0			63900			40962			FP
245	11-15-90-2#3-i-2.5-2-15‡	A	2.6	2.6	3.0	13.6	2	115600	230	115200	74103	73846	-	FP/SB
		B	2.6		2.8			114800			73590		-	FP/SB
246	11-5-90-2#3-i-3.5-2-17	A	3.6	3.6	2.1	13.4	2	107800	219290	109645	69100	70300	-	SS/FP/TK
		B	3.6		2.0			111500			71500		-	SS
247	11-5-90-2#3-i-3.5-2-14	A	3.8	3.8	1.6	13.3	2	92700	164550	82275	59400	52700	-	FP/SS
		B	3.9		2.8			81800			52400		-	SS/FP/TK
248	11-5-90-5#3-i-2.5-2-14	A	2.8	2.8	1.8	13.4	2	105600	190340	95170	67700	61000	0.397	SS/FP
		B	2.9		2.5			94100			60300		0.375	SS/FP
249	11-5-90-5#3-i-3.5-2-14	A	3.9	3.9	1.4	13.1	2	101300	195980	97990	64900	62800	-	FP/SS
		B	3.9		1.5			94700			60700		-	SS/FP
250	11-8-90-6#3-o-2.5-2-16	A	2.5	2.6	2.3	13.6	2	138900	273500	136800	89000	87700	-	SB/FB
		B	2.6		1.6			134700			86300		-	SB/FB
251	11-8-90-6#3-o-2.5-2-22	A	2.5	2.6	2.9	13.5	2	186100	337600	170200	119300	109100	-	SB
		B	2.6		2.1			170500			109300		-	SB/FB
252	11-12-90-6#3-o-2.5-2-17	A	2.5	2.4	3.6	13.8	2	116400	231800	115900	74600	74300	-	FB/SS
		B	2.4		2.0			147300			94400		-	SB/FB
253	11-12-180-6#3-o-2.5-2-17	A	2.5	2.6	2.9	13.5	2	130000	226200	113100	83300	72500	-	SB
		B	2.8		3.1			113800			72900		0.112	FB/SS
254	11-5-90-6#3-i-2.5-2-20	A	2.6	2.6	2.8	12.9	2	153100	272540	136270	98100	87400	0.274	FP/SS
		B	2.6		3.3			135000			86500		-	FP/SS
255	(2@5.35) 11-5-90-6#3-i-2.5-13-13	A	2.4	2.6	12.0	6.2	2	83800	179500	89700	53718	57500	-	FP
		B	2.8		12.3			96000			61538		-	FP
256	(2@5.35) 11-5-90-6#3-i-2.5-18-18	A	2.7	2.6	16.8	6.2	2	118500	243200	121600	75962	77949		FP
		B	2.6		16.5			128600			82436		-	FP
257	11-8-90-6#3-i-2.5-2-16	A	2.5	2.5	2.8	13.4	2	147500	266000	133000	94600	85300	-	FP/SS
		B	2.5		1.9			129700			83100		-	FP/SS
258	11-8-90-6#3-i-2.5-2-22	A	2.5	2.6	2.8	13.5	2	205000	369100	184600	131400	118300	-	*
		B	2.6		2.6			183200			117400		-	SS
259	11-8-90-6#3-i-2.5-2-22	A	2.6	2.8	2.3	13.4	2	200000	382100	191000	128200	122400	-	*
		B	2.9		2.2			191300			122600		-	SB/FB
260	11-8-90-6#3-i-2.5-2-15	A	2.8	2.6	1.5	13.5	2	142300	216600	108300	91200	69400	-	SS
		B	2.5		2.0			108000			69200		-	SS/FP
261	11-8-90-6#3-i-2.5-2-19	A	2.5	2.6	2.0	13.5	2	182700	290900	145400	117100	93200	-	FB/SS
		B	2.6		1.7			146100			93700		-	FB/SS
262	11-12-90-6#3-i-2.5-2-17	A	2.6	2.8	1.9	13.0	2	179700	323300	161600	115200	103600	0.334	FB/SB
		B	3.0		2.6			162300			104000		-	SP/SS
263	11-12-90-6#3-i-2.5-2-16	A	2.5	2.5	3.3	13.0	2	115100	230390	115195	73800	73800	-	SS/FP
		B	2.5		2.0			127500			81700		0.952	SB/FB

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

*No failure; load reached maximum capacity of jacks

Table A.3 Cont. Comprehensive test results and data for No. 11 specimens with two hooks

	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
238	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
239	(2@5.35) 11-5-90-2#3-i-2.5-13-13	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	7.0	-	-	7.90	60
240	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
241	11-12-90-2#3-i-2.5-2-25	A B	60	0.38	0.2	2	12.00	3.2	16	4.0	0.50	4.0	0.5	1	6.32	60
242	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
243	11-15-90-2#3-i-2.5-2-10.5	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	2.8	-	-	3.16	60
244	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
245	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
246	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
247	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
248	11-5-90-5#3-i-2.5-2-14	A B	60	0.38	0.6	5	4.38	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
249	11-5-90-5#3-i-3.5-2-14	A B	60	0.38	0.6	5	4.38	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
250	11-8-90-6#3-o-2.5-2-16	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.48	60
251	11-8-90-6#3-o-2.5-2-22	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.48	60
252	11-12-90-6#3-o-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	3.5	-	-	4.74	60
253	11-12-180-6#3-o-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	3.5	-	-	4.74	60
254	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
255	(2@5.35) 11-5-90-6#3-i-2.5-13-13	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	7.0	-	-	7.90	60
256	(2@5.35) 11-5-90-6#3-i-2.5-18-18	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	7.0	-	-	7.90	60
257	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
258	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
259	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
260	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
261	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
262	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
263	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

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
*No failure; load reached maximum capacity of jacks

Table A.3 Cont. Comprehensive test results and data for No. 11 specimens with two hooks

	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.
264	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
265	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
266	11-15-90-6#3-i-2.5-2-9.5	A B	90°	Horizontal	A1035	9.0 10.3	9.6	16180	63	1.41	0.085	21.5	19.5	8.375
267	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
268	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
269	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
270	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
271	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
272	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
273	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
274	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
275	11-5-90-5#4s-i-2.5-2-20	A B	90°	Horizontal	A1035	20.0 20.3	20.1	5420	7	1.41	0.085	21.5	19.5	8.375
276	11-5-90-5#4s-i-3.5-2-20	A B	90°	Horizontal	A1035	19.8 19.3	19.5	5960	8	1.41	0.085	23.5	19.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
*No failure; load reached maximum capacity of jacks

Table A.3 Cont. Comprehensive test results and data for No. 11 specimens with two hooks

	Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T lb	T_{Total} lb	T_{avg} lb	f_{su} psi	$f_{su,avg}$ psi	Slip at Failure in.	Failure Type
264	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
265	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
266	11-15-90-6#3-i-2.5-2-9.5	A B	2.5 3.0	2.8	2.5 1.3	13.3	2	58200 56600	114800	57400	37300 36300	36800	0.358 -	FP FP
267	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
268	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
269	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
270	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
271	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
272	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
273	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
274	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
275	11-5-90-5#4s-i-2.5-2-20	A B	2.5 2.8	2.6	2.3 2.0	13.4	2	141400 161600	282090	141045	90600 103600	90400	- -	FP/SS FP/SS
276	11-5-90-5#4s-i-3.5-2-20	A B	3.8 3.8	3.8	2.3 2.8	13.1	2	186700 153500	305930	152965	119700 98400	98100	- -	SS/FP FP/SS

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
*No failure; load reached maximum capacity of jacks

Table A.3 Cont. Comprehensive test results and data for No. 11 specimens with two hooks

	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
264	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
265	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
266	11-15-90-6#3-i-2.5-2-9.5	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	2.3	-	-	3.16	60
267	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
268	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
269	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
270	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
271	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
272	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
273	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
274	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
275	11-5-90-5#4s-i-2.5-2-20	A B	60	0.5	1	5	5.00	4	10	5.0	0.50	5.0	0.375	2	4.74	60
276	11-5-90-5#4s-i-3.5-2-20	A B	60	0.5	1	5	5.00	4	10	5.0	0.50	5.0	0.375	2	4.74	60

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
*No failure; load reached maximum capacity of jacks

Table A.4 Comprehensive test results and data for No. 5 specimens with multiple hooks

	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.
277	(4@4) 5-5-90-0-i-2.5-2-6	A B C D	90°	Horizontal	A1035	5.4 5.3 4.8 5.3	5.2	6430	11	0.625	0.073	13	5.3	8.375
278	(4@4) 5-5-90-0-i-2.5-2-10	A B C D	90°	Horizontal	A1035	9.0 8.0 9.3 9.9	9.0	6470	12	0.625	0.073	13	5.3	8.375
279	(4@4) 5-8-90-0-i-2.5-2-6	A B C D	90°	Horizontal	A1035	6.3 5.8 5.8 6.0	5.9	6950	18	0.625	0.073	13	5.3	8.375
280	(4@6) 5-8-90-0-i-2.5-2-6	A B C D	90°	Horizontal	A1035	6.0 6.0 5.8 6.0	5.9	6693	21	0.625	0.073	17	5.3	8.375
281	(4@6) 5-8-90-0-i-2.5-6-6	A B C D	90°	Horizontal	A1035	6.3 6.3 6.3 6.3	6.3	6693	21	0.625	0.073	17	5.3	8.375
282	(3@4) 5-8-90-0-i-2.5-2-6	A B C	90°	Horizontal	A1035	6.0 5.6 6.0	5.9	6950	18	0.625	0.073	11	5.3	8.375
283	(3@6) 5-8-90-0-i-2.5-2-6	A B C	90°	Horizontal	A1035	6.4 5.9 5.8	6.0	6950	18	0.625	0.073	13	5.3	8.375
284	(4@4) 5-5-90-2#3-i-2.5-2-6	A B C D	90°	Horizontal	A1035	6.3 6.1 6.3 6.4	6.3	6430	11	0.625	0.073	13	5.3	8.375
285	(4@4) 5-5-90-2#3-i-2.5-2-8	A B C D	90°	Horizontal	A1035	8.4 7.8 8.0 7.8	8.0	6430	11	0.625	0.073	13	5.3	8.375
286	(3@6) 5-8-90-5#3-i-2.5-2-6.25	A B C	90°	Horizontal	A1035	5.0 6.3 5.3	5.5	10110	196	0.625	0.073	13	5.3	8.375
287	(3@4) 5-8-90-5#3-i-2.5-2-6‡	A B C	90°	Horizontal	A1035	6.0 6.3 6.0	6.1	6703	22	0.625	0.073	11	5.3	8.375
288	(3@6) 5-8-90-5#3-i-2.5-2-6‡	A B C	90°	Horizontal	A1035	6.0 6.0 6.0	6.0	6703	22	0.625	0.073	13	5.3	8.375
289	(4@4) 5-5-90-5#3-i-2.5-2-7	A B C D	90°	Horizontal	A1035	6.6 7.9 7.5 6.5	7.1	6430	11	0.625	0.073	13	5.3	8.375
290	(4@4) 5-5-90-5#3-i-2.5-2-6	A B C D	90°	Horizontal	A1035	6.0 6.5 6.6 6.3	6.3	6430	11	0.625	0.073	13	5.3	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table A.4 Cont. Comprehensive test results and data for No. 5 specimens with multiple hooks

	Specimen	Hook	c_{so}	$c_{so,avg}$	c_{th}	c_h	N_h	T_{ind}	T_{total}	T	$f_{su,\ ind}$	f_{su}	Slip at Failure	Failure Type
			in.	in.	in.	in.		lb	lb	lb	psi	psi	in.	
277	(4@4) 5-5-90-0-i-2.5-2-6	A	2.4	2.6	2.8	1.9	4	12200	58000	14500	39400	46800	-	FP
		B	4.9		2.9	1.9		16800			54200		-	FP
		C	5.1		3.4	1.8		15500			50000		-	FP
		D	2.8		2.9			13700			44200		-	FP
278	(4@4) 5-5-90-0-i-2.5-2-10	A	2.6	2.7	3.3	1.8	4	27900	113600	28400	90000	91600	-	FP
		B	5.0		4.3	1.9		28600			92300		0.358	FP
		C	5.0		3.0	1.6		44800			144500		-	FP
		D	2.8		2.4	-		27600			89000		-	FP
279	(4@4) 5-8-90-0-i-2.5-2-6	A	2.5	2.5	1.8	1.9	4	17300	61900	15500	55806	50000	-	FP/SS
		B	5.0		2.3	1.6		17600			56774		-	FP/SS
		C	5.0		2.3	1.9		14100			45484		-	FP/SS
		D	2.5		2.0	-		14100			45484		-	FP/SS
280	(4@6) 5-8-90-0-i-2.5-2-6	A	2.7	2.7	2.0	3.1	4	20600	77200	19300	66452	62258	-	FP
		B	6.5		2.0	3.1		22500			72581		-	FP
		C	6.5		2.3	3.1		22900			73871		-	FP
		D	2.7		2.0	-		15100			48710		-	FP
281	(4@6) 5-8-90-0-i-2.5-6-6	A	2.5	2.6	5.8	3.1	4	16100	64200	16100	51935	51935	-	FP/SS
		B	6.3		5.8	3.1		14700			47419		-	FP/SS
		C	6.5		5.8	3.1		16500			53226		-	FP/SS
		D	2.7		5.8	-		16800			54194		-	FP/SS
282	(3@4) 5-8-90-0-i-2.5-2-6	A	2.6	2.6	2.0	1.8	3	18500	50400	16800	59677	54194	-	FP
		B	5.6		2.4	1.9		17600			56774		-	FP
		C	2.7		2.0	-		14700			47419		-	FP
283	(3@6) 5-8-90-0-i-2.5-2-6	A	2.6	2.6	1.6	3.0	3	25500	74700	24900	82258	80323	-	FP
		B	6.2		2.1	3.1		34900			112581		-	FP
		C	2.7		2.3	-		23200			74839		-	FP
284	(4@4) 5-5-90-2#3-i-2.5-2-6	A	2.5	2.5	1.9	1.9	4	22400	85600	21400	72300	69000	-	FP
		B	5.0		2.0	1.9		22200			71600		0.23	FP
		C	4.8		1.9	1.6		24000			77400		-	FP
		D	2.5		1.8	-		21700			70000		0.484	FP
285	(4@4) 5-5-90-2#3-i-2.5-2-8	A	2.5	2.5	1.8	1.9	4	24000	104000	26000	77400	83900	-	FP
		B	5.0		2.4	1.9		31200			100600		0.365	FP
		C	4.9		2.1	1.8		36000			116100		-	FP
		D	2.5		2.4	-		23700			76500		0.398	FP
286	(3@6) 5-8-90-5#3-i-2.5-2-6.25	A	2.5	2.5	3.8	2.9	3	27100	77400	25800	87400	83200	-	FP
		B	5.4		2.6	3.0		32400			104500		-	FP
		C	2.5		3.6	-		26800			86500		-	FP
287	(3@4) 5-8-90-5#3-i-2.5-2-6‡	A	2.5	2.5	2.0	2.1	3	35800	104700	34900	115484	112581	-	FP
		B	5.0		1.8	1.9		34700			111935		-	FP
		C	2.5		2.0	-		34400			110968		-	FP
288	(3@6) 5-8-90-5#3-i-2.5-2-6‡	A	2.5	2.5	2.0	3.4	3	37800	109300	36300	121935	117097	-	FP
		B	5.0		2.0	3.1		34800			112258		-	FP
		C	2.5		2.0	-		37500			120968		-	FP
289	(4@4) 5-5-90-5#3-i-2.5-2-7	A	2.5	2.4	2.5	1.5	4	27300	108400	27100	88100	87400	-	FP
		B	4.6		1.3	2.0		37000			119400		-	FP
		C	4.6		1.6	1.6		29500			95200		-	FP
		D	2.4		2.6	-		23000			74200		-	FP
290	(4@4) 5-5-90-5#3-i-2.5-2-6	A	2.5	2.6	2.5	2.0	4	24900	103600	25900	80300	83500	-	FP
		B	5.1		2.0	1.8		27200			87700		-	FP
		C	5.0		1.9	1.8		26800			86500		0.333	FP
		D	2.6		2.3	-		26600			85800		-	FP

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table A.4 Cont. Comprehensive test results and data for No. 5 specimens with multiple hooks

	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
277	(4@4) 5-5-90-0-i-2.5-2-6	A B C D	60	-	0	-	-	1.10	10	2.0	0.375	2.5	0.375	1	1.27	60
278	(4@4) 5-5-90-0-i-2.5-2-10	A B C D	60	-	0	-	-	1.10	10	2.0	0.375	3.0	0.500	1	1.27	60
279	(4@4) 5-8-90-0-i-2.5-2-6	A B C D	60	0	NA	0	0.0	-	-	-	0.375	3.0	-	-	3.16	60
280	(4@6) 5-8-90-0-i-2.5-2-6	A B C D	60	0	NA	0	0.0	-	-	-	0.375	3.0	-	-	3.16	60
281	(4@6) 5-8-90-0-i-2.5-6-6	A B C D	60	0	NA	0	0.0	-	-	-	0.375	3.0	-	-	4.74	60
282	(3@4) 5-8-90-0-i-2.5-2-6	A B C	60	0	NA	0	0	-	-	-	0.375	3.0	-	-	3.16	60
283	(3@6) 5-8-90-0-i-2.5-2-6	A B C	60	0	NA	0	0	-	-	-	0.375	3.0	-	-	3.16	60
284	(4@4) 5-5-90-2#3-i-2.5-2-6	A B C D	60	0.4	0.2	2	4.0	0.66	6	4.0	0.375	3.0	0.375	2	1.27	60
285	(4@4) 5-5-90-2#3-i-2.5-2-8	A B C D	60	0.4	0.2	2	5.0	1.20	6	2.5	0.375	3.0	0.500	2	1.27	60
286	(3@6) 5-8-90-5#3-i-2.5-2-6.25	A B C	60	0.4	0.6	5	2	-	-	-	0.50	3.0	0.375	1	1.27	60
287	(3@4) 5-8-90-5#3-i-2.5-2-6‡	A B C	60	0.4	0.6	5	2	-	-	-	0.38	3.0	-	-	3.16	120
288	(3@6) 5-8-90-5#3-i-2.5-2-6‡	A B C	60	0.4	0.6	5	2	-	-	-	0.38	3.0	-	-	3.16	120
289	(4@4) 5-5-90-5#3-i-2.5-2-7	A B C D	60	0.4	0.6	5	1.8	0.55	5	1.8	0.375	2.8	0.500	2	1.27	60
290	(4@4) 5-5-90-5#3-i-2.5-2-6	A B C D	60	0.4	0.6	5	2.0	0.55	5	2.0	0.375	3.0	0.375	2	1.27	60

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table A.4 Cont. Comprehensive test results and data for No. 5 specimens with multiple hooks

	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.
291	(4@6) 5-8-90-5#3-i-2.5-2-6‡	A B C D	90°	Horizontal	A1035	6.0 6.0 6.0 6.0	6.0	6693	21	0.625	0.073	17	5.3	8.375
292	(4@6) 5-8-90-5#3-i-2.5-6-6‡	A B C D	90°	Horizontal	A1035	6.8 6.0 6.5 6.3	6.4	6693	21	0.625	0.073	17	5.3	8.375
293	(4@4) 5-8-90-5#3-i-2.5-2-6‡	A B C D	90°	Horizontal	A1035	5.8 5.5 6.3 6.5	6.0	6703	22	0.625	0.073	17	5.3	8.375
294	(3@6) 5-8-90-5#3-i-3.5-2-6.25	A B C	90°	Horizontal	A1035	6.3 6.3 6.3	6.3	10110	196	0.625	0.073	15	5.3	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table A.4 Cont. Comprehensive test results and data for No. 5 specimens with multiple hooks

	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
291	(4@6) 5-8-90-5#3-i-2.5-2-6‡	A B C D	2.7 6.5 6.5 2.7	2.7	2.0 2.0 2.0 2.0	3.4 3.4 3.1 -	4	30300 30100 27600 25300	113300	28300	97742 97097 89032 81613	91290	- - - -	FP FP FP FP
292	(4@6) 5-8-90-5#3-i-2.5-6-6‡	A B C D	2.5 6.5 6.5 2.7	2.6	1.3 2.0 1.5 1.8	3.1 3.1 2.9 -	4	32100 29900 30800 31800	124600	31200	103548 96452 99355 102581	100645	- - - -	FP FP FP FP
293	(4@4) 5-8-90-5#3-i-2.5-2-6‡	A B C D	2.5 5.0 5.0 2.5	2.5	2.3 2.5 1.8 1.5	1.9 1.9 1.9 -	4	28000 27300 28600 26200	110000	27500	90323 88065 92258 84516	88710	- - - -	FP FP FP FP
294	(3@6) 5-8-90-5#3-i-3.5-2-6.25	A B C	3.5 6.6 3.8	3.6	2.1 2.1 2.1	2.6 3.3 -	3	36100 33800 40800	105900	35300	116500 109000 131600	113900	- - 0.454	FP FP FP

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table A.4 Cont. Comprehensive test results and data for No. 5 specimens with multiple hooks

	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
291	(4@6) 5-8-90-5#3-i-2.5-2-6‡	A B C D	60	0.4	0.6	5	1.7	-	-	-	0.375	3.0	-	-	3.16	120
292	(4@6) 5-8-90-5#3-i-2.5-6-6‡	A B C D	60	0.4	0.6	5	1.7	-	-	-	0.375	3.0	-	-	4.74	120
293	(4@4) 5-8-90-5#3-i-2.5-2-6‡	A B C D	60	0.4	0.6	5	1.7	-	-	-	0.375	3.0	-	-	3.16	120
294	(3@6) 5-8-90-5#3-i-3.5-2-6.25	A B C	60	0.4	0.6	5	2	-	-	-	0.50	3.0	0.375	1	1.27	60

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table A.5 Comprehensive test results and data for No. 8 specimens with multiple hooks

	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.
295	(3@5.5) 8-5-90-0-i-2.5-2-16	A B C	90°	Horizontal	A1035[b]	16.5 15.8 16.0	16.1	6255	13	1	0.078	17	10.5	8.375
296	(3@5.5) 8-5-90-0-i-2.5-2-10	A B C	90°	Horizontal	A1035[b]	9.0 9.4 9.8	9.4	6461	14	1	0.078	17	10.5	8.375
297	(3@5.5) 8-5-90-0-i-2.5-2-8‡	A B C	90°	Horizontal	A615	7.5 8.0 8.0	7.8	5730	18	1	0.073	17	10.5	8.375
298	(3@3) 8-5-90-0-i-2.5-2-10‡	A B C	90°	Horizontal	A615	10.0 10.3 10.0	10.1	4490	10	1	0.073	12	10.5	8.375
299	(3@5) 8-5-90-0-i-2.5-2-10‡	A B C	90°	Horizontal	A615	10.3 10.1 10.0	10.1	4490	10	1	0.073	16	10.5	8.375
300	(3@5.5) 8-8-90-0-i-2.5-2-8	A B C	90°	Horizontal	A1035[b]	7.8 8.8 7.3	7.9	8700	24	1	0.078	17	10.5	8.375
301	(3@3) 8-8-90-0-i-2.5-9-9	A B C	90°	Horizontal	A615	9.5 9.5 9.3	9.4	7510	21	1	0.073	12	10.5	8.375
302	(3@4) 8-8-90-0-i-2.5-9-9	A B C	90°	Horizontal	A615	9.3 9.3 9.3	9.3	7510	21	1	0.073	14	10.5	8.375
303	(3@3) 8-12-90-0-i-2.5-2-12‡	A B C	90°	Horizontal	A1035[c]	12.1 12.1 12.2	12.1	11040	31	1	0.073	12	10.5	8.375
304	(3@4) 8-12-90-0-i-2.5-2-12‡	A B C	90°	Horizontal	A1035[c]	12.9 12.5 12.5	12.6	11440	32	1	0.073	14	10.5	8.375
305	(3@5) 8-12-90-0-i-2.5-2-12‡	A B C	90°	Horizontal	A1035[c]	12.3 12.0 12.3	12.2	11460	33	1	0.073	16	10.5	8.375
306	(4@3) 8-8-90-0-i-2.5-9-9	A B C D	90°	Horizontal	A615	9.4 9.3 9.3 9.6	9.4	7510	21	1	0.073	15	10.5	8.375
307	(4@4) 8-8-90-0-i-2.5-9-9	A B C D	90°	Horizontal	A615	9.4 9.1 9.0 9.1	9.2	7510	21	1	0.073	18	10.5	8.375
308	(3@3) 8-5-180-0-i-2.5-2-10‡	A B C	180°	Horizontal	A615	9.8 10.0 9.8	9.8	5260	15	1	0.073	12	10.5	8.375
309	(3@5) 8-5-180-0-i-2.5-2-10‡	A B C	180°	Horizontal	A615	10.0 10.0 10.0	10.0	5260	15	1	0.073	16	10.5	8.375
310	(3@5.5) 8-5-90-2#3-i-2.5-2-14	A B C	90°	Horizontal	A1035[b]	14.6 13.9 14.8	14.4	6460	14	1	0.078	17	10.5	8.375
311	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5	A B C	90°	Horizontal	A1035[b]	9.8 8.8 8.9	9.1	6460	14	1	0.078	17	10.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

Table A.5 Cont. Comprehensive test results and data for No. 8 specimens with multiple hooks

	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	$f_{su,\text{ ind}}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
		A	2.6		1.6	4.4		65300			82700		-	FP
295	(3@5.5) 8-5-90-0-i-2.5-2-16	B	8.0	2.7	2.4	4.5	3	103700	188400	62800	131300	79500	0.191	FP
		C	2.8		2.1	-		46500			58900		-	FP
		A	2.6		3.2	4.4		26800			33900		-	FP
296	(3@5.5) 8-5-90-0-i-2.5-2-10	B	7.9	2.6	2.8	4.4	3	57400	108300	36100	72700	45700	-	FP
		C	2.5		2.4	-		26300			33300		-	FP
		A	2.5		2.5	4.5		30500			38608			FP
297	(3@5.5) 8-5-90-0-i-2.5-2-8‡	B	8.0	2.5	2.0	4.5	3	23300	73200	24400	29494	30886		FP
		C	2.5		2.0	-		19500			24684		0.15	FP
		A	2.6		2.0	2.4		30670			38800		0.09	FP
298	(3@3) 8-5-90-0-i-2.5-2-10‡	B	5.5	2.6	1.8	2.3	3	43700	85500	28500	55300	36100	0.12	FP
		C	2.5		2.0	-		21400			27100		0	FP
		A	2.3		1.8	4.0		56500			71500		0.015	FP
299	(3@5) 8-5-90-0-i-2.5-2-10‡	B	7.3	2.4	1.9	4.3	3	46300	96600	32200	58600	40800	-	FP
		C	2.5		2.0	-		55000			69600		-	FP
		A	3.0		2.4	4.3		41000			51900		-	FP
300	(3@5.5) 8-8-90-0-i-2.5-2-8	B	8.2	2.9	1.4	3.4	3	41000	123000	41000	51900	51900	-	FP
		C	2.8		2.9	-		41000			51900		-	FP
		A	2.5		8.5	2.1		24600			31139			FP
301	(3@3) 8-8-90-0-i-2.5-9-9	B	5.6	2.5	8.5	2.1	3	25000	21300	47200	31646	59747		FP
		C	2.5		8.8	-		14700			18608			FP
		A	2.5		8.8	3.0		29400			37215		0.026	FP
302	(3@4) 8-8-90-0-i-2.5-9-9	B	6.5	2.5	8.8	3.1	3	27400	79100	26400	34684	33418		FP
		C	2.5		8.8	-		22400			28354			FP
		A	2.5		1.8	2.1		56500			71500		0.194	SB
303	(3@3) 8-12-90-0-i-2.5-2-12‡	B	5.4	2.5	1.9	2.0	3	46300	144100	48000	58600	60800	-	FP
		C	2.4		1.8	-		55000			69600		-	FP
		A	2.5		1.3	2.9		56800			71900		0.255	FP/SS
304	(3@4) 8-12-90-0-i-2.5-2-12‡	B	6.4	2.5	1.6	3.0	3	76100	167500	55800	96300	70600	-	FP
		C	2.5		1.6	-		57700			73000		-	FP/SS
		A	2.4		1.8	4.0		53300			67500		-	FP
305	(3@5) 8-12-90-0-i-2.5-2-12‡	B	7.4	2.4	2.0	4.0	3	66100	157100	52400	83700	66300	-	FP
		C	2.5		1.8	-		60800			77000		-	FP
		A	2.5		8.6	2.0		22200			28101			FP
306	(4@3) 8-8-90-0-i-2.5-9-9	B	5.5	2.5	8.8	2.0	4	21200	74600	18700	26835	23671		FP
		C	5.5		8.8	2.0		18300			23165			FP
		D	2.5		8.4	-		13100			16582			FP
		A	2.5		8.6	3.1		20400			25823			FP
307	(4@4) 8-8-90-0-i-2.5-9-9	B	6.6	2.5	8.9	3.1	4	19000	72100	18000	24051	22785		FP
		C	6.5		9.0	3.0		18400			23291			FP
		D	2.5		8.9	-		14300			18101			FP
		A	2.4		2.3	2.0		37000			46835			FP
308	(3@3) 8-5-180-0-i-2.5-2-10‡	B	5.4	2.3	2.0	2.0	3	59800	141700	47200	75696	59747		FP
		C	2.3		2.3	-		44900			56835			FP
		A	2.5		2.0	4.3		41500			52532			FP
309	(3@5) 8-5-180-0-i-2.5-2-10‡	B	7.8	2.5	2.0	4.3	3	60400	137800	45900	76456	58101		FP
		C	2.5		2.0	-		37900			47975		0.123	FP
		A	2.8		1.5	4.4		66800			84600		-	FP
310	(3@5.5) 8-5-90-2#3-i-2.5-2-14	B	8.0	2.6	2.2	4.5	3	65800	171900	57300	83300	72500	-	FP
		C	2.5		1.3	-		62300			78900		-	FP
		A	2.5		0.9	4.3		25200			31900		0.215	FP
311	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5	B	7.8	2.5	1.9	4.3	3	68700	122700	40900	87000	51800	0.285	FP
		C	2.5		1.8	-		39200			49600		-	FP

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

Table A.5 Cont. Comprehensive test results and data for No. 8 specimens with multiple hooks

	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
295	(3@5.5) 8-5-90-0-i-2.5-2-16	A B C	60	-	-	-	-	2.0	10	3	0.50	3.0	0.375	1	3.16	60
296	(3@5.5) 8-5-90-0-i-2.5-2-10	A B C	60	-	-	-	-	2.0	10	3	0.50	3.0	0.500	1	3.16	60
297	(3@5.5) 8-5-90-0-i-2.5-2-8‡	A B C	60	-	-	-	-	-	-	-	0.50	4.0	-	-	6.32	120
298	(3@3) 8-5-90-0-i-2.5-2-10‡	A B C	60	-	-	-	-	-	-	-	0.38	3.0	-	-	3.16	120
299	(3@5) 8-5-90-0-i-2.5-2-10‡	A B C	60	-	-	-	-	-	-	-	0.38	4.0	-	-	3.16	120
300	(3@5.5) 8-8-90-0-i-2.5-2-8	A B C	60	-	-	0	-	2.2	20	3	0.50	1.8	-	-	3.16	60
301	(3@3) 8-8-90-0-i-2.5-9-9	A B C	60	-	-	-	-	-	-	-	0.38	4.0	-	-	4.74	60
302	(3@4) 8-8-90-0-i-2.5-9-9	A B C	60	-	-	-	-	-	-	-	0.38	4.0	-	-	4.74	60
303	(3@3) 8-12-90-0-i-2.5-2-12‡	A B C	60	0.375	-	0	-	-	-	-	0.38	3.0	-	-	3.16	120
304	(3@4) 8-12-90-0-i-2.5-2-12‡	A B C	60	0.375	-	0	-	-	-	-	0.38	3.0	-	-	3.16	120
305	(3@5) 8-12-90-0-i-2.5-2-12‡	A B C	60	0.375	-	0	-	-	-	-	0.38	3.0	-	-	3.16	120
306	(4@3) 8-8-90-0-i-2.5-9-9	A B C D	60	0.375	-	0	3.0	-	-	-	0.375	4.0	-	-	6.32	60
307	(4@4) 8-8-90-0-i-2.5-9-9	A B C D	60	0.375	-	0	0.0	-	-	-	0.375	4.0	-	-	6.32	60
308	(3@3) 8-5-180-0-i-2.5-2-10‡	A B C	60	-	-	-	-	-	-	-	0.50	4.0	-	-	6.32	120
309	(3@5) 8-5-180-0-i-2.5-2-10‡	A B C	60	-	-	-	-	-	-	-	0.50	3.0	-	-	6.32	120
310	(3@5.5) 8-5-90-2#3-i-2.5-2-14	A B C	60	0.375	0.2	2	8	2.0	10	2.5	0.38	3.0	0.500	2	3.16	60
311	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5	A B C	60	0.375	0.2	2	8	2.0	10	2.5	0.38	2.5	0.500	2	1.89	60

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

Table A.5 Cont. Comprehensive test results and data for No. 8 specimens with multiple hooks

	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.
312	(3@5.5) 8-5-90-2#3-i-2.5-2-14(1)	A B C	90°	Horizontal	A1035[c]	14.7 15.2 14.8	14.9	5450	7	1	0.073	17	10.5	8.375
313	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5(1)	A B C	90°	Horizontal	A1035[c]	7.3 8.9 8.4	8.2	5450	7	1	0.073	17	10.5	8.375
314	(3@3) 8-5-90-2#3-i-2.5-2-10‡	A B C	90°	Horizontal	A615	9.9 10.1 10.0	10.0	4760	11	1	0.073	12	10.5	8.375
315	(3@5) 8-5-90-2#3-i-2.5-2-10‡	A B C	90°	Horizontal	A615	10.5 10.6 10.4	10.5	4760	11	1	0.073	16	10.5	8.375
316	(3@3) 8-5-180-2#3-i-2.5-2-10‡	A B C	180°	Horizontal	A615	10.5 10.3 10.0	9.4	5400	16	1	0.073	12	10.5	8.375
317	(3@5) 8-5-180-2#3-i-2.5-2-10‡	A B C	180°	Horizontal	A615	9.6 9.8 9.8	9.4	5400	16	1	0.073	16	10.5	8.375
318	(3@5.5) 8-5-90-5#3-i-2.5-2-8	A B C	90°	Horizontal	A1035[b]	8.0 8.1 7.8	8.0	6620	15	1	0.078	17	10.5	8.375
319	(3@5.5) 8-5-90-5#3-i-2.5-2-12	A B C	90°	Horizontal	A1035[b]	12.4 12.1 12.1	12.2	6620	15	1	0.078	17	10.5	8.375
320	(3@5.5) 8-5-90-5#3-i-2.5-2-8(1)	A B C	90°	Horizontal	A1035[c]	7.3 8.4 7.3	7.6	5660	8	1	0.073	17	10.5	8.375
321	(3@5.5) 8-5-90-5#3-i-2.5-2-12(1)	A B C	90°	Horizontal	A1035[c]	11.4 12.5 12.0	12.0	5660	8	1	0.073	17	10.5	8.375
322	(3@5.5) 8-5-90-5#3-i-2.5-2-8(2)‡	A B C	90°	Horizontal	A615	8.0 8.0 8.5	8.2	5730	18	1	0.073	17	10.5	8.375
323	(3@3) 8-5-90-5#3-i-2.5-2-10‡	A B C	90°	Horizontal	A615	10.0 9.8 9.9	9.9	4810	12	1	0.073	12	10.5	8.375
324	(3@5) 8-5-90-5#3-i-2.5-2-10‡	A B C	90°	Horizontal	A615	10.0 10.0 9.8	9.9	4850	13	1	0.073	16	10.5	8.375
325	(3@3) 8-8-90-5#3-i-2.5-9-9	A B C	90°	Horizontal	A615	9.5 9.0 9.5	9.3	7440	22	1	0.073	12	10.5	8.375
326	(3@4) 8-8-90-5#3-i-2.5-9-9	A B C	90°	Horizontal	A615	8.9 9.1 9.3	9.1	7440	22	1	0.073	14	10.5	8.375
327	(3@3) 8-12-90-5#3-i-2.5-2-12‡	A B C	90°	Horizontal	A1035[c]	11.9 11.9 11.6	11.8	11040	31	1	0.073	12	10.5	8.375
328	(3@4) 8-12-90-5#3-i-2.5-2-12‡	A B C	90°	Horizontal	A1035[c]	12.5 12.0 12.5	12.3	11440	32	1	0.073	14	10.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

Table A.5 Cont. Comprehensive test results and data for No. 8 specimens with multiple hooks

	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	$f_{su,\text{ ind}}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
		A	2.8		1.7	4.2		58700			74300		-	FP/TK
312	(3@5.5) 8-5-90-2#3-i-2.5-2-14(1)	B	7.9	2.7	1.2	4.3	3	97100	196000	65300	122900	82700	-	FP/TK
		C	2.6		1.6	-		70200			88900		-	FP/TK
		A	2.3		3.5	4.5		36600			46300		-	FP
313	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5(1)	B	7.9	2.5	1.8	4.3	3	43600	97100	32400	55200	41000	-	FP
		C	2.6		2.3	-		35200			44600		-	FP
		A	2.6		2.1	2.0		41000			51900		0.26	FP
314	(3@3) 8-5-90-2#3-i-2.5-2-10‡	B	5.6	2.6	1.9	2.0	3	41000	122200	40700	51900	51500	0.18	FP
		C	2.5		2.0	-		37000			46800		-	FP
		A	2.5		1.5	4.5		43300			54800		0.26	FP
315	(3@5) 8-5-90-2#3-i-2.5-2-10‡	B	8.0	2.6	1.4	3.9	3	54600	134000	44700	69100	56600	0.26	FP
		C	2.8		1.6	-		42800			54200		-	FP
		A	2.5		1.5	2.0		59800			75696			FP
316	(3@3) 8-5-180-2#3-i-2.5-2-10‡	B	5.5	2.6	1.8	2.0	3	56100	163700	54600	71013	69114		FP
		C	2.8		2.0	-		47800			60506		0.32	FP
		A	2.5		2.4	4.2		59300			75063			FP
317	(3@5) 8-5-180-2#3-i-2.5-2-10‡	B	7.8	2.4	2.3	4.2	3	49300	154500	51500	62405	65190		FP
		C	2.3		2.3	-		45800			57975		0.14	FP
		A	2.5		2.2	4.1		30600			38700		0.388	FP
318	(3@5.5) 8-5-90-5#3-i-2.5-2-8	B	7.6	2.5	2.1	4.5	3	47000	111300	37100	59500	47000	0.477	FP
		C	2.5		2.4	-		34100			43200		-	FP
		A	2.5		1.8	4.3		60300			76300		0.198	FP
319	(3@5.5) 8-5-90-5#3-i-2.5-2-12	B	7.8	2.5	2.1	4.5	3	110800	198300	66100	140300	83700	-	FP
		C	2.5		2.1	-		59300			75100		-	FP
		A	2.9		2.9	3.8		29800			37700		-	FP
320	(3@5.5) 8-5-90-5#3-i-2.5-2-8(1)	B	7.6	2.9	1.8	4.1	3	30200	94100	31400	38200	39700	0.297	FP
		C	2.9		2.9	-		34700			43900		0.381	FP
		A	2.5		2.8	4.3		55500			70300		-	FP
321	(3@5.5) 8-5-90-5#3-i-2.5-2-12(1)	B	7.8	2.6	1.7	4.5	3	74600	143600	47900	94400	60600	0.435	FP
		C	2.6		2.2	-		44400			56200		0.927	FP
		A	2.8		2.0	4.5		57000			72152			FP
322	(3@5.5) 8-5-90-5#3-i-2.5-2-8(2)‡	B	8.0	2.5	2.0	4.5	3	43300	144000	48000	54810	60759		FP
		C	2.3		1.5	-		43000			54430		0.54	FP
		A	2.8		2.0	2.1		48000			60800		-	FP
323	(3@3) 8-5-90-5#3-i-2.5-2-10‡	B	5.9	2.5	2.3	2.1	3	44000	141800	47300	55700	59900	0.13	FP
		C	2.3		2.1	-		48000			60800		0	FP
		A	2.5		2.0	4.0		58900			74600		-	FP
324	(3@5) 8-5-90-5#3-i-2.5-2-10‡	B	7.5	2.6	2.0	4.0	3	63400	183900	61300	80300	77600	-	FP
		C	2.8		2.3	-		69400			87800		-	FP
		A	2.5		8.5	2.0		43300			54810			FP
325	(3@3) 8-8-90-5#3-i-2.5-9-9	B	5.5	2.5	9.0	2.0	3	49700	119300	39800	62911	50380		FP
		C	2.5		8.5	-		37200			47089			FP
		A	2.5		9.1	3.0		48500			61392		0.1	FP
326	(3@4) 8-8-90-5#3-i-2.5-9-9	B	6.5	2.5	8.9	3.0	3	38600	109700	36600	48861	46329		FP
		C	2.5		8.8	-		32000			40506			FP
		A	2.5		2.3	2.0		70400			89100		0.302	FP
327	(3@3) 8-12-90-5#3-i-2.5-2-12‡	B	5.5	2.5	2.3	2.0	3	85000	186600	62200	107600	78700	0.256	FP
		C	2.5		2.5	-		62100			78600		0.251	FP
		A	2.5		1.8	2.8		70700			89500		0.262	FP
328	(3@4) 8-12-90-5#3-i-2.5-2-12‡	B	6.3	2.5	2.3	3.0	3	100000	194800	64900	126600	82200	-	FP
		C	2.5		1.8	-		63700			80600		0.205	FP

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

Table A.5 Cont. Comprehensive test results and data for No. 8 specimens with multiple hooks

	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
312	(3@5.5) 8-5-90-2#3-i-2.5-2-14(1)	A B C	60	0.375	0.2	2	6	1.6	8	3	0.38	2.5	0.375	2	3.16	60
313	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5(1)	A B C	60	0.375	0.2	2	6	2.0	10	3	0.50	2.5	0.375	1	3.16	60
314	(3@3) 8-5-90-2#3-i-2.5-2-10‡	A B C	60	0.375	0.2	2	3	-	-	-	0.50	5.0	-	-	4.74	120
315	(3@5) 8-5-90-2#3-i-2.5-2-10‡	A B C	60	0.375	0.2	2	3	-	-	-	0.38	3.0	-	-	3.16	120
316	(3@3) 8-5-180-2#3-i-2.5-2-10‡	A B C	60	0.375	0.2	2	3	-	-	-	0.50	4.0	-	-	6.32	120
317	(3@5) 8-5-180-2#3-i-2.5-2-10‡	A B C	60	0.375	0.2	2	3	-	-	-	0.50	3.0	-	-	6.32	120
318	(3@5.5) 8-5-90-5#3-i-2.5-2-8	A B C	60	0.375	0.6	5	3	2.0	10	3.3	0.38	2.5	0.500	2	1.89	60
319	(3@5.5) 8-5-90-5#3-i-2.5-2-12	A B C	60	0.375	0.6	5	3	2.0	10	3.2	0.38	2.5	0.500	2	1.27	60
320	(3@5.5) 8-5-90-5#3-i-2.5-2-8(1)	A B C	60	0.375	0.6	5	3	2.0	10	3	0.50	2.5	0.375	1	3.16	60
321	(3@5.5) 8-5-90-5#3-i-2.5-2-12(1)	A B C	60	0.375	0.6	5	3	1.0	5	2.8	0.50	3.5	0.500	1	3.16	60
322	(3@5.5) 8-5-90-5#3-i-2.5-2-8(2)‡	A B C	60	0.375	0.6	5	3	-	-	-	0.50	4.0	-	-	6.32	120
323	(3@3) 8-5-90-5#3-i-2.5-2-10‡	A B C	60	0.375	0.6	5	3	-	-	-	0.50	4.0	-	-	4.74	120
324	(3@5) 8-5-90-5#3-i-2.5-2-10‡	A B C	60	0.375	0.6	5	3	-	-	-	0.38	3.0	-	-	3.95	120
325	(3@3) 8-8-90-5#3-i-2.5-9-9	A B C	60	0.375	0.6	5	3	-	-	-	0.38	4.0	-	-	4.74	60
326	(3@4) 8-8-90-5#3-i-2.5-9-9	A B C	60	0.375	0.6	5	3	-	-	-	0.38	4.0	-	-	4.74	60
327	(3@3) 8-12-90-5#3-i-2.5-2-12‡	A B C	60	0.375	0.6	5	3	-	-	-	0.38	3.0	-	-	3.16	120
328	(3@4) 8-12-90-5#3-i-2.5-2-12‡	A B C	60	0.375	0.6	5	3	-	-	-	0.38	3.0	-	-	3.16	120

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

Table A.5 Cont. Comprehensive test results and data for No. 8 specimens with multiple hooks

	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.
329	(3@5) 8-12-90-5#3-i-2.5-2-12‡	A B C	90°	Horizontal	A1035[c]	11.9 12.4 12.3	12.2	11460	33	1	0.073	16	10.5	8.375
330	(4@3)8-8-90-5#3-i-2.5-9-9	A B C D	90°	Horizontal	A615	9.3 9.3 9.3 9.3	9.3	7440	22	1	0.073	15	10.5	8.375
331	(4@4) 8-8-90-5#3-i-2.5-9-9	A B C D	90°	Horizontal	A615	9.5 9.5 9.3 9.6	9.5	7440	22	1	0.073	18	10.5	8.375
332	(3@3) 8-5-180-5#3-i-2.5-2-10‡	A B C	180°	Horizontal	A615	10.1 9.9 9.8	9.9	5540	17	1	0.073	12	10.5	8.375
333	(3@5) 8-5-180-5#3-i-2.5-2-10‡	A B C	180°	Horizontal	A615	9.9 9.8 9.5	9.7	5540	17	1	0.073	16	10.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

Table A.5 Cont. Comprehensive test results and data for No. 8 specimens with multiple hooks

	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	$f_{su,\ ind}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
329	(3@5) 8-12-90-5#3-i-2.5-2-12‡	A B C	2.5 7.5 2.5	2.5	2.2 1.7 1.8	4.0 4.0 -	3	59400 85500 69200	194300	64800	75200 108200 87600	82000	- - 0.18	FP FP FP
330	(4@3)8-8-90-5#3-i-2.5-9-9	A B C D	2.5 5.5 5.5 2.5	2.5	8.8 8.8 8.8 8.8	2.0 2.3 2.0 -	4	32900 38700 27300 26800	125800	31400	41646 48987 34557 33924	39747		FP FP FP FP
331	(4@4) 8-8-90-5#3-i-2.5-9-9	A B C D	2.5 6.5 6.5 2.5	2.5	8.5 8.5 8.8 8.4	3.0 3.0 3.0 -	4	33700 30700 27900 25700	117900	29500	42658 38861 35316 32532	37342		FP FP FP FP
332	(3@3) 8-5-180-5#3-i-2.5-2-10‡	A B C	2.8 5.8 2.8	2.8	1.9 2.1 2.3	2.0 2.0 -	3	50300 67400 67000	176600	58900	63671 85316 84810	74557	 0.269	FP FP FP
333	(3@5) 8-5-180-5#3-i-2.5-2-10‡	A B C	2.3 7.0 2.8	2.5	2.1 2.3 2.5	3.8 4.0 -	3	55000 60900 59900	176000	58700	69620 77089 75823	74304	 0.382	FP FP FP

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

Table A.5 Cont. Comprehensive test results and data for No. 8 specimens with multiple hooks

	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
329	(3@5) 8-12-90-5#3-i-2.5-2-12‡	A B C	60	0.375	0.6	5	3	-	-	-	0.38	3.0	-	-	3.16	120
330	(4@3)8-8-90-5#3-i-2.5-9-9	A B C D	60	0.375	0.6	5	3.0	-	-	-	0.375	4.0	-	-	4.74	60
331	(4@4) 8-8-90-5#3-i-2.5-9-9	A B C D	60	0.375	0.6	5	3.0	-	-	-	0.375	4.0	-	-	4.74	60
332	(3@3) 8-5-180-5#3-i-2.5-2-10‡	A B C	60	0.375	0.6	5	3	-	-	-	0.50	4.0	-	-	6.32	120
333	(3@5) 8-5-180-5#3-i-2.5-2-10‡	A B C	60	0.375	0.6	5	3	-	-	-	0.50	3.0	-	-	6.32	120

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

Table A.6 Comprehensive test results and data for No. 11 specimens with multiple hooks

	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.
334	(3@5.35) 11-5-90-0-i-2.5-13-13	A B C	90°	Horizontal	A615	13.8 14.3 13.5	13.8	5330	11	1.41	0.085	21.5	19.5	8.375
335	(3@5.35) 11-5-90-2#3-i-2.5-13-13	A B C	90°	Horizontal	A615	14.0 14.0 13.8	13.9	5330	11	1.41	0.085	21.5	19.5	8.375
336	(3@5.35) 11-5-90-6#3-i-2.5-13-13	A B C	90°	Horizontal	A615	13.5 13.5 13.8	13.6	5280	12	1.41	0.085	21.5	19.5	8.375
337	(3@5.35) 11-5-90-6#3-i-2.5-18-18	A B C	90°	Horizontal	A1035	18.6 18.6 18.6	18.6	5280	12	1.41	0.085	21.5	19.5	8.375

Table A.6 Cont. Comprehensive test results and data for No. 11 specimens with multiple hooks

	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	$f_{su,\ ind}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
334	(3@5.35) 11-5-90-0-i-2.5-13-13	A B C	2.6 10.0 2.6	2.6	12.3 11.8 12.5	6.6 6.3 -	3	45 50 59	155	51500	29103 31987 38013	33013	0.113 - -	FP FP FP
335	(3@5.35) 11-5-90-2#3-i-2.5-13-13	A B C	2.6 10.0 2.6	2.6	12.0 12.0 12.3	6.1 6.1 -	3	51 59 65	174	57900	32628 37500 41346	37115	- - -	FP FP FP
336	(3@5.35) 11-5-90-6#3-i-2.5-13-13	A B C	2.6 10.0 2.7	2.6	12.5 12.5 12.3	6.0 5.8 -	3	60 66 72	199	66200	38205 42308 46346	42436	- - -	FP FP FP
337	(3@5.35) 11-5-90-6#3-i-2.5-18-18	A B C	2.5 10.0 2.8	2.7	17.4 17.4 17.4	6.1 5.6 -	3	103 148 114	336	111900	66218 94744 73013	71731	- - -	FP FP FP

Table A.6 Cont. Comprehensive test results and data for No. 11 specimens with multiple hooks

	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
334	(3@5.35) 11-5-90-0-i-2.5-13-13	A B C	60	-	-	-	-	-	-	-	0.50	7.0	-	-	7.90	60
335	(3@5.35) 11-5-90-2#3-i-2.5-13-13	A B C	60	0.375	0.22	2	8	-	-	-	0.50	7.0	-	-	7.90	60
336	(3@5.35) 11-5-90-6#3-i-2.5-13-13	A B C	60	0.375	0.66	6	4	-	-	-	0.50	7.0	-	-	7.90	60
337	(3@5.35) 11-5-90-6#3-i-2.5-18-18	A B C	60	0.375	0.66	6	4	-	-	-	0.50	7.0	-	-	7.90	60

Table A.7 Test results for other researchers referenced in this study

		Specimen	Bend Angle	ℓ_{eh} in.	f_{cm} psi	f_y psi	d_b in.	b in.	h_{cl} in.	h_c in.	c_{so} in.	c_{th} in.	c_h in.	N_h	A_h in.^{2}	d_{tr} in.	A_{tr}† in.^{2}	N_{tr}	s_{tr} in.	T lb
Marques and Jirsa (1975)	338	J7-180-12-1H	180°	10.0	4350	64000	0.88	12	11.5	6	2.88	2.0	4.5	2	0.60	-	-	-	-	36600
	339	J7-180-15-1 H	180°	13.0	4000	64000	0.88	12	11.5	6	2.88	2.0	4.5	2	0.60	-	-	-	-	52200
	340	J7-90-12-1H	90°	10.0	4150	64000	0.88	12	11.5	6	2.88	2.0	4.5	2	0.60	-	-	-	-	37200
	341	J7-90-15-1-H	90°	13.0	4600	64000	0.88	12	11.5	6	2.88	2.0	4.5	2	0.60	-	-	-	-	54600
	342	J7-90-15-1- L	90°	13.0	4800	64000	0.88	12	11.5	6	2.88	2.0	4.5	2	0.60	-	-	-	-	58200
	343	J7-90-15-1M	90°	13.0	5050	64000	0.88	12	11.5	6	2.88	2.0	4.5	2	0.60	-	-	-	-	60000
	344	J11-180-15-1H	180°	13.1	4400	68000	1.41	12	11.3	6	2.88	1.5	3.4	2	1.56	-	-	-	-	70200
	345	J11-90-12-1H	90°	10.1	4600	68000	1.41	12	11.3	6	2.88	1.5	3.4	2	1.56	-	-	-	-	65520
	346	J11-90-15-1H	90°	13.1	4900	68000	1.41	12	11.3	6	2.88	1.5	3.4	2	1.56	-	-	-	-	74880
	347	J11-90-15-1L	90°	13.1	4750	68000	1.41	12	11.3	6	2.88	1.5	3.4	2	1.56	-	-	-	-	81120
Pinc et al. (1977)	348	9-12	90°	10.0	4700	65000	1.13	12	*	*	2.88	2	4	2	1.0	-	-	-		47000
	349	9-18	90°	16.0	4700	65000	1.13	12	*	*	2.88	2	4	2	1.0	-	-	-		74000
	350	11-24	90°	22.1	4200	60000	1.41	12	*	*	2.88	2	3.4	2	1.56	-	-	-		120120
	351	11-15	90°	13.1	5400	60000	1.41	12	*	*	2.88	2	3.4	2	1.56	-	-	-		78000
	352	11-18	90°	16.1	4700	60000	1.41	12	*	*	2.88	2	3.4	2	1.56	-	-	-		90480
	353	11-21	90°	19.1	5200	60000	1.41	12	*	*	2.88	2	3.4	2	1.56	-	-	-		113880
Johnson & Jirsa (1981)	354	4-3.5-8-M	90°	2.0	4500	67500	0.5	24	6	4	11.75	1.5	-	1	0.2	-	-	-	-	4400
	355	4-5-11-M	90°	3.5	4500	67500	0.5	24	9	4	11.75	1.5	-	1	0.2	-	-	-	-	12000
	356	4-5-14-M	90°	3.5	4500	67500	0.5	24	12	4	11.75	1.5	-	1	0.2	-	-	-	-	9800
	357	7-5-8-L	90°	3.5	2500	67500	0.88	24	6	4	11.56	1.5	-	1	0.6	-	-	-	-	13000
	358	7-5-8-M	90°	3.5	4600	67500	0.88	24	6	4	11.56	1.5	-	1	0.6	-	-	-	-	16500
	359	7-5-8-H	90°	3.5	5450	67500	0.88	24	6	4	11.56	1.5	-	1	0.6	-	-	-	-	19500
	360	7-5-14-L	90°	3.5	2500	67500	0.88	24	12	4	11.56	1.5	-	1	0.6	-	-	-	-	8500
	361	7-5-14-M	90°	3.5	4100	67500	0.88	24	12	4	11.56	1.5	-	1	0.6	-	-	-	-	11200
	362	7-5-14-H	90°	3.5	5450	67500	0.88	24	12	4	11.56	1.5	-	1	0.6	-	-	-	-	11900
	363	7-7-8-M	90°	5.5	4480	67500	0.88	24	6	4	11.56	1.5	-	1	0.6	-	-	-	-	32000
	364	7-7-11-M	90°	5.5	4480	67500	0.88	24	9	4	11.56	1.5	-	1	0.6	-	-	-	-	27000
	365	7-7-14-M	90°	5.5	5450	67500	0.88	24	12	4	11.56	1.5	-	1	0.6	-	-	-	-	22000
	366	9-7-11-M	90°	5.5	4500	67500	1.13	24	9	4	11.44	1.5	-	1	1	-	-	-	-	30800
	367	9-7-14-M	90°	5.5	5450	67500	1.13	24	12	4	11.44	1.5	-	1	1	-	-	-	-	24800
	368	9-7-18-M	90°	5.5	4570	67500	1.13	24	16	4	11.44	1.5	-	1	1	-	-	-	-	22300
	369	7-8-11-M	90°	6.5	5400	67500	0.88	24	9	4	11.56	1.5	-	1	1	-	-	-	-	34800
	370	7-8-14-M	90°	6.5	4100	67500	0.88	24	12	4	11.56	1.5	-	1	1	-	-	-	-	26500
	371	9-8-14-M	90°	6.5	5400	67500	1.13	24	12	4	11.44	1.5	-	1	1	-	-	-	-	30700
	372	11-8.5-11-L	90°	7.0	2400	67500	1.41	24	9	4	11.30	1.5	-	1	1.56	-	-	-	-	37000
	373	11-8.5-11-M	90°	7.0	4800	67500	1.41	24	9	4	11.30	1.5	-	1	1.56	-	-	-	-	51500
	374	11-8.5-11-H	90°	7.0	5450	67500	1.41	24	9	4	11.30	1.5	-	1	1.56	-	-	-	-	54800
	375	11-8.5-14-L	90°	7.0	2400	67500	1.41	24	12	4	11.30	1.5	-	1	1.56	-	-	-	-	31000
	376	11-8.5-14-M	90°	7.0	4750	67500	1.41	24	12	4	11.30	1.5	-	1	1.56	-	-	-	-	39000
	377	11-8.5-14-H	90°	7.0	5450	67500	1.41	24	12	4	11.30	1.5	-	1	1.56	-	-	-	-	45500
	378	7-7-11-M	90°	5.5	3800	67500	0.875	72	9	4	24.56	1.5	11	3	0.6	-	-	-	-	24000
	379	7-7-11-L	90°	5.5	3000	67500	0.875	72	9	4	14.06	1.5	22	3	0.6	-	-	-	-	22700
	380	11-8.5-11-M	90°	7.0	3800	67500	1.41	72	9	4	24.30	1.5	11	3	1.56	-	-	-	-	38000
	381	11-8.5-11-L	90°	7.0	3000	67500	1.41	72	9	4	13.80	1.5	22	3	1.56	-	-	-	-	40000
	382	7-5-8-M	90°	5.5	3640	67500	0.88	24	6	4	11.56	1.5	-	1	0.6	-	-	-	-	14700
	383	7-5-14-M	90°	5.5	3640	67500	0.88	24	12	4	11.56	1.5	-	1	0.6	-	-	-	-	11300

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

Table A.7 Cont. Test results for other researchers referenced in this study

		Specimen	Bend Angle	ℓ_{eh} in.	f_{cm} psi	f_y psi	d_b in.	b in.	h_{cl} in.	h_c in.	c_{so} in.	c_{th} in.	c_h in.	N_h	A_h in.^{2}	d_{tr} in.	A_{tr}† in.^{2}	N_{tr}	s_{tr} in.	T lb
Hamad et al. (1993)	384	7-90-U	90°	10.0	2570	60000[a]	0.88	12	11	6	3	2	4.25	2	0.60	-	-	-	-	25998
	385	7-90-U'	90°	10.0	5400	60000[a]	0.88	12	11	6	3	2	4.25	2	0.60	-	-	-	-	36732
	386	11-90-U	90°	13.0	2570	60000[a]	1.41	12	11	6	3	2	3.18	2	1.56	-	-	-	-	48048
	387	11-90-U'	90°	13.0	5400	60000[a]	1.41	12	11	6	3	2	3.18	2	1.56	-	-	-	-	75005
	388	11-180-U-HS	180°	13.0	7200	60000[a]	1.41	12	11	6	3	2	3.18	2	1.56	-	-	-	-	58843
	389	11-90-U-HS	90°	13.0	7200	60000[a]	1.41	12	11	6	3	2	3.18	2	1.56	-	-	-	-	73788
	390	11-90-U-T6	90°	13.0	3700	60000[a]	1.41	12	11	6	3	2	3.18	2	1.56	0.375	0.88	4	6	71807
Ramirez & Russel (2008)	391	I-1	90°	6.5	8910	81900	0.75	15	12	6	2.5	2.5	8.5	2	0.44	-	-	-	-	30000
	392	I-3	90°	6.5	12460	81900	0.75	15	12	6	2.5	2.5	8.5	2	0.44	-	-	-	-	30000
	393	I-5	90°	6.5	12850	81900	0.75	15	12	6	2.5	2.5	8.5	2	0.44	-	-	-	-	30500
	394	I-2	90°	12.5	8910	63100	1.41	15	12	6	2.5	2.5	7.18	2	1.56	-	-	-	-	88000
	395	I-2'	90°	15.5	9540	63100	1.41	15	12	6	2.5	2.5	7.18	2	1.56	-	-	-	-	105000
	396	I-4	90°	12.5	12460	63100	1.41	15	12	6	2.5	2.5	7.18	2	1.56	-	-	-	-	99100
	397	I-6	90°	12.5	12850	63100	1.41	15	12	6	2.5	2.5	7.18	2	1.56	-	-	-	-	114000
	398	III-13	90°	6.5	13980	81900	0.75	15	12	6	2.5	2.5	8.5	2	0.44	0.375	0.44	4	7.5	41300
	399	III-15	90°	6.5	16350	81900	0.75	15	12	6	2.5	2.5	8.5	2	0.44	0.375	0.44	4	7.5	38500
	400	III-14	90°	12.5	13980	63100	1.41	15	12	6	2.5	2.5	7.18	2	1.56	0.375	0.66	6	7.5	105000
	401	III-16	90°	12.5	16500	63100	1.41	15	12	6	2.5	2.5	7.18	2	1.56	0.375	0.66	6	7.5	120000
Lee & Park (2010)	402	H1	90°	18.7	4450	87000	0.88	14.6	*	*	3	2	7	2	0.6	-	-	-	-	86345
	403	H2	90°	11.9	8270	87000	0.88	14.6	*	*	3	2	7	2	0.6	-	-	-	-	76992
	404	H3	90°	15.0	4450	87000	0.88	14.6	*	*	3	2	7	2	0.6	0.375	0.55	4	2.63	53761

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

APPENDIX B: DATA TABLES OF SPECIMENS USED IN CHAPTER 4 ANALYSIS

Table B.1 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 B.1 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} ksi	$f_{su,avg}$ ksi	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 .330(.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 .178(.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 .146(.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 .237(.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	- .369(.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	- .329(.028)	FP/SS FP

† Specimens had constant 80 kip axial load

Table B.1 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
5-5-90-0-i-2.5-2-7	A B	60	-	-	-	-	0.80	4	2.5	0.500	3.50	-	-	1.27	60
5-8-90-0-i-2.5-2-6†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
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
5-15-90-0-i-2.5-2-7.5	A B	60	-	-	-	-	-	-	-	0.375	3.50	-	-	3.16	60
5-5-90-0-i-3.5-2-7	A B	60	-	-	-	-	0.80	4	2.5	0.375	3.50	-	-	1.27	60
5-8-90-0-i-3.5-2-6†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
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
5-8-90-0-i-3.5-2-8†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
5-8-180-0-i-2.5-2-7	A B	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60
5-8-180-0-i-3.5-2-7	A B	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60
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
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
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
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
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
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
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
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
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
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
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
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
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
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

† Specimens had constant 80 kip axial load

Table B.1 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 3

Table B.1 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
8-5-90-0-i-2.5-2-9.5†	A B	2.8 2.5	2.6	3.0 1.8	9.5	2	44600 65800	88970	44485	56500 83300	56300	- -	FP SS
8-5-90-0-i-2.5-2-12.5†	A B	2.8 2.8	2.8	1.3 1.3	9.8	2	65300 69900	131640	65820	82700 88500	83300	- -	SS/B SS
8-5-90-0-i-2.5-2-13	A B	2.5 2.5	2.5	2.0 1.8	9.8	2	73100 65200	131080	65540	92500 82500	83000	- -	SS FP/SS
8-8-90-0-i-2.5-2-10	A B	2.8 2.9	2.8	2.3 2.5	9.0	2	50000 52900	102910	51455	63300 67000	65100	0.195 0.185	FP FP
8-12-90-0-i-2.5-2-9	A B	2.8 2.6	2.7	2.4 2.4	9.6	2	50800 54800	99850	49925	64300 69400	63200	0.219	FP/SS SS/FP
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
8-12-90-0-i-2.5-2-12	A B	2.5 2.4	2.5	1.9 1.9	9.8	2	70700 65800	131800	65900	89500 83300	83400	- 0.0119	SB/FP FB/SS
8-15-90-0-i-2.5-2-13	A B	2.4 2.5	2.4	2.1 2.0	9.9	2	77200 79000	156200	78100	97700 100000	98900	- -	FB/SB FB
8-5-90-0-i-3.5-2-13	A B	3.6 3.4	3.5	1.9 1.9	9.4	2	69400 68300	136200	68100	87800 86500	86200	- -	FP/SS SS/FP
8-8-90-0-i-3.5-2-10	A B	3.8 3.8	3.8	3.3 1.3	9.0	2	55200 71900	111130	55565	69900 91000	70300	0.195 0.242	FP/SS SS/FP
8-12-90-0-i-3.5-2-9	A B	3.5 3.8	3.6	2.4 2.1	9.8	2	61400 68500	120480	60240	77700 86700	76300	0.434	FP FP/SS
8-5-180-0-i-2.5-2-11†	A B	3.0 2.8	2.9	2.0 2.0	9.8	2	45600 50500	92290	46145	57700 63900	58400	0.275 -	SS/FP SS
8-5-180-0-i-2.5-2-14†	A B	2.8 2.6	2.7	2.0 2.0	9.8	2	49400 69400	98300	49150	62500 87800	62200	0.088 0.096	SS SS
8-8-180-0-i-2.5-2-11.5	A B	3.0 3.0	3.0	4.5 4.5	9.5	2	62800 80200	125600	62800	79500 101500	79500	- -	FP/SB FP/SS
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
8-5-180-0-i-3.5-2-11†	A B	3.8 3.8	3.8	1.4 1.4	10.0	2	58600 60500	118580	59290	74200 76600	75100	0.372 0.239	FP/SS SS
8-5-180-0-i-3.5-2-14†	A B	3.9 3.8	3.8	1.6 2.1	9.8	2	63700 78000	127010	63505	80600 98700	80400	- -	SS FB/SS
8-15-180-0-i-2.5-2-13.5	A B	2.5 2.5	2.5	2.0 2.3	10.0	2	90700 89100	179800	89900	114800 112800	113800	- -	- FB/SB
8-5-90-2#3-i-2.5-2-12.5†	A B	2.8 2.8	2.8	2.6 2.6	9.5	2	74100 76300	144130	72065	93800 96600	91200	- -	FP FP/SS
8-5-90-2#3-i-2.5-2-14	A B	2.8 3.0	2.9	2.6 2.1	9.3	2	77000 77500	153930	76965	97500 98100	97400		SS/FP FP/SS
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
8-15-90-2#3-i-2.5-2-11	A B	2.5 2.5	2.5	1.9 2.4	10.0	2	99000 83600	166600	83300	125300 105800	105400	- 0.123	FB FB
8-5-90-2#3-i-3.5-2-13	A B	3.1 3.6	3.4	1.5 1.8	10.3	2	81200 86900	160720	80360	102800 110000	101700	- -	SS/FP SS/FP
8-5-180-2#3-i-2.5-2-11†	A B	2.8 2.5	2.6	2.3 2.5	9.5	2	64200 61900	120470	60235	81300 78400	76200	0.26 0.087	SS/FP SS/FP
8-5-180-2#3-i-2.5-2-14†	A B	2.8 2.8	2.8	2.5 2.0	9.8	2	87100 76900	152560	76280	110300 97300	96600	0.774 0.199	FP FP/SS

† Specimens had constant 80 kip axial load

Table B.1 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
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
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
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
8-8-90-0-i-2.5-2-10	A B	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60
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
8-12-90-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60
8-12-90-0-i-2.5-2-12	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.16	60
8-15-90-0-i-2.5-2-13	A B	60	-	-	-	-	-	-	-	0.38	5.00	-	-	4.74	60
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
8-8-90-0-i-3.5-2-10	A B	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60
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
8-5-180-0-i-2.5-2-11†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
8-5-180-0-i-2.5-2-14†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
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
8-12-180-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60
8-5-180-0-i-3.5-2-11†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
8-5-180-0-i-3.5-2-14†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
8-15-180-0-i-2.5-2-13.5	A B	60	-	-	-	-	-	-	-	0.50	4.00	-	-	4.74	60
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
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
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
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
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
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
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

† Specimens had constant 80 kip axial load

Table B.1 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 3

Table B.1 Cont. Test results for specimens used in bend angle analysis

Specimen	Hook	c_{so}	$c_{so,avg}$	c_{th}	c_h	N_h	T_{ind}	T_{total}	T	f_{su}	$f_{su,avg}$	Slip at Failure	Failure Type
		in.	in.	in.	in.		lb	lb	lb	psi	psi	in.	
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 .25(.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	0.44 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	- 0.25	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 B.1 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
8-8-180-2#3-i-2.5-2-11.5	A B	60	0.38	0.2	2	3.00	-	-	-	0.50	3.00	-	-	3.16	60
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
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
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
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
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
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
8-5-90-5#3-i-2.5-2-10a†	B	60	0.375	0.55	5	3.00	1.10	10	3.0	0.63	3.50	-	-	3.16	60
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
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
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
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
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
11-8-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.48	60
11-8-90-0-i-2.5-2-21	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
11-8-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60
11-12-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
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
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
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
11-8-180-0-i-2.5-2-21	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
11-8-180-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60

† Specimens had constant 80 kip axial load

Table B.1 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 B.1 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 B.1 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
11-12-180-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
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
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
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
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
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
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
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
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
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
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
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

Table B.2 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 B.2 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 B.3 Test results for specimens used in side cover 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-2.5-2-10	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 B.3 Cont. Test results for specimens used in side cover 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} ksi	$f_{su,avg}$ ksi	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 .330(.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 .178(.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 .146(.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 .237(.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

Table B.3 Cont. Test results for specimens used in side cover 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
5-5-90-0-i-2.5-2-10	A B	60	-	-	-	-	0.33	3	3.0	0.375	3.00	-	-	1.89	60
5-5-90-0-i-2.5-2-7	A B	60	-	-	-	-	0.80	4	2.5	0.500	3.50	-	-	1.27	60
5-8-90-0-i-2.5-2-6†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
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
5-8-90-0-i-2.5-2-8†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
5-12-90-0-i-2.5-2-10	A B	60	-	-	-	-	0.11	1	7.0	0.375	5.00	-	-	1.89	60
5-12-90-0-i-2.5-2-5	A B	60	-	-	-	-	0.66	6	2.5	0.500	3.00	-	-	1.27	60
5-15-90-0-i-2.5-2-5.5	A B	60	-	-	-	-	-	-	-	0.375	2.50	-	-	1.27	60
5-15-90-0-i-2.5-2-7.5	A B	60	-	-	-	-	-	-	-	0.375	3.50	-	-	3.16	60
5-5-90-0-i-3.5-2-10	A B	60	-	-	-	-	0.33	3	3.0	0.375	3.00	-	-	1.89	60
5-5-90-0-i-3.5-2-7	A B	60	-	-	-	-	0.80	4	2.5	0.375	3.50	-	-	1.27	60
5-8-90-0-i-3.5-2-6†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
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
5-8-90-0-i-3.5-2-8†	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
5-12-90-0-i-3.5-2-5	A B	60	-	-	-	-	0.66	6	2.5	0.500	3.00	-	-	1.27	60
5-8-180-0-i-2.5-2-7	A B	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60
5-8-180-0-i-3.5-2-7	A B	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60
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
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
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
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
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
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
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
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

† Specimens had constant 80 kip axial load

Table B.3 Cont. Test results for specimens used in side cover 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.
5-5-90-2#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 3

Table B.3 Cont. Test results for specimens used in side cover 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} ksi	$f_{su,avg}$ ksi	Slip at Failure in.	Failure Type
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
5-12-90-2#3-i-3.5-2-5	A B	3.8 3.5	3.6	1.8 2.2	6.6	2	27900 28900	56730	28365	90000 93200	91500	- 0.349	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	- .369(.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	- .329(.028)	FP/SS FP
5-5-90-5#3-i-2.5-2-7	A B	2.8 2.8	2.8	3.6 2.3	6.5	2	32100 31300	63390	31695	103500 101000	102200	- -	FP FP/SS
5-12-90-5#3-i-2.5-2-5	A B	2.6 2.6	2.6	2.1 1.5	6.5	2	33900 34900	68840	34420	109400 112600	111000	0.292 0.295	FP/SS SS/FP
5-15-90-5#3-i-2.5-2-4	A B	2.4 2.5	2.4	2.2 1.9	6.6	2	31300 31300	62600	31360	101000 101000	101200	0.603 0.378	FP FP
5-15-90-5#3-i-2.5-2-5	A B	2.4 2.3	2.4	2.1 1.9	6.8	2	38600 46200	78300	39200	124500 149000	126500	- -	FP BY
5-5-90-5#3-i-3.5-2-7	A B	3.4 3.5	3.4	2.0 2.8	7.0	2	44300 35200	72050	36025	142900 113500	116200	- -	FP FP
5-12-90-5#3-i-3.5-2-5	A B	3.3 3.3	3.3	2.5 1.5	6.6	2	31500 31300	60880	30440	101600 101000	98200	- -	FP FP
8-5-90-0-i-2.5-2-16†	A B	2.8 2.8	2.8	1.8 1.4	9.5	2	83300 86100	166480	83240	105400 109000	105400	- -	FP/SB FB/TK
8-5-90-0-i-2.5-2-9.5†	A B	2.8 2.5	2.6	3.0 1.8	9.5	2	44600 65800	88970	44485	56500 83300	56300	- -	FP SS
8-5-90-0-i-2.5-2-12.5†	A B	2.8 2.8	2.8	1.3 1.3	9.8	2	65300 69900	131640	65820	82700 88500	83300	- -	SS/B SS
8-5-90-0-i-2.5-2-18	A B	2.5 2.5	2.5	0.8 2.4	10.5	2	100200 79800	161760	80880	126800 101000	102400	- 0.153	FB/SS/TK FB/SS/TK
8-5-90-0-i-2.5-2-13	A B	2.5 2.5	2.5	2.0 1.8	9.8	2	73100 65200	131080	65540	92500 82500	83000	- -	SS FP/SS
8-5-90-0-i-2.5-2-15(1)	A B	2.5 2.6	2.5	2.8 2.0	9.6	2	64500 87300	127530	63765	81600 110500	80700	- -	FB/SB SB
8-5-90-0-i-2.5-2-15	A B	2.5 2.6	2.6	2.0 2.9	9.5	2	76300 80700	150960	75480	96600 102200	95500		SS/FP SB/FP
8-8-90-0-i-2.5-2-8	A B	2.8 2.9	2.8	1.1 2.0	8.6	2	54700 45200	90490	45245	69200 57200	57300	- -	FP/TK FP/SS
8-8-90-0-i-2.5-2-10	A B	2.8 2.9	2.8	2.3 2.5	9.0	2	50000 52900	102910	51455	63300 67000	65100	0.195 0.185	FP FP
8-8-90-0-i-2.5-2-8(1)	A B	2.8 2.8	2.8	2.8 2.8	9.5	2	38000 37700	73640	36820	48100 47700	46600	0.387 0.229	FP/SS FP/SS
8-8-90-0-i-2.5-2-9‡	A B	2.5 2.8	2.6	1.5 1.5	10.0	2	35500 34700	70	35100	44937 43924	44430	0.104 0	FB FB

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table B.3 Cont. Test results for specimens used in side cover 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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
8-5-90-0-i-2.5-2-16†	A B	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60
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
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
8-5-90-0-i-2.5-2-18	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	1	3.78	60
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
8-5-90-0-i-2.5-2-15(1)	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60
8-5-90-0-i-2.5-2-15	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60
8-8-90-0-i-2.5-2-8	A B	60	-	-	-	-	1.60	8	4.0	0.50	1.75	-	-	3.16	60
8-8-90-0-i-2.5-2-10	A B	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60
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
8-8-90-0-i-2.5sc-2tc-9‡	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.16	60

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table B.3 Cont. Test results for specimens used in side cover 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.
8-12-90-0-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 3

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

† Specimens had constant 80 kip axial load

Table B.3 Cont. Test results for specimens used in side cover 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
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
8-12-90-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60
8-12-90-0-i-2.5-2-12	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.16	60
8-15-90-0-i-2.5-2-8.5	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.78	60
8-15-90-0-i-2.5-2-13	A B	60	-	-	-	-	-	-	-	0.38	5.00	-	-	4.74	60
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
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
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
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
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
8-8-90-0-i-3.5-2-10	A B	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60
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
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
8-5-180-0-i-2.5-2-11[†]	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
8-5-180-0-i-2.5-2-14[†]	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
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
8-12-180-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60
8-5-180-0-i-3.5-2-11[†]	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
8-5-180-0-i-3.5-2-14[†]	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
8-15-180-0-i-2.5-2-13.5	A B	60	-	-	-	-	-	-	-	0.50	4.00	-	-	4.74	60
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
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
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
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
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

[†] Specimens had constant 80 kip axial load

Table B.3 Cont. Test results for specimens used in side cover 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.
8-8-90-2#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 3

Table B.3 Cont. Test results for specimens used in side cover 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
8-8-90-2#3-i-2.5-2-8	A B	3.0 2.9	2.9	2.0 1.5	9.0	2	46200 55400	95750	47875	58500 70100	60600	- -	FP/SS FP/SS
8-8-90-2#3-i-2.5-2-10	A B	2.8 2.8	2.8	2.1 2.5	8.5	2	60700 67000	122050	61025	76800 84800	77200	0.186 0.152	FP FB
8-12-90-2#3-i-2.5-2-9	A B	2.9 2.6	2.8	2.3 2.3	9.5	2	61800 60300	122030	61015	78200 76300	77200	0.345 0.361	FP/SS SS/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
8-15-90-2#3-i-2.5-2-6	A B	2.5 2.4	2.4	2.3 1.8	9.9	2	37400 37700	75100	37600	47300 47700	47600	- -	FP FP
8-15-90-2#3-i-2.5-2-11	A B	2.5 2.5	2.5	1.9 2.4	10.0	2	99000 83600	166600	83300	125300 105800	105400	- 0.123	FB FB
8-5-90-2#3-i-3.5-2-17	A B	3.3 3.5	3.4	1.8 2.3	10.1	2	102600 88600	179830	89915	129900 112200	113800	- -	SS SS/FP
8-5-90-2#3-i-3.5-2-13	A B	3.1 3.6	3.4	1.5 1.8	10.3	2	81200 86900	160720	80360	102800 110000	101700	- -	SS/FP SS/FP
8-8-90-2#3-i-3.5-2-8	A B	3.6 3.8	3.7	2.0 1.9	8.5	2	48300 49300	97550	48775	61100 62400	61700	0.31 .340(.147)	FP FP
8-8-90-2#3-i-3.5-2-10	A B	3.6 3.8	3.7	3.3 3.3	8.5	2	54000 53800	107770	53885	68400 68100	68200	- -	SS FP
8-12-90-2#3-i-3.5-2-9	A B	3.6 4.0	3.8	2.3 2.4	9.6	2	50300 49300	99550	49775	63700 62400	63000	0.15	FP/SS FP/SS
8-5-180-2#3-i-2.5-2-11†	A B	2.8 2.5	2.6	2.3 2.5	9.5	2	64200 61900	120470	60235	81300 78400	76200	0.26 0.087	SS/FP SS/FP
8-5-180-2#3-i-2.5-2-14†	A B	2.8 2.8	2.8	2.5 2.0	9.8	2	87100 76900	152560	76280	110300 97300	96600	0.774 0.199	FP FP/SS
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 .25(.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-2.5-2-15	A B	2.8 2.5	2.6	1.9 1.4	9.9	2	77100 72600	146750	73375	97600 91900	92900	0.196 -	FP/SS FP/SS
8-5-90-5#3-i-2.5-2-13	A B	2.5 2.4	2.4	1.5 1.8	10.3	2	93100 81300	164750	82375	117800 102900	104300	- -	SS/FP FP/SS
8-5-90-5#3-i-2.5-2-12(1)	A B	2.5 2.5	2.5	2.6 3.0	9.8	2	66700 75900	132730	66365	84400 96100	84000	- -	SS/FP SS/FP

† Specimens had constant 80 kip axial load

Table B.3 Cont. Test results for specimens used in side cover 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
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
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
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
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
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
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
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
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
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
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
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
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
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
8-8-180-2#3-i-2.5-2-11.5	A B	60	0.38	0.2	2	3.00	-	-	-	0.50	3.00	-	-	3.16	60
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
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
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
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
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
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
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
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
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

† Specimens had constant 80 kip axial load

Table B.3 Cont. Test results for specimens used in side cover 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.
8-5-90-5#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 3

Table B.3 Cont. Test results for specimens used in side cover 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
8-5-90-5#3-i-2.5-2-12	A B	2.5 2.4	2.4	3.0 2.0	9.8	2	84900 72000	156900	84900	107500 91100	107500	- -	SS SS
8-5-90-5#3-i-2.5-2-12(2)	A B	2.5 2.6	2.6	1.8 2.1	9.0	2	72400 77400	142940	71470	91600 98000	90500	- -	FP/SS FP/SS
8-5-90-5#3-i-2.5-2-8	A B	2.8 2.9	2.8	2.6 2.9	9.0	2	48000 47000	94960	47480	60800 59500	60100	- 0.321	FP 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 B	2.9 2.8	2.8	2.8 2.8	8.5	2	56000 51200	100530	50265	70900 64800	63600	0.3 .375 (.092)	FP FP
8-8-90-5#3-i-2.5-2-9‡	A B	2.8 3.3	3.0	2.4 2.0	9.8	2	64800 64800	129	64390	82025 82025	81506	0.047 -	FB FB
8-12-90-5#3-i-2.5-2-9	A B	2.5 2.6	2.6	2.5 2.5	9.5	2	66500 63100	129510	64755	84200 79900	82000	0.224 0.252	FP/SS 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	0.44 0.547	FB/SS SS/FP
8-12-90-5#3-i-2.5-2-12‡	A B	2.4 2.5	2.4	2.0 1.9	10.0	2	90500 86500	175400	87700	114600 109500	111000	- -	FB/SS SS/FP
8-15-90-5#3-i-2.5-2-6	A B	2.6 2.6	2.6	1.8 2.2	9.8	2	48300 48700	97000	48500	61100 61600	61400	- -	FP 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
8-5-90-5#3-i-3.5-2-15	A B	3.6 3.5	3.5	1.3 1.3	10.3	2	81200 87100	160680	80340	102800 110300	101700	.214(.026) -	SS/FP SS/FP
8-5-90-5#3-i-3.5-2-13	A B	3.4 3.5	3.4	2.1 2.4	10.4	2	89600 76000	154140	77070	113400 96200	97600	- -	SS SS/FP
8-5-90-5#3-i-3.5-2-12(1)	A B	3.5 3.4	3.5	1.6 2.1	9.8	2	78900 75900	152860	76430	99900 96100	96700	- -	SS/FP SS
8-5-90-5#3-i-3.5-2-12	A B	3.4 3.5	3.4	1.7 2.4	9.8	2	79200 79300	158300	79150	100300 100400	100200	 0.162	FP FP/SS
8-8-90-5#3-i-3.5-2-8	A B	3.5 3.6	3.6	2.0 2.0	8.9	2	55400 56200	111620	55810	70100 71100	70600	- -	FP FP
8-12-90-5#3-i-3.5-2-9*	A B	3.3 3.4	3.3	2.5 2.5	9.5	2	68800 82200	135660	67830	87100 104100	85900	 0.415	FP/SS FP/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
11-5-90-0-i-2.5-2-26	A B	2.5 2.9	2.7	2.1 2.1	13.3	2	165700 146800	297450	148725	106200 94100	95300	- -	FB/SS FB/SS/TK
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

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table B.3 Cont. Test results for specimens used in side cover 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
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
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
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
8-5-90-5#3-i-2.5-2-10a†	B	60	0.375	0.55	5	3.00	1.10	10	3.0	0.63	3.50	-	-	3.16	60
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
11-8-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.48	60

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table B.3 Cont. Test results for specimens used in side cover 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.
11-8-90-0-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 B.3 Cont. Test results for specimens used in side cover 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
11-8-90-0-i-2.5-2-21	A	2.5	2.6	3.4	13.0	2	127060	250250	125120	81400	80200	-	FP/TK
	B	2.8		2.3			147900			94800		-	FB
11-8-90-0-i-2.5-2-17	A	2.5	2.5	3.0	13.5	2	105630	209560	104780	67700	67200	-	SS
	B	2.5		1.1			115170			73800		-	FP
11-12-90-0-i-2.5-2-17	A	2.5	2.6	3.1	13.3	2	148400	239400	119700	95100	76700	-	SB
	B	2.6		2.4			120400			77200		-	SB/FP
11-12-90-0-i-2.5-2-17.5	A	3.8	3.1	2.1	13.8	2	123600	249240	124620	79200	79900	-	SS/TK
	B	2.5		2.0			125600			80500		0.25	SS
11-12-90-0-i-2.5-2-25	A	2.5	2.5	2.4	13.1	2	205100	399490	199745	131500	128000	-	SB
	B	2.5		2.9			198100			127000		-	SB
11-15-90-0-i-2.5-2-24	A	2.5	2.5	2.0	13.5	2	212600	426500	213300	136300	136700	-	SB/TK
	B	2.5		1.3			231300			148300		-	SB/TK
11-15-90-0-i-2.5-2-10‡	A	2.8	2.7	2.5	13.6	2	52100	103	51500	33397	33013	-	FP
	B	2.7		2.5			50900			32628		-	FP
11-15-90-0-i-2.5-2-15‡	A	2.8	2.8	3.0	13.0	2	93300	184	92200	59808	59103	-	SB
	B	2.8		3.0			91000			58333		-	SB
11-5-90-0-i-3.5-2-17	A	4.0	3.9	1.8	13.1	2	105000	216240	108120	67300	69300	0.187	SS/TK
	B	3.9		2.5			117600			75400		-	SS
11-5-90-0-i-3.5-2-14	A	3.8	3.8	1.5	13.3	2	82600	139030	69515	52900	44600	-	FP/SS
	B	3.9		1.0			69000			44200		-	FP/SS/TK
11-5-90-0-i-3.5-2-26	A	3.8	3.8	2.1	13.5	2	198300	364510	182255	127100	116800	-	SB/FB
	B	3.8		2.6			181700			116500		-	FB/SB
11-8-180-0-i-2.5-2-21	A	2.9	2.7	1.8	13.0	2	137800	256250	128125	88300	82100	-	FB
	B	2.4		2.2			126800			81300		-	FB/SB
11-8-180-0-i-2.5-2-17	A	2.4	2.4	1.4	13.8	2	101710	200910	100450	65200	64400	-	FP
	B	2.5		1.1			121270			77700		-	FB
11-12-180-0-i-2.5-2-17	A	3.0	2.8	2.5	13.3	2	106700	214900	107500	68400	68900	0.156	SB/FP
	B	2.5		2.5			108200			69400		-	SS
11-5-90-2#3-i-2.5-2-17	A	2.5	2.6	2.3	13.4	2	108400	201390	100695	69500	64500	-	SS/FP
	B	2.6		1.8			103200			66200		-	SS/FP
11-5-90-2#3-i-2.5-2-14	A	2.8	2.8	2.5	13.3	2	77700	154840	77420	49800	49600	0.206	FP/SS
	B	2.9		2.3			77200			49500		-	SS
11-12-90-2#3-i-2.5-2-17.5	A	2.5	2.5	1.5	13.3	2	133200	260780	130390	85400	83600	-	SS
	B	2.5		2.0			129900			83300		-	SS
11-15-90-2#3-i-2.5-2-23	A	2.8	2.8	1.5	13.0	2	232100	419200	209600	148800	134400	-	SB
	B	2.8		1.5			206900			132600		-	SB/FB
11-15-90-2#3-i-2.5-2-10‡	A	2.8	2.9	2.0	13.4	2	64300	128	63900	41218	40962	-	FP
	B	3.0		2.0			63900			40962			FP
11-15-90-2#3-i-2.5-2-15‡	A	2.6	2.6	3.0	13.6	2	115600	230	115200	74103	73846	-	FP/SB
	B	2.6		2.8			114800			73590		-	FP/SB
11-5-90-2#3-i-3.5-2-17	A	3.6	3.6	2.1	13.4	2	107800	219290	109645	69100	70300	-	SS/FP/TK
	B	3.6		2.0			111500			71500		-	SS
11-5-90-2#3-i-3.5-2-14	A	3.8	3.8	1.6	13.3	2	92700	164550	82275	59400	52700	-	FP/SS
	B	3.9		2.8			81800			52400		-	SS/FP/TK
11-5-90-6#3-i-2.5-2-20	A	2.6	2.6	2.8	12.9	2	153100	272540	136270	98100	87400	0.274	FP/SS
	B	2.6		3.3			135000			86500		-	FP/SS
11-8-90-6#3-i-2.5-2-16	A	2.5	2.5	2.8	13.4	2	147500	266000	133000	94600	85300	-	FP/SS
	B	2.5		1.9			129700			83100		-	FP/SS
11-8-90-6#3-i-2.5-2-22	A	2.5	2.6	2.8	13.5	2	205000	369100	184600	131400	118300	-	*
	B	2.6		2.6			183200			117400		-	SS

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table B.3 Cont. Test results for specimens used in side cover 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
11-8-90-0-i-2.5-2-21	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
11-8-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60
11-12-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
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
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
11-15-90-0-i-2.5-2-24	A B	60	-	-	-	-	-	-	-	0.50	3.5	-	-	6.32	60
11-15-90-0-i-2.5-2-10‡	A B	60	-	-	-	-	-	-	-	0.50	4.5	-	-	6.94	120
11-15-90-0-i-2.5-2-15‡	A B	60	-	-	-	-	-	-	-	0.50	4.5	-	-	6.94	120
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
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
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
11-8-180-0-i-2.5-2-21	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
11-8-180-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60
11-12-180-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
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
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
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
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
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
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
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
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
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
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
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

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table B.3 Cont. Test results for specimens used in side cover 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.
11-8-90-6#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 B.3 Cont. Test results for specimens used in side cover 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
11-8-90-6#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

Table B.3 Cont. Test results for specimens used in side cover 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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table B.4 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 3

Table B.4 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	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	- 0.13	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	0.44 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 B.4 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
8-12-90-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60
8-12-180-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60
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
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
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
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
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
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
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
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
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
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

APPENDIX C: MONTE CARLO ANALYSIS

Table C.1 Hooked Bars without Confining Reinforcement

Beam No.	N_h	ℓ_{dh}*	f_s	d_b	A_b	f'_c
1	2	7.06	60000	0.75	0.44	4000
2	2	10.87	60000	1	0.79	4000
3	2	13.03	60000	1.128	1	4000
4	2	18.20	60000	1.41	1.56	4000
5	2	6.38	60000	0.75	0.44	6000
6	2	9.82	60000	1	0.79	6000
7	2	11.77	60000	1.128	1	6000
8	2	16.45	60000	1.41	1.56	6000
9	2	5.94	60000	0.75	0.44	8000
10	2	9.14	60000	1	0.79	8000
11	2	10.95	60000	1.128	1	8000
12	2	15.31	60000	1.41	1.56	8000
13	2	5.62	60000	0.75	0.44	10000
14	2	8.65	60000	1	0.79	10000
15	2	10.36	60000	1.128	1	10000
16	2	14.48	60000	1.41	1.56	10000
17	2	5.37	60000	0.75	0.44	12000
18	2	8.26	60000	1	0.79	12000
19	2	9.90	60000	1.128	1	12000
20	2	13.83	60000	1.41	1.56	12000
21	2	5.07	60000	0.75	0.44	15000
22	2	7.81	60000	1	0.79	15000
23	2	9.36	60000	1.128	1	15000
24	2	13.08	60000	1.41	1.56	15000
25	2	9.42	80000	0.75	0.44	4000
26	2	14.50	80000	1	0.79	4000
27	2	17.37	80000	1.128	1	4000
28	2	24.27	80000	1.41	1.56	4000
29	2	8.51	80000	0.75	0.44	6000
30	2	13.10	80000	1	0.79	6000
31	2	15.69	80000	1.128	1	6000
32	2	21.93	80000	1.41	1.56	6000
33	2	7.92	80000	0.75	0.44	8000
34	2	12.19	80000	1	0.79	8000
35	2	14.60	80000	1.128	1	8000
36	2	20.41	80000	1.41	1.56	8000
37	2	7.49	80000	0.75	0.44	10000
38	2	11.53	80000	1	0.79	10000
39	2	13.81	80000	1.128	1	10000
40	2	19.30	80000	1.41	1.56	10000
41	2	7.15	80000	0.75	0.44	12000
42	2	11.02	80000	1	0.79	12000
43	2	13.20	80000	1.128	1	12000
44	2	18.44	80000	1.41	1.56	12000
45	2	6.77	80000	0.75	0.44	15000
46	2	10.42	80000	1	0.79	15000
47	2	12.48	80000	1.128	1	15000
48	2	17.44	80000	1.41	1.56	15000

*Values were calculated using Eq. (5.4)

Table C.1 Cont. Hooked Bars without Confining Reinforcement

Beam No.	N_h	ℓ_{dh}*	f_s	d_b	A_b	f'_c
49	2	11.77	100000	0.75	0.44	4000
50	2	18.12	100000	1	0.79	4000
51	2	21.71	100000	1.128	1	4000
52	2	30.34	100000	1.41	1.56	4000
53	2	10.64	100000	0.75	0.44	6000
54	2	16.37	100000	1	0.79	6000
55	2	19.62	100000	1.128	1	6000
56	2	27.41	100000	1.41	1.56	6000
57	2	9.90	100000	0.75	0.44	8000
58	2	15.24	100000	1	0.79	8000
59	2	18.26	100000	1.128	1	8000
60	2	25.51	100000	1.41	1.56	8000
61	2	9.36	100000	0.75	0.44	10000
62	2	14.41	100000	1	0.79	10000
63	2	17.26	100000	1.128	1	10000
64	2	24.13	100000	1.41	1.56	10000
65	2	8.94	100000	0.75	0.44	12000
66	2	13.77	100000	1	0.79	12000
67	2	16.50	100000	1.128	1	12000
68	2	23.05	100000	1.41	1.56	12000
69	2	8.46	100000	0.75	0.44	15000
70	2	13.02	100000	1	0.79	15000
71	2	15.60	100000	1.128	1	15000
72	2	21.80	100000	1.41	1.56	15000
73	2	14.12	120000	0.75	0.44	4000
74	2	21.75	120000	1	0.79	4000
75	2	26.05	120000	1.128	1	4000
76	2	36.41	120000	1.41	1.56	4000
77	2	12.76	120000	0.75	0.44	6000
78	2	19.65	120000	1	0.79	6000
79	2	23.54	120000	1.128	1	6000
80	2	32.90	120000	1.41	1.56	6000
81	2	11.88	120000	0.75	0.44	8000
82	2	18.29	120000	1	0.79	8000
83	2	21.91	120000	1.128	1	8000
84	2	30.61	120000	1.41	1.56	8000
85	2	11.23	120000	0.75	0.44	10000
86	2	17.29	120000	1	0.79	10000
87	2	20.72	120000	1.128	1	10000
88	2	28.95	120000	1.41	1.56	10000
89	2	10.73	120000	0.75	0.44	12000
90	2	16.52	120000	1	0.79	12000
91	2	19.79	120000	1.128	1	12000
92	2	27.66	120000	1.41	1.56	12000
93	2	10.15	120000	0.75	0.44	15000
94	2	15.63	120000	1	0.79	15000
95	2	18.72	120000	1.128	1	15000
96	2	26.16	120000	1.41	1.56	15000

*Values were calculated using Eq. (5.4)

Table C.2 Hooked Bars with 1 No. 3 Tie Oriented Horizontally as Confining Reinforcement

Beam No.	N_h	ℓ_{dh}*	f_s	d_b	A_b	f'_c	A_{tr}	N/n
97	2	5.84	60000	0.75	0.44	4000	0.11	1
98	2	9.66	60000	1	0.79	4000	0.11	1
99	2	11.81	60000	1.128	1	4000	0.11	1
100	2	16.99	60000	1.41	1.56	4000	0.11	1
101	2	5.28	60000	0.75	0.44	6000	0.11	1
102	2	8.72	60000	1	0.79	6000	0.11	1
103	2	10.67	60000	1.128	1	6000	0.11	1
104	2	15.35	60000	1.41	1.56	6000	0.11	1
105	2	4.91	60000	0.75	0.44	8000	0.11	1
106	2	8.12	60000	1	0.79	8000	0.11	1
107	2	9.93	60000	1.128	1	8000	0.11	1
108	2	14.28	60000	1.41	1.56	8000	0.11	1
109	2	4.65	60000	0.75	0.44	10000	0.11	1
110	2	7.68	60000	1	0.79	10000	0.11	1
111	2	9.39	60000	1.128	1	10000	0.11	1
112	2	13.51	60000	1.41	1.56	10000	0.11	1
113	2	4.44	60000	0.75	0.44	12000	0.11	1
114	2	7.34	60000	1	0.79	12000	0.11	1
115	2	8.97	60000	1.128	1	12000	0.11	1
116	2	12.91	60000	1.41	1.56	12000	0.11	1
117	2	4.20	60000	0.75	0.44	15000	0.11	1
118	2	6.94	60000	1	0.79	15000	0.11	1
119	2	8.49	60000	1.128	1	15000	0.11	1
120	2	12.21	60000	1.41	1.56	15000	0.11	1
121	2	8.20	80000	0.75	0.44	4000	0.11	1
122	2	13.28	80000	1	0.79	4000	0.11	1
123	2	16.15	80000	1.128	1	4000	0.11	1
124	2	23.05	80000	1.41	1.56	4000	0.11	1
125	2	7.41	80000	0.75	0.44	6000	0.11	1
126	2	12.00	80000	1	0.79	6000	0.11	1
127	2	14.59	80000	1.128	1	6000	0.11	1
128	2	20.83	80000	1.41	1.56	6000	0.11	1
129	2	6.89	80000	0.75	0.44	8000	0.11	1
130	2	11.17	80000	1	0.79	8000	0.11	1
131	2	13.58	80000	1.128	1	8000	0.11	1
132	2	19.39	80000	1.41	1.56	8000	0.11	1
133	2	6.52	80000	0.75	0.44	10000	0.11	1
134	2	10.56	80000	1	0.79	10000	0.11	1
135	2	12.84	80000	1.128	1	10000	0.11	1
136	2	18.33	80000	1.41	1.56	10000	0.11	1
137	2	6.23	80000	0.75	0.44	12000	0.11	1
138	2	10.09	80000	1	0.79	12000	0.11	1
139	2	12.27	80000	1.128	1	12000	0.11	1
140	2	17.52	80000	1.41	1.56	12000	0.11	1
141	2	5.89	80000	0.75	0.44	15000	0.11	1
142	2	9.54	80000	1	0.79	15000	0.11	1
143	2	11.61	80000	1.128	1	15000	0.11	1
144	2	16.57	80000	1.41	1.56	15000	0.11	1

*Values were calculated using Eq. (5.4)

Table C.2 Cont. Hooked Bars with 1 No. 3 Tie Oriented Horizontally as Confining Reinforcement

Beam No.	N_h	ℓ_{dh}*	f_s	d_b	A_b	f'_c	A_{tr}	N/n
145	2	10.55	100000	0.75	0.44	4000	0.11	1
146	2	16.90	100000	1	0.79	4000	0.11	1
147	2	20.49	100000	1.128	1	4000	0.11	1
148	2	29.12	100000	1.41	1.56	4000	0.11	1
149	2	9.54	100000	0.75	0.44	6000	0.11	1
150	2	15.27	100000	1	0.79	6000	0.11	1
151	2	18.52	100000	1.128	1	6000	0.11	1
152	2	26.31	100000	1.41	1.56	6000	0.11	1
153	2	8.87	100000	0.75	0.44	8000	0.11	1
154	2	14.21	100000	1	0.79	8000	0.11	1
155	2	17.23	100000	1.128	1	8000	0.11	1
156	2	24.49	100000	1.41	1.56	8000	0.11	1
157	2	8.39	100000	0.75	0.44	10000	0.11	1
158	2	13.44	100000	1	0.79	10000	0.11	1
159	2	16.30	100000	1.128	1	10000	0.11	1
160	2	23.16	100000	1.41	1.56	10000	0.11	1
161	2	8.02	100000	0.75	0.44	12000	0.11	1
162	2	12.84	100000	1	0.79	12000	0.11	1
163	2	15.57	100000	1.128	1	12000	0.11	1
164	2	22.13	100000	1.41	1.56	12000	0.11	1
165	2	7.58	100000	0.75	0.44	15000	0.11	1
166	2	12.15	100000	1	0.79	15000	0.11	1
167	2	14.73	100000	1.128	1	15000	0.11	1
168	2	20.93	100000	1.41	1.56	15000	0.11	1
169	2	12.91	120000	0.75	0.44	4000	0.11	1
170	2	20.53	120000	1	0.79	4000	0.11	1
171	2	24.83	120000	1.128	1	4000	0.11	1
172	2	35.19	120000	1.41	1.56	4000	0.11	1
173	2	11.66	120000	0.75	0.44	6000	0.11	1
174	2	18.55	120000	1	0.79	6000	0.11	1
175	2	22.44	120000	1.128	1	6000	0.11	1
176	2	31.80	120000	1.41	1.56	6000	0.11	1
177	2	10.85	120000	0.75	0.44	8000	0.11	1
178	2	17.26	120000	1	0.79	8000	0.11	1
179	2	20.88	120000	1.128	1	8000	0.11	1
180	2	29.59	120000	1.41	1.56	8000	0.11	1
181	2	10.26	120000	0.75	0.44	10000	0.11	1
182	2	16.33	120000	1	0.79	10000	0.11	1
183	2	19.75	120000	1.128	1	10000	0.11	1
184	2	27.99	120000	1.41	1.56	10000	0.11	1
185	2	9.81	120000	0.75	0.44	12000	0.11	1
186	2	15.60	120000	1	0.79	12000	0.11	1
187	2	18.87	120000	1.128	1	12000	0.11	1
188	2	26.74	120000	1.41	1.56	12000	0.11	1
189	2	9.27	120000	0.75	0.44	15000	0.11	1
190	2	14.75	120000	1	0.79	15000	0.11	1
191	2	17.85	120000	1.128	1	15000	0.11	1
192	2	25.29	120000	1.41	1.56	15000	0.11	1

*Values were calculated using Eq. (5.4)

Table C.3 Hooked Bars with 2 No. 3 Ties Oriented Horizontally as Confining Reinforcement

Beam No.	N_h	ℓ_{dh}*	f_s	d_b	A_b	f'_c	A_{tr}	N/n
193	2	4.63	60000	0.75	0.44	4000	0.11	2
194	2	8.44	60000	1	0.79	4000	0.11	2
195	2	10.59	60000	1.128	1	4000	0.11	2
196	2	15.77	60000	1.41	1.56	4000	0.11	2
197	2	4.18	60000	0.75	0.44	6000	0.11	2
198	2	7.62	60000	1	0.79	6000	0.11	2
199	2	9.57	60000	1.128	1	6000	0.11	2
200	2	14.25	60000	1.41	1.56	6000	0.11	2
201	2	3.89	60000	0.75	0.44	8000	0.11	2
202	2	7.10	60000	1	0.79	8000	0.11	2
203	2	8.91	60000	1.128	1	8000	0.11	2
204	2	13.26	60000	1.41	1.56	8000	0.11	2
205	2	3.68	60000	0.75	0.44	10000	0.11	2
206	2	6.71	60000	1	0.79	10000	0.11	2
207	2	8.42	60000	1.128	1	10000	0.11	2
208	2	12.54	60000	1.41	1.56	10000	0.11	2
209	2	3.52	60000	0.75	0.44	12000	0.11	2
210	2	6.41	60000	1	0.79	12000	0.11	2
211	2	8.05	60000	1.128	1	12000	0.11	2
212	2	11.98	60000	1.41	1.56	12000	0.11	2
213	2	3.33	60000	0.75	0.44	15000	0.11	2
214	2	6.06	60000	1	0.79	15000	0.11	2
215	2	7.61	60000	1.128	1	15000	0.11	2
216	2	11.33	60000	1.41	1.56	15000	0.11	2
217	2	6.98	80000	0.75	0.44	4000	0.11	2
218	2	12.06	80000	1	0.79	4000	0.11	2
219	2	14.93	80000	1.128	1	4000	0.11	2
220	2	21.84	80000	1.41	1.56	4000	0.11	2
221	2	6.31	80000	0.75	0.44	6000	0.11	2
222	2	10.90	80000	1	0.79	6000	0.11	2
223	2	13.49	80000	1.128	1	6000	0.11	2
224	2	19.73	80000	1.41	1.56	6000	0.11	2
225	2	5.87	80000	0.75	0.44	8000	0.11	2
226	2	10.14	80000	1	0.79	8000	0.11	2
227	2	12.56	80000	1.128	1	8000	0.11	2
228	2	18.36	80000	1.41	1.56	8000	0.11	2
229	2	5.55	80000	0.75	0.44	10000	0.11	2
230	2	9.59	80000	1	0.79	10000	0.11	2
231	2	11.88	80000	1.128	1	10000	0.11	2
232	2	17.37	80000	1.41	1.56	10000	0.11	2
233	2	5.30	80000	0.75	0.44	12000	0.11	2
234	2	9.17	80000	1	0.79	12000	0.11	2
235	2	11.35	80000	1.128	1	12000	0.11	2
236	2	16.59	80000	1.41	1.56	12000	0.11	2
237	2	5.02	80000	0.75	0.44	15000	0.11	2
238	2	8.67	80000	1	0.79	15000	0.11	2
239	2	10.73	80000	1.128	1	15000	0.11	2
240	2	15.69	80000	1.41	1.56	15000	0.11	2

*Values were calculated using Eq. (5.4)

Table C.3 Cont. Hooked Bars with 2 No. 3 Ties Oriented Horizontally as Confining Reinforcement

Beam No.	N_h	ℓ_{dh}*	f_s	d_b	A_b	f'_c	A_{tr}	N/n
241	2	9.34	100000	0.75	0.44	4000	0.11	2
242	2	15.69	100000	1	0.79	4000	0.11	2
243	2	19.27	100000	1.128	1	4000	0.11	2
244	2	27.91	100000	1.41	1.56	4000	0.11	2
245	2	8.44	100000	0.75	0.44	6000	0.11	2
246	2	14.17	100000	1	0.79	6000	0.11	2
247	2	17.42	100000	1.128	1	6000	0.11	2
248	2	25.22	100000	1.41	1.56	6000	0.11	2
249	2	7.85	100000	0.75	0.44	8000	0.11	2
250	2	13.19	100000	1	0.79	8000	0.11	2
251	2	16.21	100000	1.128	1	8000	0.11	2
252	2	23.47	100000	1.41	1.56	8000	0.11	2
253	2	7.42	100000	0.75	0.44	10000	0.11	2
254	2	12.47	100000	1	0.79	10000	0.11	2
255	2	15.33	100000	1.128	1	10000	0.11	2
256	2	22.19	100000	1.41	1.56	10000	0.11	2
257	2	7.09	100000	0.75	0.44	12000	0.11	2
258	2	11.92	100000	1	0.79	12000	0.11	2
259	2	14.65	100000	1.128	1	12000	0.11	2
260	2	21.20	100000	1.41	1.56	12000	0.11	2
261	2	6.71	100000	0.75	0.44	15000	0.11	2
262	2	11.27	100000	1	0.79	15000	0.11	2
263	2	13.85	100000	1.128	1	15000	0.11	2
264	2	20.05	100000	1.41	1.56	15000	0.11	2
265	2	11.69	120000	0.75	0.44	4000	0.11	2
266	2	19.31	120000	1	0.79	4000	0.11	2
267	2	23.62	120000	1.128	1	4000	0.11	2
268	2	33.97	120000	1.41	1.56	4000	0.11	2
269	2	10.56	120000	0.75	0.44	6000	0.11	2
270	2	17.45	120000	1	0.79	6000	0.11	2
271	2	21.34	120000	1.128	1	6000	0.11	2
272	2	30.70	120000	1.41	1.56	6000	0.11	2
273	2	9.83	120000	0.75	0.44	8000	0.11	2
274	2	16.24	120000	1	0.79	8000	0.11	2
275	2	19.86	120000	1.128	1	8000	0.11	2
276	2	28.57	120000	1.41	1.56	8000	0.11	2
277	2	9.30	120000	0.75	0.44	10000	0.11	2
278	2	15.36	120000	1	0.79	10000	0.11	2
279	2	18.78	120000	1.128	1	10000	0.11	2
280	2	27.02	120000	1.41	1.56	10000	0.11	2
281	2	8.88	120000	0.75	0.44	12000	0.11	2
282	2	14.67	120000	1	0.79	12000	0.11	2
283	2	17.94	120000	1.128	1	12000	0.11	2
284	2	25.81	120000	1.41	1.56	12000	0.11	2
285	2	8.40	120000	0.75	0.44	15000	0.11	2
286	2	13.88	120000	1	0.79	15000	0.11	2
287	2	16.97	120000	1.128	1	15000	0.11	2
288	2	24.41	120000	1.41	1.56	15000	0.11	2

*Values were calculated using Eq. (5.4)

Table C.4 Hooked Bars with No. 3 Ties Spaced at 3d_b Oriented Horizontally as Confining Reinforcement

Beam No.	N_h	ℓ_{dh}*	f_s	d_b	A_b	f'_c	A_{tr}	N/n
289	2	3.41	60000	0.75	0.44	4000	0.11	3
290	2	7.22	60000	1	0.79	4000	0.11	3
291	2	9.37	60000	1.128	1	4000	0.11	3
292	2	14.55	60000	1.41	1.56	4000	0.11	3
293	2	3.08	60000	0.75	0.44	6000	0.11	3
294	2	6.52	60000	1	0.79	6000	0.11	3
295	2	8.47	60000	1.128	1	6000	0.11	3
296	2	13.15	60000	1.41	1.56	6000	0.11	3
297	2	2.87	60000	0.75	0.44	8000	0.11	3
298	2	6.07	60000	1	0.79	8000	0.11	3
299	2	7.88	60000	1.128	1	8000	0.11	3
300	2	12.24	60000	1.41	1.56	8000	0.11	3
301	2	2.71	60000	0.75	0.44	10000	0.11	3
302	2	5.74	60000	1	0.79	10000	0.11	3
303	2	7.45	60000	1.128	1	10000	0.11	3
304	2	11.57	60000	1.41	1.56	10000	0.11	3
305	2	2.59	60000	0.75	0.44	12000	0.11	3
306	2	5.49	60000	1	0.79	12000	0.11	3
307	2	7.12	60000	1.128	1	12000	0.11	3
308	2	11.06	60000	1.41	1.56	12000	0.11	3
309	2	2.45	60000	0.75	0.44	15000	0.11	3
310	2	5.19	60000	1	0.79	15000	0.11	3
311	2	6.74	60000	1.128	1	15000	0.11	3
312	2	10.46	60000	1.41	1.56	15000	0.11	3
313	2	5.76	80000	0.75	0.44	4000	0.11	3
314	2	10.85	80000	1	0.79	4000	0.11	3
315	2	13.72	80000	1.128	1	4000	0.11	3
316	2	20.62	80000	1.41	1.56	4000	0.11	3
317	2	5.21	80000	0.75	0.44	6000	0.11	3
318	2	9.80	80000	1	0.79	6000	0.11	3
319	2	12.39	80000	1.128	1	6000	0.11	3
320	2	18.63	80000	1.41	1.56	6000	0.11	3
321	2	4.85	80000	0.75	0.44	8000	0.11	3
322	2	9.12	80000	1	0.79	8000	0.11	3
323	2	11.53	80000	1.128	1	8000	0.11	3
324	2	17.34	80000	1.41	1.56	8000	0.11	3
325	2	4.58	80000	0.75	0.44	10000	0.11	3
326	2	8.62	80000	1	0.79	10000	0.11	3
327	2	10.91	80000	1.128	1	10000	0.11	3
328	2	16.40	80000	1.41	1.56	10000	0.11	3
329	2	4.38	80000	0.75	0.44	12000	0.11	3
330	2	8.24	80000	1	0.79	12000	0.11	3
331	2	10.42	80000	1.128	1	12000	0.11	3
332	2	15.67	80000	1.41	1.56	12000	0.11	3
333	2	4.14	80000	0.75	0.44	15000	0.11	3
334	2	7.79	80000	1	0.79	15000	0.11	3
335	2	9.86	80000	1.128	1	15000	0.11	3
336	2	14.82	80000	1.41	1.56	15000	0.11	3

*Values were calculated using Eq. (5.4)

Table C.4 Cont. Hooked Bars with No. 3 Ties Spaced at 3d_b Oriented Horizontally as Confining Reinforcement

Beam No.	N_h	ℓ_{dh}*	f_s	d_b	A_b	f'_c	A_{tr}	N/n
337	2	8.12	100000	0.75	0.44	4000	0.11	3
338	2	14.47	100000	1	0.79	4000	0.11	3
339	2	18.06	100000	1.128	1	4000	0.11	3
340	2	26.69	100000	1.41	1.56	4000	0.11	3
341	2	7.34	100000	0.75	0.44	6000	0.11	3
342	2	13.07	100000	1	0.79	6000	0.11	3
343	2	16.32	100000	1.128	1	6000	0.11	3
344	2	24.12	100000	1.41	1.56	6000	0.11	3
345	2	6.83	100000	0.75	0.44	8000	0.11	3
346	2	12.17	100000	1	0.79	8000	0.11	3
347	2	15.18	100000	1.128	1	8000	0.11	3
348	2	22.44	100000	1.41	1.56	8000	0.11	3
349	2	6.46	100000	0.75	0.44	10000	0.11	3
350	2	11.51	100000	1	0.79	10000	0.11	3
351	2	14.36	100000	1.128	1	10000	0.11	3
352	2	21.22	100000	1.41	1.56	10000	0.11	3
353	2	6.17	100000	0.75	0.44	12000	0.11	3
354	2	10.99	100000	1	0.79	12000	0.11	3
355	2	13.72	100000	1.128	1	12000	0.11	3
356	2	20.28	100000	1.41	1.56	12000	0.11	3
357	2	5.83	100000	0.75	0.44	15000	0.11	3
358	2	10.40	100000	1	0.79	15000	0.11	3
359	2	12.98	100000	1.128	1	15000	0.11	3
360	2	19.18	100000	1.41	1.56	15000	0.11	3
361	2	10.47	120000	0.75	0.44	4000	0.11	3
362	2	18.09	120000	1	0.79	4000	0.11	3
363	2	22.40	120000	1.128	1	4000	0.11	3
364	2	32.76	120000	1.41	1.56	4000	0.11	3
365	2	9.46	120000	0.75	0.44	6000	0.11	3
366	2	16.35	120000	1	0.79	6000	0.11	3
367	2	20.24	120000	1.128	1	6000	0.11	3
368	2	29.60	120000	1.41	1.56	6000	0.11	3
369	2	8.81	120000	0.75	0.44	8000	0.11	3
370	2	15.21	120000	1	0.79	8000	0.11	3
371	2	18.84	120000	1.128	1	8000	0.11	3
372	2	27.54	120000	1.41	1.56	8000	0.11	3
373	2	8.33	120000	0.75	0.44	10000	0.11	3
374	2	14.39	120000	1	0.79	10000	0.11	3
375	2	17.81	120000	1.128	1	10000	0.11	3
376	2	26.05	120000	1.41	1.56	10000	0.11	3
377	2	7.96	120000	0.75	0.44	12000	0.11	3
378	2	13.75	120000	1	0.79	12000	0.11	3
379	2	17.02	120000	1.128	1	12000	0.11	3
380	2	24.89	120000	1.41	1.56	12000	0.11	3
381	2	7.53	120000	0.75	0.44	15000	0.11	3
382	2	13.00	120000	1	0.79	15000	0.11	3
383	2	16.10	120000	1.128	1	15000	0.11	3
384	2	23.54	120000	1.41	1.56	15000	0.11	3

*Values were calculated using Eq. (5.4)

Table C.5 Hooked Bars with No. 3 Ties Spaced at $3d_b$ Oriented Vertically as Confining Reinforcement

Beam No.	N_h	ℓ_{dh}*	f_s	d_b	A_b	f'_c	A_{tr}	N/n
385	2	6.67	60000	0.75	0.44	4000	0.11	1.5
386	2	10.48	60000	1	0.79	4000	0.11	1.5
387	2	12.50	60000	1.128	1	4000	0.11	2
388	2	17.68	60000	1.41	1.56	4000	0.11	2
389	2	6.12	60000	0.75	0.44	6000	0.11	1.5
390	2	9.43	60000	1	0.79	6000	0.11	1.5
391	2	11.37	60000	1.128	1	6000	0.11	1.5
392	2	15.92	60000	1.41	1.56	6000	0.11	2
393	2	5.67	60000	0.75	0.44	8000	0.11	1
394	2	8.75	60000	1	0.79	8000	0.11	1.5
395	2	10.56	60000	1.128	1	8000	0.11	1.5
396	2	14.91	60000	1.41	1.56	8000	0.11	1.5
397	2	5.35	60000	0.75	0.44	10000	0.11	1
398	2	8.25	60000	1	0.79	10000	0.11	1.5
399	2	9.96	60000	1.128	1	10000	0.11	1.5
400	2	14.08	60000	1.41	1.56	10000	0.11	1.5
401	2	5.10	60000	0.75	0.44	12000	0.11	1
402	2	8.00	60000	1	0.79	12000	0.11	1
403	2	9.50	60000	1.128	1	12000	0.11	1.5
404	2	13.44	60000	1.41	1.56	12000	0.11	1.5
405	2	4.81	60000	0.75	0.44	15000	0.11	1
406	2	7.55	60000	1	0.79	15000	0.11	1
407	2	8.96	60000	1.128	1	15000	0.11	1
408	2	12.69	60000	1.41	1.56	15000	0.11	1.5
409	2	8.89	80000	0.75	0.44	4000	0.11	2
410	2	13.97	80000	1	0.79	4000	0.11	2
411	2	16.71	80000	1.128	1	4000	0.11	2.5
412	2	23.61	80000	1.41	1.56	4000	0.11	2.5
413	2	8.11	80000	0.75	0.44	6000	0.11	1.5
414	2	12.57	80000	1	0.79	6000	0.11	2
415	2	15.17	80000	1.128	1	6000	0.11	2
416	2	21.27	80000	1.41	1.56	6000	0.11	2.5
417	2	7.52	80000	0.75	0.44	8000	0.11	1.5
418	2	11.66	80000	1	0.79	8000	0.11	2
419	2	14.08	80000	1.128	1	8000	0.11	2
420	2	19.75	80000	1.41	1.56	8000	0.11	2.5
421	2	7.09	80000	0.75	0.44	10000	0.11	1.5
422	2	11.00	80000	1	0.79	10000	0.11	2
423	2	13.28	80000	1.128	1	10000	0.11	2
424	2	18.77	80000	1.41	1.56	10000	0.11	2
425	2	6.76	80000	0.75	0.44	12000	0.11	1.5
426	2	10.62	80000	1	0.79	12000	0.11	1.5
427	2	12.67	80000	1.128	1	12000	0.11	2
428	2	17.91	80000	1.41	1.56	12000	0.11	2
429	2	6.37	80000	0.75	0.44	15000	0.11	1.5
430	2	10.02	80000	1	0.79	15000	0.11	1.5
431	2	12.08	80000	1.128	1	15000	0.11	1.5
432	2	16.91	80000	1.41	1.56	15000	0.11	2

*Values were calculated using Eq. (5.5)

Table C.5 Cont. Hooked Bars with No. 3 Ties Spaced at $3d_b$ Oriented Vertically as Confining Reinforcement

Beam No.	N_h	ℓ_{dh}*	f_s	d_b	A_b	f'_c	A_{tr}	N/n
433	2	11.11	100000	0.75	0.44	4000	0.11	2.5
434	2	17.33	100000	1	0.79	4000	0.11	3
435	2	20.92	100000	1.128	1	4000	0.11	3
436	2	29.42	100000	1.41	1.56	4000	0.11	3.5
437	2	10.11	100000	0.75	0.44	6000	0.11	2
438	2	15.71	100000	1	0.79	6000	0.11	2.5
439	2	18.96	100000	1.128	1	6000	0.11	2.5
440	2	26.62	100000	1.41	1.56	6000	0.11	3
441	2	9.37	100000	0.75	0.44	8000	0.11	2
442	2	14.58	100000	1	0.79	8000	0.11	2.5
443	2	17.60	100000	1.128	1	8000	0.11	2.5
444	2	24.72	100000	1.41	1.56	8000	0.11	3
445	2	8.83	100000	0.75	0.44	10000	0.11	2
446	2	13.88	100000	1	0.79	10000	0.11	2
447	2	16.60	100000	1.128	1	10000	0.11	2.5
448	2	23.47	100000	1.41	1.56	10000	0.11	2.5
449	2	8.42	100000	0.75	0.44	12000	0.11	2
450	2	13.24	100000	1	0.79	12000	0.11	2
451	2	15.84	100000	1.128	1	12000	0.11	2.5
452	2	22.39	100000	1.41	1.56	12000	0.11	2.5
453	2	8.06	100000	0.75	0.44	15000	0.11	1.5
454	2	12.49	100000	1	0.79	15000	0.11	2
455	2	15.07	100000	1.128	1	15000	0.11	2
456	2	21.14	100000	1.41	1.56	15000	0.11	2.5
457	2	13.33	120000	0.75	0.44	4000	0.11	3
458	2	20.82	120000	1	0.79	4000	0.11	3.5
459	2	25.13	120000	1.128	1	4000	0.11	3.5
460	2	35.35	120000	1.41	1.56	4000	0.11	4
461	2	12.10	120000	0.75	0.44	6000	0.11	2.5
462	2	18.86	120000	1	0.79	6000	0.11	3
463	2	22.62	120000	1.128	1	6000	0.11	3.5
464	2	31.97	120000	1.41	1.56	6000	0.11	3.5
465	2	11.22	120000	0.75	0.44	8000	0.11	2.5
466	2	17.49	120000	1	0.79	8000	0.11	3
467	2	21.11	120000	1.128	1	8000	0.11	3
468	2	29.69	120000	1.41	1.56	8000	0.11	3.5
469	2	10.57	120000	0.75	0.44	10000	0.11	2.5
470	2	16.63	120000	1	0.79	10000	0.11	2.5
471	2	19.93	120000	1.128	1	10000	0.11	3
472	2	28.16	120000	1.41	1.56	10000	0.11	3
473	2	10.20	120000	0.75	0.44	12000	0.11	2
474	2	15.86	120000	1	0.79	12000	0.11	2.5
475	2	19.13	120000	1.128	1	12000	0.11	2.5
476	2	26.87	120000	1.41	1.56	12000	0.11	3
477	2	9.62	120000	0.75	0.44	15000	0.11	2
478	2	14.97	120000	1	0.79	15000	0.11	2.5
479	2	18.06	120000	1.128	1	15000	0.11	2.5
480	2	25.37	120000	1.41	1.56	15000	0.11	3

*Values were calculated using Eq. (5.5)