ANCHORAGE STRENGTH OF REINFORCING BARS WITH STANDARD HOOKS

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A Report on Research Sponsored by

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Structural Engineering and Engineering Materials

SM Report No. 125

April 2017

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.

2385 Irving Hill Road, Lawrence, Kansas 66045-7563

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ABSTRACT

Hooked bars are often used to anchor reinforcing steel where concrete dimensions are not sufficient to provide the required development length for straight reinforcement, such as in external beam-column joints. The purpose of this study is to expand the understanding of the behavior of hooked bars in high-strength concrete and to develop design guidelines allowing for the use of high-strength reinforcing steel and high-strength concrete. In this study, 122 simulated beam-column joints were tested as a continuation of previous work at the University of Kansas. The test parameters included bar size (No. 5, No. 8 and No. 11), hook bend angle (90° or 180°), embedment length (5.5 to 23.5 in.), amount of confining reinforcement within the joint (no confining reinforcement to nine No. 3 hoops), location of the hooked bar with respect to member depth, hooked bar stresses (22,800 to 138,800 psi), concrete compressive strength (4,490 to 14,050 psi), center-to-center spacing between hooked bars (2 to 11.8d_b), number of hooked bars (2, 3, 4, or 6), arrangement of hooked bars (one or two layers), and ratios of beam effective depth to embedment length (0.6 to 2.13). Some specimens contained strain gauges mounted along the straight portion of the hooked bars and on the confining reinforcement within the joint rejoin. Test results from this study, along with test results from earlier work covering specimens without and with confining reinforcement, concrete compressive strengths between 2,570 and 16,510 psi, and bars stresses at anchorage failure ranging from 22,800 and 144,100 psi, were used to develop descriptive equations for the anchorage strength of hooked bars.

The results of this study show that the current Code provisions overestimate the contribution of the concrete compressive strength and the bar size on the anchorage strength of hooked bars. The incorporation of the modification factors for cover and confining reinforcement in the provisions in the ACI Building Code (ACI 318-14) produces an unconservative estimation of anchorage strength of hooked bars, particularly with large hooked bars and closely-spaced hooked bars (hooked bars with center-to-center spacing less than 6d_b). Closely-spaced hooked bars exhibit less anchorage strength than widely-spaced hooked bars. The reduction in anchorage strength of closely-spaced hooked bars is a function of both the spacing between hooked bars and the amount of confining reinforcement. Both the hooks and the straight portion of hooked bars contribute to anchorage strength. The anchorage strength of staggered hooked bars can be

represented by considering the minimum spacing between the bars. Hooked bars anchored in beam-column joints with ratio of beam effective depth to embedment length greater than 1.5 exhibit low anchorage strengths compared to hooked bars with a ration below 1.5. These observations are used to develop proposed Code provisions for the development length of reinforcing bars anchored with standard hooks. The proposed provisions provide a higher level of reliability than current provisions and can be used for reinforcing steels with yield strengths up to 120,000 psi and concretes with compressive strengths up to 16,000 psi.

Keywords: anchorage, beam-column joints, bond and development, concrete, high-strength concrete, high-strength steel, hooks, closely-spaced hooks, staggered-hooks, reinforcement, reinforcement strain

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CHAPTER 1: INTRODUCTION

1.1 GENERAL

For a reinforced concrete member to efficiently transfer internal stresses between reinforcing steel and concrete, the reinforcing steel must be adequately bonded to the surrounding concrete. Friction and bearing between deformations on the reinforcing steel and the surrounding concrete provide the primary mechanism for force transfer for straight reinforcing bars.

Reinforced concrete members are designed so that the steel reaches its yield strength at sections where forces are at a maximum. To do so, a sufficient length of the reinforcing steel, called the development length, must be provided beyond the critical section. In some cases where the concrete dimensions are not sufficient to provide the required development length for straight reinforcement, such as in external beam-column joints, 90° and 180°, hooked bars are often employed. Current code provisions (ACI 318 Building Code, AASHTO Bridge Specifications, and ACI 349 Code Requirements for Nuclear Safety-Related Concrete Structures) for the development length of hooked bars in tension are based on work of limited scope conducted in the 1970s. The studies included 34 simulated exterior beam-column joints constructed using reinforcement with a specified minimum yield strength of 60,000 psi and concrete compressive strengths ranging from 3,750 to 5,400 psi. The influence of multiple hooked bars, spacing between the hooked bars, and hooked bar arrangement (staggered hooks) was not studied, nor was the effect of high-strength steel or concrete. The purpose of this study is to expand the understanding of the behavior of hooked bars in high-strength concrete and to develop design guidelines allowing for the use of high-strength reinforcing steel and high-strength concrete.

1.2 PREVIOUS WORK

1.2.1 Bond Behavior

For optimal design, an efficient force transfer between the reinforcing steel and the surrounding concrete is required. This transfer is commonly called bond. Bond is influenced by a wide range of factors, including concrete mechanical priorities, the volume of the concrete surrounding the bars, the amount of transverse reinforcement, bar surface conditions, and bar geometry (deformation properties)

1.2.1.1 Straight Bars

Three primary mechanisms are recognized for the force transfer between the straight reinforcing steel and the concrete: chemical adhesion, friction, and mechanical interlock, as shown in Figure 1.1. Adhesion is lost promptly after a deformed bar moves relative to the surrounding concrete. As the slip increases, friction force along the bar surface (between the ribs) decreases, while friction and bearing force between the bar deformations and the surrounding concrete increase and serve as the primary bond mechanisms.

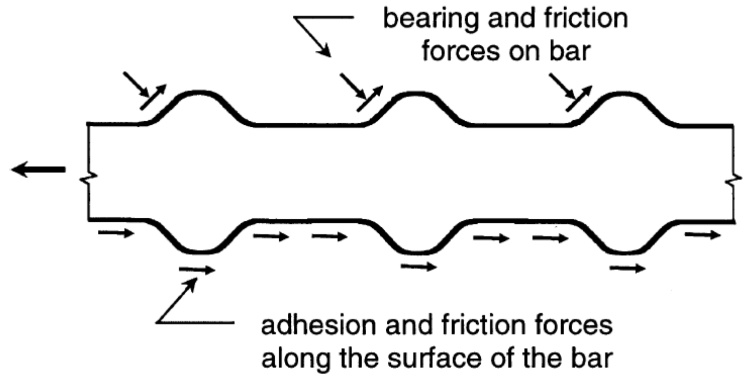


Figure 1.1 Bond mechanisms (ACI 408R-03)

With continued slip, the bar deformations act as wedges that result in tensile hoop stresses in the surrounding concrete. With relatively small spacing between reinforcing bars or small concrete cover, the hoop stresses cause cracks that propagate between the bars or from the bars to the exterior of the concrete, leading to a splitting failure. When a splitting failure is prevented by sufficient concrete cover and spacing between bars or by transverse reinforcement, the bars exhibit a pullout failure, shearing or crushing the concrete between the deformations.

1.2.1.2 Hooked Bars

In cases where the concrete dimensions are not adequate to provide the required development length for the straight bars, such as in beam-column joints, 90° and 180° hooked bars are often employed. The anchorage strength of a hooked bar is achieved by bond and direct bearing on concrete, as illustrated in Figure 1.2. Hooked bars with a 90° bend angle tend to slip around the bend, straightening the tail extensions, and inducing a compressive force on the back concrete cover. Hooked bars with a 180° bend angle tend to engage the concrete without slipping around the bend (Thompson et al. 2002). Pinc, Watkins, and Jirsa (1977) observed that spalling of the concrete side cover is the primary mode of failure due to the wedging action of the bent portion of the bar. However, with multiple hooked bars and/or a short embedment length, a breakout failure may control (Joh, Goto, and Shibata 1995).

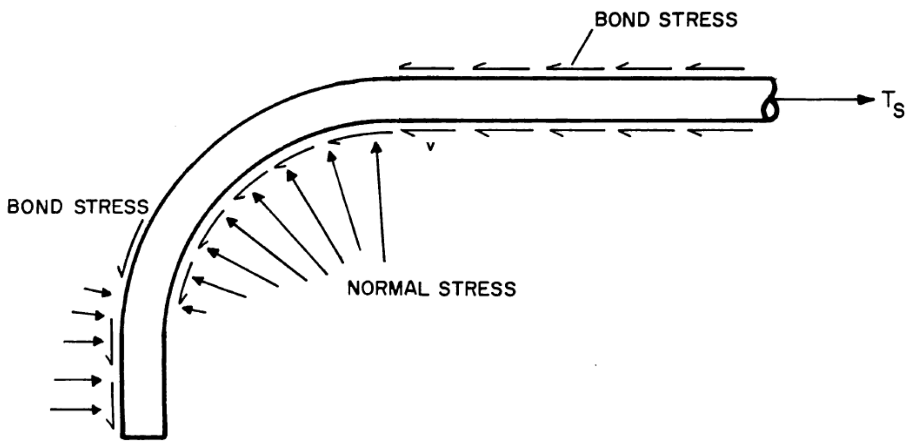


Figure 1.2 Stress transfer in a 90° hooked bar [adapted from Minor and Jirsa (1975)]

1.2.2 Hooked Bar Tests

Hribar and Vasko (1969)

Hribar and Vasko (1969) tested 96 deformed straight and hooked bars in concrete blocks. Eighteen specimens contained individual hooked bars embedded in small blocks, as shown in Figure 1.3; the other specimens consisted of three 16 × 16 × 5 ft concrete blocks, in which the bars were embedded; the bars were spaced far apart to reduce interaction during the tests. The bars were subjected to a pullout force by a hydraulic ram centered on the bar and in direct contact with the concrete surface. They felt that the effect of the loading device was minimized using a bond breaker along the straight portion of the hooked bar (lead embedment), although such an assumption is not, in general, accepted (ACI Committee 408 2003). Test parameters included bar size (No. 4, No. 7, and No. 11), bend angle (90° and 180°), extension beyond the bend or tail extension (0 to 12 bar diameters d_b), embedment length (4 to 33 in.), bend radius (5 to $12d_b$), and concrete compressive strength (3,700 to 4,750 psi).

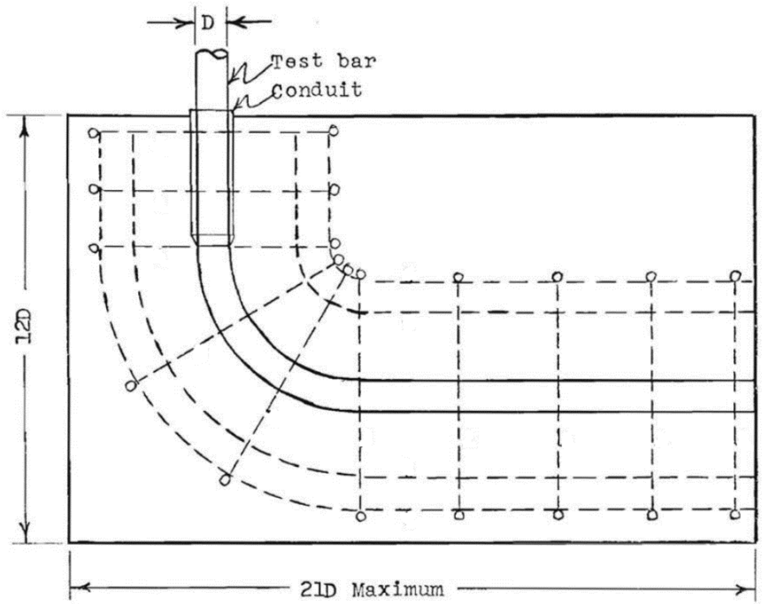


Figure 1.3 Specimens designed by Hribar and Vasko (1969)

The majority of the hooked bars experienced a bar fracture, while all straight bars failed with bar pullout. No cracks were observed during the tests. Hribar and Vasko observed that in the initial loading stages, prior to the steel reaching its proportional limit, increasing the extension beyond the bend increased the anchorage stiffness (stress divided by slip). The anchorage stiffness increased as the radius of the bend increased, with a more pronounced effect for 90° hooked bars than 180° hooked bars. At failure, all hooked bars with a 180° bend angle failed due to bar fracture, regardless of the length of the extension beyond the bend. In contrast, hooked bars with a 90° bend angle exhibited both bar fracture and pullout failures, with bar pullout failure becoming more likely as the length of the extension beyond the bend decreased from 12 to $4d_b$. The likelihood of fracture increased as the hook angle and the radius of the bend increased. Hribar and Vasko suggested that the anchorage capacity of hooked bars was proportional to the square root of the concrete compressive strength.

Minor and Jirsa (1975)

Minor and Jirsa (1975) tested 80 deformed straight and hooked bars in concrete blocks. The dimensions of the concrete blocks were chosen to provide a suitable concrete sufficient to prevent splitting failure. Hooked bars were subjected to a pullout force using a center-hole hydraulic ram mounted on a test frame to produce reactions presented in Figure 1.4. Each specimen had one hooked bar without confining reinforcement. The lead embedment was covered with a loose-fitting plastic tube for all specimens so that bond was provided only by the hooked portion of the bar and the tail extension. The test parameters included bar size (No. 5, No. 7, and No. 9), bond length measured from the beginning of the bend (1.6 to 6 in.), bend angle (0° to 180°), and internal radius (1.15 to 4.6d_b). The nominal concrete compressive strengths were 4,500, 5,500, and 3,300 psi for specimens containing No. 5, 7, and 9 hooked bars, respectively.

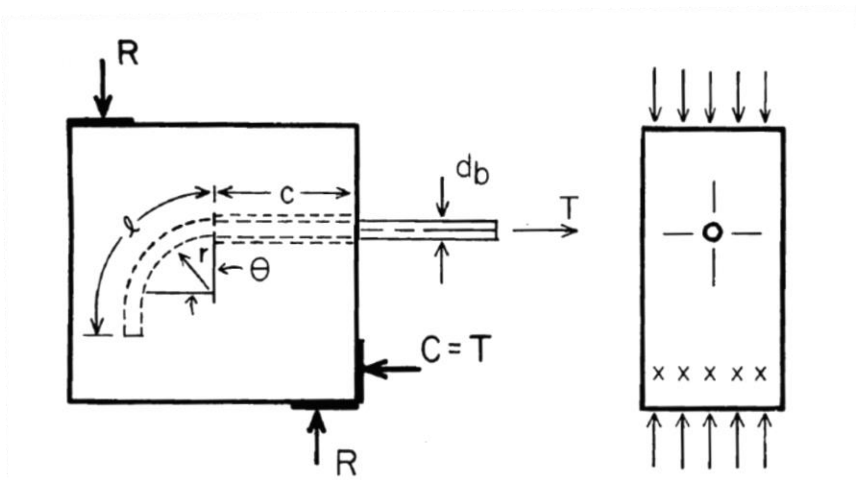


Figure 1.4 Specimen detailing and test setup by Minor and Jirsa (1975)

For most of the specimens, hooked bars pulled out of concrete blocks (bond failure). Based on their results, Minor and Jirsa concluded that in specimens with an equivalent ratio of bond length to bar diameter, bar slip increased with increasing bend angle and with decreasing the ratios of the bend radius to the bar diameter. Minor and Jirsa stated that for hooked bars with a straight tail extension most of the slip occurred in the bent portion of the bar. They observed no significant difference existed in the strength of straight and bent bars with the same length of bar in contact with the concrete (see ℓ in Figure 1.4). Minor and Jirsa stated that 90° hooked bars were preferable to 180° hooked bars and that the maximum practical bend radius should be used to minimize slip.

Marques and Jirsa (1975)

Marques and Jirsa (1975) tested 22 full-scale exterior beam-column joints to evaluate the anchorage capacity of hooked bars with different levels of lateral confinement within the joints. The specimens were columns, with beams represented by hooked bars and a compression reaction, as illustrated in Figure 1.5. Each specimen contained two hooked bars tied to the column longitudinal reinforcement, maintaining a specified concrete side cover, and a 2-in. tail cover.

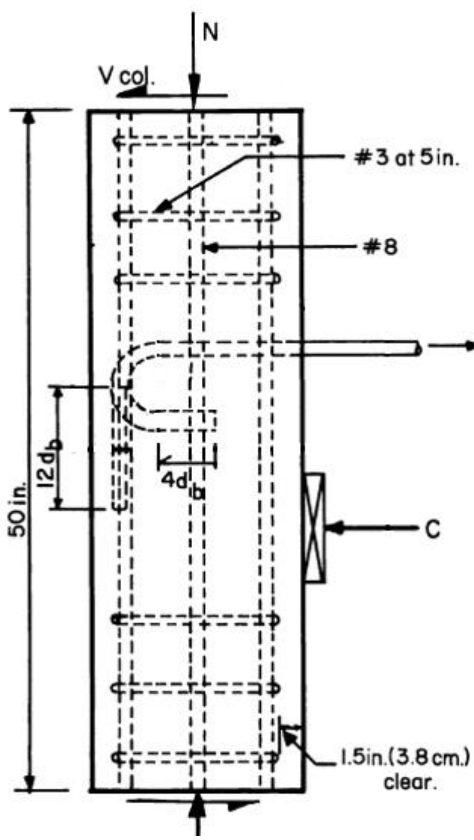


Figure 1.5 Specimens details and test setup by Marques and Jirsa (1975)

The primary test parameters were concrete side cover ($1^1/_2$ to $2^7/_8$ in.), confining reinforcement within the hooked bar region (none and No. 3 ties spaced at 2.5 and 5 in.), location of the hooked bars with respect to the column longitudinal reinforcement (inside and outside), and column axial load (135 to 540 kips). The tests included No. 7 and No. 11 hooked bars with 90° and 180° bend angles conforming to ACI 318-71. The lead embedment length (the length of the straight portion ahead of the bend) ranged from 6.5 to 9.5 in. for No. 7 hooked bars and 3 to 6 in. for No. 11 hooked bars. The nominal concrete compressive strength was 4,500 psi.

Most of the specimens exhibited similar crack progression. Initial cracks appeared on the front face of the column radiating from the hooked bar towards the side faces of the column. Vertical cracks occurred on the side faces of the column near the vertical columns bars near the beam. At higher stress levels, cracks appeared adjacent to the bent portion of the hooked bar on the side faces of the specimens. The failure was a sudden and involved spalling of the concrete side cover.

Marques and Jirsa found that tail extension slip was minimal; most of the slip occurred on the bend and in the straight lead embedment. Marques and Jirsa concluded that the influence of the column axial load was negligible. Specimens with 90° hooked bars and 180° hooked bars exhibited very similar behavior. Marques and Jirsa also found that the effect of closely spaced confining reinforcement in the beam-column joint was greater with larger diameter hooked bars. The anchorage strength of hooked bars increased as the concrete side cover increased from $1^1/_2$ to $2^7/_8$ in.

Based on their results, Marques and Jirsa proposed a design equation to predict the anchorage strength of standard hooks:

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

where f_h is the tensile stress developed by a standard hooked bar in psi, d_b is the hooked bar diameter, and f_c' is the concrete compressive strength. ψ equals 1.4 for No. 11 hooked bars or smaller with a lead embedment length of at least the larger of $4d_b$ or 4 in., a concrete side cover of at least 2.5 in., and concrete tail cover of at least 2 in. In addition, if confining reinforcement is present in the beam-column joint, ψ equals 1.8. Otherwise, ψ equals 1.0. For cases where additional development length was needed, Marques and Jirsa proposed Eq. (1.2) to calculate the straight lead embedment length ℓ_1.

$$\ell_1 = \left[\frac{0.04A_b\left(f_y - f_h\right)}{\sqrt{f_c'}}\right] + \ell' \tag{1.2}$$

where ℓ' is the greater of $4d_b$ or 4 in.

Pinc, Watkins, and Jirsa (1977)

Pinc et al. (1977) tested 16 exterior beam-column joints to investigate the influence of the lead embedment length and lightweight concrete on the anchorage strength of hooked bars. Each specimen had two hooked bars inside the column longitudinal reinforcement, maintaining a concrete side cover of $2^7/_8$ in. and a tail cover of 2 in. The variables considered were the size of the hooked bar and the lead embedment length. The tested hooked bars were No. 9 and No. 11 with a 90° bend angle. The width of the columns was kept constant at 12 in., while the depth of the columns was varied to satisfy the required lead embedment lengths which ranged from $4^3/_8$ to $13^3/_8$ in. and 6 to 15 in. for No. 9 and No. 11 hooked bars, respectively. No confining reinforcement was provided within the beam-column joints. All specimens were subjected to a nominal axial stress of 800 psi. The concrete compressive strength ranged from 3,600 to 5,400 psi.

In four cases, the bars yielded. For all other specimens, failure was sudden with spalling of the concrete side cover. Similar cracking initiation and propagation patterns were noticed on all specimens. First cracks appeared in the front face of the specimen from hooked bars and propagated horizontally and diagonally towards the side faces. On the side faces of the specimens, the horizontal crack that appeared on the front face extended to the back of the column, with vertical cracks developing at about the location of the column longitudinal reinforcement. At higher stress levels, a vertical crack appeared adjacent to the bent portions of hooked bars and propagated radially above and below the hooked bars.

Pinc et al. concluded that the primary mode of failure that governed the anchorage strength of hooked bars was the loss of the concrete side cover. Under low stresses, most of the anchorage stresses developed in the lead embedment length of the hooked bars. At failure, however, the contribution of the lead embedment length dramatically decreased, particularly with low lead embedment lengths and large hooked bars. Slip occurred mostly along the bend and the lead embedment. Hooked bars in lightweight concrete reached 75 to 85% of the strength of hooked bars in normalweight concrete. Replacing normalweight fine aggregate with lightweight fine aggregate had an insignificant effect on the anchorage strength of the hooked bars.

Based on these results and the results from Marques and Jirsa (1975), Pinc et al. developed three equations to estimate the anchorage strength of standard hooked bars in tension. First, the anchorage strength of hooked bars was established by combining the contributions of the bend and the lead embedment, as presented in Eq. (1.3). This approach was similar to that used in ACI 318-71 and by Marques and Jirsa (1975).

$$f_u = 550\left(1 - 0.4d_b + 0.8\ell_\ell/d_b\right)\psi\sqrt{f_c'} \tag{1.3}$$

where f_u is the total strength of anchored bar in psi, d_b is the hooked bar diameter in in., f_c' is the concrete compressive strength in psi, ℓ_ℓ is the lead embedment length, and ψ is a confinement modification factor. Pinc et al. derived two simplified equations based on either the straight lead embedment ℓ_ℓ [Eq. (1.4)] or the sum of bend radius of the hook and the straight lead embedment ℓ_{dh} [Eq. (1.5)].

$$f_u = \left(250 + 54\ell_\ell/d_b\right)\psi\sqrt{f_c'} \tag{1.4}$$

$$f_u = 50\psi\ell_{dh}\sqrt{f_c'}/d_b \tag{1.5}$$

For practical applications, Pinc et al. preferred Eq. (1.5). Pinc et al. also suggested that the embedment length could be multiplied by a modification factor of 0.7 for No. 11 hooked bars or smaller with a minimum concrete side cover of 2.5 in. Moreover, the embedment length could be multiplied by a modification factor of 0.55 for No. 11 hooked bars or smaller cast with a minimum concrete side cover of 2.5 in., a minimum concrete tail cover of 2 in., and with confining reinforcement (closed stirrups) within the joint spaced not more than $3d_b$.

Johnson and Jirsa (1981)

Jonson and Jirsa (1981) tested 36 full-scale exterior beam-wall joints to evaluate the anchorage strength of hooked bars with short embedment lengths. The specimens were walls, with beams represented by hooked bars and a compression reaction. Thirty- two specimens contained one standard 90° hooked bar placed in a 24×52 in. walls and four specimens contained three standard 90° hooked bars placed in a 72×52 in. walls. The test parameters consisted of bar size (No. 4, No. 7, No. 9, and No. 11), lead embedment length (zero to 3 in), this was conducted by changing the wall thickness (3.5 to 8.5 in.) with a constant tail cover (1.5 in.), transverse reinforcement within the hook region (none or No. 4 bar), beam depth (8 to 18 in.), spacing between hooked bars (11 or 22 in). The concrete compressive strength ranged from 2,500 to 5,450 psi.

All specimens exhibited a similar cracking pattern. Initial cracks started on the front face of the specimen radiating horizontally towards the side faces as higher load applied. Generally, the failure was sudden with concrete spalling off the front side of the specimens "pullout cone" similar to that observed with an anchorage bolt or stud. Jonson and Jirsa concluded that, for the concrete compressive strengths investigated, the anchorage strength was proportional to the square root of the concrete compressive strength. Increasing beam depth decreased confinement provided by the compression zone on the hook, therefore less anchorage force could be developed. Transverse reinforcement within the hooked bar region had insignificant influence on the anchorage strength of hooked bars. Jonson and Jirsa stated that the interaction of stresses between the closely spaced hooked bars resulted in a reduced strength, and suggested that either hooked bar equation recommended by ACI 408 [Eq. (1.9)] with spacing of at least $12d_b$ be used, or that the anchorage bolt provisions of ACI 349 be applied.

Soroushian et al. (1988)

Soroushian et al. (1988) tested seven simulated exterior beam-column joints to study the pullout behavior of hooked bars in a reinforced concrete joint and to evaluate the requirements in ACI 318-83. The specimens were similar to the beam-column joints tested by Marques and Jirsa (1975). The hooked bars were subjected to a pullout force using two hydraulic rams bearing on the concrete above and below the hooked bars as shown in Figure 1.6. Each specimen had two hooked bars placed inside the column longitudinal reinforcement with a 2-in. tail cover and a 2.5-in. concrete side cover. The test parameters consisted of bar size (No. 6, No. 8, and No. 10), confining reinforcement within the beam-column joint (No. 3 hoops spaced at 4 in., No. 3 hoops spaced at 3 in., and No. 4 hoops spaced at 3 in., hoops spaced at 3 in. conformed to the ACI 318-83 requirements for high seismic risk region), and concrete compressive strength (3,780 to 6,050 psi). The tested hooked bars were with a 90° bend angle. The straight lead embedment of the hooked bar was covered with a plastic tube to eliminate its contribution to the anchorage strength of the hooked bar.

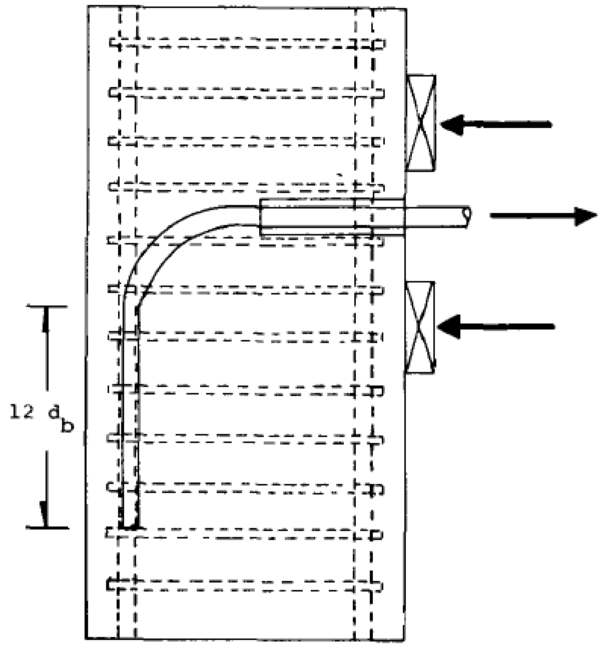


Figure 1.6 Specimens details and test setup by Soroushian et al. (1988)

All specimens exhibited a similar cracking pattern. Cracks initiated along the horizontal plane between the hooked bars at about half of the peak load. As the stress increased, the cracks propagated horizontally along the straight portion of the hooked bars. At stresses close to the failure, other radial cracks normal to the plane of the hooked bars appeared. All specimens exhibited spalling of the concrete side cove at failure.

Soroushian et al. concluded that the anchorage strength of hooked bars increased as the hooked bar diameter increased and as the confining reinforcement within the beam-column joint increased. Concrete compressive strength did not have a pronounced effect on the behavior of hooked bars over the range of 3780 to 6050 psi. Soroushian et al. also stated that embedding hooked bars with a clear spacing less than $4d_b$ might decrease the peak anchorage strength.

Hamad, Jirsa, and D'Abreu de Paulo (1993)

Hamad et al. (1993) tested 25 exterior beam-column joints tested as cantilevers to determine the influence of the epoxy-coating on the anchorage strength of the hooked bars. The hooks on 12 specimens were uncoated. The specimens contained two hooked bars located inside the column longitudinal reinforcement. The test parameters included bar size (No. 7 and No. 11), bend angle (90° and 180°), concrete compressive strength (2,570 to 7,200 psi), concrete side cover (1.75 to 3 in.), confining reinforcement within the beam-column joint (none, No. 3 ties spaced at 6 in., or No. 3 ties spaced at 4 in.), and bar surface condition (black vs. epoxy-coated). Specimens had a concrete tail cover of 2 in. The majority of the specimens exhibited similar cracking patterns. On the side face of the column, cracks appeared in the vicinity of the assumed beam compression region, then extended to the location of the bent portion of the hooked bar at an approximate angle of 45°. Horizontal and vertical cracks were also observed on the front face initiating from the two hooked bars. The failure was sudden with an immediate loss of the anchorage strength.

Hamad et al. concluded that large hooked bars (No. 11) had more slip than small hooked bars (No. 7) at a given stress level. The anchorage strength of hooked bars increased as the concrete compressive strength increased. Reducing the concrete side cover from 3 to 1.75 in., decreased the anchorage strength of hooked bars by about 8%. The anchorage strength of hooked bars increased as the spacing of No. 3 ties within the joint region decreased from 6 to 3 in. The ACI 318-89 provisions modifies the development length of No. 11 and smaller hooked bars enclosed with ties spaced at not greater than $3d_b$ by a 0.8 factor. Results from this study indicated that the Code provision was appropriate. At load levels close to failure, 90° hooked bars performed stiffer than 180° hooked bars

Joh, Goto, and Shibata (1995)

Joh et al. (1995) tested 19 exterior beam-column joints to study the behavior of multiple hooked bars. The specimens were columns with beams represented by hooked bars and a compression reaction. Eighteen specimens had four 19-mm (¾-in.) hooked bars with 90° bend angles, arranged in one layer, placed inside the column longitudinal reinforcement. Unlike the specimens tested by Marques and Jirsa (1975), the depth of the columns was kept constant and the embedment length was varied by embedding the hooked bars in different positions through the columns. The test parameters included embedment length [130 to 320 mm (5.2 to 12.6 in.) from column face to center of tail extension], concrete compressive strength [300 to 700 kgf/cm^2 (4,270 to 9,960 psi)], moment arm of the beam [228 to 428 mm (8.97 to 16.85 in.)], center-to-center spacing between hooked bars (2.5 to $3.5d_b$.), thickness of the concrete side cover (3.4 to $6d_b$), lateral reinforcement ratio (the total area of the lateral reinforcement within the joint divided by the area of the joint cross-section normal to the plane of the hooked bars) ranged from 0.2 to 0.8 (lateral reinforcement was 6 mm in diameter), column axial load (none to 33.4% of the nominal concrete compressive strength), and the type of the applied load (monotonic vs. reversal). One specimen contained eight hooked bars arranged in two layers at a center-to-center spacing of 47 mm (1.85 in.) between the layers and 57 mm (2.24 in.) between the bars.

At failure, all specimens had a common cracking pattern with three types of cracks: A diagonal crack starting from the bent portion of the hooked bar to the assumed beam compression zone, a vertical crack starting from the bent portion of the hooked bar extending along the tail extension of the hooked bar, and an inclined crack starting from the bent portion of the hooked bar to the front face of the column away from the joint. Joh et al. described three modes of failure, shown in Figure 1.7. The first mode, side splitting, occurred in exterior beam-column joints with thin concrete side covers due to the wedging effect of the bent portions of hooked bars. The second mode, raking-out failure, involved a block of concrete pulling out towards the beam side with a simultaneous drop in the anchorage capacity for all hooked bars. Raking-out failure occurred in specimens with short embedment length and/or multiple hooked bars. Third, local compression failure occurred in specimens with thick concrete side cover that suitable to prevent side splitting failure, and contained hooked bars spaced apart so that the raking-out failure not likely to happen. Local compression failures occurred when concrete inside the bend crushes, often with hooked bars with small bend radius.

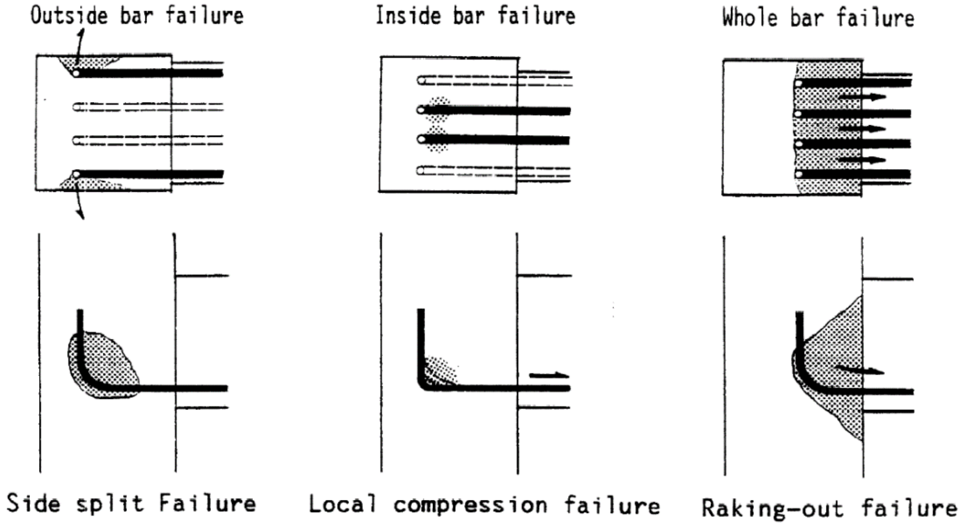


Figure 1.7 Failure mode types (Joh et al. 1995)

Joh et al. concluded that the anchorage strength of hooked bars was proportional to the square root of the concrete compressive strength and to the reciprocal of sin θ, where θ is the angle between the compression strut, formed from the bend portion to the assumed beam compression zone, and the plane of the hooked bars. The contribution of the lateral reinforcement within the joint was linearly proportional to the lateral reinforcement ratio. Joh et al. also indicated that the anchorage strength of hooked bars improved as column axial load increased, but only to a certain limit.

Joh and Shibata (1996)

Joh and Shibata (1996) continued the work of Joh et al. (1995) by testing 13 beam-column joints to determine the influence of the column axial load and concrete side cover on the anchorage strength of hooked bars. Each specimen contained four 19-mm (¾-in.) hooked bars with 90° bend angles. The hooked bars were embedded halfway through the column. Five specimens had concrete side covers between 64.5 and 264.5 mm (2.5 and 10.4 in.), and no column axial load. The other specimens had column axial stresses ranging from 0 to 33% of the concrete compressive strength, and a constant concrete side cover [64.5 mm (2.5 in.)]. The center-to-center spacing between hooked bars was 57 mm (2.25 in.). The moment arm of the beam was 328 mm (12.9 in.).

The lateral confining reinforcement ratio in the joints was 0.2%. The concrete compressive strength ranged from 300 to 600 kgf/cm^2 (4,260 to 8,530 psi).

Specimens with different column axial loads and constant concrete side cover exhibited similar cracking patterns to those observed by Joh et al. (1995), with the exception that the failure cone above the hooked bars were larger as the column axial load increased. For specimens with different concrete side covers and no column axial load, cracking patterns consisted of three main cracks forming a trapezoidal failure surface, as shown in Figure 1.8. As the concrete side cover increased, the depth of the failure cone decreased as observed from the side face of the column.

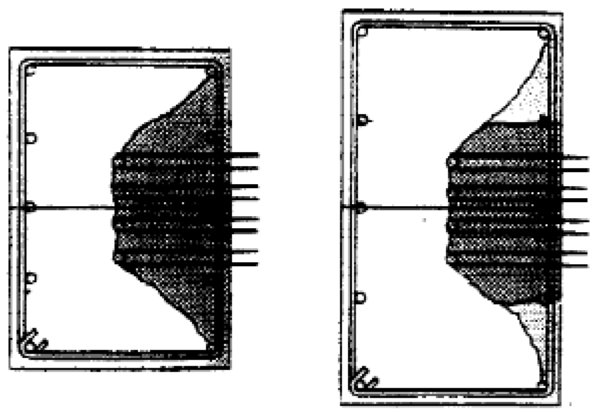


Figure 1.8 Failure mode for specimens with different side covers (Joh and Shibata 1996)

Joh and Shibata concluded that the anchorage strength of hooked bars increased as the column axial stresses increased up to 8% of the concrete compressive strength. Joh and Shibata previously found that the anchorage strength of hooked bars increased as the quantity of lateral reinforcement crossing the failure cone increased [Joh et al. (1995)]. The anchorage strength of hooked bars increased linearly as the concrete side cover increased, until the concrete side cover was large enough so that the ties were too far away to intercept the inclined cracks and resist the cracking propagation.

Scott (1996)

Scott (1996) tested 17 monolithic beam-column joints to investigate the steel strain along the beam hooked bars and the column longitudinal reinforcement. Fifteen specimens were subjected to a monotonic loading, and two specimens were subjected to reverse cyclic loading. The specimens contained two hooked bars inside the column longitudinal reinforcement. The test parameters included hooked bar size (12 or 16 mm), depth of the beam [210 to 300 mm (8.27 to 11.8 in.)], and column axial load [50 and 270 kN (11.24 and 60.7 kips]. The hooked bars had a $3d_b$ internal radius of bend. Three hooked bar detailing patterns were tested: hooked bars with a 90° bend angle with a tail extension positioned inside the beam-column joint, hooked bars with a 90° bend angle with a tail extension positioned outside the beam-column joint, and a single bar with two closely spaced 90° bends (within the column) that served as both the top and bottom reinforcement for the beam. The length of the tail extension beyond the bend ranged from 18 to $44d_b$. Concrete compressive strength ranged from 41.1 to 61.7 MPa (5,960 to 8,950 psi).

The cracking pattern consisted of flexural cracks on the beam at early loading stages followed by diagonal cracks in the joints (from the bend in the hooked bar to the beam compression zone). Specimens with low column axial load had flexural cracks above and below the joints on the tensile face of the column. Most of the specimens failed with extensive cracking in the beam-column joints. A total of 225 electric resistance strain gages were installed along the main beam and column reinforcement of one side of each specimen. Within the beam-column joints, the strain gages were spaced at 0.5 in. inside a machined cavity on the interior of the reinforcing steel. Figures 1.9a-c show the strain along the 16 mm hooked bars with the tail extension positioned inside the beam-column joint. The dashed lines indicate the strain when first cracking appeared in the joints, while the solid lines indicate the strain at the peak load. Small dots on the solid line indicate strains exceeding those corresponding to the yield stress.

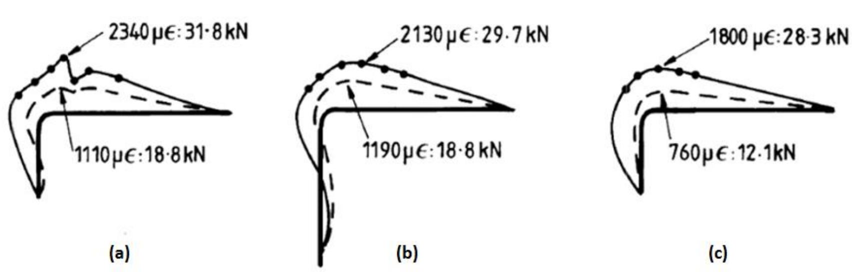


Figure 1.9 Strain along hooked bars (adapted from Scott 1996)

For specimens with 90° hooked bars positioned inside the column, Scott observed that at the cracking load, the bent portions, as well as the horizontal leg of the hooked bars experienced tensile stress; specimens with low column axial load had a longer portion of the vertical leg in tension (Figure 1.9c). The tensile stresses progressed steadily along the vertical leg of the hooked bars between joint cracking and failure. Specimens with long tail extensions ($48d_b$) had compressive stresses close to the end of the tail, as shown in Figure 1.9b. In general, the behavior of the three hooked bar detailing patterns was similar up to the point of joint cracking. Beyond this point, specimens with hooked bars with tail extensions positioned outside of the joint had lower tensile stresses along the vertical legs of hooked bars than specimens with the other two hook configurations.

Ramirez and Russell (2008)

Ramirez and Russell (2008) tested 21 exterior beam-column joints to investigate the anchorage strength of standard hooked bars in high-strength concrete. Ten of the specimens contained epoxy-coated hooked bars and eleven of the specimens contained uncoated hooked bars. Each specimen contained two hooked bars with a 90° bend angle, inside the column longitudinal reinforcement. The concrete side cover was 3.5 in. The test parameters included hooked bar size (No. 6 or No. 11), concrete compressive strength (8,910 to 16,500 psi), amount of confining reinforcement in the joint (none and with ties spaced at $3d_b$), and tail cover (0.75 to 2.5 in.). The hooked bars had embedment lengths between 6.5 and 15.5 in.

The loading procedure was similar to that used by Marques and Jirsa (1975) with the exception that the specimens were tested as cantilevers with no column axial load. In most of the tests, the cracking pattern was similar, with flexural cracks appearing on the back side of the column near the tail end of the hook followed by shear cracks on the side face of the column running from the compression reaction towards the bent portions of the hooked bars. At failure, concrete pulled out with the hooked bars for specimens with no confining reinforcement in the joints. Specimens with confining reinforcement in the joints exhibited a partial spalling of the concrete side cover as the concrete near the hook failed.

Ramirez and Russell concluded that the limit on concrete compressive strength in the ACI 318-05 provisions for anchoring hooked bars in tension could be increased to 15,000 psi. However, a minimum requirement for confining reinforcement in the joints should be provided. Ramirez and Russell also suggested that the minimum requirement of the tail concrete cover could be reduced from 2 in. to the hooked bar diameter as long as confining reinforcement along the anchoring zone was satisfied.

Hamad and Jumaa (2008)

Hamad and Jumaa (2008) tested 12 monolithic exterior beam-column joints to investigate the effect of galvanizing on the anchorage strength of the hooked bars in high strength concrete. Six specimens contained galvanized hooked bars and six specimens contained uncoated bars. Each specimen consisted of two cantilever beams connected to a single column, as shown in Figure 1.10. The beams were forced apart using two hydraulic rams installed between the top ends of the cantilevers. The test parameters included hooked bar size (No. 5, No. 8, and No. 10), hook location with respect to the columns bars (inside or outside), and surface condition (uncoated vs. galvanized). The hooked bars had a 90° bend angle. No confining reinforcement was provided within the beam-column joints. The embedment lengths were 5.9 in. for No. 5 hooked bars, 7.9 in. for No. 8 hooked bars, and 9.9 in. for No. 10 hooked bars. The nominal concrete compressive strength was 8,700 psi.

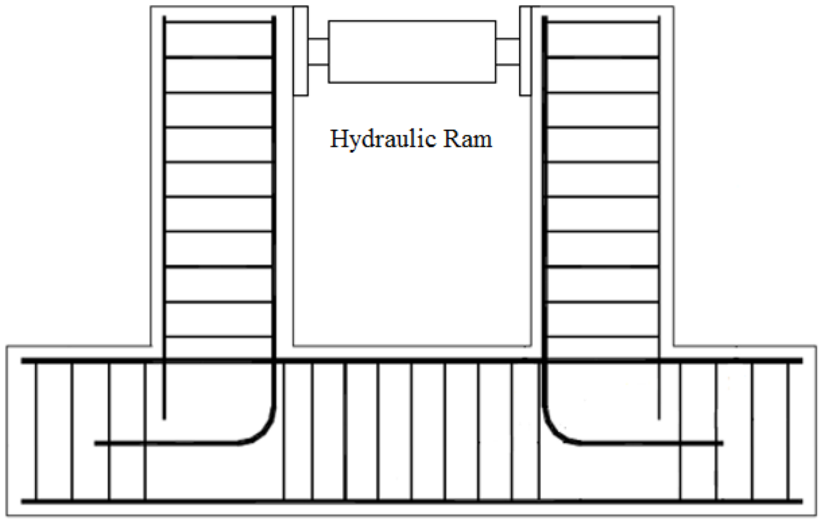


Figure 1.10 Specimen tested by (adapted from Hamad and Jumaa 2008)

In all specimens, cracks initiated along the internal corners between the beams and the column, with flexural cracks observed along the interior faces of the beams and on the top surface the column between the beams. Then, cracks propagated vertically along the hooked bars on the side face of the column. Eventually, two cracks branched from the vertical cracks at a location close to the bend towards the top surface of the column. The final failure mode was spalling of the concrete side cover. Hamad and Jumaa concluded that hooked bars placed outside the column longitudinal reinforcement developed less anchorage strength than hooked bars placed inside the column longitudinal reinforcement.

Sperry et al. (2015)

Sperry et al. (2015a, 2015b) tested 337 simulated beam-column joint specimens to determine the key factors that influence the anchorage strength of hooked bars in concrete and to develop characterizing equations and design guidelines for development length allowing for the use of high-strength reinforcing steel and concrete. The specimens were columns with beams represented by hooked bars and a compression reaction. Of the 337 specimens, 276 included two hooked bars and 61 included three or four hooked bars. The test parameters consisted of concrete compressive strength (4,300 to 16,510 psi), bar diameter (No. 5, No. 8, and No. 11), concrete side cover (1.5 to 4 in.), amount of confining reinforcement in the joint region, center-to-center spacing between the hooked bars (3 to 11 d_b), hook bend angle (90° or 180°), placement of the hook (inside or outside the column core, and inside or outside the column compression region), and embedment length.

Similar cracking initiation and propagation patterns were noticed on almost all specimens. Cracks first initiated on the front face of the column from the hooked bars and propagated horizontally towards the side face of the column. As the load on the hooked bars increased, the horizontal cracks on the front face of the column continued to grow on the side face of the column along the lead embedment length to approximately the location of the hook. At that load, radial cracks formed on the front face of the column from the hooked bars. On the side face of the column, vertical and diagonal cracks extended from the horizontal crack and continued to grow to the front face of the column above and below the level of the hooked bar. Near failure, the inclined cracks on the side face of the column extended around the column corner to the front face and widened as a concrete block pulled out of the front face of the column.

Based on the behavior of these specimens, Sperry et al. (2015a, 2015b) suggested that there were five failure modes: (1) Front pullout failure occurred when a concrete block pulled out with the hooked bars from the front face of the column. (2) Front blowout failure was similar to the front pullout failure; however, specimens exhibited more sudden failure and energy release. (3) Side splitting failure happened when the side face of the columns adjacent to the hooked bars cracked and split off due to the wedging effect of the hook. (4) Side blowout was similar to the side splitting failure; however, specimens exhibited higher energy release at failure. Each of these four failure modes was often coupled with one or two of the other failure types. (5) Tail kickout failure occurred when the tail extension of a 90° hooked bar pushed the concrete cover off of the back side of the column. This failure was observed for a few specimens and accompanied one or more of the other failure modes.

The experimental results from this study along with others from previous studies were analyzed by Sperry et al. (2015a) to develop equations to characterize the anchorage capacity of hooked bars with and without confining reinforcement [Eq. (1.6) and (1.7)]

$$T_c = 304 f_{cm}^{0.29} \ell_{eh}^{1.1} d_b^{0.5} \quad (1.6)$$

$$T_h = 486 f_{cm}^{0.24} \ell_{eh}^{1.09} d_b^{0.49} + 31{,}350 \left(\frac{NA_{tr}}{n} \right)^{1.11} d_b^{0.45} \quad (1.7)$$

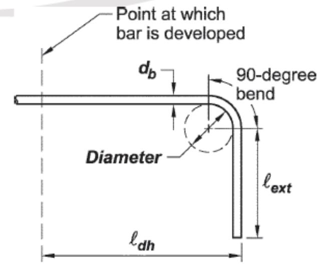
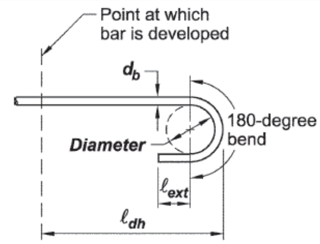
where T_c is the anchorage strength of hooked bar without confining reinforcement in lb, T_h is the anchorage strength of hooked bar confined by confining reinforcement in lb, f_{cm} is the measured concrete compressive strength in psi, ℓ_{eh} is the embedment length of the hooked bar in in., d_b is the diameter of the hooked bar in in., N is the number of legs of confining reinforcement, A_{tr} is area of a single leg of the confining reinforcement, in in^2 , and n is the number of the hooked being confined. Sperry et al. (2015b) found that only confining reinforcement within $8d_b$ (for No. 3 through No. 8 bars) or $10d_b$ (for No. 9 and No. 11 bars) of the straight portion of the hooked bar was effective in increasing the capacity of the joint. Sperry et al. (2015b) found that the strength of hooked bars could be characterized by Eq. (1.8)

$$T_h = 332 f_{cm}^{0.29} \ell_{eh}^{1.06} d_b^{0.54} + 54{,}250 \left(\frac{NA_{tr}}{n} \right)^{1.06} d_b^{0.59} \quad (1.8)$$

Sperry et al. concluded that the current provisions in ACI 318-14 for the development of standard hooks in tension overpredict the anchorage strength of large hooked bars, the influence of concrete compressive strength, and the influence of confining reinforcement on the anchorage strength of hooked bars. For a given embedment length, the anchorage strength of hooked bars increased as the bar diameter increased, with or without confining reinforcement in the hook region. The anchorage strength of hooked bars did not increase as the side concrete cover increased from 2.5 in. to 3.5 in. Hooked bars with bend angles of 90° and 180° exhibited similar anchorage strengths. The influence of the concrete compressive strength on the anchorage strength of the hooked bars was best represented by the concrete compressive strength to the 0.29 power. Closely-spaced (three or four) hooked bars developed less anchorage capacity per bar than obtained in specimens with two widely-spaced hooked bars.

1.3 DEVELOPMENT OF CODE PROVISIONS

The ACI 318 Building Code, AASHTO Bridge Specifications, and ACI 349 Code Requirements for Nuclear Safety-Related Concrete Structures specify standard hooked bars as shown in Figure 1.11.

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 1.11 Standard hook geometry (ACI 318-14)

The equation in ACI 318-77 for use in designing the development length of hooks was based on previous provisions (ACI 318-71, ACI 318-63), which were not supported by the results of the tests by Marques and Jirsa (1975). The procedure in ACI 318-77 separated the contributions of the hook and the straight lead embedment. The tensile stress contributed by the hooked portion of the bar was equal to

$$f_h = \xi \times \sqrt{f_c'} \tag{1.9}$$

where f_h is the tensile stress developed by the hooked portion of the bar, in psi, and f_c' is the concrete compressive strength. The values of ξ were given in a table as a function of the bar size, yield stress, and the casting position. The value of ξ could be increased 30% where transverse reinforcement was provided perpendicular to the plane of the hooked bar. The difference in stress between f_y and f_h was carried by substituting a value of stress equal to $f_y - f_h$ in place of f_y in the basic development length equation for straight reinforcement. The use of this approach underestimated the contribution of the hooked portion of the bar and, for some bar sizes, produced inconsistent results for identical bars with different yield strengths. For example, the anchorage strength of a No. 6 hook with 60 ksi yield strength was 50 % greater than a No. 6 hook with 40 ksi yield strength. A simplified procedure for the basic development length that combined the contribution of the hook and the straight portions was proposed in ACI 408.1R-79, shown in Eq. (1.10), based on data from Marques and Jirsa (1975) and Pinc et al. (1977).

$$\ell_{dh} = \frac{960 \times d_b}{\phi\sqrt{f_c'}} \tag{1.10}$$

where ℓ_{dh} is the basic development length of hooked bars, d_b is the hooked bar diameter, and f_c' is the concrete compressive strength. The procedure was discussed and explained by Jirsa, Lutz, and Gergely (1979) who suggested that $\phi = 0.8$ be directly introduced into the development equation to maintain the ratio test/calculated above 1.0. The new provisions were adopted in ACI 318-83 with modification factors to account for the bar yield strength, presence of confinement (concrete cover or transverse ties), and lightweight concrete. Practically speaking, the design equation has been maintained the same form since 1983 with revisions to reflect code notation updates and, based on tests conducted by Hamad et al. (1993), a new provision was adopted in ACI 318-95 accounting for the increased the development length required by epoxy-coated hooked bars. Equation (1.11) presents the current version of the design equation (ACI 318-14) for the tension development length of hooked bars.

$$\ell_{dh} = \left(\frac{f_y \psi_e \psi_c \psi_r}{50\lambda\sqrt{f_c'}}\right) d_b \tag{1.11}$$

where ℓ_{dh} is the development length in in., ψ_e equals 1.2 for epoxy-coated or zinc and epoxy dual-coated bar; ψ_e equals 1.0 for uncoated or zinc-coated (galvanized) bar; ψ_c equals 0.7 for No. 11 and smaller bars with side cover not less than 2.5 in. and tail cover not less than 2 in. (for 90° hook), otherwise, ψ_c equals 1.0; ψ_r equals 0.8 for No. 11 and smaller bars with 90° or 180° bend angle enclosed along the lead embedment with ties or stirrups perpendicular to the lead embedment at $3d_b$ spacing or smaller; ψ_r equals 0.8 for No. 11 bar and smaller with 90° bend angle enclosed along the tail extension with ties or stirrups perpendicular to the tail extension at $3d_b$ spacing or smaller, otherwise, ψ_r equals 1.0; λ equals 0.75 for lightweight concrete and 1.0 for normalweight concrete.

1.4 DISCUSSION

Prior to 1983, ACI Code provisions for the development length of hooked bars uncoupled the contribution of hook and straight lead embedment. This approach underestimated the hook contribution and produced inconsistent results for identical bars with different yield strengths. For these reasons, Marques and Jirsa (1975) and Pinc et al. (1977) tested 34 simulated exterior beam-column joints containing Grade 60 hooked bars with sizes ranging from No. 5 to No. 11. The concrete compressive strength ranged from 3,600 to 5,200 psi. Spalling of the concrete side cover was the primary mode of failure. Based on these two test series, simplified code provisions that combined the contribution of the hook and straight lead embedment were adopted in ACI 318-83. Since then, a small number of other studies have been conducted to evaluate the strength of multiple and closely spaced hooked bars, and hooked bars in high-strength concrete, each with limited scope. In 2012, a large-scale research program was initiated at the University of Kansas to study the anchorage behavior of the hooked bars. Sperry et al. (2015a, 2015b) reported on a total of 337 simulated beam-column joints tested containing conventional and high-strength bars with different sizes (No. 5, No. 8 and No. 11). The concrete compressive strength ranged from 4,300 to 16,510 psi. The majority of the specimens contained two hooks spaced at 9 to $12d_b$. The result of that study indicated that more needed to be known about the anchorage strength of hooked bars in cases when multiple and closely-spaced hooked bars or hooked bars arranged in more than one layer were used, hooked bars in deep beam-column joints, hooked bars not embedded to the far side of the member, and the strain distribution in hooked bars and confining reinforcement within the joints.

1.5 OBJECTIVE AND SCOPE

The objectives of this study are to expand the understanding of the anchorage behavior of hooked bars in concrete and develop new guidelines that will allow the full use of hooked bars in reinforced concrete structures incorporating high-strength reinforcing steel and high-strength concrete. A total of 122 simulated beam-column joints, 54 with two hooked bars and 68 with three, four, or six hooked bars, were tested. The tests included No. 5, 8, and 11 hooked bars with bend angles of 90° and 180°. Some of the tests were reported in Sperry et al. (2015a, 2015b). The test parameters included embedment length (5.5 to 23.5 in.), amount of confining reinforcement within the joint (no confining reinforcement to nine No. 3 hoops), location of the hooked bar with respect to member depth, hooked bar stresses (22,800 to 138,800 psi), concrete compressive strength (4,490 to 14,050 psi), center-to-center spacing between hooked bars (2 to 11.8d_b), number of hooked bars (2, 3, 4, or 6), arrangement of hooked bars (one or two layers), and ratios of beam effective depth to embedment length (0.6 to 2.13). The experimental study is a continuation of previous work at the University of Kansas (Peckover and Darwin 2013, Searle et al. 2014, and Sperry et al. 2015a, 2015b) and focuses on closely-spaced hooked bars, staggered hooked bars, ratios of beam effective depth to embedment length, and the strain in the hooked bars and confining reinforcement within the joints. The goal of the analytical portion of this research is to develop an equation that characterizes the anchorage strength of hooked bars based on the results of this study and earlier work by Marques and Jirsa (1975), Pinc et al. (1977), Hamad et al. (1993), Ramirez and Russell (2008), Lee and Park (2010), Peckover and Darwin (2013), Searle et al. (2014), and Sperry et al. (2015a, 2015b, 2017a, 2017b). The characterizing expression is then used to develop code provisions for the development length of reinforcing bars terminated in standard hooks incorporating the effects of bar size, bend angle, concrete compressive strength, concrete side cover, concrete tail cover, hook location (inside or outside the column core and with respect to member depth), confining reinforcement, spacing between hooks, hook arrangement (staggered hooks), and ratio of beam effective depth to embedment length.

CHAPTER 2: EXPERIMENTAL WORK

2.1 GENERAL

Simulated beam-column joint specimens were tested to determine the influence of bar size, hook bend angle, embedment length, amount of confining reinforcement within the joint, location of hooked bars with respect to the member depth, concrete compressive strength, number of hooked bars, center-to-center spacing between hooked bars, arrangement of hooked bars (staggered hooks), and ratio of beam effective depth to embedment length on the anchorage strength of hooked bars. The ranges of these variables are presented in Table 2.1.

Table 2.1 Range of variables tested

Parameters	**Range**
Hooked Bar Size	No. 5, No. 8, No. 11
Hook Bend Angle	90°, 180°
Embedment Length (in.)	5.5 to 23.5
Amount of Confining Reinforcement within the Joint	None, 2 No. 3, 5 No. 3, 6 No. 3, 7 No. 3, 8 No. 3, 9 No. 3
Location of Hooked Bars	Embedded to Far Side of Member or to Middle Depth of Member
Nominal Concrete Compressive Strength, psi	5000, 8000, 12000, 15000
Number of Hooked Bars	2, 3, 4, 6
Center-to-Center Spacing*	2 to 11.8d_b
Number of Layers	1, 2
Ratio of Beam Effective Depth to Embedment Length	0.6 to 2.13

* of hooked bars

One hundred twenty two beam-column joint specimens, containing No. 5, No. 8 and No. 11 hooked bars with 90° and 180° bend angles, were tested as a continuation of prior research at the University of Kansas (Peckover and Darwin 2013, Searle et al. 2014, and Sperry et al. 2015a, 2015b). The specimens were cast in 12 groups using normalweight ready-mix concrete with concrete compressive strengths ranging from 4,490 to 14,050 psi. The hooked bars were fabricated from conventional and high-strength steel. The stresses in the hooked bars at failure ranged from

22,800 to 138,800 psi. The hooked bars were placed inside the column core (that is, inside the column longitudinal reinforcement) with a nominal side cover of 2.5 in.

The specimens tested in this portion of the study are grouped into five categories. The first category consists of specimens containing two hooked bars embedded to the far side of the column with a 2 in. nominal tail cover. These two-hook specimens include specimens with relatively wide spacing between hooked bars (center-to-center spacing between 10.7 and 11.8d_b), which serve as "standard specimens," and specimens with closely-spaced hooked bars (specimens with center-to-center spacing between hooked bars of 6d_b or less). The second category consists of specimens containing three or four hooked bars arranged in one layer with a nominal tail cover of 2 in. The third category consists of specimens with staggered hooks. Staggered-hook specimens contain four or six hooked bars arranged in two layers with a nominal tail cover over the external hooks of 2 in. The fourth category consists of specimens with hooked bars that were not embedded to the far side of the column core (nominal tail cover ranging from 6 to 18 in.). The final category consists of specimens containing two hooked bars with a ratio of beam effective depth to embedment length greater than 1.75, which will be identified as deep-beam specimens.

The specimen designation system used in this study provides information about key specimen parameters. For example, in the specimen with two hooked bars designation 8-5-90-5#3-i-2.5-2-8, the first number (8) represents the size of the hooked bar using the ASTM in.-lb designation; the second number (5) is the nominal concrete compressive strength; the third number (90) represents the hook bend angle; the fourth number (5#3) is the number and size of the bars used as confining reinforcement within the joint region; the fifth character (i) indicates that the hooked bars are located inside the column core; the sixth number (2.5) is the nominal side cover in in.; the seventh number (2) is the nominal tail cover in in.; and the last number (8) is the nominal embedment length in in.. Specimens with more than two hooked bars and with closely-spaced hooks are identified by adding the number of hooked bars and center-to-center spacing between the hooked bars in front of the designation, such as (4@3) 5-8-90-0-i-2.5-2-6, with (4@3) indicating four hooked bars spaced at three times the bar diameter (center-to-center). Specimens with staggered hooked bars are identified by denoting the number of staggered hook groups and the letter "s" in front of the identification title such as (3s) 5-5-90-6#3-i-2.5-2-8. The (3s) indicates three groups of staggered hooks (six hooks in total) in the specimens. Finally, with deep-beam specimens are identified by the number of hooked bars and the letter "d" denoted in front of the designation, such as (2d) 8-5-90-2#3-i-2.5-2-10.

2.2 MATERIAL PROPERTIES

2.2.1 Concrete

Non-air-entrained normalweight ready-mix concrete was used to cast the specimens. The nominal compressive strengths were 5,000, 8,000, 12,000, and 15,000 psi. The concrete contained Type I/II portland cement, Kansas River sand, crushed limestone or granite with a maximum size of 0.75 in., and a high-range water-reducer admixture, as shown in Table 2.2. The 12,000 psi concrete mixtures also contained pea gravel to improve the workability of the mix. AVDA 140 was used in the 5,000 and 8,000-psi mixtures and ADVA 575 was used in the 12,000 and 15,000-psi mixtures. Both ADVA 140 and ADVA 575 are produced by W.R. Grace.

Table 2.2 Concrete mixture proportions

Material	Quantity (SSD)			
Design Compressive Strength	**5000 psi**	**8000 psi**	**12000 psi**	**15000 psi**
Type I/II Cement, lb/yd^3	600	700	750	760
Type C Fly Ash, lb/yd^3	-	-	-	160
Silica Fume, lb/yd^3	-	-	-	100
Water, lb/yd^3	263	225	217	233
Kansas River Sand[a], lb/yd^3	1396	1375	1050	1138
Pea Gravel[b], lb/yd^3	-	-	316	-
Crushed Limestone[c], lb/yd^3	1734	1683	1796	-
Granite[d], lb/yd^3	-	-	-	1693
Estimated Air Content, %	1	1	1	1
High-Range Water-Reducer, oz (US)	30[e]	171[e]	78[f]	205[f]
w/cm ratio	0.44	0.32	0.29	0.24

BSG (SSD): [a]2.63, [b]2.60, [c]2.59, [d]2.61
[e]ADVA 140. [f]ADVA 575

2.2.2 Reinforcing Steel

The hooked bars used in this study were ASTM A615 Grade 80 and ASTM A1035 Grade 120 steel. Yield strength, tensile strength, nominal diameter, average rib spacing, average rib height, gap width, and the relative rib area of the hooked bars are presented in Table 2.3. For most of the specimens, ASTM A615 Grade 60 bars were used as column longitudinal reinforcement and confining reinforcement inside and outside the joint rejoin. In a few specimens that had larger flexure demand, ASTM A1035 Grade 120 steel was used. These specimens are identified in Chapter 3.

Table 2.3 Hooked bar properties

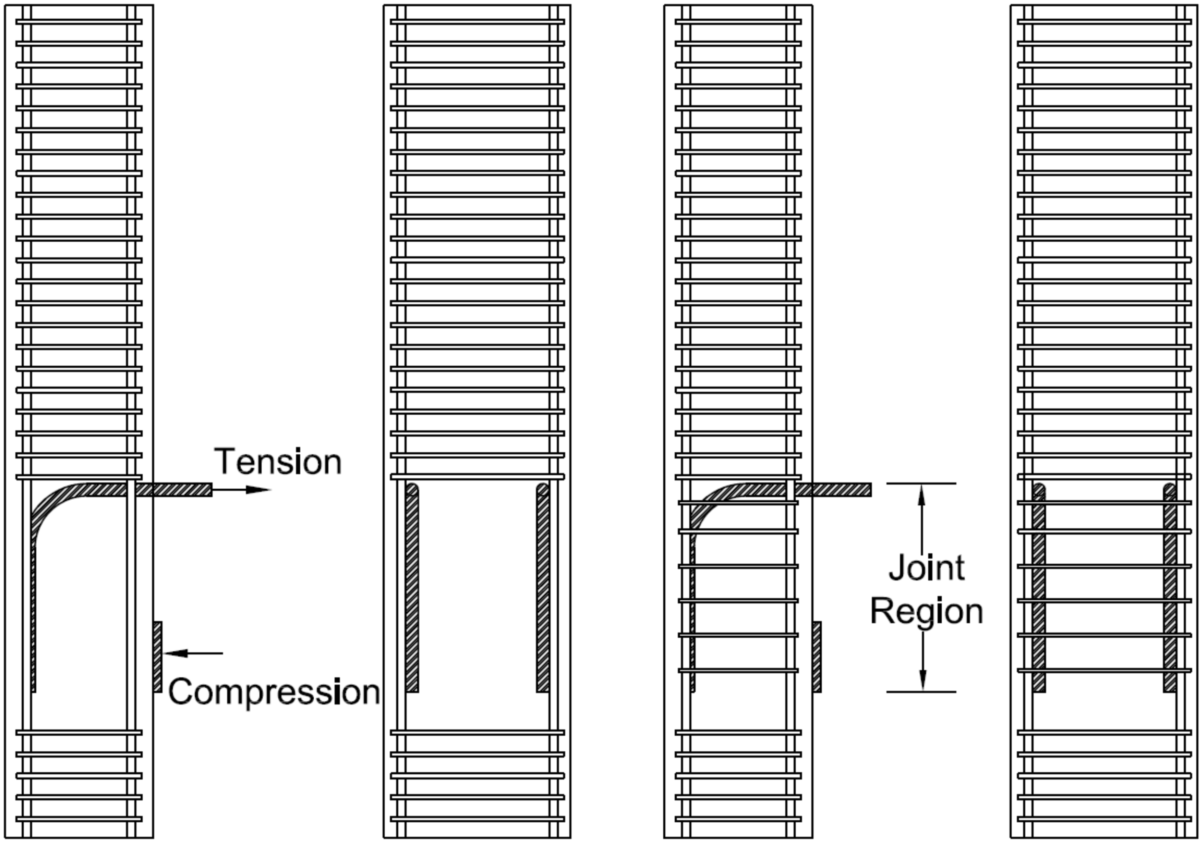
Bar Size	ASTM Designation	Yield Strength (ksi)[1]	Tensile Strength (ksi)[1]	Nominal Diameter (in.)	Average Rib Spacing (in.)	Average Rib Height		Gap Width		Relative Rib Area[4]
						A[3] (in.)	B[4] (in.)	Side 1 (in.)	Side 2 (in.)	
5	A1035	119.5	162.5	0.625	0.391	0.038	0.034	0.200	0.175	0.073
8	A615	94.0	128.3	1	0.666	0.059	0.056	0.146	0.155	0.073
8	A1035[a]	120.0[2]	168.0[2]	1	0.666	0.059	0.056	0.146	0.155	0.073
8	A1035[b]	122.0[2]	168.0[2]	1	0.686	0.068	0.065	0.186	0.181	0.084
8	A1035[c]	129.0	167.3	1	0.666	0.056	0.059	0.146	0.155	0.073
11	A615	88.2	122.1	1.41	0.894	0.080	0.074	0.204	0.196	0.069
11	A1035	131.0	165.7	1.41	0.830	0.098	0.088	0.248	0.220	0.085

[1] Tests performed as part of this study, [2]from mill report, [3] Per ASTM A615, A706, [4] Per ACI 408R-3, [a] Heat 1, [b] Heat 2, [c] Heat 3

2.3 SPECIMEN DESIGN

The specimens were designed to simulate exterior beam-columns joints, fabricated as columns without casting the associated beam. The reaction forces from the beam on the column were represented by tensile forces on the hooked bars and a compression reaction representing the compression region of the beam, as shown in Figure 2.1. Figures 2.1a and b show the side and front views of a specimen without confining reinforcement within the joint region, while Figures 2.1c and d show similar views of a specimen with No. 3 hoops spaced at $3d_b$ as confining reinforcement within the joint region. Specimens with No. 3 hoops spaced at $3d_b$ had the first hoop centered $1.5d_b$ from the center of the straight portion of the hooked bars and the other hoops spaced at $3d_b$ intervals (center-to-center) from the first hoop. In addition, some specimens contained two No. 3 hoops as confining reinforcement within the joint region. For specimens with two hoops and No. 5 hooked bars, the first and second hoops were spaced at 3-in. intervals from the center of the straight portion of the hooked bars. For specimens with No. 8 hooked bars, the first hoop was spaced 3-in. from the center of the straight portion of the hooked bars and the second hoop was spaced at 8-in. from the center of the first hoop. Specimens with No. 11 hooked bars had the first and second hoops spaced at 8-in. intervals from the center of the straight portion of the hooked bars. Column heights of 54 in. were used for specimens containing No. 5 and No. 8 hooked bars and 96 in. for specimens containing No. 11 hooked bars. The column heights were chosen to prevent compressive stresses from the support reactions from interfering with the joint region. Column depth was calculated by adding the tail cover to the desired embedment length ℓ_{eh}. For this study, embedment length ℓ_{eh} is the distance from the front face of the column to the back of the hook. During the design process, the embedment lengths ℓ_{eh} were selected to insure anchorage failure before bar fracture. This was accomplished by using trend lines of test results from earlier tests. The nominal column width equaled the out-to-out spacing between the hooked bars plus two times the side cover.

The column longitudinal reinforcement and confining reinforcement outside the joint region were chosen so that the column could resist the shear and flexural demand assuming all hooked bars reached their failure stress simultaneously. The amount and configuration of column longitudinal and confining reinforcement outside the joint region are presented in Appendix B. To prevent bond failure along the column longitudinal reinforcement, transverse bars were welded on the top and bottom ends of the steel cage. Specific design details for each category of specimen will be explained in the following sections.

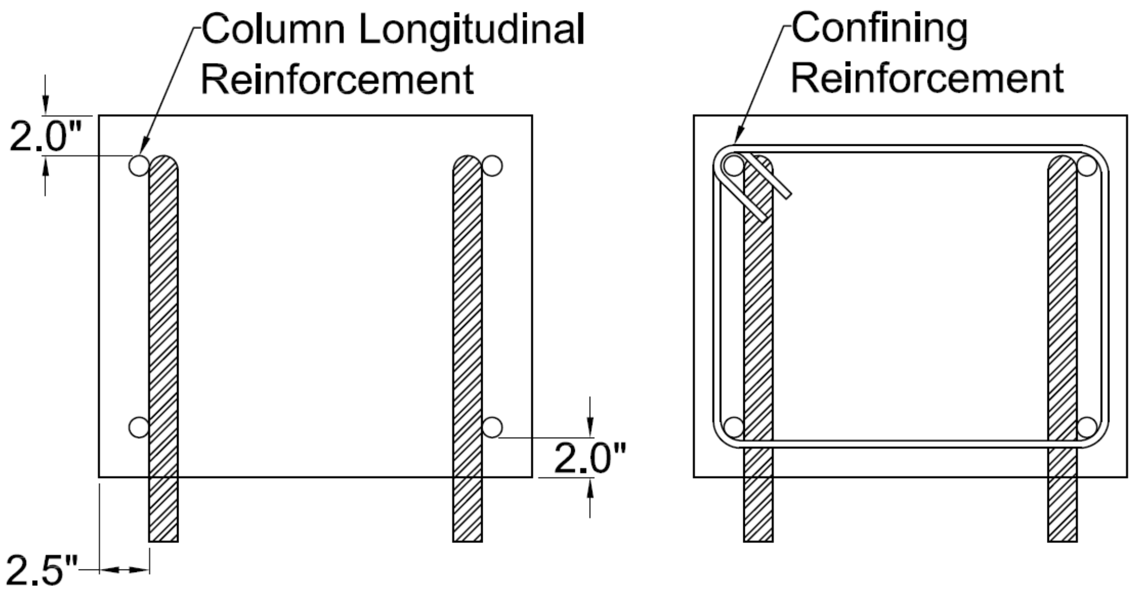


(a) **(b)** **(c)** **(d)**

Figure 2.1 Details of specimens with two hooked bars (a) side view of specimen with no confinement (b) front view of specimen with no confinement (c) side view of specimen with No. 3 hoops spaced at $3d_b$ (d) front view of specimen with No. 3 hoops spaced at $3d_b$

2.3.1 Specimens with Two Hooked Bars

Figure 2.2 shows the plan view of specimens with two hooked bars (a) without and (b) with confining reinforcement within the joint region. The hooked bars were arranged in one layer, inside the column longitudinal reinforcement, and embedded on the far side of the column. Three levels of confining reinforcement were investigated for specimens containing two hooked bars: no confining reinforcement, two No. 3 hoops within the joint region, and No. 3 hoops spaced at $3d_b$ (where d_b is the hooked bar diameter). No. 3 hoops spaced at $3d_b$ meet the requirements of ACI 318-14 Section 25.4.3 that allow for the use of a 0.8 modification factor when calculating the development length of hooked bars with a 90° bend. Specimens containing No. 5 and No. 8 hooked bars with hoops spaced at $3d_b$ have five hoops along the hook and tail extension, while those containing No. 11 hooked bars have six hoops along the hook and tail extension. Specimens with relatively wide spacing between the hooked bars (standard specimen) had widths of 13, 17, and 21.5 in. for No. 5, No. 8, and No. 11 hooked bars, respectively. For closely-spaced hook specimens, the width was varied to achieve the desired center-to-center spacing between the hooked bars. The ranges of variables investigated for specimens with two hooked bars are presented in Table 2.4.



(a) **(b)**

Figure 2.2 Plan view of specimens with two hooked bars (a) without confining reinforcement (b) with confining reinforcement within the joint rejoin

Table 2.4 Range of variables for specimens with two hooked bars

Parameters	**Range**
Hooked Bar Size	No. 5, No. 8, No. 11
Hook Bend Angle	90°, 180°
Embedment Length (in.)	5.75 to 17.5
Amount of Confining Reinforcement within the Joint	None, 2 No. 3, 5 No. 3, 6 No. 3
Location of Hooked Bars	Embedded to Far Side of Member
Nominal Concrete Compressive Strength, psi	5000, 8000, 15000
Number of Hooked Bars	2
Center-to-Center Spacing*(c_{ch})	3 to 11.8d_b
Number of Layers*	1
Ratio of Beam Effective Depth to Embedment Length	0.81 to 1.6

* of hooked bars

2.3.2 Specimens with Three or Four Hooked Bars

Figure 2.3 shows plan views for specimens with three or four hooked bars with confining reinforcement within the joint region and with different center-to-center spacing between the hooked bars. The specimens contained No. 5, No. 8 or No. 11 hooked bars with 90° and 180° bend angles. The center-to-center spacing between the hooked bars ranged from 3 to 10d_b. In the design procedure, the column width was varied to achieve the desired center-to-center spacing between hooked bars. Hooked bars were placed inside the column longitudinal reinforcement and embedded to the far side of the column. Three levels of confining reinforcement were investigated; no confining reinforcement, two No. 3 hoops, and No. 3 hoops spaced at 3d_b. The ranges of variables investigated for specimens with three or four hooked bars are presented in Table 2.5.

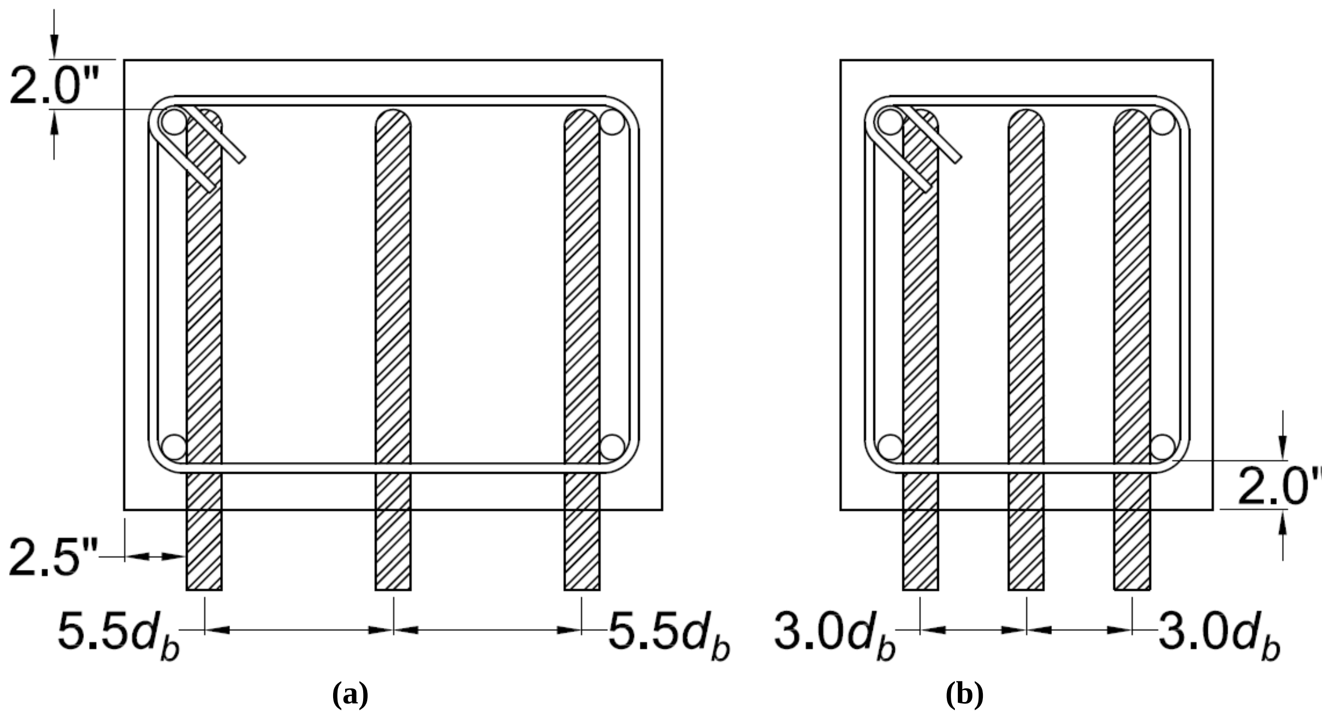


Figure 2.3 Plan views of specimens with three or four hooked bars (a) with 5.5d_b center-to-center spacing (b) 3d_b center-to-center spacing

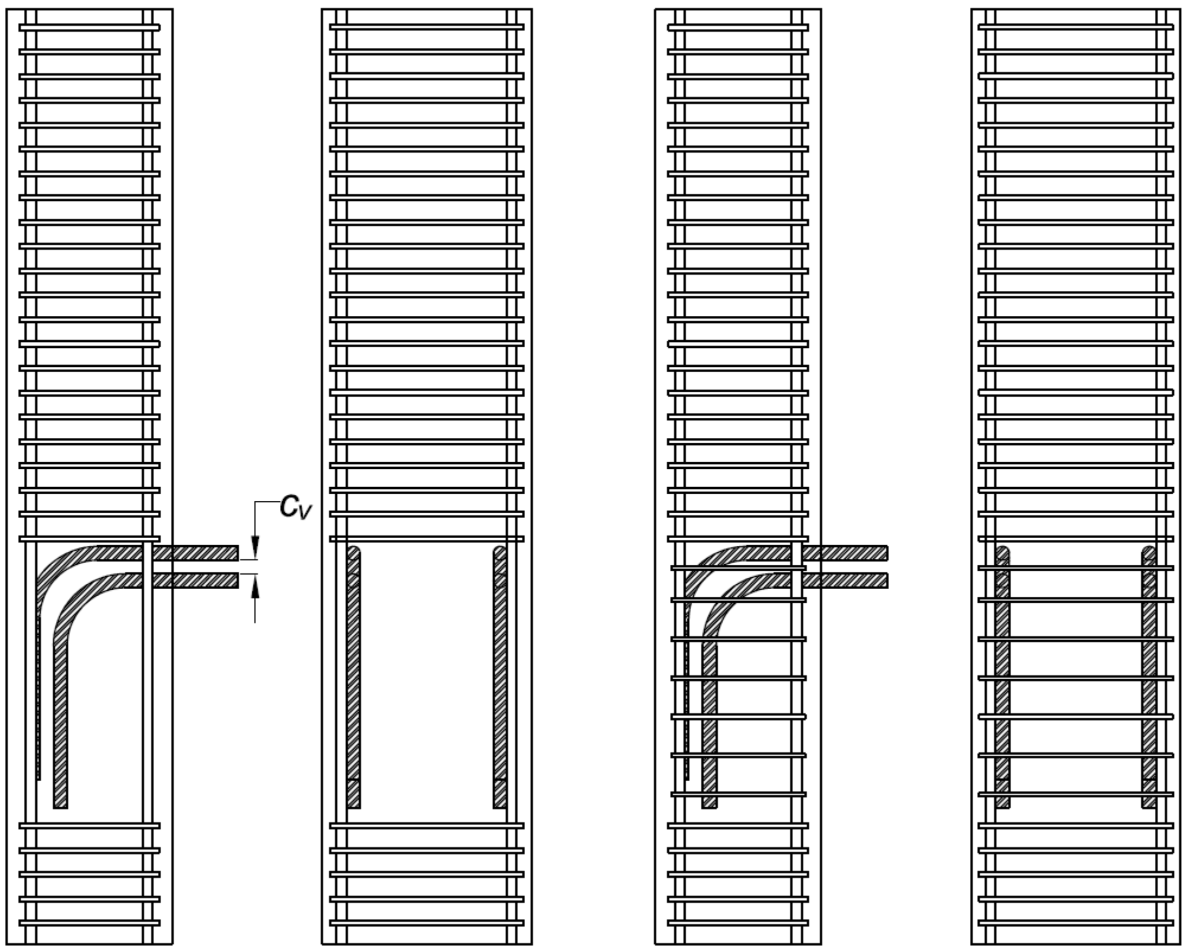
Table 2.5 Range of variables for specimens with three of four hooked bars

Parameters	Range
Hooked Bar Size	No. 5, No. 8, No. 11
Hook Bend Angle	90°, 180°
Embedment Length (in.)	5.5 to 23.5
Amount of Confining Reinforcement within the Joint	None, 2 No. 3, 5 No. 3, 6 No. 3
Location of Hooked Bars	Embedded to Far Side of Member
Nominal Concrete Compressive Strength, psi	5000, 8000, 12000
Number of Hooked Bars	3, 4
Center-to-Center Spacing*(c_{ch})	3 to 10d_b
Number of Layers	1
Ratio of Beam Effective Depth to Embedment Length	0.84 to 1.5

* of hooked bars

2.3.3 Specimens with Staggered Hooked Bars

When reinforcing bars arranged in more than one layer terminate in standard hooks, the hooks must be staggered to avoid interference with each other (staggered hooked bars). To investigate the effect of this practice on the anchorage strength of hooked bars, specimens with four or six hooked bars arranged in two layers were fabricated, as shown in Figure 2.4. Figures 2.4a and b show the side and front views of a specimen with staggered hooked bars with no confining reinforcement within the joint region, while Figures 2.4c and d show the side and front views of a specimen with staggered hooked bars with No. 3 hoops spaced at 3d_b as confining reinforcement within the joint region. Specimens with staggered hooked bars contained No. 5 or No. 11 bars. For specimens containing No. 5 staggered hooked bars, six No. 3 hoops spaced along the bend of the hook and the tail extensions were used to meet the requirements of ACI 318-14 Section 25.4.3 for the use of a 0.8 modification factor; seven No. 3 hoops were required for specimens with No. 11 staggered hooked bars. The additional hoop, compared to the number required in specimens with hooked bars arranged in one layer, was added to confine the last portion of the tail extension of the second layer of bars, as shown in Figures 2.4c and d. The horizontal center-to-center spacing between hooked bars ranged from 5.9 to 11.8d_b. Vertical clear spacing between hooked bars (c_v) was 1.0 in. for specimens containing No. 5 staggered hooked bars and 1.0d_b for specimens containing No. 11 staggered hooked bars. In addition to the two levels of confinement shown in Figure 2.4, specimens with intermediate levels of confinement (two and five No. 3 hoops within the joint region) and confining reinforcement exceeding that required by ACI 318-14 Section 25.4.3 (up to eight No. 3 hoops within the joint region) were also investigated. The ranges of variables investigated for specimens with staggered hooked bars are presented in Table 2.6.



(a) (b) (c) (d)

Figure 2.4 Details of specimens with staggered hooked bars (a) side view of specimen without confinement (b) front view of specimen without confinement (c) side view of specimen with No. 3 hoops spaced at 3db (d) front view of specimen with No. 3 hoops spaced at 3db

Table 2.6 Range of variables for specimens with staggered hooked bars

Parameters	**Range**
Hooked Bar Size	No. 5, No. 11
Hook Bend Angle	90°
Embedment Length (in.)	8 to 16
Amount of Confining Reinforcement within the Joint	None, 2 No. 3, 5 No. 3, 6 No. 3, 7 No. 3, 8 No. 3
Location of Hooked Bars	Embedded to Far Side of Member
Nominal Concrete Compressive Strength, psi	5000
Number of Hooked Bars	4, 6
Horizontal Center-to-Center Spacing* (c_{ch})	5.5 to 11.8d_b
Vertical Center-to-Center Spacing* (c_{cv})	2.0 to 2.6d_b
Number of Layers	2
Ratio of Beam Effective Depth to Embedment Length	1.1 to 1.4

* of hooked bars

2.3.4 Specimens with Hooks Not Embedded to Far Side of Member

The majority of the specimens had hooked bars embedded to the far side of the column. In some specimens, however, the hooked bars were embedded in the middle of the column, as shown in Figure 2.5. Since the provisions in the ACI Code do not require hooked bars to be embedded to the far side of the member, it was desired to investigate how shorter embedment would affect anchorage strength. Specimens with two, three, or four hooked bars arranged in one layer with center-to-center spacings ranging from 3 to 11d_b were investigated. The specimens contained No. 5, No. 8, or No. 11 hooked bars. The column depth was double the desired embedment length; that is, hooked bars were embedded at the center of the column. Tail cover ranged from 6 to 18 in. Three different levels of confining reinforcement were investigated; no confining reinforcement, two No. 3 hoops, and No. 3 hoops spaced at 3d_b. The ranges of variables investigated for specimens with hooks not embedded to far side of member are presented in Table 2.7.

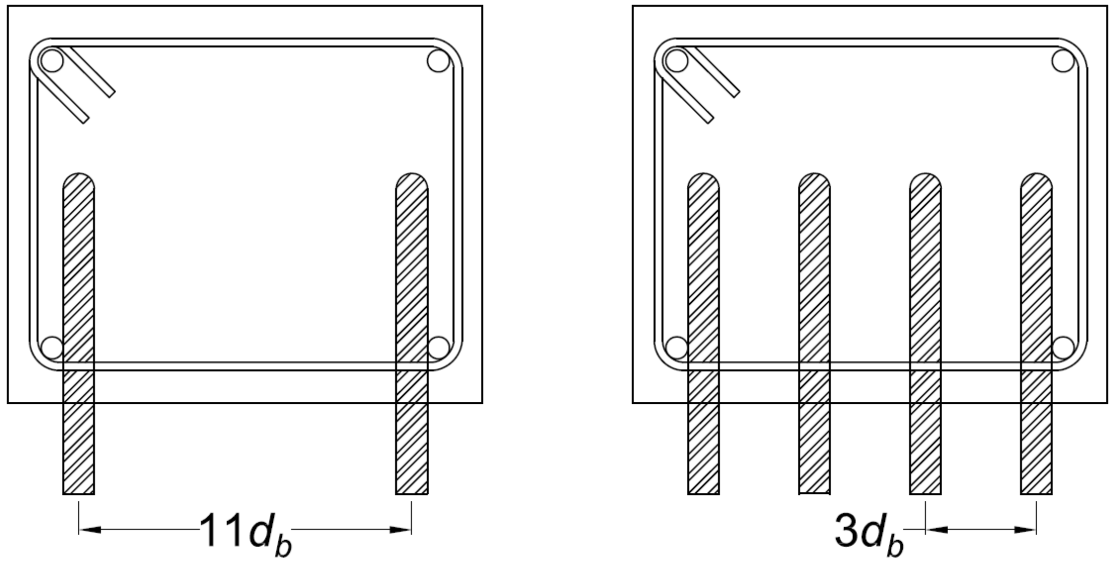


Figure 2.5 Cross section details of specimens with hooked bars not embedded to the far side of member (a) 11db center-to-center spacing (b) 3db center-to-center spacing

Table 2.7 Range of variables for specimens with hooks not embedded to the far side of the member

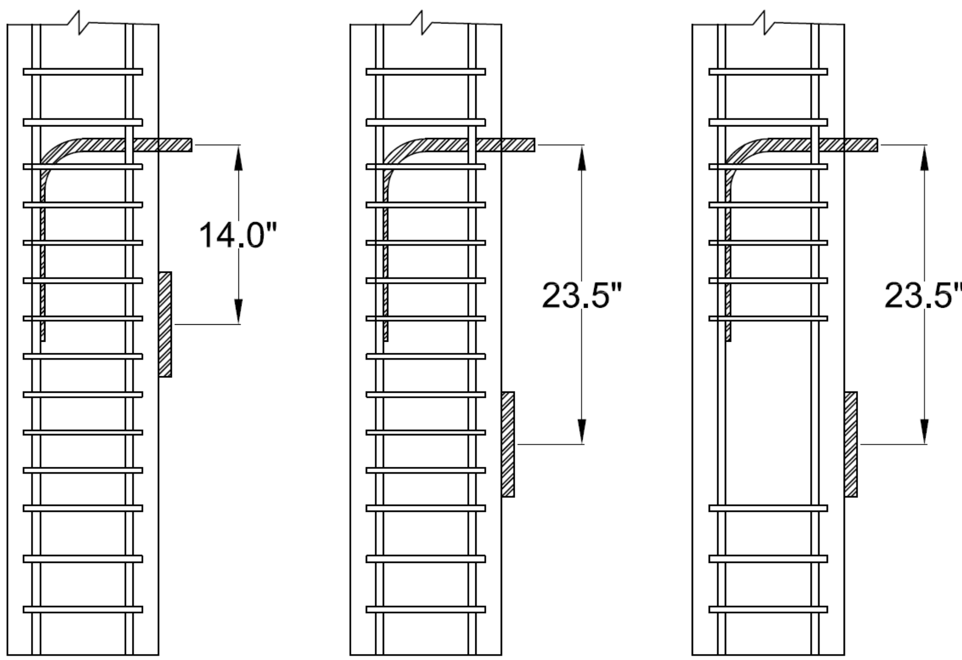
Parameters	**Range**
Hooked Bar Size	No. 5, No. 8, No. 11
Hook Bend Angle	90°
Embedment Length (in.)	6 to 18
Amount of Confining Reinforcement within the Joint	None, 2 No. 3, 5 No. 3, 6 No. 3
Location of Hooked Bars	Embedded to Middle Depth of the Member
Nominal Concrete Compressive Strength, psi	5000, 8000
Number of Hooked Bars	2, 3, 4
Center-to-Center Spacing* (c_{ch})	3 to 11d_b
Number of Layers	1
Ratio of Beam Effective Depth to Embedment Length	0.93 to 1.67

* of hooked bars

2.3.5 Deep-Beam Specimens with Two Hooked Bars

Deep-beam specimens had similar reinforcement configurations to specimens with two hooked bars, with the exception that the location of the compression reaction (representing the beam compression zone) was moved down to simulate a deep beam-column joint, as shown in

Figures 2.6a and b. Two hooked bars were placed inside the column longitudinal reinforcement and embedded to the far side of the column with 2 in. nominal tail cover. The column width was constant (17 in. for specimens containing No. 8 hooked bars and 21.5 in. for specimens containing No. 11 hooked bars). Three different levels of confining reinforcement were investigated; no confining reinforcement, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$. For No. 3 hoops spaced at $3d_b$, two configurations of hoops were investigated; hoops along the whole depth of the joint (nine hoops), and hoops extending only to the tail of the hook (five hoops), as shown in Figure 2.6c. The ranges of variables for deep-beam specimens are presented in Table 2.8.



(a) (b) (c)

Figure 2.6 Details of deep-beam specimens (a) side view of specimen with regular ratio of beam to column depth (b) side view of specimen with large ratio of beam to column depth and hoops along the joint region (c) side view of specimen with large ratio of beam to column depth and hoops along the hook region

Table 2.8 Range of variables for deep-beam specimens

Parameters	Range
Hooked Bar Size	No. 8, No. 11
Hook Bend Angle	90°
Embedment Length (in.)	10
Amount of Confining Reinforcement within the Joint	None, 2 No. 3, 5 No. 3, 6 No. 3, 9 No. 3
Location of Hooked Bars	Embedded to Far Side of Member
Nominal Concrete Compressive Strength, psi	5000, 15000
Number of Hooked Bars	2
Center-to-Center Spacing* (c_{ch})	$11d_b$
Number of Layers	1
Ratio of Beam Effective Depth to Embedment Length	2.0 to 2.13

* of hooked bars

2.4 INSTRUMENTATION AND TEST PROCEDURE

A self-reacting system was used to simulate axial, tensile, and compression forces acting on an exterior beam-column joint as shown in Figure 2.7. The system was a modified version of the test apparatus used by Marques and Jirsa (1975). The modified system consisted of a steel frame supporting upper compression member, bearing member, lower tension member, and hydraulic rams. The upper compression and lower tension members prevented specimens from rotation. Reaction on the bearing member simulated the virtual beam compression zone. Table 2.9 presents the location of the reaction members for the specimens tested in this study. The system also included an external axial load mechanism that consisted of two spreader beams located on the top and bottom edges of the specimens and connected by threaded rods as shown in Figure 2.7. For specimens containing closely-spaced hooked bars, a spreader beam was used to transfer load from the hydraulic rams to the hooked bars. The spreader beam was constructed of two steel channel sections bolted to connecting plates with 2 in. clear spacing between the two channels. When testing specimens with staggered hooked bars, the spreader beam was modified to provide an adequate clear space between the two channels for the two layers of hooked bars.

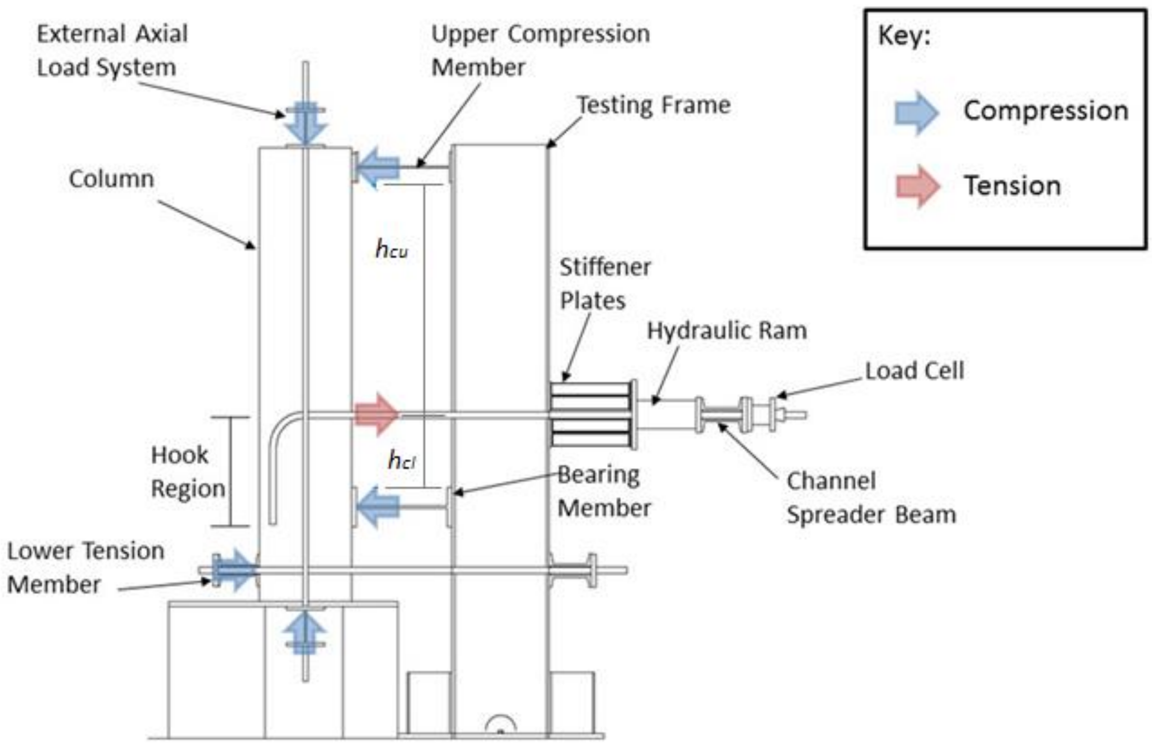


Figure 2.7 Schematic of self-reacting system

Table 2.9 Location of reaction forces

	No. 5 Hook	**No. 8 Hook**	**No. 11 Hook**	**Deep-Beam Specimens**
Height of Specimen, (in.)	54	54	96	96
Distance from Center of Hook to Top of Bearing Member Flange, h_{cl} (in.)[1]	5.25	10	19.5	19.5
Distance from Center of Hook to Bottom of Upper Compression Member Flange, h_{cu} (in.)[1]	18.5	18.5	48.5	48.5

[1]See Figure 2.7

The load on the individual hooked bars was measured using calibrated load cells. The load cells were installed between the hydraulic rams (or the spreader beam in cases where it was used) and wedge grips on the ends of the hooked bars. For specimens with staggered hooked bars, the second layer of hooked bars were gripped at the same distance as the first layer of hooked bars from the back of the hook to the grips to produce the same nominal tensile forces at the hook location for hooked bars in the two layers at loading levels near failure (Figure 2.8). Loaded-end slip of hooked bars was measured using linear variable differential transformers (LVDTs). LVDTs were installed on one external and one middle hooked bar, for specimens with three or four hooked bars, and on the external hooked bars on one side of specimens with staggered hooked bars.

Seven specimens with two hooked bars, four specimens with three hooked bars, and four deep-beam specimens had 120 Ω strain gauges mounted on hoops to monitor the strain in the confining reinforcement within the joint region. Strain gauges were also mounted along the straight lead embedment of hooked bars, as shown in Figure 2.9. Specimens containing strain gauges are discussed in detail in Section 3.5.6.

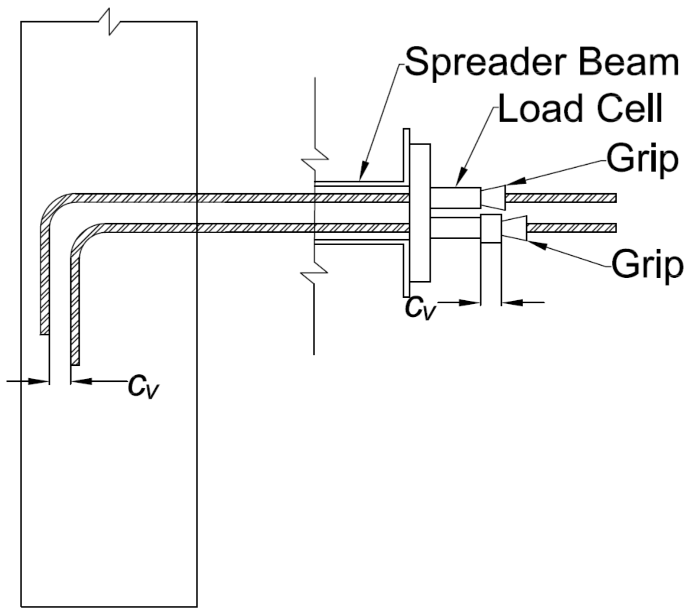


Figure 2.8 Positions of grips on staggered-hooked bars

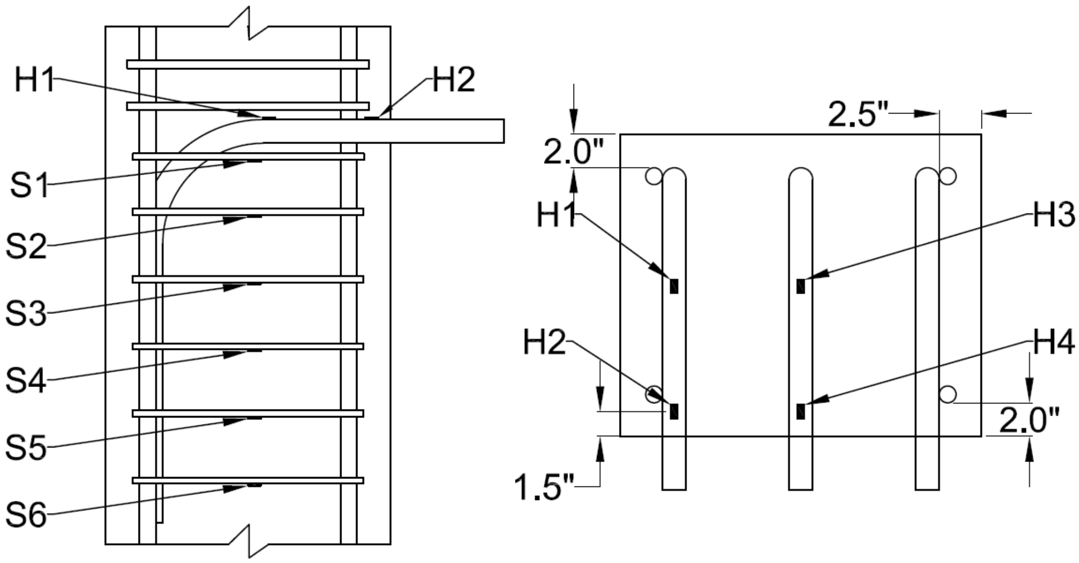


Figure 2.9 Strain gauge locations

The test procedure was similar for all specimens. First, the specimen was mounted in the testing system. To prevent stresses concentrations between the specimen and the reaction members, high-strength gypsum cement was used at the contact locations. Second, an axial load was applied to the specimen. For specimens with No. 5 and No. 8 hooked bars, a constant axial load of 30,000 lb was applied (corresponding to axial stress ranging from 125 to 513 psi); for specimens with No. 11 hooked bars, a constant axial stress of 280 psi was applied. Marques and Jirsa (1975) found that the influence of axial load on the anchorage capacity of hooked bars was negligible; therefore, the effect of varying the axial load was not considered in this study. Third, load cells and LVDTs were placed on the hooked bars and connected to a data acquisition system. Fourth, tensile forces were applied monotonically to the hooked bars, pausing at several intervals to mark the cracks. Crack marking was discontinued at about 80 percent of the expected failure load, after which the specimen was continuously loaded to failure.

2.5 TEST PROGRAM

Tables 2.10 through 2.14 summarize the test parameters of the specimens with two hooked bars, specimens with three or four hooked bars, specimens with staggered hooked bars , specimens with hooks not embedded to the far side of the member, and deep-beam specimens, respectively.

The parameters include bar size, bend angle, amount of confining reinforcement within the joint region, and number of hooked bars being developed. The study included 33 specimens with two hooked bars (Table 2.10), of which 14 specimens had no confining reinforcement, eight specimens had two No. 3 hoops, nine specimens had five No. 3 hoops, and five had six No. 3 hoops within the joint region. Six specimens contained 180° hooks and 30 specimens contained 90° hooks.

Table 2.10 Specimens with two hooked bars

Bar Size	**Bend Angle**	**Amount of Confining Transverse Reinforcement (Number and Bar Size)**			
		None	2 No. 3	5 No. 3	6 No. 3
No. 5	90°	3	-	1	-
No. 8	90°	4	3	4	-
	180°	2	2	1	-
No. 11	90°	5	3	-	4
	180°	-	-	-	1

Thirty-five specimens with three or four hooked bars were tested (Table 2.11), of which 31 had three hooks and four had four hooks. Of the 35 specimens, 14 specimens had no confining reinforcement, seven had two No. 3 hoops, 13 had five No. 3 hoops, and three had six No. 3 hoops within the joint region. Six specimens had 180° hooks and 29 specimens contained 90° hooks.

Table 2.11 Specimens with three or four hooked bars

Bar Size	**Bend Angle**	**Amount of Confining Transverse Reinforcement (Number and Bar Size)**			
		None	2 No. 3	5 No. 3	6 No. 3
No. 5		Specimens with three hooks			
	90°	4	1	4	-
		Specimens with four hooks			
	90°	2	-	2	-
No. 8		Specimens with three hooks			
	90°	3	2	3	-
	180°	2	2	2	-
No. 11		Specimens with three hooks			
	90°	3	2	-	2
	180°	-	-	-	1

Thirteen specimens with staggered hooked bars were tested, of which nine had four hooks and four had six hooks. Of the 13 specimens, three specimens had no confining reinforcement, three had two No. 3 hoops, two had five No. 3 hoops, three had six No. 3 hoops, one had seven No. 3 hoops, and one had eight No. 3 hoops within the joint region. All specimens contained 90° hooks.

Table 2.12 Specimens with staggered hooked bars

Bar Size	**Bend Angle**	**Amount of Confining Transverse Reinforcement (Number and Bar Size)**					
		None	2 No. 3	5 No. 3	6 No. 3	7 No. 3	8 No. 3
No. 5		Specimens with four hooks					
	90°	1	1	1	1	-	-
		Specimens with six hooks					
	90°	1	1	1	1	-	-
No. 11		Specimens with four hooks					
	90°	1	1	-	1	1	1

Thirty-three specimens with hooks not embedded to the far side of the member were tested, of which 13 had two hooks, 11 specimens had three hooks, and nine had four hooks. Of the 33 specimens, 13 specimens had no confining reinforcement, five had two No. 3 hoops, 11 had five No. 3 hoops, and four had six No. 3 hoops within the joint region. All specimens contained 90° hooks.

Table 2.13 Specimens with hooks not embedded to far side of member

Bar Size	Bend Angle	Amount of Confining Transverse Reinforcement (Number and Bar Size)			
		None	2 No. 3	5 No. 3	6 No. 3
No. 5		Specimens with two hooks			
	90°	1	1	1	-
		Specimens with three hooks			
	90°	1	1	1	-
		Specimens with four hooks			
	90°	2	1	2	-
No. 8		Specimens with two hooks			
	90°	3	-	3	-
		Specimens with three hooks			
		2	-	2	-
		Specimens with four hooks			
		2	-	2	-
No. 11		Specimens with two hooks			
	90°	1	1	-	2
		Specimens with three hooks			
		1	1	-	2

Eight deep-beam specimens were tested (Table 2.14). Of the eight specimens, two had no confining reinforcement, two had two No. 3 hoops, one had five No. 3 hoops, two had six No. 3 hoops, and one had nine No. 3 hoops within the joint region. All specimens contained 90° hooks.

Table 2.14 Deep beam specimens

Bar Size	Bend Angle	Amount of Confining Transverse Reinforcement (Number and Bar Size)						
		None	2 No. 3	5 No. 3	6 No. 3	7 No. 3	8 No. 3	9 No. 3
No. 8	90°	1	1	1	-	-	-	1
No. 11	90°	1	1		2			

CHAPTER 3: EXPERIMENTAL RESULTS

3.1 GENERAL

This chapter describes the test results for 122 beam-column joint specimens, including crack progression detected during the tests, load-slip behavior, and failure modes. They included 33 specimens with two hooked bars, 35 specimens with three or four hooked bars, and 13 specimens with four or six staggered hooked bars, 33 specimens with hooked bars not embedded to the far side of the member, and 8 specimens with two hooked bars with deep beam. Specimens had different levels of confining reinforcement within the joint region ranging from no confining reinforcement to nine No. 3 hoops spaced at $3d_b$. Some specimens had strain gauges mounted along the straight portion of the hooked bars and on the confining reinforcement within the joint region. Comprehensive tables describing the test specimens can be found in Appendix B. In addition to these specimens, the results on 270 tests performed at the University of Kansas and reported by Sperry et al. (2015a, 2015b, 2017a) are also included in Appendix B and used in the analyses described in Chapter 4.

3.2 CRACK PROGRESSION

For most of the specimens, cracking progressed as shown in Figure 3.1. The first crack appeared on the front face of the column, initiating from the external hooked bars and propagating horizontally towards both the interior and the side face of the column (Figure 3.1a). In specimens with closely spaced hooked bars, the first crack was more prone to propagate towards the internal hooked bars than to propagate towards the side face of the column. As the load increased, the horizontal cracks continued to grow on the side face of the column along the straight portion of the hooked bars up to approximately the location of the bend (Figure 3.1b). At this point, vertical and diagonal cracks appeared on the front face of the column originating from the external hooked bars and on the side face of the column originating from the horizontal crack. As the load further increased, the vertical and diagonal cracks on the side face of the column continued to grow toward the front face of the column above and below the hook location (Figure 3.1c). Near failure, the inclined cracks on the side face of the column extended around the column corner to the front face and widened (Figure 3.1d). Failure was marked by a concrete block pulling out of the front face of the column or the concrete cover over the side of the hook splitting along the side face of the column.

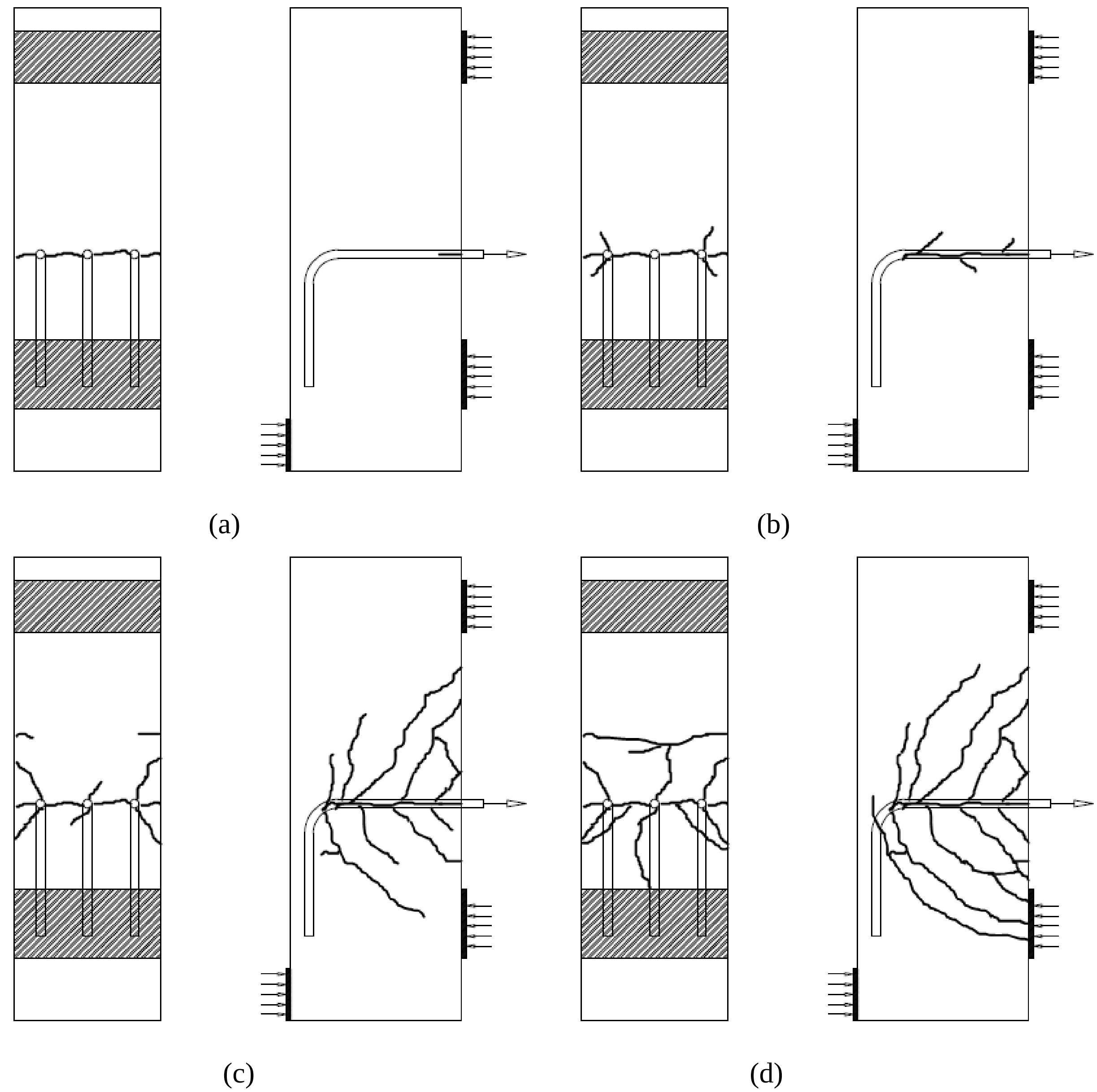


Figure 3.1 Front and side views depicting crack progression

3.3 LOAD-SLIP BEHAVIOR

Examples of load-slip curves for specimens with two hooked bars, with three hooked bars, and with staggered hooked bars are shown in Figures 3.2 through 3.4. The loads shown are the individual loads applied to the hooked bars ($T_{ind.}$). Slip is the measured displacement at the front face of the column. The slip was measured using Linear Variable Differential Transformers (LVDTs). Figure 3.2 shows the load-slip behavior of specimen 5-5-90-0-2.5-2-8, which contained two No. 5 hooked bars with a 90° bend angle without confining reinforcement within the joint region. LVDTs were installed on both hooked bars. As shown in Figure 3.2, at initial loading levels, the slip increased almost linearly with the load. Then, at load levels close to failure, a rapid increase in slip occurred as the hooked bars pulled out of the column.

Figure 3.3 shows the load-slip behavior for specimen (3)5-5-90-5#3-2.5-2-8, which contained three No. 5 hooked bars with a 90° bend angle and five No. 3 hoops as confining reinforcement within the joint region. The LVDTs were installed on one external hook (Hook A) and the middle hook (Hook B). This specimen with three hooked bars exhibited similar load-slip behavior to that of the specimen with two hooked bars.

Figure 3.4 shows the load-slip behavior for specimen (2s) 5-5-90-2#3-2.5-2-8, which contained four No. 5 hooked bars in two layers. The hooks had a 90° bend angle and were confined by two No. 3 hoops within the joint region. The hoops were spaced at 3-in. intervals from the center of the straight portion of the hooked bars from the upper layer. LVDTs were installed on one hook in the upper layer (Hook A) and on the adjacent bar in the lower layer (Hook C). The hook in the lower layer Hook C exhibited less slip than the hook in the upper layer; this could be a result of the additional confinement provided by the compression strut formed between hook A and the compression reaction.

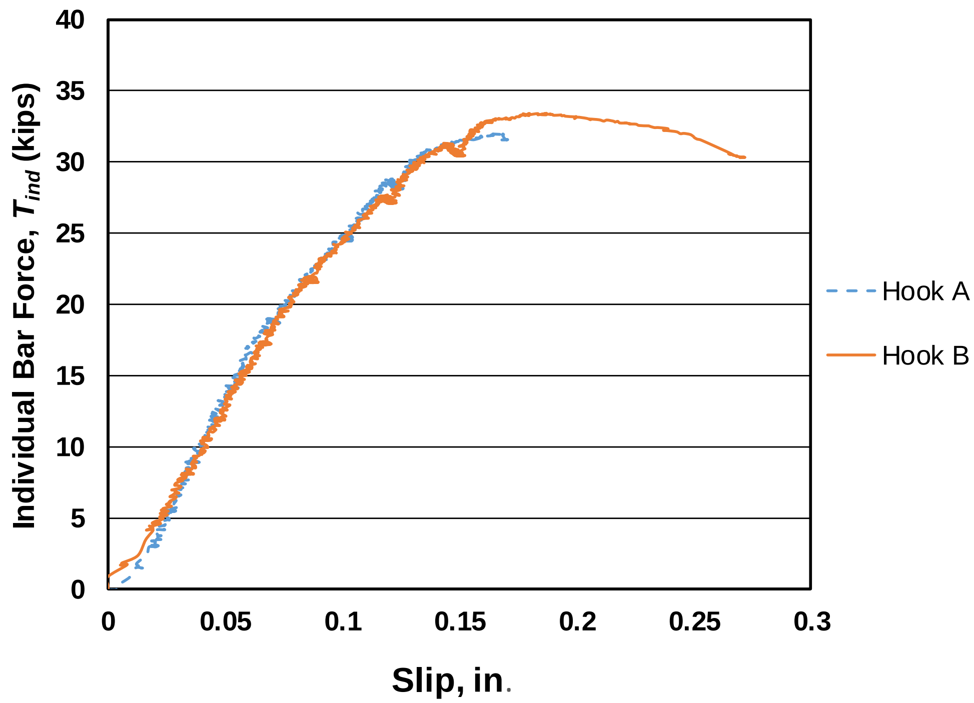


Figure 3.2 Load-slip behavior of specimen with two hooked bars [5-5-90-0-2.5-2-8]

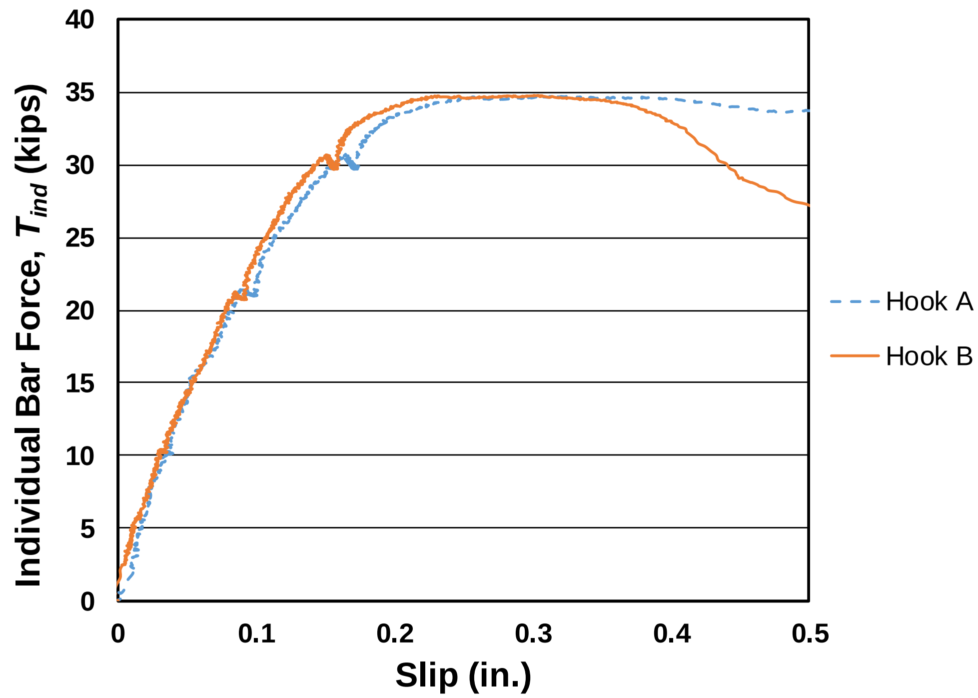


Figure 3.3 Load-slip behavior of specimen with three hooked bars [(3) 5-5-90-5#3-2.5-2-8]

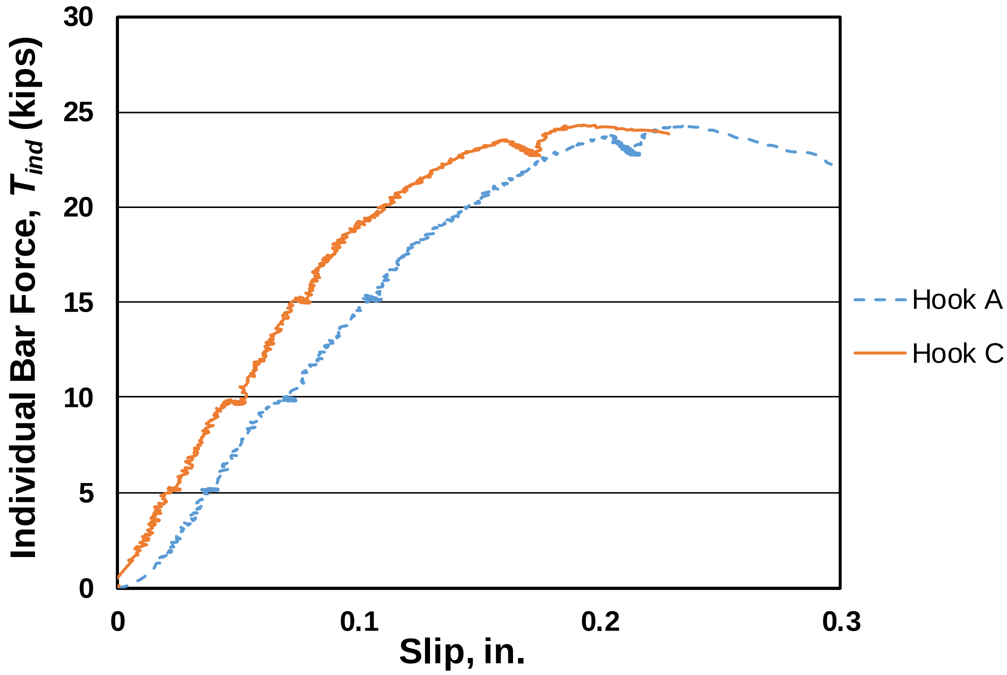
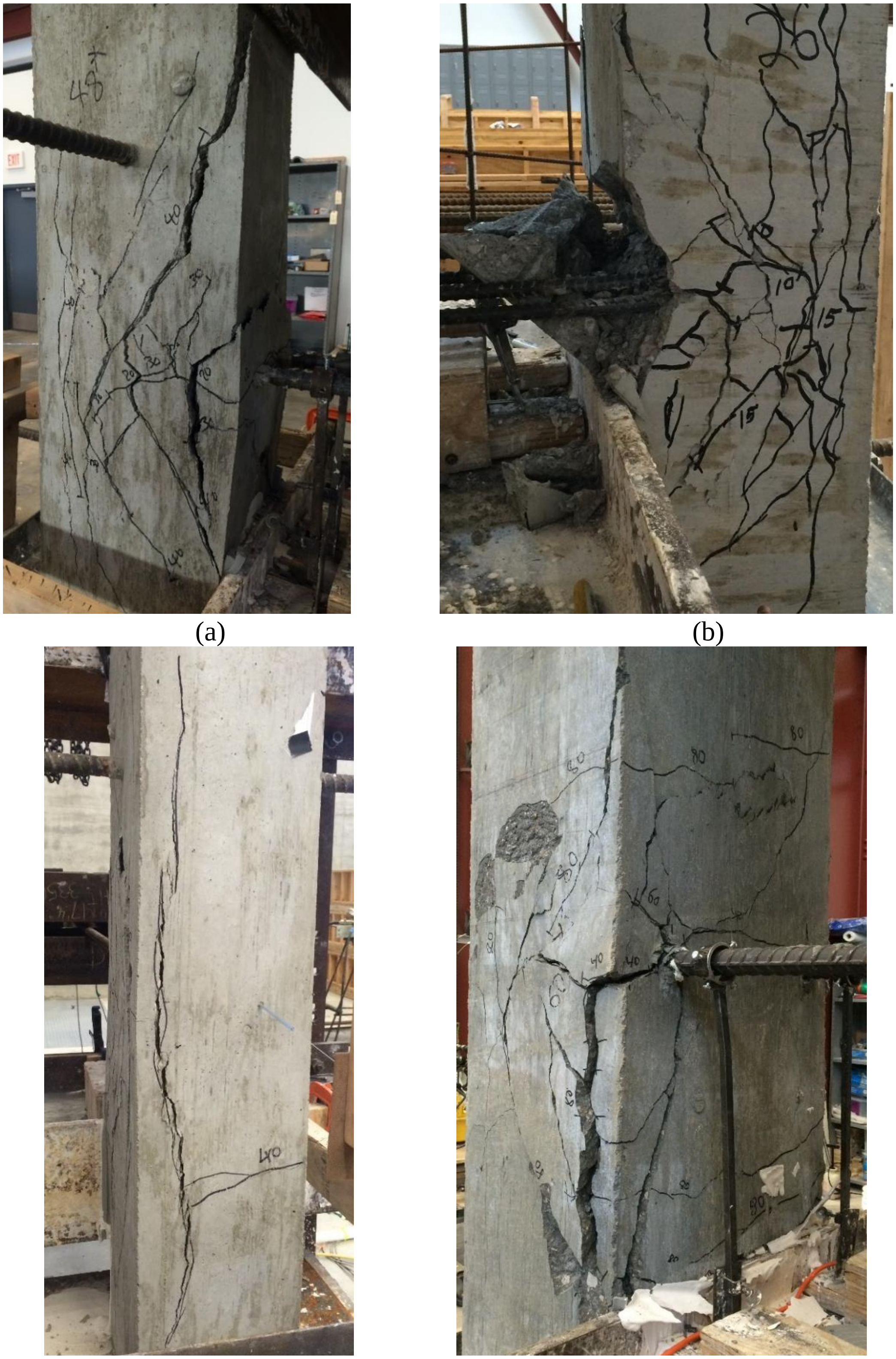


Figure 3.4 Load-slip behavior of specimen with staggered hooked bars [(2s) 5-5-90-2#3-2.5-2-8]

3.4 FAILURE MODES

Four primary modes of failure were observed during the tests of the 122 beam-column joints investigated in this experimental work. Front pullout (FP) occured when a concrete block pulled out with the hooked bars of the front face of the column (Figure 3.5a). Front blowout (FB) was similar but more sudden than front pullout failure with greater energy release (Figure 3.5.b). Side splitting failure (SS) occurred when the side of the column split off due to the wedging action of the hook (Figure 3.5c). Side blowout failure (SB) was similar to a side splitting failure, but was more sudden than SS failure and exhibited greater energy release (Figure 3.5d). Typically, a specimen would exhibit multiple failure modes, with one mode being more dominant. The primary mode of failure was established by comparing the relative amounts of damage between the front and side faces of the column.



(a) (b)

(c) (d)

Figure 3.5 Failure modes (a) Front Pullout (FP), (b) Front Blowout (FB), Side Splitting (SS), (d) Side Blowout (SB)

3.5 TEST RESULTS

This section presents the results for the tests performed in this study. Two loads are reported for each hook, T_{ind} and T; T_{ind} is the load carried by the hooked bar at failure, and T is the peak total load carried by the specimen divided by number of hooked bars (average bar force). In addition, the data include embedment length ℓ_{eh}, concrete compressive strength f_{cm}, hooked bar type and grade (A615 Grade 80 or A1035 Grade 120), column width b, center-to-center spacing between hooked bars c_{ch}, number of hooked bars n, area of single leg of confining reinforcement $A_{tr.l}$, number of hoops provided as confining reinforcement N_{tr}, and failure type. Other data such as maximum load on individual hooked bar T_{max}, concrete side cover c_{so}, concrete cover over the tail of the hooked bar c_{th}, axial load applied on the column during the test, and slip of hooked bar can be found in comprehensive tables in Appendix B. Reinforcement strain results of hooked bars and confining reinforcement are presented in Section 3.5.6.

3.5.1 Specimens with Two Hooked Bars

Specimens with Two No. 5 Hooked Bars

Table 3.1 presents results for four specimens containing two No. 5 (Grade 120) hooked bars with a 90° bend angle. The specimens had two levels of confining reinforcement within the joint region, none and No. 3 hoops spaced at $3d_b$. Embedment length ranged from 5.75 to 8.13 in., and concrete compressive strength ranged from 4,660 to 6,950 psi. The column width ranged from $8^1/_8$ to 13 in. Specimens had $2^1/_2$-in. nominal side cover and 2-in. nominal tail cover. The center-to-center spacing between the hooked bars ranged from $2^1/_2$ to $7^3/_8$ in. The average bar forces at failure ranged from 22,350 to 43,030 lb, corresponding to bar stresses between 72,100 and 138,800 psi.

Table 3.1 Specimens with two No. 5 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
5-5-90-0-i-2.5-2-8[h]	A B	90°	8.1 8.0	4830	13.0	7.4	2	-	-	31463 33433	32448	FP/SB FP/SB
(2@4) 5-8-90-0-i-2.5-2-6[c,h]	A B	90°	5.8 6.0	6950	8.1	2.5	2	-	-	23089 21617	22353	FP FP
(2@6) 5-8-90-0-i-2.5-2-6[c,h]	A B	90°	6.0 6.0	6950	9.4	3.8	2	-	-	25052 22850	23951	FP/SS FP/SS
5-5-90-5#3-i-2.5-2-8[h]	A B	90°	7.8 7.8	4660	13.0	7.1	2	0.11	5	42711 43348	43030	FP/SB FP/SB

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[c]Specimen had column longitudinal reinforcement ratio > 4.0%
[h]Specimen contained A1035 Grade 120 hooked bars

Specimens with Two No. 8 Hooked Bars

The results for 16 specimens containing two No. 8 hooked bars with 90° and 180° bend angles are presented in Table 3.2. The specimens contained Grade 120 and Grade 80 hooked bars. The specimens had three levels of confining reinforcement within the joint region, none, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$. Embedment length ranged from 8.63 to 10.63 in., and concrete compressive strength ranged from 4,490 to 7,710 psi. The column width ranged from 9 to 17 in. Specimens had $2^1/_2$-in. nominal side cover and 2-in. nominal tail cover. The center-to-center spacing between the hooked bars ranged from 3 to $11^1/_4$ in. The average bar forces at failure ranged from 35,090 to 70,360 lb, corresponding to bar stresses between 44,420 and 89,060 psi. Three specimens contained strain gauges on the hooked bars and the confining reinforcement.

Table 3.2 Specimens with two No. 8 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
8-8-90-0-i-2.5-2-9[l]	A B	90°	9.5 9.5	7710	17.0	11.0	2	-	-	35543 34656	35100	FB FB
8-5-90-0-i-2.5-2-10[d,e,l]	A B	90°	10.0 10.0	5920	17.0	11.3	2	-	-	47731 47631	47681	SS/SB SS
(2@3) 8-5-90-0-i-2.5-2-10[d,l]	A B	90°	10.4 10.6	4490	9.0	3.0	2	-	-	38908 41718	40313	FP FP
(2@3) 8-5-180-0-i-2.5-2-10[c,d,l]	A B	180°	10.3 10.0	5260	9.0	3.0	2	-	-	47587 56064	51825	FP FP
(2@5) 8-5-90-0-i-2.5-2-10[d,l]	A B	90°	10.1 10.1	4490	11.0	5.1	2	-	-	41853 38251	40052	FP FB/SS
(2@5) 8-5-180-0-i-2.5-2-10[c,d,l]	A B	180°	10.0 10.0	5260	11.0	5.1	2	-	-	52300 54030	53165	FP FP
8-5-90-2#3-i-2.5-2-10[d,e,l]	A B	90°	10.0 10.3	5920	17.0	11.3	2	0.11	2	55820 56585	56203	FP/SS FP/SS
(2@3) 8-5-90-2#3-i-2.5-2-10[d,l]	A B	90°	10.0 10.5	4760	9.0	3.3	2	0.11	2	58435 35184	46810	FP FP
(2@5) 8-5-90-2#3-i-2.5-2-10[d,l]	A B	90°	9.6 10.0	4760	11.0	4.9	2	0.11	2	48412 48617	48515	FB FB
(2@3) 8-5-180-2#3-i-2.5-2-10[c,d,l]	A B	180°	10.3 10.3	5400	9.0	3.0	2	0.11	2	57188 58114	57651	FP FP
(2@5) 8-5-180-2#3-i-2.5-2-10[c,d,l]	A B	180°	10.3 9.8	5400	11.0	5.0	2	0.11	2	63640 60130	61885	FB FB
8-8-90-5#3-i-2.5-2-9[d,l]	A B	90°	8.6 9.0	7710	17.0	10.8	2	0.11	5	64834 63961	64397	FB FB
8-5-90-5#3-i-2.5-2-10[d,e,h]	A B	90°	10.0 9.3	5920	17.0	11.3	2	0.11	5	70322 70390	70356	FP/SS FP/SS
(2@3) 8-5-90-5#3-i-2.5-2-10[d,l]	A B	90°	10.0 10.5	4810	9.0	3.0	2	0.11	5	57620 58224	57922	FB/SS FB/SS
(2@5) 8-5-90-5#3-i-2.5-2-10[d,l]	A B	90°	9.9 9.5	4810	11.0	5.3	2	0.11	5	59715 52205	55960	FB FB
(2@5) 8-5-180-5#3-i-2.5-2-10[c,d,l]	A B	180°	10.0 10.3	5540	11.0	5.0	2	0.11	5	58132 75155	66644	FB FB

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[c]Specimen had column longitudinal reinforcement ratio > 4.0%
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement
[e]Specimen had strain gauges
[h]Specimen contained A1035 Grade 120 hooked bars
[l]Specimen contained A615 Grade 80 hooked bars

Specimens with Two No. 11 Hooked Bars

Table 3.3 presents results for 13 specimens containing two No. 11 hooked bars with bend angles of 90° and 180° fabricated from Grade 120 and Grade 80 reinforcement. The specimens had three levels of confining reinforcement within the joint region, none, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$. Embedment length ranged from 13.5 to 17.5 in., and concrete compressive strength ranged from 4,890 to 14,050 psi. The column width ranged from 17 to $21^1/_2$ in. Specimens had $2^1/_2$-in. nominal side cover and 2-in. nominal tail cover. The center-to-center spacing between the hooked bars ranged from $10^1/_2$ to $15^1/_4$ in. The average bar forces at failure ranged from 75,310 to 145,260 lb, corresponding to bar stresses between 48,275 and 93,115 psi. Four specimens contained strain gauges on the hooked bars and confining reinforcement.

Table 3.3 Specimens with two No. 11 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
11-15-90-0-i-2.5-2-15[d,h]	A B	90°	14.0 14.0	14050	21.5	14.4	2	-	-	93327 91008	92168	SB SB
11-5-90-0-i-2.5-2-16[h]	A B	90°	16.3 15.8	4890	21.5	15.3	2	-	-	80730 98062	89396	SS SS
(2@7.5) 11-8-90-0-i-2.5-2-15[h]	A B	90°	14.8 14.8	7070	17.0	10.8	2	-	-	76635 73991	75313	FP/SS FP/SS
(2@7.5) 11-8-90-0-i-2.5-2-18[h]	A B	90°	17.3 17.0	7070	17.0	10.8	2	-	-	99278 95479	97379	FP/SS FP/SS
(2@7.5) 11-12-90-0-i-2.5-2-17[e,l]	A B	90°	17.3 17.5	11460	17.0	11.0	2	-	-	105142 108295	106718	SS SS
11-15-90-2#3-i-2.5-2-15[d,h]	A B	90°	14.0 14.3	14050	21.5	15.0	2	0.11	2	115577 114801	115189	FP/SB FP/SB
(2@7.5) 11-8-90-2#3-i-2.5-2-17[h]	A B	90°	16.3 16.5	7070	17.0	10.8	2	0.11	2	104665 107397	106031	FP/SS FP/SS
(2@7.5) 11-12-90-2#3-i-2.5-2-16[e,l]	A B	90°	15.4 15.3	11850	17.0	10.5	2	0.11	2	107954 109482	108718	SS/FP SS/FP
11-15-90-6#3-i-2.5-2-15[d,h]	A B	90°	14.5 15.0	14050	21.5	15.0	2	0.11	6	145664 144870	145267	FP FP
11-5-90-6#3-i-2.5-2-16[h]	A B	90°	15.5 15.3	5030	21.5	15.0	2	0.11	6	120540 110707	115623	SS SS
(2@7.5) 11-8-90-6#3-i-2.5-2-15[h]	A B	90°	13.8 14.3	7070	17.0	10.8	2	0.11	6	107442 104938	106190	FP/SS FP/SS
(2@7.5) 11-12-90-6#3-i-2.5-2-14[e,h]	A B	90°	13.5 13.6	11960	17.0	10.5	2	0.11	6	100724 103353	102038	SS/FP SS/FP
(2@7.5) 11-12-180-6#3-i-2.5-2-14[e,h]	A B	180°	14.4 14.4	12190	17.0	10.5	2	0.11	6	90862 97049	93955	SS/FP SS/FP

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[d]Specimens had ASTM A1035 Grade 120 longitudinal reinforcement
[e]Specimen had strain gauges
[h]Specimen contained A1035 Grade 120 hooked bars
[l]Specimen contained A615 Grade 80 hooked bars

3.5.2 Specimens with Three or Four Hooked Bars

Specimens with Three or Four No. 5 Hooked Bars

The results for 13 specimens containing three or four No. 5 (Grade 120) hooked bars with a 90° bend angle are presented in Table 3.4. The specimens had three levels of confining reinforcement within the joint region, none, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$. Embedment length ranged from 5.5 to 8.0 in., and concrete compressive strength ranged from 4,660 to 6,950 psi. The column width ranged from $10^5/_8$ to $18^1/_8$ in. Specimens had $2^1/_2$-in. nominal side cover and 2-in. nominal tail cover. The center-to-center spacing between the hooked bars ranged from $2^1/_4$ to $6^1/_2$ in. The average bar forces at failure ranged from 15,500 to 36,300 lb, corresponding to bar stresses between 50,000 and 117,100 psi.

Table 3.4 Specimens with three or four No. 5 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
(3@4) 5-8-90-0-i-2.5-2-6[h]	A	90°	6.0	6950	10.6	2.4	3	-	-	18326	16805	FP
	B		5.6							17370		FP
	C		6.0			2.5				14720		FP
(3@6) 5-8-90-0-i-2.5-2-6[h]	A	90°	6.4	6950	13.1	3.6	3	-	-	25526	24886	FP
	B		5.9							25964		FP
	C		5.8			3.8				23167		FP
(3@10) 5-5-90-0-i-2.5-2-7[h]	A	90°	6.3	5880	18.1	6.3	3	-	-	20743	21034	FP
	B		6.8							21207		FP
	C		7.0			6.3				21152		FP
(3) 5-5-90-0-i-2.5-2-8[h]	A	90°	8.0	4830	13.0	3.8	3	-	-	23610	27869	FP
	B		8.0							32864		FP
	C		7.8			3.6				27134		FP
(4@4) 5-8-90-0-i-2.5-2-6[h]	A	90°	6.3	6950	13.1	2.5	4	-	-	17307	15479	FP/SS
	B		5.8			2.3				17430		FP/SS
	C		5.8							13684		FP/SS
	D		6.0			2.6				13495		FP/SS
(4@6) 5-8-90-0-i-2.5-2-6[h]	A	90°	6.0	6690	16.9	3.8	4	-	-	17356	19303	FP
	B		6.0			3.8				22123		FP
	C		5.8							22649		FP
	D		6.0			3.8				15082		FP
(3@10) 5-5-90-2#3-i-2.5-2-7[h]	A	90°	6.9	5950	18.1	6.4	3	0.11	2	29751	31296	FP/SB
	B		7.0				3			34654		FP/SB
	C		7.0			6.4	3			29482		FP/SB

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement
[h]Specimen contained A1035 Grade 120 hooked bars

Table 3.4 Cont. Specimens with three or four No. 5 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
	A		6.0			2.7				35751		FP
(3@4) 5-8-90-5#3-i-2.5-2-6[d,h]	B	90°	6.3	6700	10.6		3	0.11	5	34518	34889	FP
	C		6.0			2.5				34397		FP
	A		6.0			4.0				37754		FP
(3@6) 5-8-90-5#3-i-2.5-2-6[d,h]	B	90°	6.0	6700	13.1		3	0.11	5	34152	36448	FP
	C		6.0			3.8				37439		FP
	A		6.9			6.1				27458		FP/SB
(3@10) 5-5-90-5#3-i-2.5-2-7[h]	B	90°	7.0	5950	18.1		3	0.11		34719	31684	FP/SB
	C		6.8			6.5				32875		FP/SB
	A		7.8			3.5				34636		FP/SB
(3) 5-5-90-5#3-i-2.5-2-8[h]	B	90°	7.8	4660	13.0		3	0.11	5	34483	33260	FP
	C		7.8			3.6				30662		FP
	A		6.0			4.0				30282		FP
(4@6) 5-8-90-5#3-i-2.5-2-6[d,h]	B	90°	6.0	6690	16.9	4.0	4	0.11	5	30085	28321	FP
	C		6.0							27573		FP
	D		6.0			3.8				25344		FP
	A		5.8			2.5				27968		FP
(4@4) 5-8-90-5#3-i-2.5-2-6[d,h]	B	90°	5.5	6700	13.1	2.5	4	0.11	5	27348	27493	FP
	C		6.3							28551		FP
	D		6.5			2.5				26103		FP

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement
[h]Specimen contained A1035 Grade 120 hooked bars

Specimens with Three No. 8 Hooked Bars

Table 3.5 presents results for 14 specimens containing three No. 8 (Grade 80) hooked bars with bend angles of a 90° and 180°. The specimens had three levels of confining reinforcement within the joint region, none, two No. 3 hoops, and No. 3 hoops spaced at 3d_b. Embedment length ranged from 7.5 to 10.6 in., and concrete compressive strength ranged from 4,490 to 5,730 psi. The column width ranged from 12 to 17 in. Specimens had 2$^1/_2$-in. nominal side cover and 2-in. nominal tail cover. The center-to-center spacing between the hooked bars ranged from 3 to 5$^1/_2$ in. The average bar forces at failure ranged from 24,400 to 61,300 lb, corresponding to bar stresses between 30,890 and 77,600 psi.

Table 3.5 Specimens with three No. 8 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
	A		7.5			5.5				30459		FP
(3@5.5) 8-5-90-0-i-2.5-2-8[d,l]	B	90°	8.0	5730	17.0	5.5	3	-	-	23292	24411	FP
	C		8.0							19482		FP
	A		10.0			3.4				30671		FP
(3@3) 8-5-90-0-i-2.5-2-10[d,l]	B	90°	10.3	4490	12.0	3.3	3	-	-	33363	28480	FP
	C		10.0							21405		FP
	A		10.3			5.0				30145		FP
(3@5) 8-5-90-0-i-2.5-2-10[d,l]	B	90°	10.1	4490	16.0	5.3	3	-	-	34709	32300	FP
	C		10.0							32045		FP
	A		9.8			3.0				37064		FP
(3@3) 8-5-180-0-i-2.5-2-10[c,d,l]	B	180°	10.0	5260	12.0	3.0	3	-	-	59799	47249	FP
	C		9.8							44884		FP
	A		10.0			5.3				40204		FP
(3@5) 8-5-180-0-i-2.5-2-10[d,l]	B	180°	10.0	5260	16.0	5.3	3	-	-	59739	45930	FP
	C		10.0							37846		FP
	A		9.9			3.0				42191		FP
(3@3) 8-5-90-2#3-i-2.5-2-10[d,l]	B	90°	10.1	4760	12.0	3.0	3	0.11	2	41586	40721	FP
	C		10.0							38385		FP
	A		10.5			5.5				43030		FP
(3@5) 8-5-90-2#3-i-2.5-2-10[d,l]	B	90°	10.6	4760	16.0	4.9	3	0.11	2	48236	44668	FP
	C		10.4							42739		FP
	A		10.5			3.0				59807		FP
(3@3) 8-5-180-2#3-i-2.5-2-10[c,d,l]	B	180°	10.3	5400	12.0	3.0	3	0.11	2	56145	54576	FP
	C		10.0							47776		FP
	A		9.6			5.2				59313		FP
(3@5) 8-5-180-2#3-i-2.5-2-10[d,l]	B	180°	9.8	5400	16.0	5.2	3	0.11	2	49344	51501	FP
	C		9.8							45845		FP
	A		8.0			5.5				57652		FP
(3@5.5) 8-5-90-5#3-i-2.5-2-8[d,l]	B	90°	8.0	5730	17.0	5.5	3	0.11	5	43309	47994	FP
	C		8.5							43021		FP
	A		10.0			3.1				48766		FP
(3@3) 8-5-90-5#3-i-2.5-2-10[d,l]	B	90°	9.8	4810	12.0	3.1	3	0.11	5	44503	47276	FP
	C		9.9							48560		FP
	A		10.0			5.0				58896		FP
(3@5) 8-5-90-5#3-i-2.5-2-10[d,l]	B	90°	10.0	4850	16.0	5.0	3	0.11	5	55612	61305	FP
	C		9.8							69408		FP
	A		10.1			3.0				46175		FP
(3@3) 8-5-180-5#3-i-2.5-2-10[d,l]	B	180°	9.9	5540	12.0	3.0	3	0.11	5	65274	58877	FP
	C		9.8							65183		FP
	A		9.9			4.8				55236		FP
(3@5) 8-5-180-5#3-i-2.5-2-10[d,l]	B	180°	9.8	5540	16.0	5.0	3	0.11	5	60892	58669	FP
	C		9.5							59877		FP

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[c]Specimen had column longitudinal reinforcement ratio > 4.0%
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement
[l]Specimen contained A615 Grade 80 hooked bars

Specimens with Three No. 11 Hooked Bars

The results for eight specimens containing three No. 11 (Grade 120 or Grade 80) hooked bars with a 90° and 180° bend angle are presented in Table 3.6. The specimens had three levels of confining reinforcement within the joint region, none, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$. Embedment length ranged from 18.1 to 23.5 in., and concrete compressive strength ranged from 7,070 to 12,190 psi. The column width was 17 in. Specimens had $2^1/_2$-in. nominal side cover and 2-in. nominal tail cover. The average bar forces at failure ranged from 98,480 to 127,810 lb, corresponding to bar stresses between 63,130 and 81,930 psi. Four specimens contained strain gauges on the hooked bars and the confining reinforcement.

Table 3.6 Specimens with three No. 11 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
	A		19.6			5.3				99284		FP/SS
(3@3.75) 11-8-90-0-i-2.5-2-20[h]	B	90°	20.0	7070	17.0		3	-	-	91009	98488	FP/SS
	C		20.0			5.5				105171		FP/SS
	A		23.5			5.4				118707		FP/SS
(3@3.75) 11-8-90-0-i-2.5-2-24[h]	B	90°	23.5	7070	17.0		3	-	-	132010	126976	FP/SS
	C		23.5			5.5				130212		FP/SS
	A		21.9			5.5				126150		SS/FP
(3@3.75) 11-12-90-0-i-2.5-2-22[e,l]	B	90°	21.3	11460	17.0		3	-	-	125954	123180	SS/FP
	C		21.9			5.5				117434		SS/FP
	A		22.0			5.3				117909		FP/SS
(3@3.75) 11-8-90-2#3-i-2.5-2-23[h]	B	90°	22.0	7070	17.0		3	0.11	2	120432	116589	FP/SS
	C		21.9			5.5				111428		FP/SS
	A		21.0			5.5				129578		SS
(3@3.75) 11-12-90-2#3-i-2.5-2-21[e,l]	B	90°	21.0	11850	17.0		3	0.11	2	127727	127812	SS
	C		20.9			5.5				126130		SS
	A		19.9			5.6				118209		FP/SS
(3@3.75) 11-8-90-6#3-i-2.5-2-21[h]	B	90°	20.1	7070	17.0		3	0.11	6	112198	111288	FP/SS
	C		20.2			5.6				103456		FP/SS
	A		18.4			5.4				115766		FP/SS
(3@3.75) 11-12-90-6#3-i-2.5-2-19[e,h]	B	90°	18.1	11960	17.0		3	0.11	6	120824	118300	FP/SS
	C		18.4			5.5				118310		FP/SS
	A		18.9			5.3				119075		FP/SS
(3@3.75) 11-12-180-6#3-i-2.5-2-19[e,h]	B	180°	18.8	12190	17.0		3	0.11	6	120760	119045	FP/SS
	C		18.9			5.4				117301		FP/SS

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[e]Specimen had strain gauges
[h]Specimen contained A1035 Grade 120 hooked bars
[l]Specimen contained A615 Grade 80 hooked bars

3.5.3 Specimens with Staggered Hooked Bars

Specimens with Four or Six No. 5 Staggered Hooked Bars

The results for eight specimens containing four of six No. 5 (Grade 120) staggered hooked bars with a 90° bend angle are presented in Table 3.7. The specimens had four levels of confining reinforcement within the joint region, none, two No. 3 hoops, five No. 3 hoops, and No. 3 hoops spaced at $3d_b$. Nominal embedment length of hooked bars of the top layer was 8.0 in. and nominal embedment length of hooked bars of the second layer was 6.8 in. The nominal concrete compressive strength was 5,000 psi, with actual strengths between 4660 and 4860 psi. The column width was 13 in. Specimens had $2^1/_2$-in. nominal side cover and 2-in. nominal tail cover over the tail extension of hooked bars in the top layer. The horizontal center-to-center spacing between the hooked bars ranged from $3^1/_2$ to $7^3/_8$ in. The vertical clear spacing between hooked bars equaled 1.0 in. The average bar forces at failure ranged from 16,720 to 29,500 lb, corresponding to bar stresses between 53,940 and 95,160 psi.

Table 3.7 Specimens with four or six No. 5 staggered hooked bars

Specimen[a]	**Hook**	**Bend Angle**	ℓ_{eh} **in.**	f_{cm} **psi**	***b*** **in.**	c_{ch} **in.**	N_h	$A_{tr,l}$ **in.**^{2}	N_{tr}	T_{ind} **lb**	***T*** **lb**	**Failure Type**[b]
(2s) 5-5-90-0-i-2.5-2-8[h]	A	90°	8.0	4660	13.0	7.4	4	-	-	16402	16727	FP
	B		8.0							17626		FP
	C		6.5							15896		FP
	D		6.4							16986		FP
(3s) 5-5-90-0-i-2.5-2-8[h]	A	90°	8.0	4830	13.0	3.5 3.5	6	-	-	18970	16804	FP/SB
	B		7.8							17190		FP/SB
	C		8.0							16415		FP/SB
	D		6.6							17256		FP/SB
	E		6.5							16221		FP/SB
	F		6.8							14769		FP/SB
(2s) 5-5-90-2#3-i-2.5-2-8[h]	A	90°	7.5	4860	13.0	7.1	4	0.11	2	24192	24730	FP
	B		7.3							25851		FP
	C		5.8							24318		FP
	D		5.8							24560		FP
(3s) 5-5-90-2#3-i-2.5-2-8[h]	A	90°	7.6	4860	13.0	3.5 3.9	6	0.11	2	17684	20283	FP/SB
	B		7.9							18646		FP/SB
	C		7.8							19132		FP/SB
	D		6.0							20090		FP/SB
	E		5.9							19481		FP/SB
	F		6.3							26667		FP/SB

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[h]Specimen contained A1035 Grade 120 hooked bars

Table 3.7 Cont. Specimens with four or six No. 5 staggered hooked

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
(2s) 5-5-90-5#3-i-2.5-2-8[h]	A B C D	90°	7.8 7.5 6.3 6.0	4660	13.0	7.4	4	0.11	5	26565 24572 26610 26975	26180	FP/SB FP/SB FP/SB FP/SB
(3s) 5-5-90-5#3-i-2.5-2-8[h]	A B C D E F	90°	7.3 7.3 7.3 5.6 5.6 5.6	4860	13.0	3.8 3.9	6	0.11	5	19569 19702 21518 26016 25085 23697	22598	FP/SB FP/SB FP/SB FP/SB FP/SB FP/SB
(2s) 5-5-90-6#3-i-2.5-2-8[h]	A B C D	90°	8.0 8.0 6.3 6.1	4660	13.0	7.4	4	0.11	6	30675 28481 30220 28737	29528	FP/SB FP/SB FP/SB FP/SB
(3s) 5-5-90-6#3-i-2.5-2-8[h]	A B C D E F	90°	7.5 7.6 7.6 6.0 6.0 6.0	4860	13.0	3.6 3.8	6	0.11	6	21119 17707 19794 25862 25053 22953	22081	FP/SB FP/SB FP/SB FP/SB FP/SB FP/SB

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[h]Specimen contained A1035 Grade 120 hooked bars

Specimens with Four No. 11 Staggered Hooked Bars

The results for four specimens containing four No. 11 (Grade 120) staggered hooked bars with a 90° bend angle are presented in Table 3.8. The specimens had five levels of confining reinforcement within the joint region, none, two No. 3 hoops, six No. 3 hoops, seven No. 3 hoops, and eight No. 3 hoops. Nominal embedment length of hooked bars of the top layer was 16.0 in. and nominal embedment length of hooked bars of the second layer was 13.2 in. Nominal concrete compressive strength was 5,000 psi, with actual strengths of 5030 and 5140 psi. The column width was $21^1/_2$ in. Specimens had $2^1/_2$-in. nominal side cover and 2-in. nominal tail cover over the tail extension of hooked bars of the top layer. The horizontal center-to-center spacing between the hooked bars was $15^1/_8$ in. The vertical clear spacing between hooked bars equaled 1.41 in. The average bar forces at failure ranged from 47,490 to 70,500 lb, corresponding to bar stresses between 30,440 and 45,190 psi.

Table 3.8 Specimens with four No. 11 staggered hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
(2s) 11-5-90-0-i-2.5-2-16[h]	A	90°	16.0	5030	21.5	15.0	4	-	-	55287	47950	SS
	B		16.3							59571		SS
	C		13.3							37353		SS
	D		13.5							39589		SS
(2s) 11-5-90-2#3-i-2.5-2-16[h]	A	90°	15.9	5140	21.5	15.3	4	0.11	2	57407	57998	SS
	B		16.0							62971		SS
	C		13.3							53239		SS
	D		13.3							58377		SS
(2s) 11-5-90-6#3-i-2.5-2-16[h]	A	90°	15.5	5030	21.5	15.0	4	0.11	6	61701	62177	SS
	B		15.5							67354		SS
	C		12.3							61978		SS
	D		12.8							57676		SS
(2s) 11-5-90-7#3-i-2.5-2-16[h]	A	90°	15.5	5140	21.5	14.9	4	0.11	7	73124	67432	SS
	B		15.5							77621		SS
	C		13.0							60239		SS
	D		13.0							58743		SS
(2s) 11-5-90-8#3-i-2.5-2-16[h]	A	90°	15.9	5140	21.5	15.3	4	0.11	8	77857	70505	SS
	B		15.9							74134		SS
	C		13.3							65363		SS
	D		13.3							64664		SS

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[h]Specimen contained A1035 Grade 120 hooked bars

3.5.4 Specimens with Hooked Bars Not Embedded to Far Side of Member

Specimens with No. 5 hooked bars not embedded to the far side of the member

The results for 11 specimens with Grade 120 No. 5 hooked bars embedded to the mid-depth of the columns are presented in Table 3.9. The specimens contained two, three, or four hooked bars with a 90° bend angle. The specimens had three levels of confining reinforcement within the joint region, none, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$. Embedment length ranged from 6.0 to 7.3 in., and concrete compressive strength ranged from 5,880 to 6,690 psi. The column width ranged from 11$^1/_4$ to 16$^7/_8$ in. Specimens had 2$^1/_2$-in. nominal side cover. The nominal tail cover ranged from 6 to 7 in. The center-to-center spacing between the hooked bars ranged from 2 to 5$^3/_4$ in. The average bar forces at failure ranged from 15,040 to 40,950 lb, corresponding to bar stresses between 48,520 and 132,100 psi.

Table 3.9 Specimens with No. 5 hooked bars not embedded to the far side of the member

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
(2@9) 5-5-90-0-i-2.5-7-7[h]	A	90°	6.8	5880	11.3		2	-	-	28014	28980	FP/SB
	B		7.0			5.8				29946		FP/SB
(3@4.5) 5-5-90-0-i-2.5-7-7[h]	A	90°	7.1	5880	11.3	2.8	3	-	-	24271	22363	FP
	B		7.0							22471		FP
	C		7.0			3.1				20347		FP
(4@3) 5-5-90-0-i-2.5-7-7[h]	A	90°	7.0	5880	11.2	2.0	4	-	-	13009	15048	FP
	B		7.3			2.3				16790		FP
	C		7.0							14874		FP
	D		7.0			2.0				15518		FP
(4@6) 5-8-90-0-i-2.5-6-6[d,h]	A	90°	6.3	6690	16.9	3.8	4	-	-	16185	16051	FP/SS
	B		6.3			3.8				14728		FP/SS
	C		6.3							16472		FP/SS
	D		6.3			3.8				16819		FP/SS
(2@9) 5-5-90-2#3-i-2.5-7-7[h]	A	90°	7.0	5880	11.3		2	0.11	2	33408	34232	FP/SB
	B		7.0			5.8				35055		FP/SB
(3@4.5) 5-5-90-2#3-i-2.5-7-7[h]	A	90°	6.4	5880	11.3	3.0	3	0.11	2	23612	23305	FP
	B		6.6							23163		FP
	C		6.5			2.9				23142		FP/SB
(4@3) 5-5-90-2#3-i-2.5-7-7[h]	A	90°	7.0	5950	11.3	2.3	4	0.11	2	16337	19577	FP
	B		7.0			2.0				21322		FP
	C		7.0							20389		FP
	D		7.0			2.0				20259		FP
(2@9) 5-5-90-5#3-i-2.5-7-7[h]	A	90°	6.8	5950	11.3		2	0.11	5	41678	40954	FP/SB
	B		7.0			5.8				40229		FP/SB
(3@4.5) 5-5-90-5#3-i-2.5-7-7[h]	A	90°	6.8	5950	11.3	2.6	3	0.11	5	34328	35112	FP/SB
	B		6.8							34633		FP/SB
	C		7.0			3.0				36376		FP/SB
(4@3) 5-5-90-5#3-i-2.5-7-7[h]	A	90°	7.3	5950	11.3	2.1	4	0.11	5	29016	29370	FP/SB
	B		7.0			2.1				29505		FP/SB
	C		6.9							29298		FP/SB
	D		7.0			2.0				29664		FP/SB
(4@6) 5-8-90-5#3-i-2.5-6-6[d,h]	A	90°	6.8	6690	16.9	3.8	4	0.11	5	32083	31152	FP
	B		6.0			3.8				29930		FP
	C		6.5							30839		FP
	D		6.3			3.5				31755		FP

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement
[h]Specimen contained A1035 Grade 120 hooked bars

Specimens with No. 8 hooked bars not embedded to the far side of the member

The results for 14 specimens with Grade 80 No. 8 hooked bars embedded to the mid-depth of the columns are presented in Table 3.10. The specimens contained two, three, or four hooked bars with a 90° bend angle. The specimens had two levels of confining reinforcement within the joint region, none, and No. 3 hoops spaced at $3d_b$. Nominal embedment length was 9 in. Nominal concrete compressive strength was 8,000 psi, with actual strengths of 7440 and 7510 psi. The column width ranged from 9 to 18 in. Specimens had $2^1/_2$-in. nominal side cover and 9-in. nominal tail cover. The center-to-center spacing between the hooked bars ranged from 3 to 11 in. The average bar forces at failure ranged from 18,030 to 63,290 lb, corresponding to bar stresses between 22,820 and 80,110 psi.

Table 3.10 Specimens No. 8 with hooked bars not embedded to the far side of the member

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
8-8-90-0-i-2.5-9-9[l]	A B	90°	9.3 9.0	7710	17.0	11.0	2	-	-	38519 36839	37679	FB FB
(2@3) 8-8-90-0-i-2.5-9-9[l]	A B	90°	9.3 9.0	7510	9.0	3.0	2	-	-	33826 27518	30672	FP FP
(2@4) 8-8-90-0-i-2.5-9-9[l]	A B	90°	9.9 10.0	7510	10.0	4.1	2	-	-	32856 35534	34195	FP FP
(3@3) 8-8-90-0-i-2.5-9-9[l]	A B C	90°	9.5 9.5 9.3	7510	12.0	3.1 3.1	3	-	-	24580 25019 14714	21438	FP FP FP
(3@4) 8-8-90-0-i-2.5-9-9[l]	A B C	90°	9.3 9.3 9.3	7510	14.0	4.0 4.1	3	-	-	29403 27226 22429	26353	FP FP FP
(4@3) 8-8-90-0-i-2.5-9-9[l]	A B C D	90°	9.4 9.3 9.3 9.6	7510	15.0	3.0 3.0 3.0	4	-	-	22181 21153 18251 13052	18659	FP FP FP FP
(4@4) 8-8-90-0-i-2.5-9-9[l]	A B C D	90°	9.4 9.1 9.0 9.1	7510	18.0	4.1 4.1 4.0	4	-	-	20362 19012 18449 14323	18036	FP FP FP FP
8-8-90-5#3-i-2.5-9-9[l]	A B	90°	9.0 9.3	7710	17.0	11.0	2	0.11	5	61894 64703	63298	FB FB
(2@3) 8-8-90-5#3-i-2.5-9-9[l]	A B	90°	9.3 9.5	7440	9.0	3.0	2	0.11	5	56420 61165	58792	FP FP
(2@4) 8-8-90-5#3-i-2.5-9-9[l]	A B	90°	8.9 9.1	7440	10.0	4.3	2	0.11	5	55603 59307	57455	FB FB
(3@3) 8-8-90-5#3-i-2.5-9-9[l]	A B C	90°	9.5 9.0 9.5	7440	12.0	3.0 3.0	3	0.11	5	43346 38730 37211	39762	FP FP FP
(3@4) 8-8-90-5#3-i-2.5-9-9[l]	A B C	90°	8.9 9.1 9.3	7440	14.0	4.0 4.0	3	0.11	5	48534 30171 30973	36559	FP FP FP
(4@3) 8-8-90-5#3-i-2.5-9-9[l]	A B C D	90°	9.3 9.3 9.3 9.3	7440	15.0	3.0 3.3 3.0	4	0.11	5	32930 38749 27290 26794	31441	FP FP FP FP
(4@4)8-8-90-5#3-i-2.5-9-9[l]	A B C D	90°	9.5 9.5 9.3 9.6	7440	18.0	4.0 4.0 4.0	4	0.11	5	33657 30723 27886 25671	29484	FP FP FP FP

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[l]Specimen contained A615 Grade 80 hooked bars

Specimens with No. 11 hooked bars not embedded to the far side of the member

The results for eight specimens with Grade 120 and Grade 80 No. 11 hooked bars embedded to the mid-depth of the columns are presented in Table 3.11. The specimens contained two or three hooked bars with a 90° bend angle. The specimens had three levels of confining reinforcement within the joint region, none, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$. Nominal embedment length ranged from 13 to 18 in. Nominal concrete compressive strength was 5,000 psi, with actual strengths of 5280 and 5330 psi. The column width ranged from 14 to $21\frac{1}{2}$ in. Specimens had $2\frac{1}{2}$-in. nominal side cover. The nominal tail cover ranged from 13 to 18 in. The average bar forces at failure ranged from 51,500 to 121,600 lb, corresponding to bar stresses between 33,010 and 77,950 psi.

Table 3.11 Specimens with No. 11 hooked bars not embedded to the far side of the member

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
(2@5.35) 11-5-90-0-i-2.5-13-13[l]	A B	90°	14.0 13.9	5330	14.0	7.6	2	-	-	58206 62981	60593	FP FP
(3@5.35) 11-5-90-0-i-2.5-13-13[l]	A B C	90°	13.8 14.3 13.5	5330	21.5	8.0 7.8	3	-	-	45405 49897 59215	51506	FP FP FP
(2@5.35) 11-5-90-2#3-i-2.5-13-13[l]	A B	90°	13.9 13.8	5330	14.0	7.6	2	0.11	2	68250 69997	69123	FP FP
(3@5.35) 11-5-90-2#3-i-2.5-13-13[l]	A B C	90°	14.0 14.0 13.8	5330	21.5	7.5 7.5	3	0.11	2	50926 58487 64349	57921	FP FP FP
(2@5.35) 11-5-90-6#3-i-2.5-13-13[l]	A B	90°	14.0 13.8	5280	14.0	7.6	2	0.11	6	83556 95940	89748	FP FP
(2@5.35) 11-5-90-6#3-i-2.5-18-18[h]	A B	90°	19.3 19.5	5280	14.0	7.6	2	0.11	6	116107 127103	121605	FP FP
(3@5.35) 11-5-90-6#3-i-2.5-13-13[l]	A B C	90°	13.5 13.5 13.8	5280	21.5	7.4 7.3	3	0.11	6	59647 66536 72350	66178	FP FP FP
(3@5.35) 11-5-90-6#3-i-2.5-18-18[h]	A B C	90°	18.6 18.6 18.6	5280	21.5	7.5 7.0	3	0.11	6	100804 121063 113733	111867	FP FP FP

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[h]Specimens contained A1035 Grade 120 hooked bars
[l]Specimen contained A615 Grade 80 hooked bars

3.5.5 Deep-Beam Specimens with Two Hooked Bars

Specimens with Two No. 8 Hooked Bars

The results for four deep-beam specimens containing two No. 8 hooked bars with a 90° bend angle are presented in Table 3.12. The specimens contained Grade 120 and Grade 80 hooked bars. The specimens had four levels of confining reinforcement within the joint region, none, two No. 3 hoops, five No. 3 hoops, and No. 3 hoops spaced at $3d_b$. Nominal embedment length was 10 in. Nominal concrete compressive strength was 5,000 psi, with an actual strength of 5910 psi. The column width was 17 in. Specimens had $2^1/_2$-in. nominal side cover and 2-in. nominal tail cover. The nominal center-to-center spacing between the hooked bars was 11 in. The average bar forces at failure ranged from 32,370 to 54,760 lb, corresponding to bar stresses between 40,980 and 69,320 psi.

Table 3.12 Deep-beam specimens with two No. 8 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
(2d) 8-5-90-0-i-2.5-2-10[d,e,l]	A B	90°	10.3 10.0	5920	17.0	11.0	2	-	-	33147 31600	32373	SS SS
(2d) 8-5-90-2#3-i-2.5-2-10[d,e,l]	A B	90°	10.0 10.3	5920	17.0	11.1	2	0.11	2	45802 45358	45580	SS SS
(2d) 8-5-90-5#3-i-2.5-2-10[d,e,l]	A B	90°	9.9 10.0	5920	17.0	11.3	2	0.11	5	54654 54816	54735	FB/SS FB/SS
(2d) 8-5-90-9#3-i-2.5-2-10[d,e,h]	A B	90°	10.3 10.0	5920	17.0	11.3	2	0.11	9	54261 55261	54761	FB/SS FB/SS

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement
[e]Specimen had strain gauges
[h]Specimens contained A1035 Grade 120 hooked bars
[l]Specimen contained A615 Grade 80 hooked bars

Specimens with Two No. 11 Hooked Bars

The results for four deep-beam specimens containing two No. 11 (Grade 80) hooked bars with a 90° bend angle are presented in Table 3.13. The specimens had three levels of confining reinforcement within the joint region, none, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$. Nominal embedment length was 10 in. Nominal concrete compressive strength was 15,000 psi, with an actual strength of 14,050 psi. The column width was $21^1/_2$ in. Specimens had $2^1/_2$-in. nominal side cover and 2-in. nominal tail cover. The nominal center-to-center spacing between the hooked bars was 15 in. The average bar forces at failure ranged from 51,480 to 82,680 lb, corresponding to bar stresses between 33,000 and 53,000 psi.

Table 3.13 Deep-beam specimens with two No. 11 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	N_{tr}	T_{ind} lb	T lb	Failure Type[b]
(2d) 11-15-90-0-i-2.5-2-10[l]	A B	90°	9.5 9.5	14050	21.5	15.0	2	-	-	52097 50866	51481	FP FP
(2d) 11-15-90-2#3-i-2.5-2-10[l]	A B	90°	10.0 10.0	14050	21.5	14.8	2	0.11	2	64250 63631	63940	FP FP
(2d) 11-15-90-6#3-i-2.5-2-10a[l]	A B	90°	9.5 10.0	14050	21.5	14.8	2	0.11	6	83558 81804	82681	FP FP
(2d) 11-15-90-6#3-i-2.5-2-10b[l]	A B	90°	9.5 9.8	14050	21.5	14.4	2	0.11	6	76605 74553	75579	FP FP

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.4
[l]Specimen contained A615 Grade 80 hooked bars

3.5.6 Reinforcement Strain

Fifteen specimens were equipped with strain gauges to monitor the strain in the hooked bars and hoops (Table 3.14). Seven specimens contained two No. 8 or No. 11 hooked bars with a 90° and 180° bend angle and with three levels of confining reinforcement, none, two No. 3 hoops, and No. 3 hoops spaced at 3d_b; four specimens contained three No. 11 hooked bars with a 90° and 180° bend angle and with three levels of confining reinforcement, none, two No. 3 hoops and No. 3 hoops spaced at 3d_b; and four specimens contained two No. 8 hooked bars with deep beam with a 90° bend angle and four levels of confining reinforcement, none, two No. 3 hoops, five No. 3 hoops, and nine No. 3 hoops.

Table 3.14 Reinforcement strain at peak load

Specimen	Hooked Bar Strain				Confining Reinforcement Strain						
	External Hook		Internal Hook								
	H1	H2	H3	H4	S1	S2	S3	S4	S5	S6	S8
	Specimens with two hooked bars										
8-5-90-0-i-2.5-2-10	0.00186	0.00205	-	-	-	-	-	-	-	-	-
8-5-90-2#3-i-2.5-2-10	0.00287	0.00308	-	-	0.01233[b]	0.00083[a]	-	-	-	-	-
8-5-90-5#3-i-2.5-2-10	0.00075	0.00354	-	-	0.01556[b]	0.00493[b]	0.00317[b]	0.00144[a]	0.00084[a]	-	-
(2@7.5) 11-12-90-0-i-2.5-2-17	*	0.00314[b]	-	-	-	-	-	-	-	-	-
(2@7.5) 11-12-90-2#3-i-2.5-2-16	0.0024	0.00388[b]	-	-	0.01597[b]	0.00638[b]	-	-	-	-	-
(2@7.5) 11-12-90-6#3-i-2.5-2-14	*	0.00223	-	-	0.01891[b]	0.01575[b]	0.0187[b]	0.01283[b]	0.00204	0.00074[a]	-
(2@7.5) 11-12-180-6#3-i-2.5-2-14	*	0.00146	-	-	0.01358[b]	0.01569[b]	0.01832[b]	0.02114[b]	0.01403[b]	0.00114[a]	-
	Specimens with three hooked bars										
(3@3.75) 11-12-90-0-i-2.5-2-22	0.00335[b]	0.00296	0.00274	0.00452[b]	-	-	-	-	-	-	-
(3@3.75) 11-12-90-2#3-i-2.5-2-21	*	0.00321[b]	0.00352[b]	0.00371[b]	0.00732[b]	0.00341[b]	-	-	-	-	-
(3@3.75) 11-12-90-6#3-i-2.5-2-19	*	0.00275	*	0.00282	0.01855[b]	*	0.01292[b]	0.01107[b]	0.00182	0.00039[a]	-
(3@3.75) 11-12-180-6#3-i-2.5-2-19	*	0.00289	*	*	0.01168[b]	0.01384[b]	*	0.01913[b]	0.00227	*	-
	Deep-beam specimens with two hooked bars										
(2d) 8-5-90-0-i-2.5-2-10	0.00120	0.00216	-	-	-	-	-	-	-	-	-
(2d) 8-5-90-2#3-i-2.5-2-10	*	0.00247	-	-	0.01823[b]	0.00928[b]	-	-	-	-	-
(2d) 8-5-90-5#3-i-2.5-2-10	0.00116	0.0024	-	-	0.01679[b]	0.01215[b]	0.01065[b]	0.00224	0.00278[b]	-	-
(2d) 8-5-90-9#3-i-2.5-2-10	0.00199	0.00285	-	-	0.01768[b]	0.00258[b]	0.00265[b]	0.00263[b]	0.00248[b]	0.00145	0.00008[a]

*Strain gauge was stopped before the peak load
[a]Hoop located under the compression member
[b]Strain indicates that bar yielded

The strain gauges, shown in Figure 3.6, were mounted on the top surface of the straight portion of hooked bars at two locations [strain gauges (H1, H3) located at the beginning of the bend, and strain gauges (H2, H4) located on the straight portion of the hook, 1.5 in. from the column face]. On one side of the specimen (the side with the gauged hooked bar), strain gauges were mounted on the bottom surface of the confining reinforcement within the joint region (Si), with i equal to the hoop number counting down from the first hoop below the top-most hooked bar.

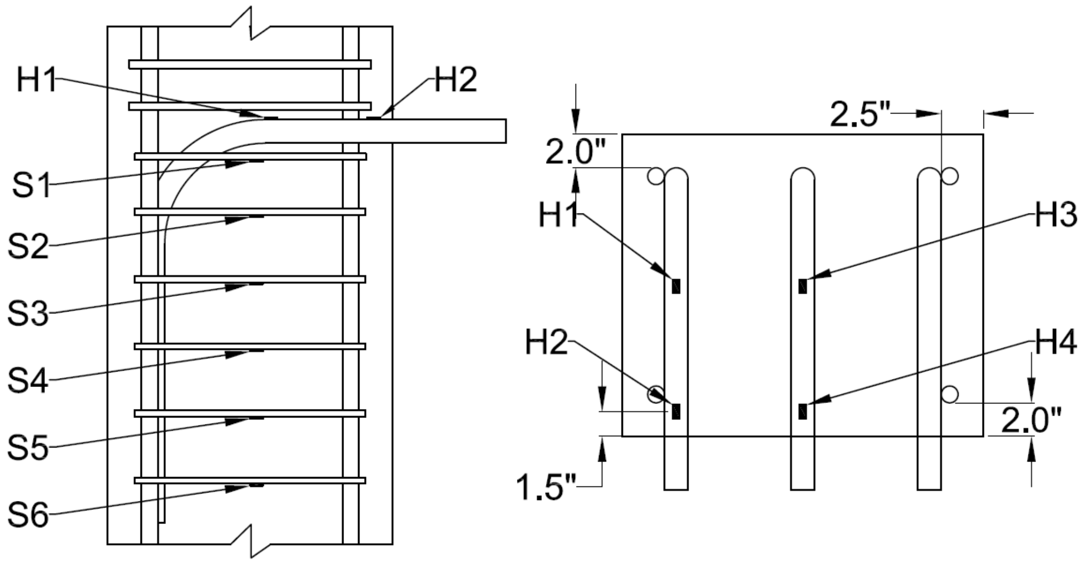


Figure 3.6 Strain gauge locations

Table 3.14 presents the strain in the hooked bars at the peak load. In most cases, the strains in hooked bars at the face of the column were higher than the strains at the bend, demonstrating that the straight portion of hooked bars contributes to anchorage strength even at failure.

Table 3.14 also shows the strain in each hoop at the peak load. Specimens with 90° hooked bars generally exhibited the greatest hoop strain at the hoop closest to the straight portion of the bar, with strains decreasing as the distance from the bar increased. Specimens with 180° hooked bars exhibited the greatest hoop strain on hoops adjacent to the tail extension of the hooked bars [as can be seen in specimens (2@7.5) 11-12-180-6#3-i-2.5-2-14 and (3@3.75) 11-12-180-6#3-i-2.5-2-19]. Strains again decreased as the distance from the hook increased. This indicates that there is a limit to the region over which confining reinforcement will contribute to the anchorage strength of hooked bars.

Figure 3.7 shows the load-strain curves for specimen 8-5-90-5#3-i-2.5-2-10. The specimen contained two No. 8 hooked bars with a 90° bend angle confined by five No. 3 hoops within the joint region. The average embedment length for the hooks was 9.63 in., and the concrete compressive strength was 5,920 psi. Strain gauge H1 was located on the top surface of the straight portion of the hooked bar (Figure 3.6) at the beginning of the bend; strain gauge H2 was located on the same bar, 1.5 in. from the column front face. Strain gauges S1 through S5 were located on the bottom surface of the hoops within the joint region. The first hoop was 2 in. from the top edge of the straight portion of the hooked bars; hoops 2 through 5 were spaced at 3-in. intervals (center-to-center) from the first hoop. The dashed lines indicate strain in the hooked bar. At a given load, the strain in the hooked bar at the face of the column (H2) was higher than the strain in the hooked bar at the bend (H1); the difference between the strains corresponds to the force carried by the straight portion of the hooked bar. The solid lines show strain developed in the confining reinforcement. As shown in Figure 3.7, the hoops close to the straight portion of the hooked bar (S1, S2) showed increases in strain at lower loads and exhibited greater strains at the peak load than the hoops placed further from the bend of the hooked bar (S3, S4, and S5). At the peak load, the first three hoops (S1, S2, and S3) exhibited strains greater than that corresponding to the yield. The strain in hoop S1 exceeded the yield strain at 80% of the peak load, while the strain in hoops S2 and S3 exceeded the yield strain at 95% of the peak load. Hoops 4 and 5 (S4 and S5) were located under the bearing member and exhibited very low strains throughout the test.

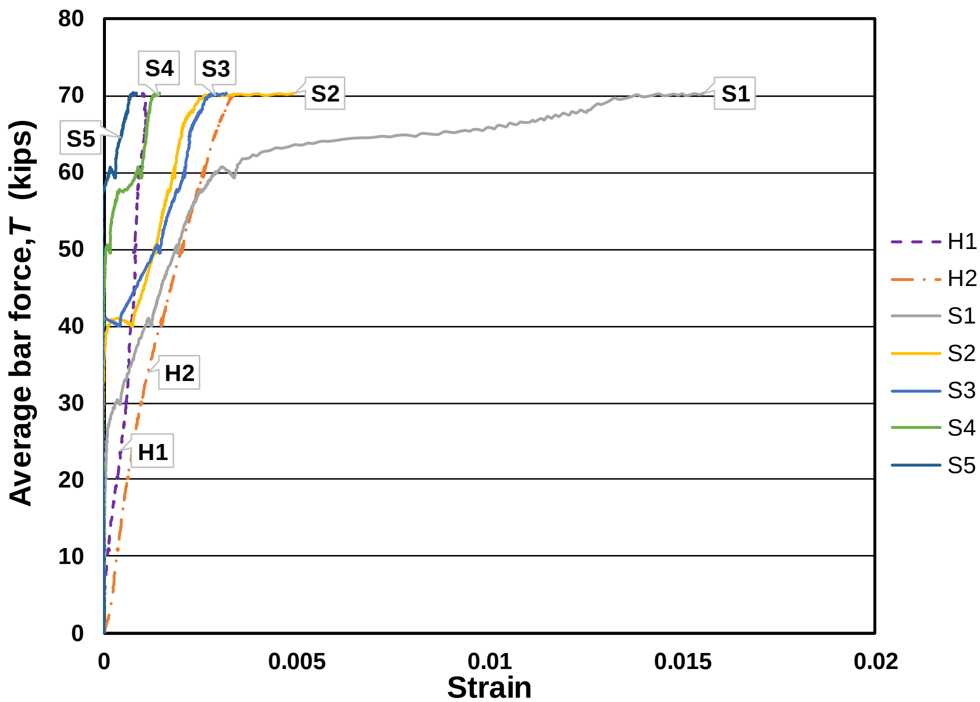


Figure 3.7 Load-strain curves for specimen 8-5-90-5#3-i-2.5-2-10 with two hooked bars

Figure 3.8 shows the load-strain curves for specimen (3@3.75) 11-12-90-6#3-i-2.5-2-19. The specimen contained three No. 11 hooked bars with a 90° bend angle confined by six No. 3 hoops within the joint region. The average embedment length was 18.3 in., and the concrete compressive strength was 11,960 psi. Strain gauges H1 and H3 were located on the top surface of the straight portion of the hooked bars (Figure 3.6) at the beginning of the bend; strain gauges H2 and H4 were located away from the bend on the same bars, 1.5 in. from the column front face. Strain gauges S1 through S6 were located on the bottom surface of the hoops within the joint region. Strain gauges H3 and S2 failed prior to the peak load. The first hoop was 2.75 in. from the top edge of the straight portion of the hooked bar; hoops 2 through 6 were spaced at 4-in. intervals (center-to-center) from the first hoop. The hooked bars in this specimen exhibited similar strain behavior to bars in the specimen with two hooked bars. At a given load, the strain in the hooked bar at the face of the column (H2) was higher than the strain in the hooked bar at the bend (H1). Hoops close to the straight portion of the hooked bar (S1, S3) showed increases in strain at lower loads and exhibited greater strains at peak load than hoops placed further from the bend of the hooked bar (S4, S5, and S6). At the peak load, hoops S1, S3, and S4 exhibited strain greater than that corresponding to yield. The strain in hoops S1 and S4 exceeded yield strain at 75% of the peak load, while the strains in hoop S3 exceeded yield strain at 93% of the peak load. Hoop 6 (S6) was located under the bearing member and exhibited very low strain throughout the test.

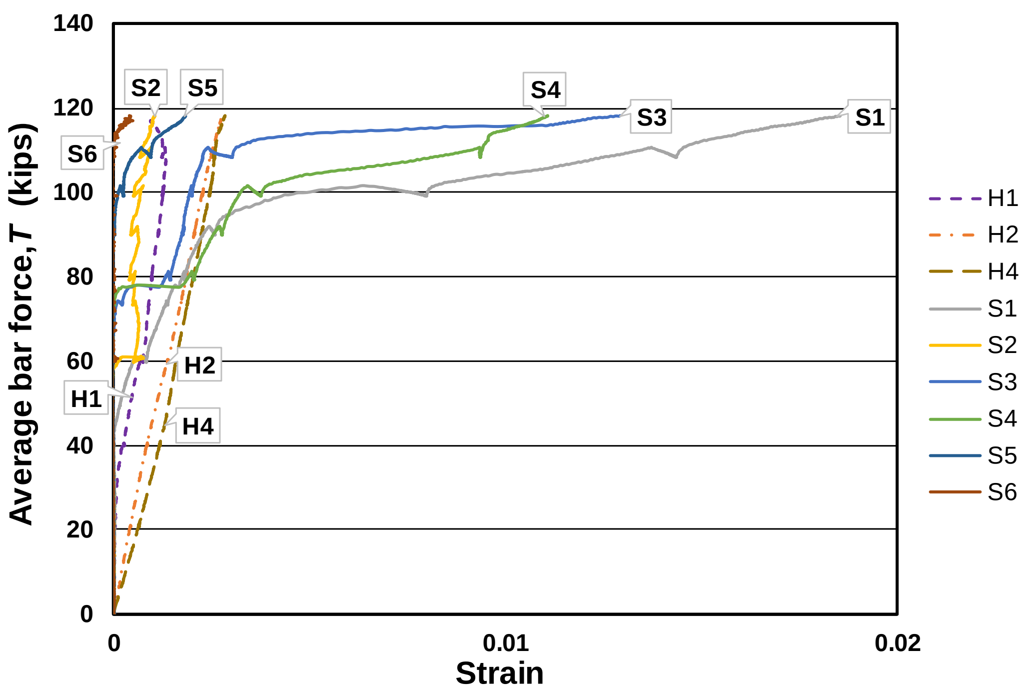


Figure 3.8 Load-strain curves for specimen (3@3.75) 11-12-90-6#3-i-2.5-2-19 with three hooked bars

Figure 3.9 shows the load-strain curves for deep-beam specimen (2d) 8-5-90-5#3-i-2.5-2-10. The specimen contained two No. 8 hooked bars with a 90° bend angle with five No. 3 hoops as confining reinforcement within the joint region (distributed along the bend and tail portions of the hooked bars). The average embedment length was 9.95 in., and distance from the center of the straight portion of the hooked bars to the top of the bearing member was 19.5 in., compared to 10 in. for most specimens containing No. 8 bars. The concrete compressive strength was 5,920 psi. Strain gauge H1 was located on the top surface of the straight portion of the hooked bar at the beginning of the bend (Figure 3.6); strain gauge H2 was located on the same bar, 1.5 in. from the column front face. Strain gauges S1 through S5 were located on the bottom surface of the hoops within the joint region. The first hoop was centered 2 in. from the top edge of the straight portion of the hooked bar; hoops 2 through 5 were spaced at 3-in. intervals (center-to-center) from the first hoop.

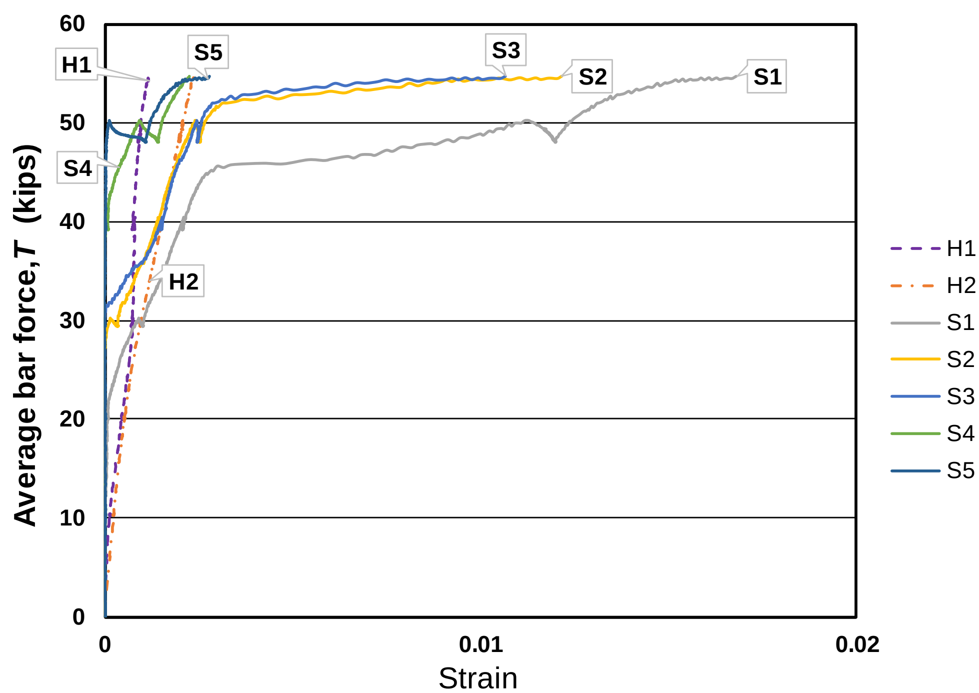


Figure 3.9 Load-strain curves for deep-beam specimen (2d) 8-5-90-5#3-i-2.5-2-10 with two hooked bars

As in the specimen with three hooked bars, the hooked bars in the deep-beam specimen with two hooked bars exhibited strain behavior that was similar to the bars in the earlier specimen with two hooked bars (specimen 8-5-90-5#3-i-2.5-2-10, Figure 3.7). At any given load, the strain in the hooked bar at the face of the column (H2) was higher than the strain in the hooked bar at the bend (H1). Hoops close to the straight portion of the hooked bar (S1, S2) showed increases in strain at lower loads and exhibited greater strains at the peak load than hoops placed further from the bend of the hooked bar (S3, S4, and S5). At the peak load, hoops S1, S2, S3, and S5 exhibited strain greater than that corresponding to yield. The strain in hoop S1 exceeded the yield strain at 78% of the peak load, while strains in hoops S2 and S3 exceeded yield strain at 90% of the peak load, and the strain in hoop S5 exceeded yield strain at 99% of the peak load. None of the hoops were located under the bearing member for this specimen.

CHAPTER 4: ANALYSIS AND DISCUSSION

4.1 GENERAL

This chapter presents an analysis of test results for the beam-column joint specimens evaluated in this study along with test results from earlier work (Marques and Jirsa 1975, Pinc et al. 1977, Hamad et al. 1993, Joh et al. 1995, Joh and Shibata 1996, Ramirez and Russell 2008, Lee and Park 2010, Peckover and Darwin 2013, Searle et al. 2014, Sperry et al. 2015a, 2015b, 2017a). Table 4.1 summarizes the number and source of specimens included in this analysis. The goal of the analysis is to expand the understanding of the factors that control the anchorage strength and to develop an equation that characterizes the anchorage strength of hooked bars.

Table 4.1 Number and Sources of Specimens

Specimen Type	Size of Hooked Bars	Number of Specimens	Source
Specimens with Two Hooked Bars	No. 5	4	**Current investigation**
		74	Sperry et al. (2015a,b)
	No. 6	5	Ramirez and Russell (2008)
	No. 7	12	Marques and Jirsa (1975)
		2	Hamad et al. (1993)
		3	Lee and Park (2010)
	No. 8	16	**Current investigation**
		113	Sperry et al. (2015a,b)
	No. 9	1	Pinc et al. (1977)
	No. 11	13	**Current investigation**
		54	Sperry et al. (2015a,b)
		2	Marques and Jirsa (1975)
		2	Pinc et al. (1977)
		7	Hamad et al. (1993)
		5	Ramirez and Russell (2008)
Specimens with Three or Four Hooked Bars	No. 5	13	**Current investigation**
		8	Sperry et al. (2015a,b)
	No. 8	14	**Current investigation**
		17	Sperry et al. (2015a,b)
	No. 11	8	**Current investigation**
Staggered-Hook Specimens	No. 5	8	**Current investigation**
	No. 11	5	**Current investigation**
Specimens with Hooks Not Embedded to Far Side	No. 5	11	**Current investigation**
	3/4 in. (19 mm)	13	Joh et al. (1995)
	3/4 in. (19 mm)	13	Joh and Shibata (1996)
	No. 8	14	**Current investigation**
	No. 11	8	**Current investigation**
Deep-Beam Specimens	No. 8	4	**Current investigation**
	No. 11	4	**Current investigation**

Initially, the anchorage strengths for simulated beam-column joint test specimens are compared with those based on the development length provisions for standard hooks in the ACI 318-14 Building Code. Then, test results for specimens containing two hooks are used to develop a descriptive equation for anchorage strength of hooked bars incorporating the effects of embedment length, concrete compressive strength, bar diameter, and amount of confining reinforcement within the joint region. The specimens used to develop the equation contained two hooked bars inside the column core and embedded to the far side of the column with a nominal tail cover of 2 in. Sperry et al. (2015a, 2015b) found that the anchorage strength of hooked bars did not increase as the concrete side cover increased from 2.5 to 3.5 in. and that hooked bars with bend angles of 90° and 180° exhibited similar anchorage strengths. In addition, Marques and Jirsa (1975) found that column axial load had a negligible effect on the anchorage strength of hooked bars. Based on these findings, the effect of concrete side cover, bend angle, and column axial load are omitted in the analysis. Other factors that could affect anchorage strength – spacing between hooked bars, staggering hooks, ratio of beam effective depth to embedment length, hooked bar location (inside or outside the column core and with respect to member depth), orientation of confining reinforcement, and confining reinforcement above the joint region – are evaluated using the descriptive equation. Finally, test results of other specimen types (monolithic beam-column joint, beam-wall) and beam-column joint specimens excluded from the initial analysis are compared with values calculated using the descriptive equation.

Throughout this chapter, a regression analysis technique based on dummy variables (Draper and Smith 1981) is used to identify the trend lines of the data. Dummy variable analysis is a least square regression analysis method that allows differences in populations to be considered when formulating relationships between principle variables.

4.2 TEST RESULTS COMPARED TO ACI 318-14

Test results for two-hook specimens, multiple-hook specimens, and staggered-hook specimens with different levels of confining reinforcement are compared with the stress calculated based on the development length provisions in the current Code [Eq. (4.1) and (4.2)]. The purpose of this comparison is to determine the degree to which the current Code provisions represent the anchorage strength of hooked bars. In Eq. (4.1), the development length ℓ_{dh} is the minimum embedment length ℓ_{eh} required to develop the yield strength of the bars.

$$\ell_{dh} = \left(\frac{f_y \psi_e \psi_c \psi_r}{50\lambda\sqrt{f'_c}} \right) d_b \tag{4.1}$$

where f_y is the yield strength of hooked bars; f'_c is the specified concrete compressive strength; d_b is the hooked bar diameter; ψ_e equals 1.2 for epoxy-coated or zinc and epoxy dual-coated bar and 1.0 for uncoated or zinc-coated (galvanized) bar; ψ_c equals 0.7 for No. 11 and smaller bars with concrete side cover not less than 2.5 in. and tail cover not less than 2 in. (this limit on tail cover is required for hooked bars with a 90° bend angle), otherwise, ψ_c equals 1.0; ψ_r equals 0.8 for No. 11 and smaller bars with 90° or 180° bend angle enclosed along the straight portion of the bar with ties or stirrups perpendicular to the straight portion of the bar at $3d_b$ spacing or smaller; ψ_r equals 0.8 for No. 11 bar and smaller with 90° bend angle enclosed along the tail extension with ties or stirrups perpendicular to the tail extension at $3d_b$ spacing or smaller, otherwise, ψ_r equals 1.0; λ equals 0.75 for lightweight concrete and 1.0 for normalweight concrete. Since all specimens involved in this analysis contained uncoated hooked bars cast with normalweight concrete, ψ_e and λ equal 1.0.

For the purpose of comparison, Eq. (4.1) can be solved for the bar stress, using $f_{s,\text{ACI}}$ in place of f_y. The development length ℓ_{dh} is replaced by the embedment length ℓ_{eh} and the specified concrete compressive strength f'_c is replaced by the measured concrete compressive strength f_{cm}.

$$f_{,\text{ACI}} = \frac{50\ell_{eh}\sqrt{f_{cm}}}{\psi_c \psi_r d_b} \tag{4.2}$$

When calculating bar stress $f_{s,\text{ACI}}$, measured values of embedment length ℓ_{eh} and concrete compressive strength f_{cm} are used. The concrete compressive strength f_{cm} is measured on the day of the test. Specimens included in this analysis had a nominal concrete side cover of 2.5 or 3.5 in. and a nominal concrete tail cover of 2 in.; thus, ψ_c equaled 0.7 for all cases. The current Code provisions limit the square root of concrete compressive strength to 100 psi; this limit is not applied in the comparisons. Specimens with a column longitudinal reinforcement ratio greater than 4%, not common in practical applications, were excluded from the analysis.

Figure 4.1 compares ratios of average bar stress at anchorage failure to the value calculated using Eq. (4.2) $f_{su}/f_{s,\text{ACI}}$ for two-hook specimens without confining reinforcement within the joint region plotted versus concrete compressive strength f_{cm}. The bar stress f_{su} is calculated based on the average hooked-bar force T (the peak total load carried by the specimen divided by the number of hooked bars). The plot includes test results for 101 specimens containing two hooked bars with 90° and 180° bend angles, with results from this and previous studies (See Table 4.1 for the references). The trend lines (from dummy variable analysis with the data separated based on the bar size) have a negative slope and intercepts with the vertical axis that decrease with increasing bar size. This shows that the bar stress predicted by Eq. (4.2) becomes less conservative as the concrete compressive strength and bar size increase. The trend line for the ratio of average bar stress $f_{su}/f_{s,\text{ACI}}$ for No. 5 hooked bars falls below 1.0 at a concrete compressive strength of 18,700 psi; for No. 11 hooked bars, this occurs at 4,600 psi. The trend lines for No. 8 through No. 11 bars and data points for No. 8 and No. 11 bars fall below 1.0 at concrete compressive strengths below 10,000 psi, the limit set by ACI 318-14. This comparison indicates that the current Code provisions overestimate the contribution of the concrete compressive strength and the bar size. In addition, the provisions produce an unsafe design for No. 8 or larger hooked bars at concrete compressive strengths well below 10,000 psi.

Figure 4.2 compares the ratio $f_{su}/f_{s,\text{ACI}}$ for multiple-hook and staggered-hook specimens without confining reinforcement within the joint region plotted with concrete compressive strength f_{cm}. The plot includes test results for 21 multiple-hook specimens containing three or four hooked bars with 90° or 180° bend angles arranged in one layer and test results for three staggered-hook specimens containing four or six hooked bars with a 90° bend angle arranged in two layers.

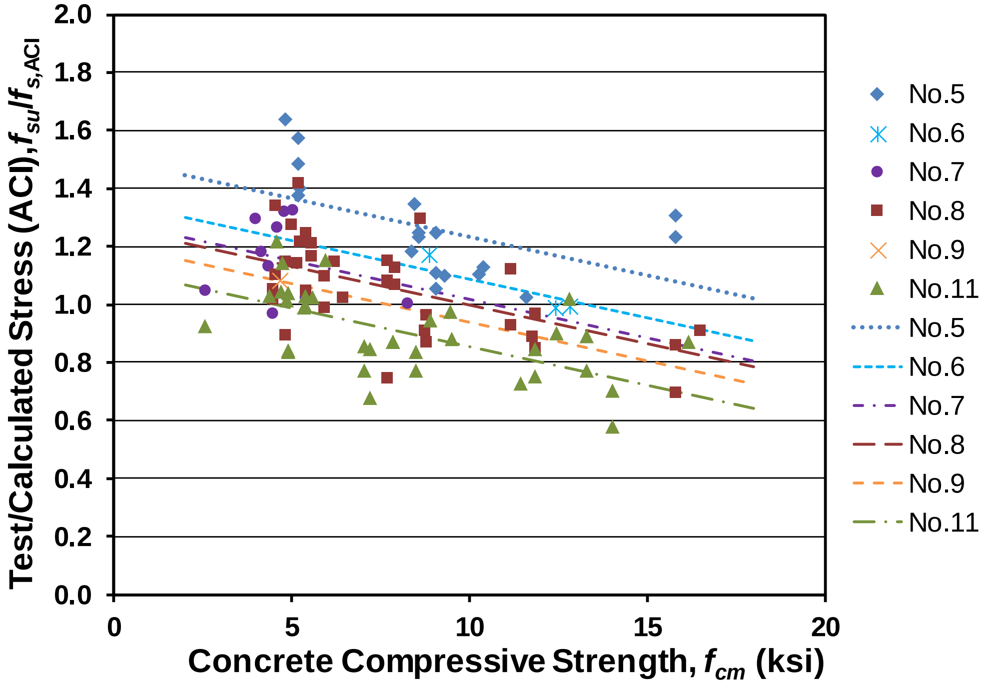


Figure 4.1 Ratio of test-to-calculated stress $f_{su}/f_{s,\text{ACI}}$ versus concrete compressive strength f_{cm} for two-hook specimens without confining reinforcement

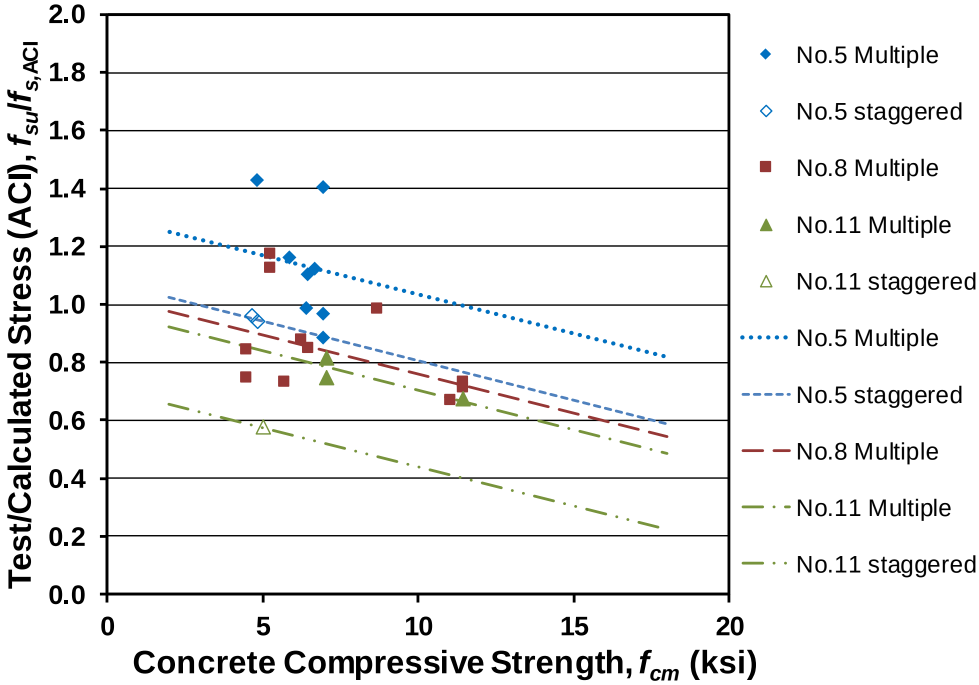


Figure 4.2 Ratio of test-to-calculated stress $f_{su}/f_{s,\text{ACI}}$ versus concrete compressive strength f_{cm} for multiple-hook and staggered-hook specimens without confining reinforcement

As for two-hook specimens without confining reinforcement within the joint region (Figure 4.1), the trend lines for the multiple-hook and staggered-hook specimens (Figure 4.2) have a negative slope and decreased intercepts with the larger bar sizes. The trend line for the ratio $f_{su}/f_{s,\mathrm{ACI}}$ for multiple-hook specimens with No. 5 hooked bars falls below 1.0 at a concrete compressive strength of 11,300 psi, for staggered-hook specimens with No. 5 hooked bars at 2,800 psi, and for multiple-hook specimens with No. 8 hooked bars at 1,150 psi. The trend lines for the multiple-hook and staggered-hook specimens with No. 11 hooked bars have vertical axis intercepts below 1.0. With the exception of the trend line for multiple-hook specimens with No. 5 hooked bars, all trends lines fall below 1.0 at a concrete compressive strength less than 10,000 psi. The trend lines for multiple-hook and staggered-hook specimens (Figure 4.2) fall below 1.0 at a lower concrete compressive strengths than the trend lines for two-hook specimens (Figure 4.1). This results because current Code provisions do not account for closely-spaced hooked bars.

Figure 4.3 compares the ratio $f_{su}/f_{s,\mathrm{ACI}}$ for two-hook specimens with 2 No. 3 hoops as confining reinforcement within the joint region with concrete compressive strength f_{cm}. Two No. 3 hoops within the joint region do not satisfy the Code requirements allowing the use of the 0.8 modification factor ψ_r. The figure includes test results for 51 specimens containing two hooked bars with 90° or 180° bend angles. As in the other comparisons, the trend lines have a negative slope. The trend line for the No. 8 hooked bars falls below 1.0 at a concrete compressive strength of 14,900 psi, and for the No. 11 hooked bars at 6,800 psi. In general, the two-hook specimens with 2 No. 3 hoops as confining reinforcement have ratios of average bar stress $f_{su}/f_{s,\mathrm{ACI}}$ greater than two-hook specimens without confining reinforcement; this is expected, because current Code provisions to not account for this low amount of confining reinforcement. Regardless, the trend lines still show that the current Code provisions can produce unsafe designs for No. 11 hooked bars at a concrete compressive strength as low as 6,800 psi.

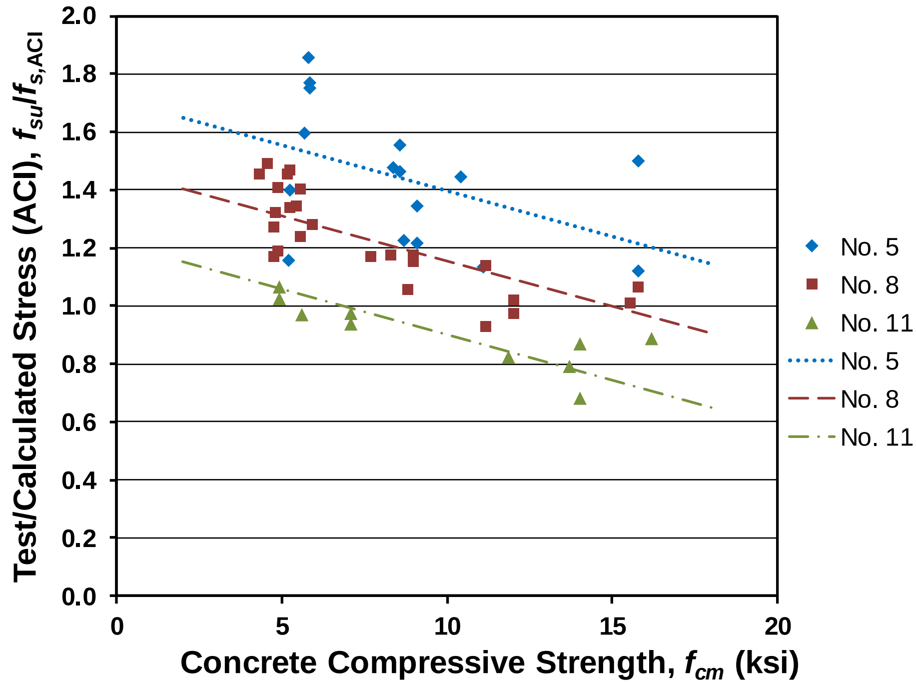


Figure 4.3 Ratio of test-to-calculated stress $f_{su}/f_{s,\text{ACI}}$ versus concrete compressive strength f_{cm} for two-hook specimens with 2 No. 3 hoops as confining reinforcement

Figure 4.4 compares the ratio $f_{su}/f_{s,\text{ACI}}$ for multiple-hook and staggered-hook specimens with 2 No. 3 hoops as confining reinforcement within the joint region with the concrete compressive strength f_{cm}. The plot includes test results of 10 multiple-hook specimens containing three or four hooked bars with 90° or 180° bend angles arranged in one layer, and three staggered-hook specimens containing four or six hooked bars with a 90° bend angle arranged in two layers. The trend line for the staggered-hook specimens with No. 5 hooked bars falls below 1.0 at a concrete compressive strength of 15,000 psi; for the multiple-hook specimens with No. 11 hooked bars, this occurs at 2,500 psi. The trend line for the staggered-hook specimens with No. 11 bars intercepts the vertical axis below 1.0. The trend lines for multiple-hook specimens with No. 8, multiple-hook specimens with No. 11, and staggered-hook specimens with No. 11 hooked bars fall below 1.0 at concrete compressive strengths below 10,000 psi. Even though the ratios of test-to-calculated stress for multiple-hook and staggered-hook specimens with 2 No. 3 hoops (Figure 4.4) are higher relative to those for the multiple-hook and staggered-hook specimens without confining reinforcement (Figure 4.2), the trend lines still fall below 1.0 at a concrete compressive strengths lower than that of two-hook specimens with 2 No. 3 hoops (Figure 4.3).

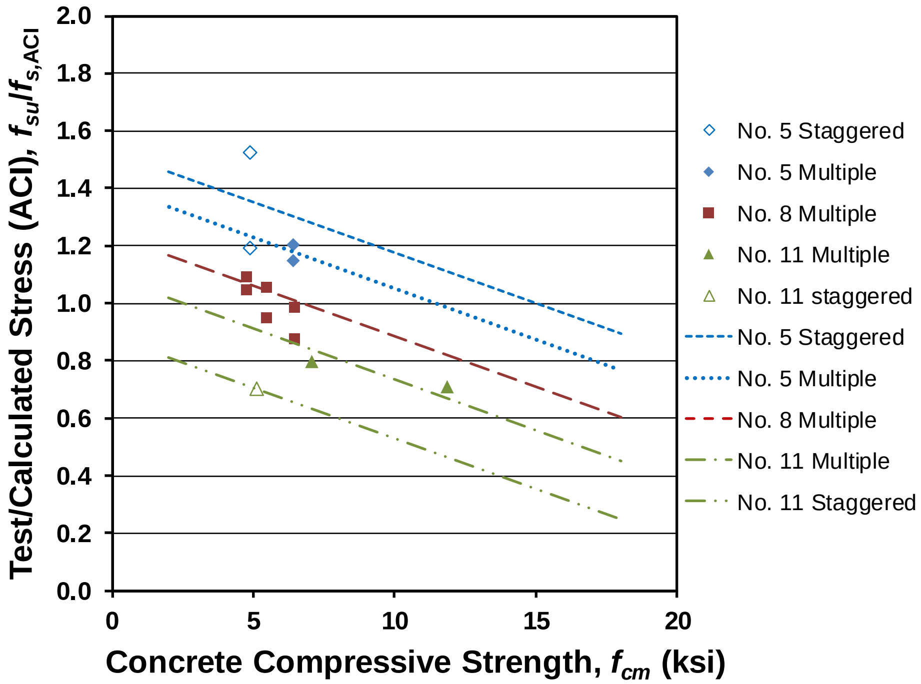


Figure 4.4 Ratio of test-to-calculated stress $f_{su}/f_{s,\mathrm{ACI}}$ versus concrete compressive strength f_{cm} for multiple-hook and staggered-hook specimens with 2 No. 3 hoops as confining reinforcement

Figure 4.5 compares the ratio $f_{su}/f_{s,\mathrm{ACI}}$ for two-hook specimens with No. 3 hoops spaced at not greater than $3d_b$ as confining reinforcement within the joint region with the concrete compressive strength f_{cm}. The figure includes data from 63 specimens containing hooked bars with 90° or 180° bend angles confined along either the straight portion of the bar (perpendicular hoops) or the tail extension (parallel hoops). The calculated values of $f_{s,\mathrm{ACI}}$ include ψ_r for all specimens. The figure includes specimens containing hooked bars with 180° bend angle and parallel hoops (not allowed by ACI 318-14) based on the findings by Sperry et al. (2015a, 2015b) that hooked bars with 90° and 180° bend angles achieve similar increases in strength with the addition of confining reinforcement.

The trend lines in Figure 4.5 have a negative slope and intercepts that decrease with increasing bar size. The trend line for the No. 6 hooked bars falls below 1.0 at a concrete compressive strength of 13,800 psi; for No. 11 hooked bars, this occurs at 4,700 psi. The trend lines for No. 7 and No. 11 hooked bars fall below 1.0 at a concrete compressive strengths less than 10,000 psi. Even though more confining reinforcement was provided within the joint region than for the specimens with 2 No. 3 hoops as confining reinforcement, the trend lines in Figure 4.5 fall below 1.0 at concrete compressive strengths lower than those for the specimens with 2 No. 3 hoops as confining reinforcement shown in Figure 4.3, indicating that Eq. (4.1), incorporating the modification factors 0.8 and 0.7, is unconservative, particularly with large hooked bars.

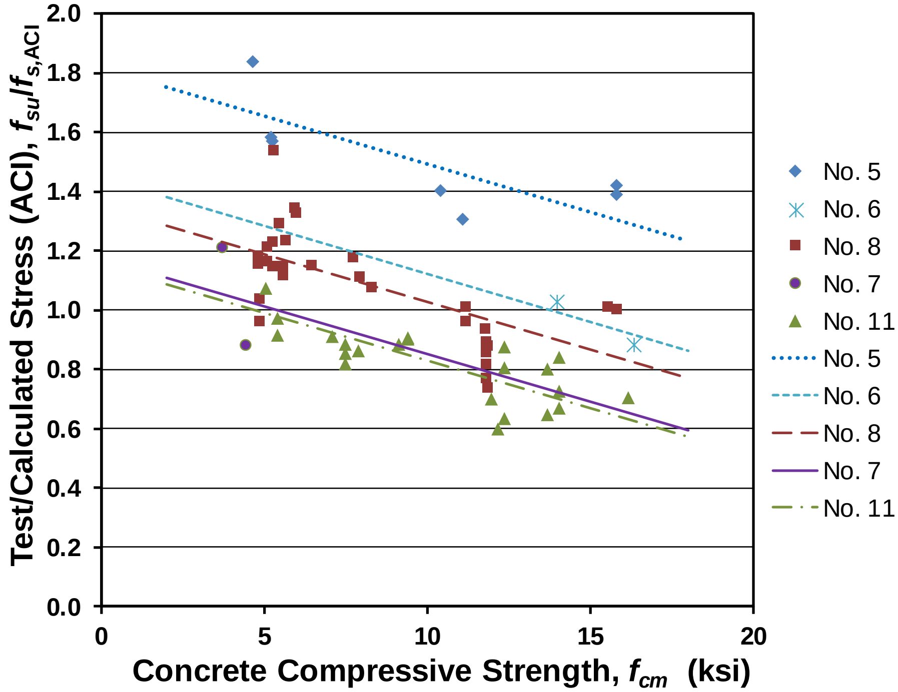


Figure 4.5 Ratio of test-to-calculated stress $f_{su}/f_{s,ACI}$ versus concrete compressive strength f_{cm} for two-hook specimens with No. 3 hoops spaced at $3d_b$ as confining reinforcement

Figure 4.6 compares the ratio $f_{su}/f_{s,ACI}$ for multiple-hook and staggered-hook specimens with No. 3 hoops spaced at not greater than $3d_b$ as confining reinforcement within the joint rejoin with the concrete compressive strength f_{cm}. The plot includes results of 22 multiple-hook specimens containing three and four hooked bars with 90° or 180° bend angles arranged in one layer, and seven staggered-hook specimens containing four or six hooked bars with a 90° bend angle arranged in two layers. The trend line for the multiple-hook specimens with No. 5 bars falls below 1.0 at a concrete compressive strength of 14,300 psi, for staggered-hook specimens with No. 5 hooked bars at 11,800 psi, and for multiple-hook specimens with No. 8 hooked bars at 4,700 psi. The trend lines for multiple-hook and staggered-hook specimens with No. 11 hooked bars have y-intercepts below 1.0. The trend lines for multiple-hook specimens with No. 8 bars, multiple-hook specimens with No. 11 bars, and staggered-hook specimens with No. 11 hooked bars fall below 1.0 at a concrete compressive strength less than 10,000 psi. This comparison shows the cumulative detrimental effect of using the Code modification factors (ψ_r and ψ_c) for closely-spaced hooked bars.

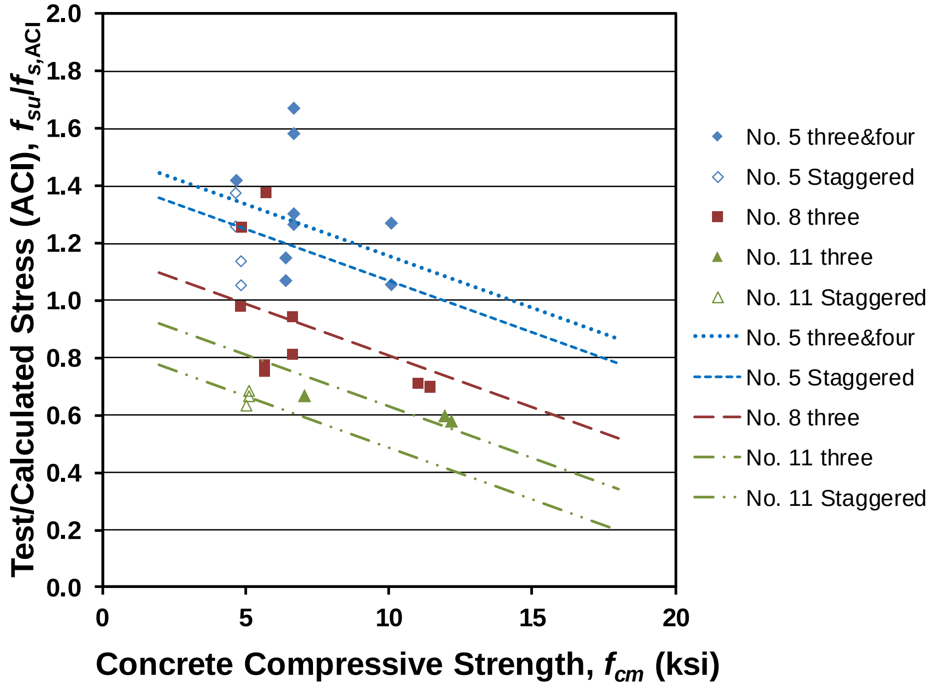


Figure 4.6 Ratio of test-to-calculated stress $f_{su}/f_{s,ACI}$ versus concrete compressive strength f_{cm} for multiple-hook and staggered-hook specimens with No. 3 hoops spaced at $3d_b$ as confining reinforcement

4.3 DESCRIPTIVE EQUATIONS FOR ANCHORAGE STRENGTH OF HOOKED BARS

Two hundred thirty seven two-hook specimens from the current and previous studies containing widely-spaced hooked bars are used to develop a descriptive expression incorporating hooked bar size, concrete compressive strength, embedment length, and confining reinforcement. The specimens have a nominal center-to-center spacing c_{ch} between bars of at least $6d_b$. Other factors – spacing between hooked bars, arrangement of hooked bars (staggered hooks), ratio of beam effective depth to embedment length, hooked bar location (inside or outside column core and with respect to member depth), orientation of confining reinforcement, and confining reinforcement above the joint region – are addressed using test results for specimens containing three or four hooked bars, specimens with staggered hooks, deep-beam specimens, and specimens with hooked bars not embedded to the far side of the member.

The two-hook specimens contained No. 5, 6, 7, 8, and 11 hooked bars with 90° and 180° bend angles embedded to the far side of the column with a nominal tail cover of 2 in. and a nominal concrete side cover of 2.5 or 3.5 in. The specimens had different levels of confining reinforcement within the joint region: no confinement, 1 No. 3 hoop, 1 No. 4 hoop, 2 No. 3 hoops, 4 No. 3 hoops, 4 No. 4 hoops, 5 No. 4 hoops, and No. 3 hoops spaced at $3d_b$ (5 No. 3 hoops for No. 5 and No. 8 hooked bars and six No. 3 hoops for No, 11 hooked bars). Specimens with a ratio of column longitudinal reinforcement greater than 4 percent were excluded from this analysis. The analytical approach used to develop the characterizing equations follows the approach used by Sperry et al. (2015a, 2015b).

4.3.1 Hooked Bars without Confining Reinforcement

Figure 4.7 shows the average bar force at failure T for 88 two-hook specimens without confining reinforcement within the joint region plotted versus the embedment length ℓ_{eh}. The specimens contained two No. 5, No. 6, No. 7, No. 8, or No. 11 hooked bars with a 90° or 180° bend angle. The average bar forces at failure ranged from 19,200 to 213,300 lb, which corresponds to an average bar stresses ranging from 33,000 to 136,730 psi. The specimens had embedment lengths ℓ_{eh} ranging from 4.9 to 26 in. and concrete compressive strengths ranging from 2,570 to 16,510 psi. The trend lines (based on dummy variable analysis) show that the average bar force at failure increases with an increase in embedment length.

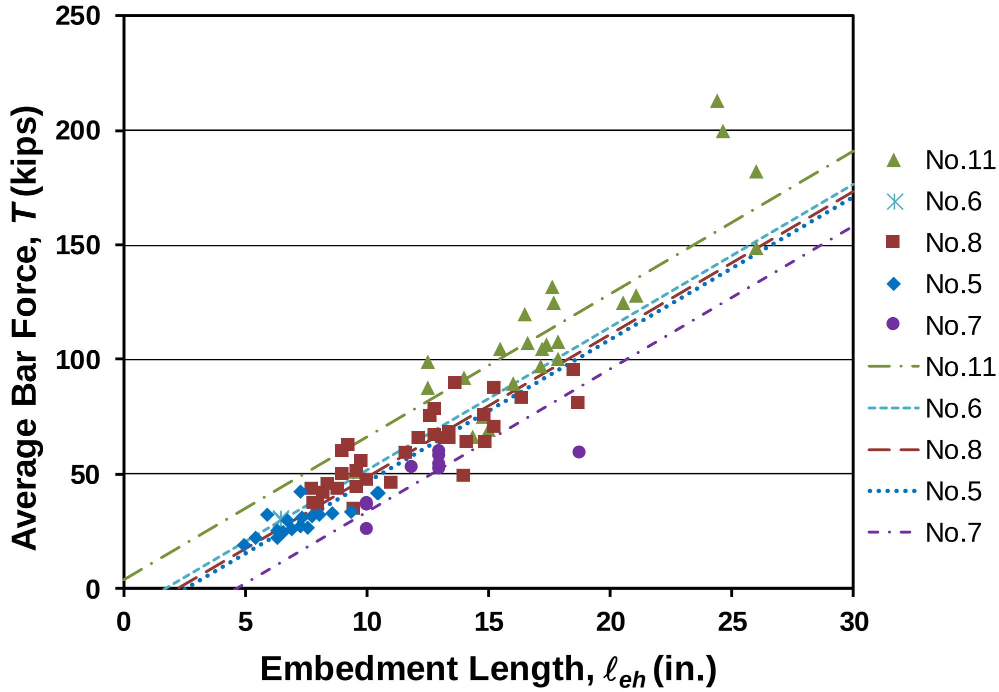


Figure 4.7 Average bar force at failure T versus embedment length ℓ_{eh} for two-hook specimens without confining reinforcement

The effect of the concrete compressive strength is not represented in Figure 4.7. To do so, the average bar force at failure T for each specimen can be normalized with respect to the concrete compressive strength to a power p_1, $T/f_{cm}^{p_1}$. Through several iterations, the power p_1 is varied to obtain the linear relationship that minimized the relative intercept. The relative intercept is the ratio of the difference between the maximum and minimum values of the trend line intercepts to the difference between the maximum and minimum values of the normalized average bar forces, $T/f_{cm}^{p_1}$. Following this approach, the optimal value of the power p_1, is 0.295, closely matching the value of 0.29 obtained by Sperry et al. (2015a, 2015b, 2017b) for a somewhat smaller database. Figure 4.8 shows the normalized average bar force at failure $T/f_{cm}^{0.295}$ plotted versus the embedment length ℓ_{eh}. The slope and average intercept of the trend lines are used to develop Eq. (4.3).

$$\frac{T_c}{f_{cm}^{0.295}} = 416\ell_{eh} - 604 \qquad (4.3)$$

where T_c is the calculated anchorage strength of hooked bars without confining reinforcement within the joint region. Figure 4.9 compares the ratio of the average bar force at failure T to the calculated bar force using Eq. (4.3) T_c with the concrete compressive strength f_{cm}. The horizontal slope of the trend lines in Figure 4.9 indicates that the concrete compressive strength to the 0.295 power properly represents the contribution of the concrete compressive strength to the anchorage strength of hooked bars. The mean ratio of T/T_c is 1.0, with a maximum value of 1.372 and a minimum value 0.689. The standard deviation and the coefficient of variation are 0.159. The trend line intercepts ranged from 0.855 to 1.165

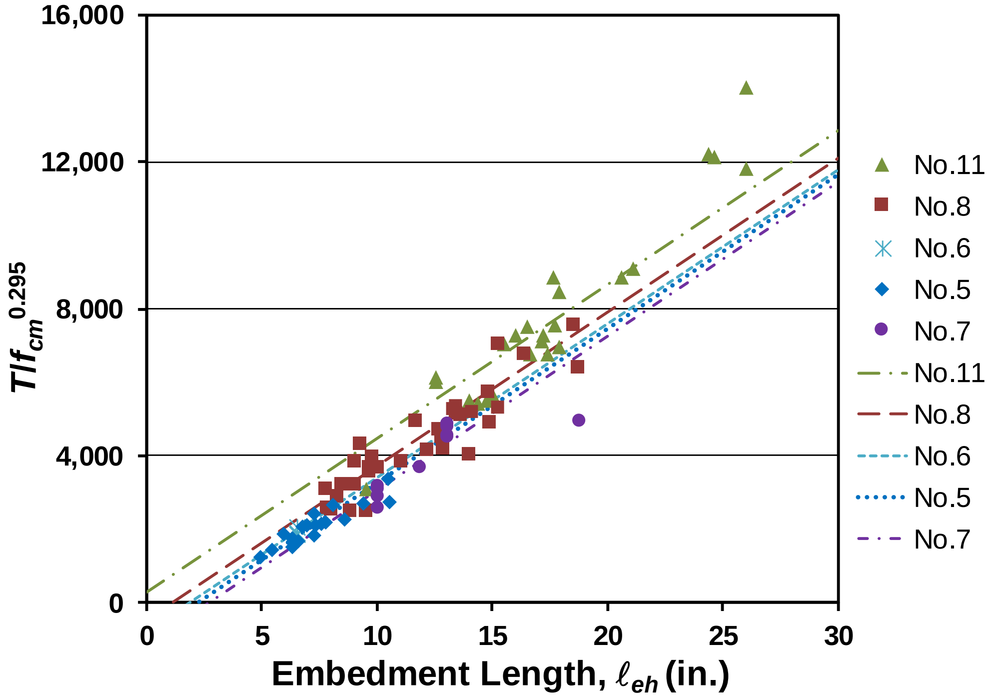


Figure 4.8 Average bar force at failure normalized to $f_{cm}^{0.295}$ versus embedment length ℓ_{eh} for two-hook specimens without confining reinforcement

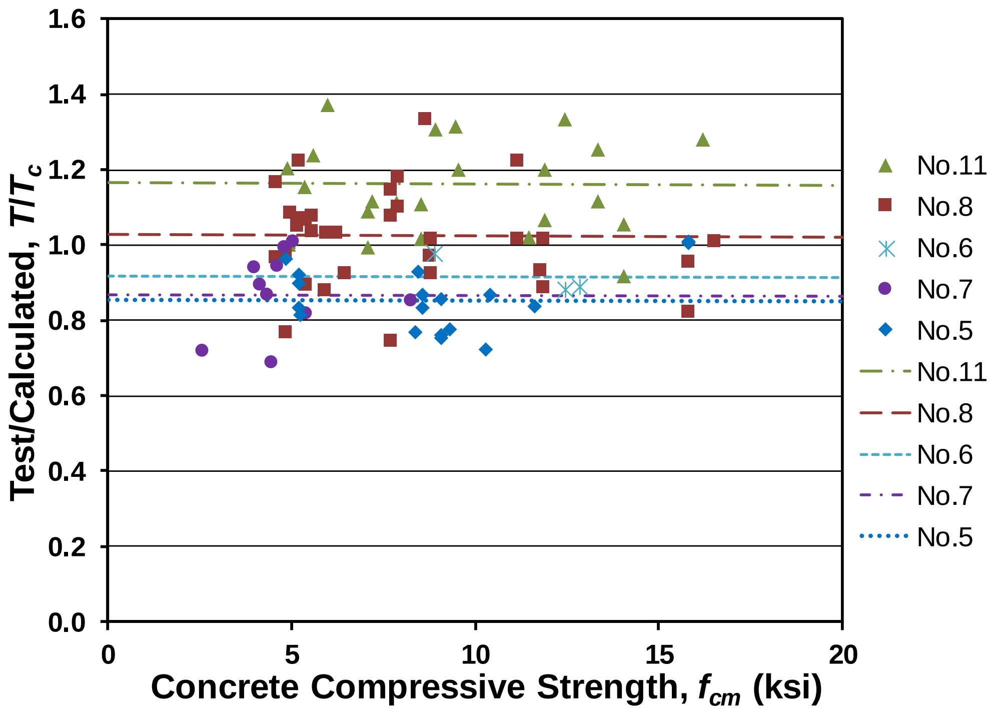


Figure 4.9 Ratio of test-to-calculated bar force at failure T/T_c versus concrete compressive strength f_{cm} for two-hook specimens without confining reinforcement, with T_c calculated using Eq. (4.3)

Figures 4.8 and 4.9 show that large bars develop greater anchorage strength than small bars for a given embedment length, which indicates that bar size has an effect on the anchorage strength. To incorporate the bar size effect, the embedment length was multiplied by the bar size to a power p_2. The power p_2 was varied to minimize the relative intercept following the same approach used to obtain p_1. Based on this, the optimal value of the power p_2 was 0.47. Figure 4.10 shows the normalized average bar force at failure, $T/f_{cm}^{0.295}$, plotted versus the embedment length times bar diameter to 0.47 power, $\ell_{eh}d_b^{0.47}$. The trend lines have less spread compared to trend lines in Figure 4.8, indicating that $d_b^{0.47}$captures the contribution of bar size to the anchorage strength of hooked bars. The slope and average intercept of the trend lines were used to develop the descriptive equation for hooked bars without confining reinforcement within the joint region, Eq. (4.4).

$$\frac{T_c}{f_{cm}^{0.295}} = 431\ell_{eh}d_b^{0.47} - 664 \tag{4.4}$$

Figure 4.11 shows the ratio of the average bar force at failure T to the calculated bar force using Eq. (4.4) plotted versus the concrete compressive strength. The mean ratio of T/T_c is 1.0, with a maximum value of 1.35 and a minimum value of 0.71. The standard deviation and the coefficient of variation are 0.137. The trend line intercepts ranged from 0.91 to 1.12. The nearly horizontal slope of the trend lines indicates that with the addition of bar diameter the concrete compressive strength to the 0.295 power still properly represents the contribution of the concrete compressive strength to the anchorage strength of hooked bars.

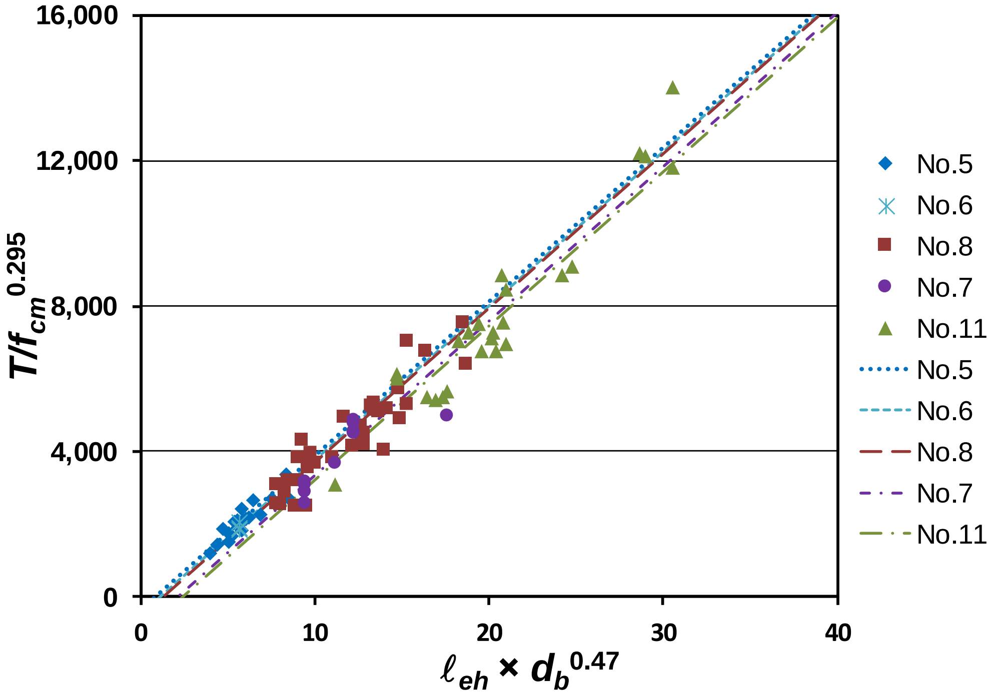


Figure 4.10 Average bar force at failure T normalized to $f_{cm}^{0.295}$ versus embedment length multiplied by bar diameter d_b to 0.47 power for two-hook specimens without confining reinforcement

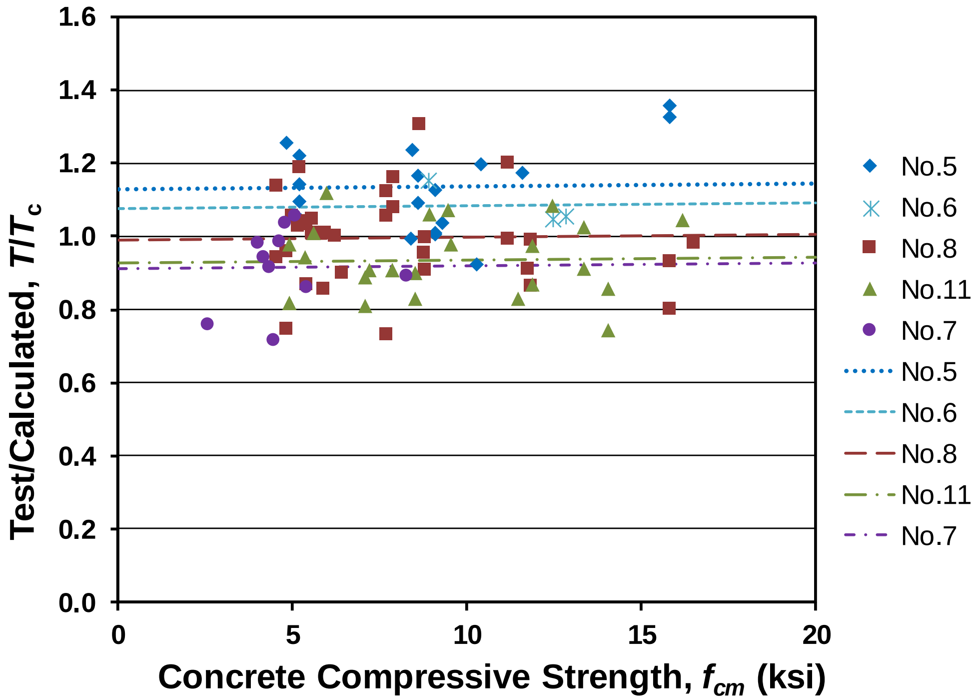


Figure 4.11 Ratio of test-to-calculated bar force at failure T/T_h versus concrete compressive strength f_{cm} for two-hook specimens without confining reinforcement, with T_c calculated using Eq. (4.4)

In Figure 4.10, the trend lines have a negative intercept and the specimens with the deepest embedment length and highest anchorage strength fall above the trend lines; this suggests a nonlinear relationship between anchorage strength and embedment length. To capture this nonlinear behavior, the embedment length was raised to a power p_3 and the data were reanalyzed to minimize the sum of the squared differences $\left(1-T/T_c\right)^2$. Equation (4.5) describes the nonlinear relationship between anchorage strength and embedment length for hooked bars without confining reinforcement. The mean ratio of T/T_c is 1.0, with a maximum value of 1.32 and a minimum value of 0.74. The standard deviation and the coefficient of variation are 0.115. Table 4.2 presents the maximum, minimum, mean, standard deviation, and coefficient of variation for different bar sizes.

$$\frac{T_c}{f_{cm}^{0.295}} = 294\ell_{eh}^{\ 1.0845} d_b^{0.47} \tag{4.5}$$

In Figure 4.12, the measured failure load T is compared with the calculated failure load T_c using Eq. (4.5). The broken line is the equality line for which the calculated failure loads equal the measured failure loads. The solid line is the trend line for the data. As shown in the figure, the trend line and the broken line are very close, which indicts that the descriptive equation [Eq. (4.5)] accurately estimates the anchorage strength of hooked bars without confining reinforcement.

Table 4.2 statistical properties of Eq. (4.5)

	All	No. 5	No. 6	No. 7	No. 8	No. 11
Max.	1.32	1.20	1.05	1.09	1.32	1.18
Min.	0.74	0.88	0.95	0.75	0.74	0.77
Mean	1.00	1.02	0.98	0.93	1.02	0.99
STD	0.115	0.101	0.055	0.117	0.128	0.109
COV	0.115	0.099	0.056	0.126	0.985	0.110

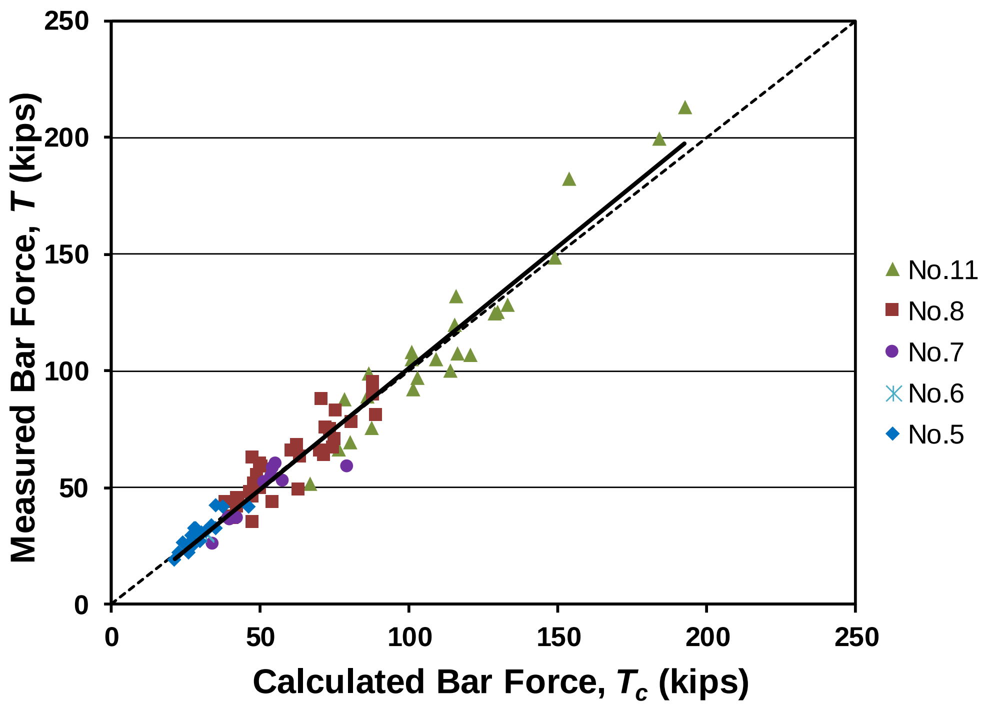


Figure 4.12 Measured bar force at failure T versus calculated bar force T_c for two-hook specimens without confining reinforcement, with T_c calculated using Eq. (4.5)

4.3.2 Hooked Bars with Confining Reinforcement

The contribution of the confining reinforcement within the joint region to the anchorage strength of hooked bars T_s was assumed equal to the difference between the measured bar force at failure T and the calculated bar force T_c based on Eq. (4.5). Sperry at el. (2015b) found that only hoops within $8d_b$ of the top of the hooked bars for No. 3 through No. 8 bars or within $10d_b$ for No. 9 though No. 11 bars (the dimensions of a standard 180° hook) were effective in increasing the anchorage strength of hooked bars. To investigate the impact of the effective confining reinforcement on the anchorage strength of hooked bars, strain gauges were mounted on the confining reinforcement within the joint region (see Section 3.4.6). Specimens with 90° hooked bars generally exhibited the greatest hoop strain at the hoop closest to the bend of the hook, with strains decreasing as the distance from the bend increased. Specimens with 180° hooked bars had the greatest hoop strain on hoops adjacent to the tail extension of the hooked bars. Strains again decreased as the distance from the hook increased. This suggests that there is a limit to the region in which hoops can be placed to provide effective confinement, confirming, at least in part, the previous findings of Sperry et al. (2015b, 2017b).

The amount of the effective confining reinforcement within the joint region is represented by the term A_{th}/n. Based on the strain-gauge results and analysis by Sperry et al. (2015b, 2017b), A_{th} is considered to be the total cross-sectional area of confining reinforcement parallel to the straight portion of the bars within $8d_b$ of the top of the hooked bars for No. 3 through No. 8 bars or within $10d_b$ for No. 9 though No. 11 bars. For hooked bars with confining reinforcement perpendicular to the straight portion of the bar, A_{th} is the total cross-sectional area along a length equal to the development length. n is the number of hooked bars.

The 149 specimens included in this analysis contained two hooked bars (No. 5, 8, and 11) with 90° and 180° bend angles, and with different levels of confining reinforcement parallel to the straight portion of bars (1 No. 3 hoop, 1 No. 4 hoop, 2 No. 3 hoops, 4 No. 3 hoops, 4 No. 4 hoops, 5 No. 4 hoops, and No. 3 hoops spaced at $3d_b$). Specimens with confining reinforcement perpendicular to the straight portion of the bar will be evaluated later in this chapter. The average bar forces at failure ranged from 18,700 to 209,600 lb, corresponding to average bar stresses between 40,990 to 138,810 psi. The specimens had embedment lengths ranging from 3.75 to 23.5 in. and concrete compressive strengths ranging from 4,300 to 16,480 psi. The specimens included in this analysis were tested in this portion of the study and as part of prior research at the University of Kansas (Peckover and Darwin 2013, Searle et al. 2014, Sperry et al. 2015a, 2015b, 2017a, 2017b). Specimens from earlier work (Marques and Jirsa 1975, Hamad et al. 1993, Ramirez and Russell 2008, Lee and Park 2010) were excluded because the number of the specimens was relatively small, 12 in total, and because of the inherent variability in the contribution of confining reinforcement to the anchorage strength of hooked bars as a result of the variations in test setup.

In Figure 4.13, the contribution of confining reinforcement T_s is plotted versus the term A_{th}/n . The values of T_s range from -6,330 to 44,570 lb, which shows a high level of scatter. This scatter is mostly a product of variations in the concrete contribution T_c since the confining contribution T_s is only a small portion of the average bar force at failure T (17% on average). The term A_{th}/n ranges from 0.11 to 0.6; A_{th}/n of 0.33 corresponds to hooked bars with No. 3 hoops spaced at $3d_b$, which corresponds to the provisions in ACI 318-14 that permit use of the 0.8 modification factor; values of A_{th}/n greater than 0.33 correspond to hooked bars with confinement required in special moment frames (ACI 318-14 section 18.8.3). As shown by the trend lines (from dummy variable analysis) in Figure 4.13, the contribution of confining reinforcement T_s increases as the area of effective confining reinforcement per hooked bar A_{th}/n increases. The trend lines for the No. 11, No. 8, and No. 5 hooked bars have intercepts of 2,170, 1,910, and -4,540, respectively. The trend line for the No. 5 hooked bars falls below the trend lines of No. 8 and No. 11 hooked bars, which indicates that there may be a bar size effect on the contribution of the confining reinforcement T_s, with larger bars obtaining a greater increase in anchorage strength than smaller bars for a given amount of confining reinforcement.

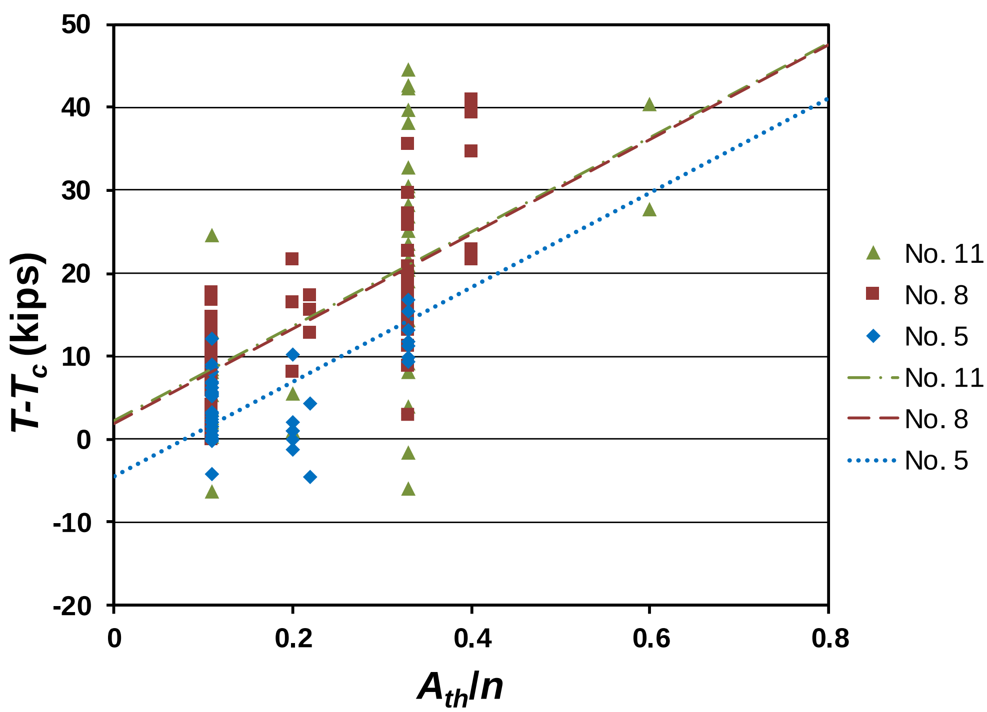


Figure 4.13 Contribution of confining reinforcement to anchorage strength T-T_c versus area of confining reinforcement per hooked bar A_{th}/n, with T_c based on Eq. (4.5)

As for hooked bars without confining reinforcement, the effect of the bar size can be incorporated by multiplying the term A_{th}/n by the bar size to a power p_4. The power p_4 was varied to minimize the relative intercept, the same approach used to obtain p_1. The optimal value of p_4 was 0.72. Figure 4.14 shows the contribution of confining reinforcement T_s plotted versus the term $(A_{th}/n)d_b^{0.72}$. The trend lines for No. 8, No. 11, and No. 5 bars have intercepts of 2,430, -1,480, and -1,550, respectively. These trend lines have less spread compared to the trend lines in Figure 4.13 and are no longer in order of bar size. Using the slope and average intercepts of the trend lines, an equation describing the contribution of confining reinforcement T_s can be expressed as

$$T_s = 54724\frac{A_{th}}{n}d_b^{0.72} - 203 \tag{4.6}$$

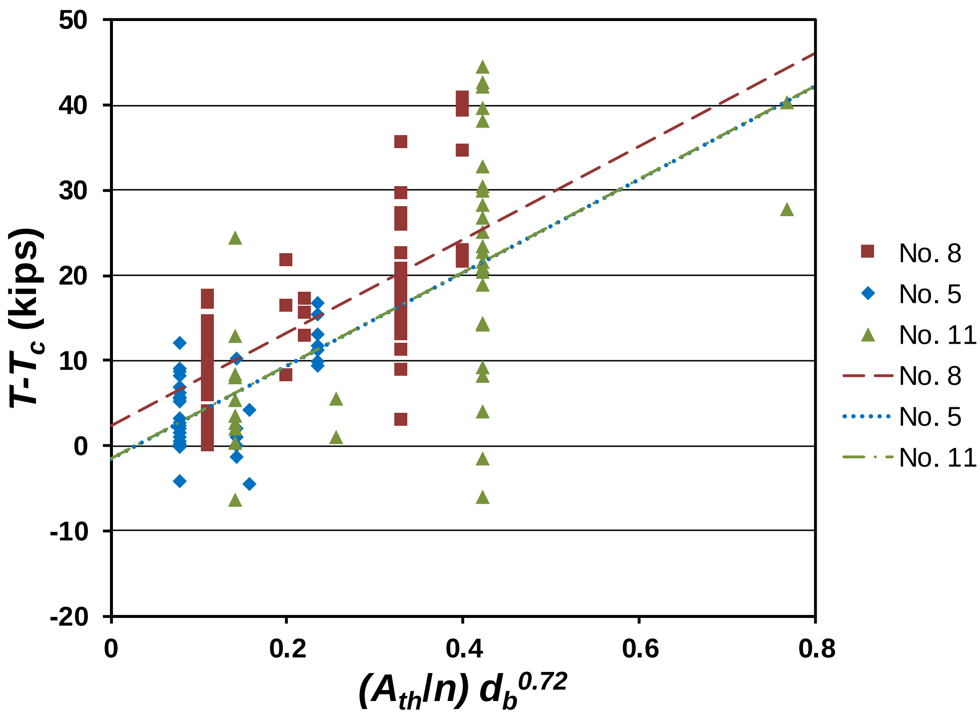


Figure 4.14 Confining reinforcement contribution T-T_c versus amount of confining reinforcement and bar size, with T_c calculated using Eq. (4.5)

In Figure 4.15, the ratio of the average bar force at failure T to the calculated bar force T_h is plotted versus the concrete compressive strength f_{cm} for two-hook specimens with confining reinforcement within the joint region. The calculated bar force T_h is found by adding the contribution of concrete T_c from Eq. (4.5) to the contribution of the confining reinforcement T_s

from Eq. (4.6) ($T_h = T_c + T_s$). The mean ratio of T/T_h is 1.0, with a maximum value of 1.27 and a minimum value 0.67. The standard deviation and the coefficient of variation are 0.112. The trend line intercepts ranged from 0.96 to 1.04. The nearly horizontal slope of the trend lines indicates that with the addition of confining reinforcement contribution the concrete compressive strength to the 0.295 power still properly represents the contribution of the concrete compressive strength to the anchorage strength of hooked bars.

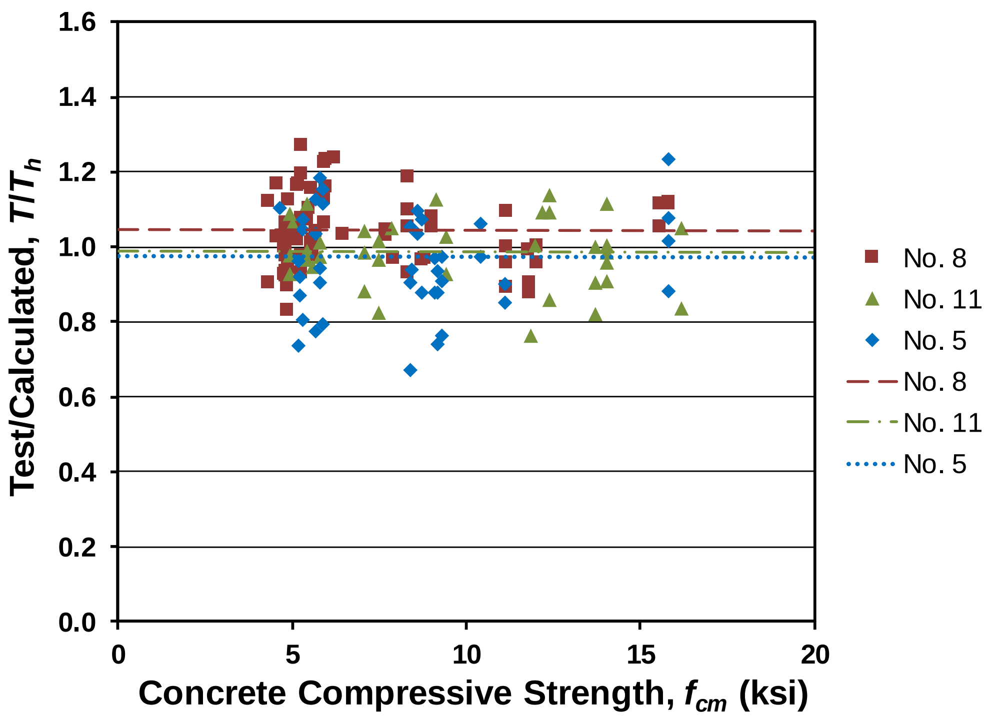


Figure 4.15 Ratio of test-to-calculated bar force at failure T/T_h versus concrete compressive strength for two-hook specimens with confining reinforcement, with T_h calculated based on Eq. (4.5) and (4.6)

The negative intercept of Eq. (4.6) indicates that the confining reinforcement contribution T_s exhibits a nonlinear relationship with the term $(A_{th}/n)d_b^{0.72}$. To capture this behavior, the term $(A_{th}/n)d_b^{0.72}$ was raised to a power p_5 and the data were analyzed to minimize the sum of the squared differences $[(T{-}T_c) - T_s]^2$. Equation (4.7) describes the nonlinear relationship between the confining reinforcement contribution T_s and the term $(A_{th}/n)d_b^{0.72}$.

$$T_s = 55050\left(\frac{A_{th}}{n}\right)^{1.0175} d_b^{0.73} \tag{4.7}$$

A descriptive equation for widely-spaced ($c_{ch} \geq 6d_b$) hooked bars in beam-column joints [Eq. (4.8)] can be obtained by adding the concrete contribution T_c from Eq. (4.5) to the confining reinforcement contribution T_s from Eq. (4.7). Table 4.3 presents the maximum, minimum, mean, standard deviation, and coefficient of variation for different bar sizes. The mean ratio of T/T_h is 1.0 with a maximum value of 1.27 and a minimum value of 0.67. The standard deviation and the coefficient of variation are 0.112. The mean values for No. 5, No. 8 and No. 11 bars are 0.95, 1.04, and 0.98, respectively.

$$T_h = 294 f_{cm}^{0.295} \ell_{eh}^{1.0845} d_b^{0.47} + 55050\left(\frac{A_{th}}{n}\right)^{1.0175} d_b^{0.73} \tag{4.8}$$

Table 4.3 Statistical properties of Eq. (4.8)

	All	**No. 5**	**No. 8**	**No. 11**
Max.	1.27	1.23	1.27	1.14
Min.	0.67	0.67	0.83	0.76
Mean	1.00	0.95	1.04	0.98
STD	0.112	0.132	0.095	0.092
COV	0.112	0.139	0.091	0.094

In Figure 4.16, the measured failure load T is plotted versus calculated failure load T_h based on Eq. (4.8). The broken line is the equality line for which the calculated failure loads equal the measured failure loads. The solid line is the trend line for the data. As shown in the figure, the trend line and the broken line are almost identical, which indicts that the descriptive equation [Eq. (4.8)] accurately estimates the anchorage strength of hooked bars with confining reinforcement within the joint region.

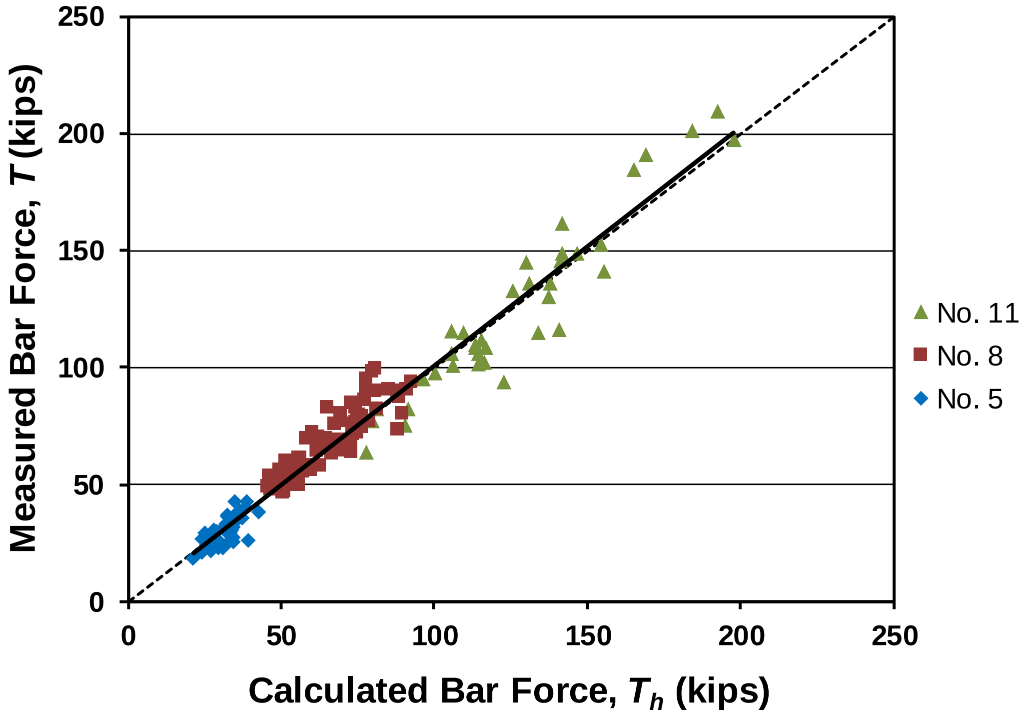


Figure 4.16 Measured bar force at failure versus calculated bar force for two-hook specimens with confining reinforcement, with T_h calculated using Eq. (4.8)

4.4 FACTORS CONTROLLING ANCHORAGE STRENGTH

Equations (4.5) and (4.8) were developed based on test results of specimens containing two widely-spaced hooked bars (center-to-center spacing of $6d_b$ or greater), placed inside the column core, and embedded to the far side of the column with a nominal tail cover of 2 in. In practice, however, it is common to have more than two hooked bars anchored with horizontal center-to-center spacing as close as $2d_b$ and vertical clear spacing as close as 1 in. Hooked bars can be embedded at a location with respect to the depth of the member other than to the far side, outside the column core, and in deep beam-column joints – cases not represented by the test specimens used to develop Eq. (4.5) and (4.8). This section discusses the effect of spacing between hooked bars, using staggered hooks, the ratio of beam effective depth to embedment length, hooked bar location (inside or outside column core and with respect to member depth), orientation of confining reinforcement, and confining reinforcement above the hooked bars.

4.4.1 Spacing between Hooked Bars

The effect of spacing between hooked bars was investigated using specimens containing closely-spaced No. 5, 8, and 11 hooked bars (center-to-center spacing not greater than $6d_b$) with 90° and 180° bend angles. The hooked bars had a nominal side cover of 2.5 in. and a nominal tail cover of 2 in. The width of the specimens was varied to achieve the desired center-to-center spacing between the hooked bars. Two types of comparisons are used. First, the average bar force at failure T of specimens cast in two groups is compared with others in the same group (cast from the same batch of concrete) with different center-to-center spacing between the hooked bars. Second, the values of T for a larger number of specimens are compared with the bar force at failure calculated using the descriptive equation for widely-spaced hooked bars, Eq. (4.8). The test parameters for the specimens used in this analysis are presented in Appendix B. Specimens used in each analysis are identified in Appendix E.

For the first of two groups cast from the same batch of concrete, Figures 4.17 and 4.18 show the average bar force at failure T for eight specimens; four specimens contained three No. 5 hooked bars and four contained four No. 5 hooked bars. The hooked bars had a 90° bend angle. The nominal embedment length was 6 in., and concrete compressive strengths ranged from 6,700 to 6,950 psi. For each combination of four specimens, two had a nominal center-to-center spacing between hooked bars c_{ch} of $4d_b$, and two had c_{ch} of $6d_b$. Two levels of confining reinforcement were used: no confinement and No. 3 hoops spaced at $3d_b$ (five No. 3 hoops). Tables 4.4 and 4.5 present the test parameters for the specimens. As shown in Figures 4.17 and 4.18, the average bar force increased when hoops were added. The average bar force also increased with increasing center-to-center spacing between the hooked bars with a much lower increase when confining reinforcement was used.

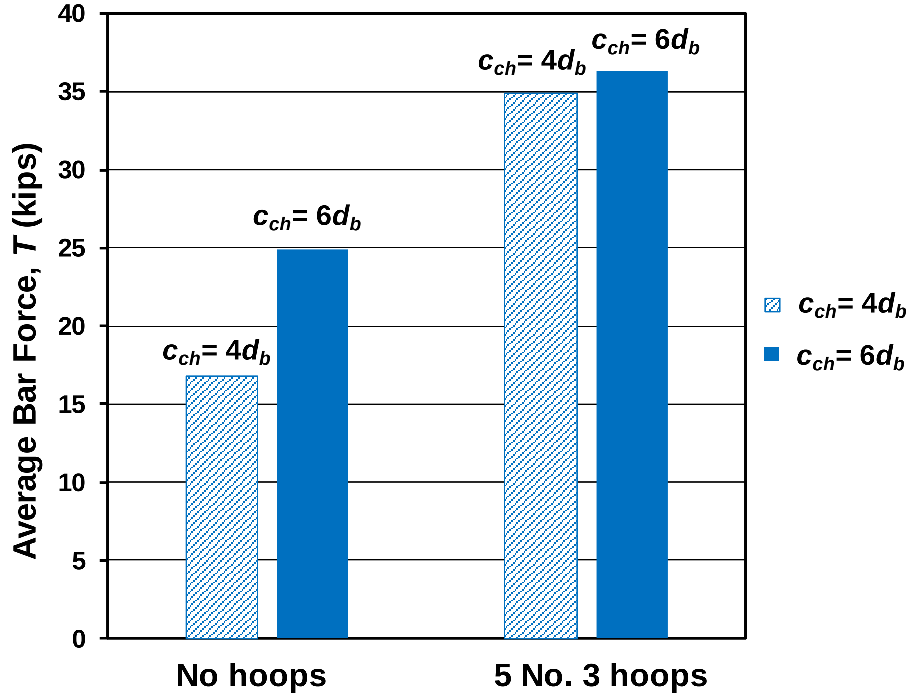


Figure 4.17 Average bar forces at failure T for the specimens containing three No. 5 hooked bars; c_{ch} is center-to-center spacing of the hooked bars

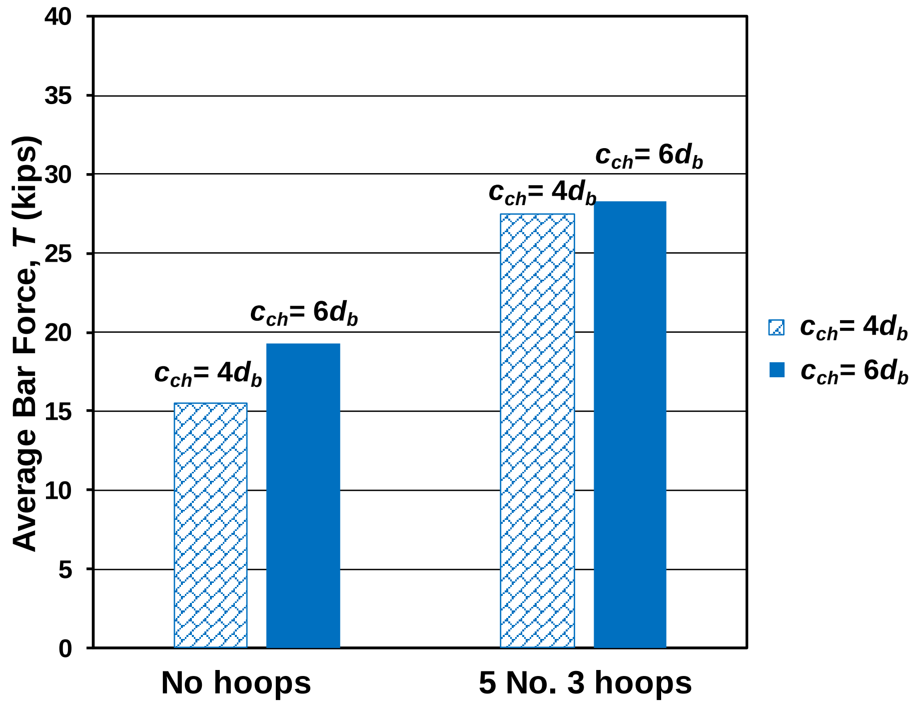


Figure 4.18 Average bar forces at failure T for specimens containing four No. 5 hooked bars; c_{ch} is center-to-center spacing of the hooked bars

Table 4.4 Test parameters for specimens containing three No. 5 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	Hook Bar Type	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.[2]	T lb	Failure Type[b]
(3@4) 5-8-90-0-i-2.5-2-6	A	90°	6.0	6950	A1035 Grade 120	10.6	2.4	3	-	16805	FP
	B		5.6								FP
	C		6.0				2.5				FP
(3@6) 5-8-90-0-i-2.5-2-6	A	90°	6.4	6950	A1035 Grade 120	13.1	3.6	3	-	24886	FP
	B		5.9								FP
	C		5.8				3.8				FP
(3@4) 5-8-90-5#3-i-2.5-2-6[d]	A	90°	6.0	6700	A1035 Grade 120	10.6	2.7	3	0.11	34889	FP
	B		6.3								FP
	C		6.0				2.5				FP
(3@6) 5-8-90-5#3-i-2.5-2-6[d]	A	90°	6.0	6700	A1035 Grade 120	13.1	4.0	3	0.11	36449	FP
	B		6.0								FP
	C		6.0				3.8				FP

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type (described in Section 3.3)
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement

Table 4.5 Test parameters for specimens containing four No. 5 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	Hook Bar Type	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.[2]	T lb	Failure Type[b]
(4@4) 5-8-90-0-i-2.5-2-6	A	90°	6.3	6950	A1035 Grade 120	13.1	2.5	4	-	15479	FP/SS
	B		5.8				2.3				FP
	C		5.8								FP
	D		6.0				2.6				FP/SS
(4@6) 5-8-90-0-i-2.5-2-6	A	90°	6.0	6690	A1035 Grade 120	16.9	3.8	4	-	19303	FP
	B		6.0				3.8				FP
	C		5.8								FP
	D		6.0				3.8				FP
(4@4) 5-8-90-5#3-i-2.5-2-6[d]	A	90°	5.8	6700	A1035 Grade 120	16.9	2.5	4	0.11	27493	FP
	B		5.5				2.5				FP
	C		6.3								FP
	D		6.5				2.5				FP
(4@6) 5-8-90-5#3-i-2.5-2-6[d]	A	90°	6.0	6690	A1035 Grade 120	16.9	4.0	4	0.11	28321	FP
	B		6.0				4.0				FP
	C		6.0								FP
	D		6.0				3.8				FP

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.3
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement

For the second group cast from the same batch of concrete, Figure 4.19 shows the average bar force at failure T for six specimens that contained three No. 8 hooked bars with a 90° bend angle. The nominal embedment length was 10 in., and the concrete compressive strength ranged from 4,490 to 4,850 psi. Of the six specimens, three had c_{ch} equal to $3d_b$, and three had c_{ch} equal to $5d_b$. Three levels of confining reinforcement were used: no confinement, 2 No. 3 hoops, and No. 3 hoops spaced at $3d_b$ (five No. 3 hoops). Table 4.6 presents the test parameters for these six specimens. As for the first group of specimens, Figure 4.19 shows that the average bar force at failure increased as the amount of confinement and spacing between hooked bars increased. The specimens without confining reinforcement and with 2 No. 3 hoops as confining reinforcement exhibited a similar increase in anchorage strength with increasing spacing between hooked bars. Unlike the No. 5 bars specimens shown in Figures 4.17 and 4.18, however, the specimens with five No. 3 hoops exhibited a higher, not lower, increase in anchorage strength when confining reinforcement was used; in this case, the specimen with the $5d_b$ spacing had a different distribution of column longitudinal reinforcement (with the reinforcement distributed along the front face of the column for specimen with $5d_b$ spacing compared to reinforcement placed only at the corners for other specimens in this group), which might be the reason of the high increase in anchorage strength.

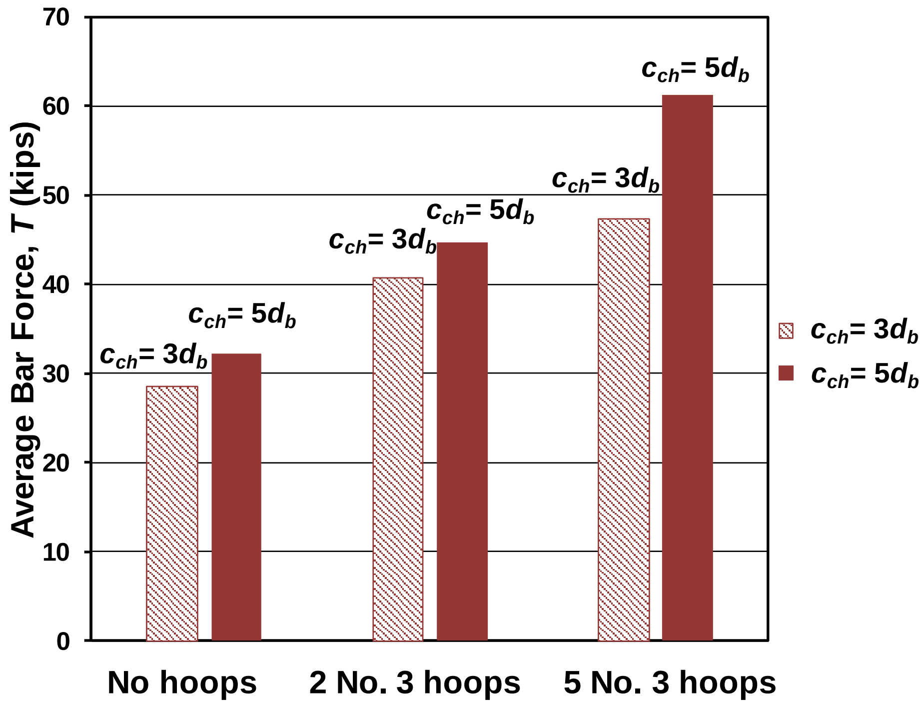


Figure 4.19 Average bar forces at failure T for specimens containing three No. 8 hooked bars; c_{ch} is center-to-center spacing of the hooked bars

Table 4.6 Test parameters for specimens containing three No. 8 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	Hook Bar Type	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	T lb	Failure Type[b]
(3@3) 8-5-90-0-i-2.5-2-10[d]	A B C	90°	10.0 10.3 10.0	4490	A615 Grade 80	12.0	3.4 3.3	3	-	28480	FP FP FP
(3@5) 8-5-90-0-i-2.5-2-10[d]	A B C	90°	10.3 10.1 10.0	4490	A615 Grade 80	16.0	5.0 5.3	3	-	32300	FP FP FP
(3@3) 8-5-90-2#3-i-2.5-2-10[d]	A B C	90°	9.9 10.1 10.0	4760	A615 Grade 80	12.0	3.0 3.0	3	0.11	40721	FP FP FP
(3@5) 8-5-90-2#3-i-2.5-2-10[d]	A B C	90°	10.5 10.6 10.4	4760	A615 Grade 80	16.0	5.5 4.9	3	0.11	44668	FP FP FP
(3@3) 8-5-90-5#3-i-2.5-2-10[d]	A B C	90°	10.0 9.8 9.9	4810	A615 Grade 80	12.0	3.1 3.1	3	0.11	47276	FP FP FP
(3@5) 8-5-90-5#3-i-2.5-2-10[d]	A B C	90°	10.0 10.0 9.8	4850	A615 Grade 80	16.0	5.0 5.0	3	0.11	61305	FP FP FP

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.3
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement

The analysis addressed in Figures 4.17 through 4.19 suggests that the reduction in anchorage strength of hooked bars is a function of the spacing between the bars and the amount of confining reinforcement. Figure 4.20 compares the test-to-calculated ratios for average bar force at failure T/T_h for 108 specimens without confining reinforcement, six of which appear in Figures 4.17 through 4.19, with the ratio of center-to-center spacing between the hooked bars to the bar diameter c_{ch}/d_b. The hooked bars had bend angles of 90° or 180°, nominal side covers of 2½ or 3½ in., were arranged in one layer, and embedded to the far side of the column with a nominal tail cover of 2 in. Seventy-seven specimens had $c_{ch}/d_b > 6$, all with two hooked bars. Thirty-one specimens had $c_{ch} \leq 6d_b$, 11 with two hooked bars and 20 with three or four hooked bars. The values of T_h are based on Eq. (4.5), the descriptive equation for widely-spaced hooked bars without confining reinforcement. Specimens included in this analysis are from this and earlier studies (Marques and Jirsa 1975, Hamad et al. 1993, Ramirez and Russell 2008, Lee and Park 2010).

The specimens with closely-spaced hooked bars had embedment lengths ranging from 5.2 to 23.5 in. and concrete compressive strengths ranging from 2,570 to 12,460 psi. The average bar forces at failure ranged from 14,500 to 126,970 lb, corresponding to a range in stress of 30,900 to 100,000 psi. As shown in Figure 4.20, the anchorage strength of the closely-spaced hooked bars decreases with decreasing c_{ch}/d_b; specimens with c_{ch}/d_b of 3 had T/T_h as low as 0.66. The trend line indicates no reduction in anchorage strength of the hooked bars with a center-to-center spacing greater than approximately $6d_b$, although the five specimens with c_{ch}/d_b between 6 and 9 were below 1.0.

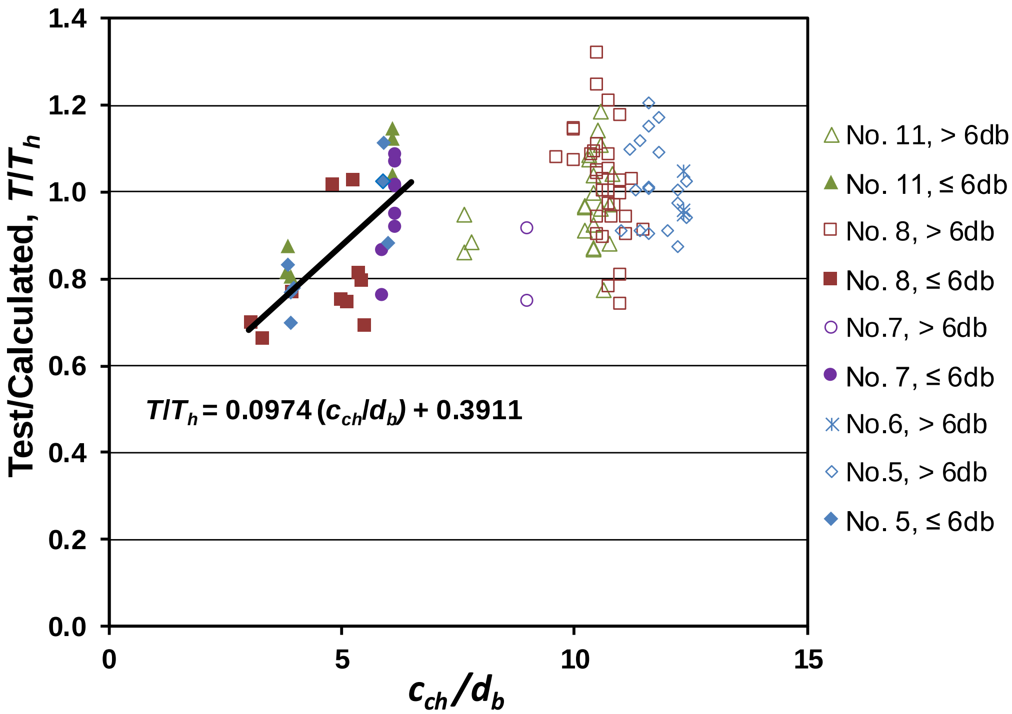


Figure 4.20 Ratio of test-to-calculated bar force at failure T/T_h for specimens without confining reinforcement versus c_{ch}/d_b, with T_h calculated using Eq. (4.5); c_{ch} is center-to-center spacing of the hooked bars

The trend line of the specimens with closely-spaced hooked bars can be used to modify the descriptive equation [Eq. (4.5)] to account for the effect of spacing between hooked bars, giving

$$T_c = \left(294 f_{cm}^{0.295} \ell_{eh}^{1.0845} d_b^{0.47}\right)\left(0.0974 \frac{c_{ch}}{d_b} + 0.3911\right) \tag{4.9}$$

in which the spacing term $\left(0.0974 \frac{c_{ch}}{d_b} + 0.3911\right) \le 1.0$

Figure 4.21 compares the test-to-calculated ratios of average bar force at failure T/T_h with c_{ch}/d_b for the specimens without confining reinforcement; the average bar forces at failure T_h are based on Eq. (4.9). The mean value of T/T_h is 1.0 with a maximum of 1.32 and a minimum of 0.74. The standard deviation and the coefficient of variation are 0.115.

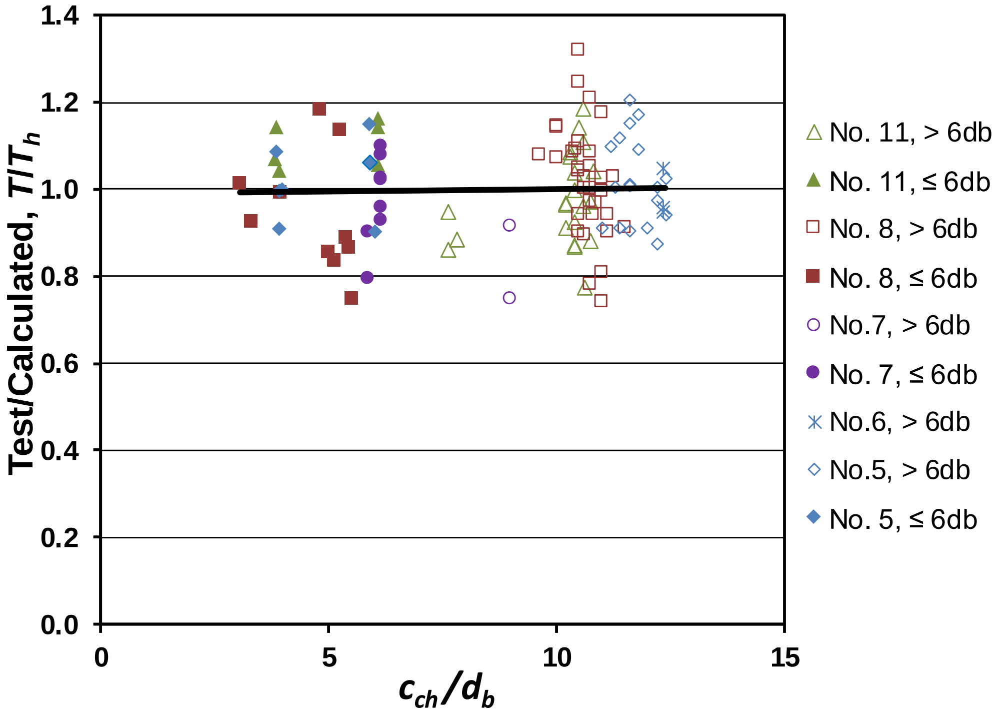


Figure 4.21 Ratio of test-to-calculated bar force at failure T/T_h for specimens without confining reinforcement versus c_{ch}/d_b, with T_h calculated using Eq. (4.9); c_{ch} is center-to-center spacing of the hooked bars

Figure 4.22 compares the test-to-calculated ratios of average bar force at failure T/T_h for 76 specimens with No. 3 hoops spaced at $3d_b$ as confining reinforcement, six of which appear in Figures 4.17 through 4.19, with the ratio of center-to-center spacing between hooked bars to bar diameter c_{ch}/d_b. Like the specimens without confining reinforcement, the hooked bars had bend angles of 90° or 180°, nominal side covers of 2½ or 3½ in., were arranged in one layer, and embedded to the far side of the column with a nominal tail cover of 2 in. Fifty-three specimens had $c_{ch}/d_b > 6$, all with two hooked bars. Twenty-three had $c_{ch} \leq 6d_b$, all with three or four hooked bars. The values of T_h are based on Eq. (4.8), the descriptive equation for widely-spaced hooked bars with confining reinforcement.

The specimens with closely-spaced hooked bars had embedment lengths ranging from 5.5 to 20.0 in. and concrete compressive strengths ranging from 4,660 to 12,190 psi. The average bar force at failure ranged from 25,000 to 119,040 lb, corresponding to stresses between 39,700 and 117,100 psi. The data in Figure 4.22 demonstrate that as for hooked bars without confining reinforcement, anchorage strength decreases with decreasing c_{ch}/d_b. The trend line suggests no reduction in anchorage strength for hooked bars with a center-to-center spacing of greater than 6.65d_b. At a given value of c_{ch}/d_b, closely-spaced hooked bars with five No. 3 hoops (Figure 4.22) exhibited less reduction in anchorage strength than closely-spaced hooked bars without confining reinforcement (Figure 4.20).

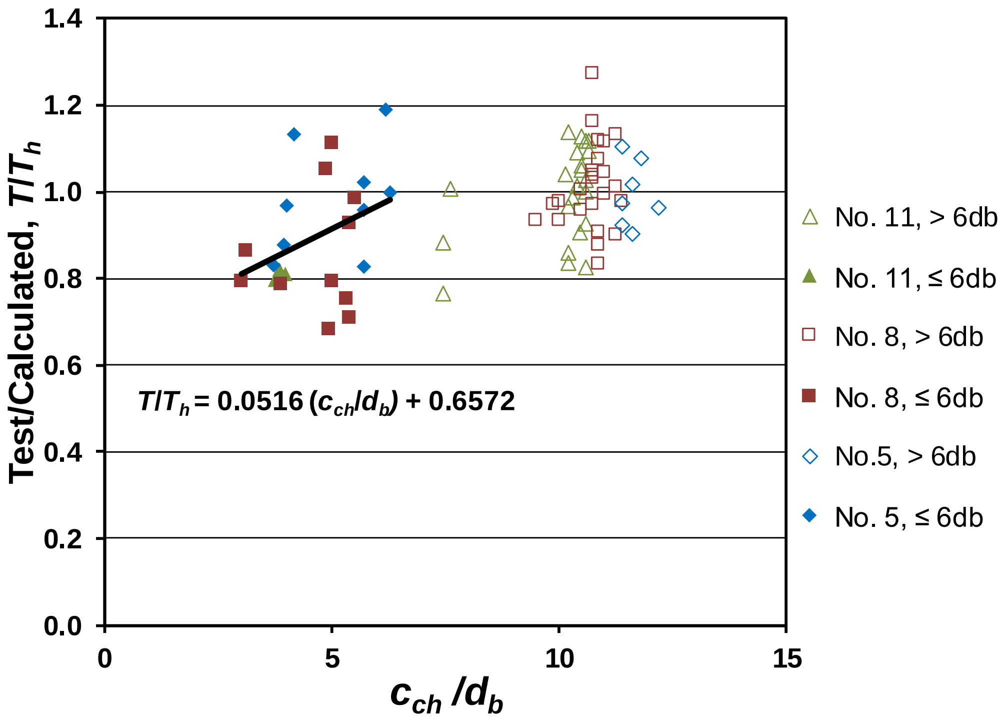


Figure 4.22 Ratio of test-to-calculated bar force at failure T/T_h for specimens with No. 3 hoops spaced at 3d_b as confining reinforcement versus c_{ch}/d_b, with T_h calculated using Eq. (4.8); c_{ch} is center-to-center spacing of the hooked bars

As for the specimens without confining reinforcement, the trend line for the specimens with closely-spaced hooked bars and five No. 3 hoops can be used to modify the descriptive equation [Eq. (4.8)] to account for the effect of spacing between hooked bars, giving

$$T_h = \left(294 f_{cm}^{0.295} \ell_{eh}^{1.0845} d_b^{0.47} + 55050 \left(\frac{A_{th}}{n} \right)^{1.0175} d_b^{0.73} \right) \left(0.0516 \frac{c_{ch}}{d_b} + 0.6572 \right) \tag{4.10}$$

in which the spacing term $\left(0.0516 \frac{c_{ch}}{d_b} + 0.6572 \right) \leq 1.0$

Figure 4.23 compares the test-to-calculated ratios of average bar force at failure T/T_h with c_{ch}/d_b for the specimens with No. 3 hoops spaced at 3d_b as confining reinforcement; the average bar forces at failure T_h are based Eq. (4.10). The mean value of T/T_h is 1.0, with a maximum of 1.29 and a minimum of 0.75. The standard deviation and the coefficient of variation equal 0.113.

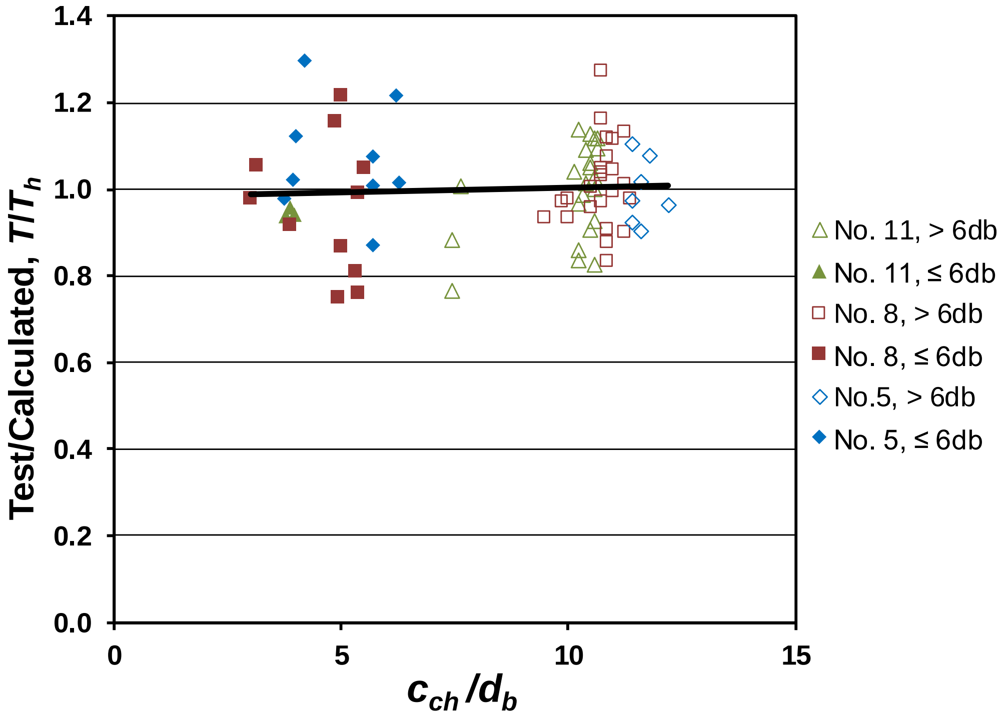


Figure 4.23 Ratio of test-to-calculated bar force at failure T/T_h for specimens with No. 3 hoops spaced at $3d_b$ as confining reinforcement versus c_{ch}/d_b, with T_h calculated using Eq. (4.10); c_{ch} is center-to-center spacing of the hooked bars

In Eq. (4.8), the spacing term was developed using specimens containing closely-spaced hooked bars without confining reinforcement within the joint region. In Eq. (4.10), the spacing term was developed using specimens containing closely-spaced hooked bars with No. 3 hoops spaced at $3d_b$ corresponding to confining reinforcement per hooked bar A_{th}/n ranging from 0.165 to 0.220. In cases where closely-spaced hooked bars are confined by an intermediate amount of confining reinforcement within the joint region, such as two No. 3 hoops, the calculated anchorage strength T_h can be modified for spacing between hooked bars by interpolating between values of the spacing terms in Eq. (4. 9) and (4.10) using the following:

$$\beta_{w/i} = \beta_{w/o} + f_1\left(\beta_w - \beta_{w/o}\right) \tag{4.11}$$

in which $f_1 = \left(\dfrac{A_{th}}{n} \Big/ \left(\dfrac{A_{th}}{n}\right)_{\max}\right) \le 1.0$

where $\beta_{w/i}$ is the values of the spacing term for hooked bars with an intermediate amount of confining reinforcement, $\beta_{w/o}$ is the value of the spacing term for hooked bars without confining reinforcement in Eq. (4.9), β_w is the value of the spacing term for hooked bars with No. 3 hoops in Eq. (4.10). In f_1, the value of the effective confining reinforcement per hooked bar $(A_{th}/n)_{max}$ is set to 0.22 (the maximum value of A_{th}/n used in the derivation of the spacing term for hooked bars with No. 3 hoops as confining reinforcement). Test parameters and comparisons with the descriptive equation for the small number of the specimens containing closely spaced hooked bars and an intermediate amount of confining reinforcement (two No. 3 hoops) are presented in Table 4.7. Of the specimens, two contained four No. 5 hooked bars with a 90° bend angle, seven contained three No. 8 hooked bars with 90° and 180° bend angles, and two contained three No. 11 hooked bars with a 90° bend angle. The specimens had a center-to-center spacing between the hooked bars ranging from 3.0 to 5.4d_b. The ratios of test-to-calculated bar force T/T_h with T_h based on Eq. (4.10) with the spacing term calculated using Eq. (4.11) range from 0.83 to 1.20 with an average of 1.02.

Table 4.7 **Test parameters for specimens with closely-spaced hooked bars with intermediate amount of confining reinforcement and comparisons with the descriptive equation**

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	T lb	T/T_h[b]	T/T_h[c]
(4@4) 5-5-90-2#3-i-2.5-2-6	A B C D	90°	6.3 6.1 6.3 6.4	6430	13	2.5 2.5 2.3	4	0.11	21405	0.86	1.09
(4@4) 5-5-90-2#3-i-2.5-2-8	A B C D	90°	8.4 7.8 8.0 7.8	6430	13	2.5 2.5 2.4	4	0.11	26017	0.82	1.03
(3@5.5) 8-5-90-2#3-i-2.5-2-14	A B C	90°	14.6 13.9 14.8	6461	17	5.4 5.5	3	0.11	57261	0.77	0.83
(3@5.5) 8-5-90-2#3-i-2.5-2-8.5	A B C	90°	9.8 8.8 8.9	6461	17	5.3 5.3	3	0.11	40885	0.87	0.96
(3@5.5) 8-5-90-2#3-i-2.5-2-14	A B C	90°	14.7 15.2 14.8	5450	17	5.2 5.3	3	0.11	65336	0.89	0.98
(3@5.5) 8-5-90-2#3-i-2.5-2-8.5	A B C	90°	7.3 8.9 8.4	5450	17	5.5 5.3	3	0.11	32368	0.80	0.87
(3@3) 8-5-90-2#3-i-2.5-2-10	A B C	90°	9.9 10.1 10.0	4760	12	3.0 3.0	3	0.11	40721	0.86	1.19
(3@5) 8-5-90-2#3-i-2.5-2-10	A B C	90°	10.5 10.6 10.4	4760	16	5.5 4.9	3	0.11	44668	0.90	0.99
(3@5) 8-5-180-2#3-i-2.5-2-10	A B C	180°	9.6 9.8 9.8	5400	16	5.2 5.2	3	0.11	51501	1.08	1.20
(3@3.75) 11-8-90-2#3-i-2.5-2-23	A B C	90°	22.0 22.0 21.9	7070	17	5.3 5.5	3	0.11	116589	0.83	1.05
(3@3.75) 11-12-90-2#3-i-2.5-2-21	A B C	90°	21.0 21.0 20.9	11850	17	5.5 5.5	3	0.11	127812	0.83	1.04

[a]Notation described in Section 2.1 and Appendix A
[b] Calculated anchorage strength is based on Eq. (4.8)
[c] Calculated anchorage strength is based on Eq. (4.10) with spacing term calculated using Eq. (4.11).

4.4.2 Hooked Bars Arrangement (Staggered Hooks)

The effect on anchorage strength of arranging hooked bars in more than one layer was investigated using two groups of specimens containing No. 5 and No. 11 hooked bars with a 90° bend angle. The specimens had a nominal side cover of 2.5 in. and a nominal tail cover of 2 in. The column width was kept constant (13 in. for specimens with No. 5 hooked bars, and 21.5 in. for specimens with No. 11 hooked bars). The results for the specimens with No. 5 hooked bars will be discussed first.

Twelve specimens with No. 5 hooked bars consisted of two specimens containing two hooked bars, two specimens containing three hooked bars, and eight specimens containing staggered hooked bars. The specimens were cast from the same batch of concrete. Of the eight staggered-hook specimens (Figure 4.24), four contained four hooked bars and four contained six hooked bars. The nominal embedment length for the upper layer of hooked bars was 8 in.; the tail of hooked bars in the lower layer were located with 1-in. clear spacing from those in the upper layer, resulting in a nominal embedment length of 6.3 in. The nominal horizontal center-to-center spacing between bars c_{ch} was 11.8d_b (7.4 in.) for specimens with two hooked bars or two pairs of staggered hooked bars and 5.9d_b (3.7 in.) for specimens with three hooked bars or three pairs of staggered hooked bars. The nominal vertical center-to-center spacing between staggered hooked bars c_{cv} was 2.6d_b (1.6 in.). The staggered hooked bars are closely spaced in the vertical direction only. Concrete compressive strengths ranged from 4,660 to 4,830 psi.

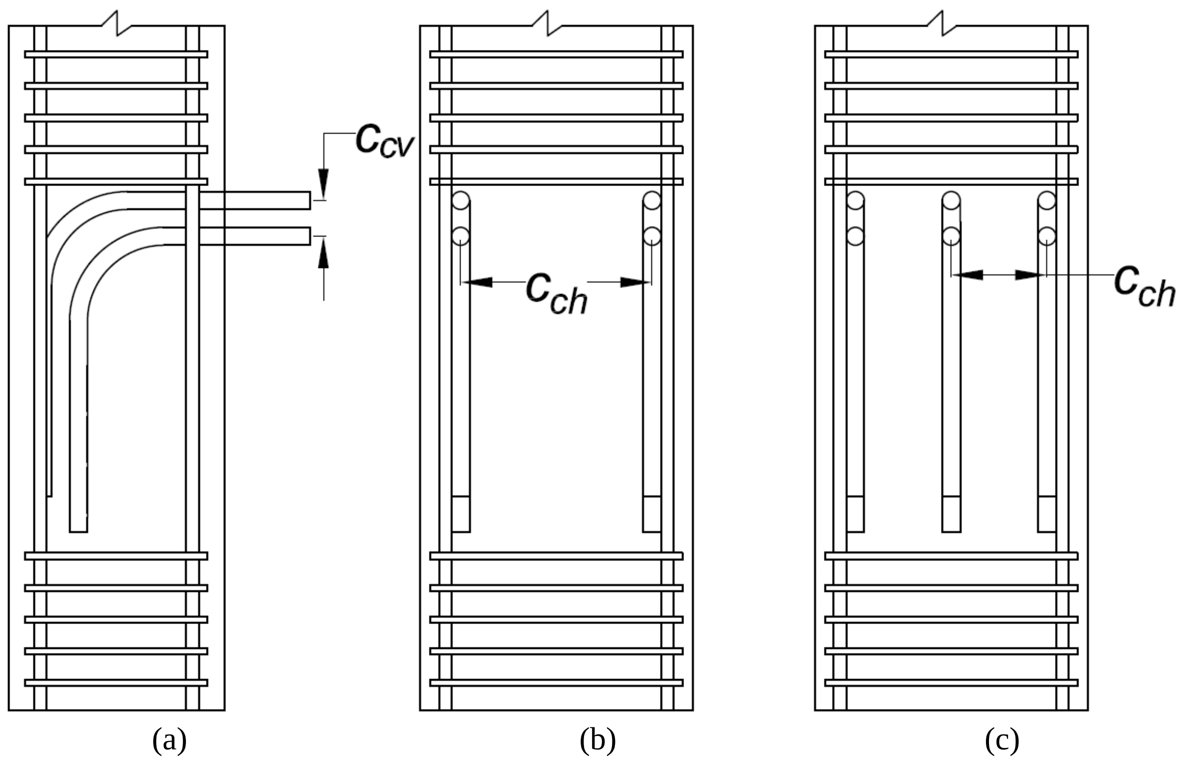


Figure 4.24 Arrangement of staggered hooked bars (a) side view of staggered-hook specimens, (b) front view of a staggered-hook specimen with four hooks, and (c) front view of a staggered-hook specimen with six hooks. Confining reinforcement within the joint region was eliminated for clarity

Four levels of confining reinforcement within the joint region were investigated, no hoops and two, five, and six No. 3 hoops. Specimens with two hoops as confining reinforcement had the hoops spaced at 3-in. intervals from the center of the straight portion of the hooked bars or the center of the straight portion of the upper layer of the hooked bars in specimens with staggered hooks. Specimens with five hoops as confining reinforcement had the first hoop centered $1.5d_b$ from the center of the straight portion of the hooked bars or the center of the straight portion of the lower layer of the hooked bars in specimens with staggered hooks; the other hoops were spaced at $3d_b$ (center-to-center) from the first hoop. Staggered-hook specimens with six hoops had the first hoop centered between the straight portions of the hooked bars in the two layers, the second hoop was centered $1.5d_b$ from the center of the straight portion of the hooked bars of the lower layer, and the other hoops were spaced at $3d_b$ (center-to-center) from the second hoop (see Section 2.3.3 for more details on the reinforcement configurations). As observed in Section 4.3.2, confining reinforcement within the joint region is effective in increasing the anchorage strength of hooked bars only if the confining reinforcement is located within a range of $8d_b$ of the top of the hooked bars for No. 3 through No. 8 bars or within $10d_b$ for No. 9 though No. 11 bars. For staggered hooked bars, the confining reinforcement would be considered effective when located within this range of hooked bars of all layers. Based on this, the specimens with No. 5 staggered hooked bars with two hoops as confining reinforcement have both hoops effective, those with five hoops have three hoops effective, and those with six hoops have four hoops effective.

Table 4.8 presents the test parameters for specimens with No. 5 hooked bars. The table also presents the ratio of test-to-calculated bar forcer at failure T/T_h for two values of calculated bar force; T_h^{b} calculated using the descriptive equations for widely-spaced hooked bars [Eq. (4.5 and 4.8)] without and with confining reinforcement, respectively; T_h^{c} calculated using the descriptive equations for closely-spaced hooked bars [Eq. (4.9 and 4.10)] without and with confining reinforcement, respectively.

Table 4.8 Test parameters for specimens with No. 5 hooked bars including staggered-hook specimens

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	Hook Bar Type	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	T lb	T/T_h[b]	T/T_h[c]	Failure Type[d]
5-5-90-0-i-2.5-2-8	A B	90°	8.1 8.0	4830	A1035 Grade 120	13.0	7.4	2	-	32448	1.17	1.17	FP/SB FP/SB
(3)5-5-90-0-i-2.5-2-8	A B C	90°	8.0 8.0 7.8	4830	A1035 Grade 120	13.0	3.8 3.6	3	-	27869	1.02	1.06	FP FP FP
(2s) 5-5-90-0-i-2.5-2-8	A B C D	90°	8.0 8.0 6.5 6.4	4660	A1035 Grade 120	13.0	7.4	4	-	16727	0.69	1.07	FP FP FP FP
(3s) 5-5-90-0-i-2.5-2-8	A B C D E F	90°	8.0 7.8 8.0 6.6 6.5 6.8	4830	A1035 Grade 120	13.0	3.5 3.5	6	-	16804	0.67	1.05	FP/SB FP/SB FP/SB FP/SB FP/SB FP/SB
(2s) 5-5-90-2#3-i-2.5-2-8	A B C D	90°	7.5 7.3 5.8 5.8	4860	A1035 Grade 120	13.0	7.1	4	0.11	24730	0.94	1.30	FP FP FP FP
(3s) 5-5-90-2#3-i-2.5-2-8	A B C D E F	90°	7.6 7.9 7.8 6.0 5.9 6.3	4860	A1035 Grade 120	13.0	3.5 3.9	6	0.11	20283	0.78	1.12	FP/SB FP/SB FP/SB FP/SB FP/SB FP/SB
5-5-90-5#3-i-2.5-2-8	A B	90°	7.8 7.8	4660	A1035 Grade 120	13.0	7.1	2	0.11	43030	1.10	1.10	FP/SB FP/SB
(3) 5-5-90-5#3-i-2.5-2-8	A B C	90°	7.8 7.8 7.8	4660	A1035 Grade 120	13.0	3.5 3.6	3	0.11	33260	0.95	1.00	FP/SB FP FP
(2s) 5-5-90-5#3-i-2.5-2-8	A B C D	90°	7.8 7.5 6.3 6.0	4660	A1035 Grade 120	13.0	7.4	4	0.11	26180	0.89	1.13	FP/SB FP/SB FP/SB FP/SB
(3s) 5-5-90-5#3-i-2.5-2-8	A B C D E F	90°	7.3 7.3 7.3 5.6 5.6 5.6	4860	A1035 Grade 120	13.0	3.8 3.9	6	0.11	22598	0.87	1.10	FP/SB FP/SB FP/SB FP/SB FP/SB FP/SB
(2s) 5-5-90-6#3-i-2.5-2-8	A B C D	90°	8.0 8.0 6.3 6.1	4660	A1035 Grade 120	13.0	7.4	4	0.11	29528	0.92	1.16	FP/SB FP/SB FP/SB FP/SB
(3s) 5-5-90-6#3-i-2.5-2-8	A B C D E F	90°	7.5 7.6 7.6 6.0 6.0 6.0	4860	A1035 Grade 120	13.0	3.6 3.8	6	0.11	22081	0.77	0.98	FP/SB FP/SB FP/SB FP/SB FP/SB FP/SB

[a]Notation described in Section 2.1 and Appendix A, [b] Calculated anchorage strength is based on Eq. (4.5) and (4.8)
[c] Calculated anchorage strength is based on Eq. (4.9) and (4.10), specimens with intermediate amount of confining reinforcement involved linear interpolation for spacing effect using Eq. (4.11).
[d]Failure type described in Section 3.3

Figures 4.25a and b show, respectively, the total and average bar forces in the hooked bars at failure, T_{total} and T, for specimens with No. 5 hooked bars without confining reinforcement and with five No. 3 hoops. Three of the five hoops are effective in increasing the anchorage strength of the hooked bars. The figures compare specimens with a single layer of hooked bars with specimens with staggered hooked bars.

For the specimens without confining reinforcement, the total bar force T_{total} for the staggered-hook specimen with four hooked bars was just 3 percent higher than T_{total} for the specimen with two hooks, while T_{total} for the staggered-hook specimen with six hooked bars was 20% higher than that for the specimen with three hooks. The average bar force T (Figure 4.25b) dropped dramatically for staggered-hook specimens compared to the two-hook specimens, with effectively no difference in average force at failure between the staggered-hook specimens containing four hooked bars and those containing six hooked bars. The limited increase in total force and the drop in force carried by each hooked bar at failure with the addition of hooked bars is likely due to the limited amount of concrete available to resist the forces in the closely-spaced hooked bars. The specimens with five No. 3 hoops as confining reinforcement developed higher anchorage strengths than specimens without confining reinforcement, with an increase in total force (Figure 4.25a) and a decrease in average bar force (Figure 4.25b) as the number of hooked bars increased. The total bar force for the staggered-hook specimen with four hooked bars was 22% higher than the total bar force for the specimen with two hooked bars, and the total bar force for the staggered-hook specimen with six hooks was 36% higher than that of the specimen with a single layer of three hooked bars. As observed for the specimens with closely-spaced bars in a single layer, confining reinforcement appears to reduce the negative effects on anchorage strength of closely-spaced staggered hooked bars.

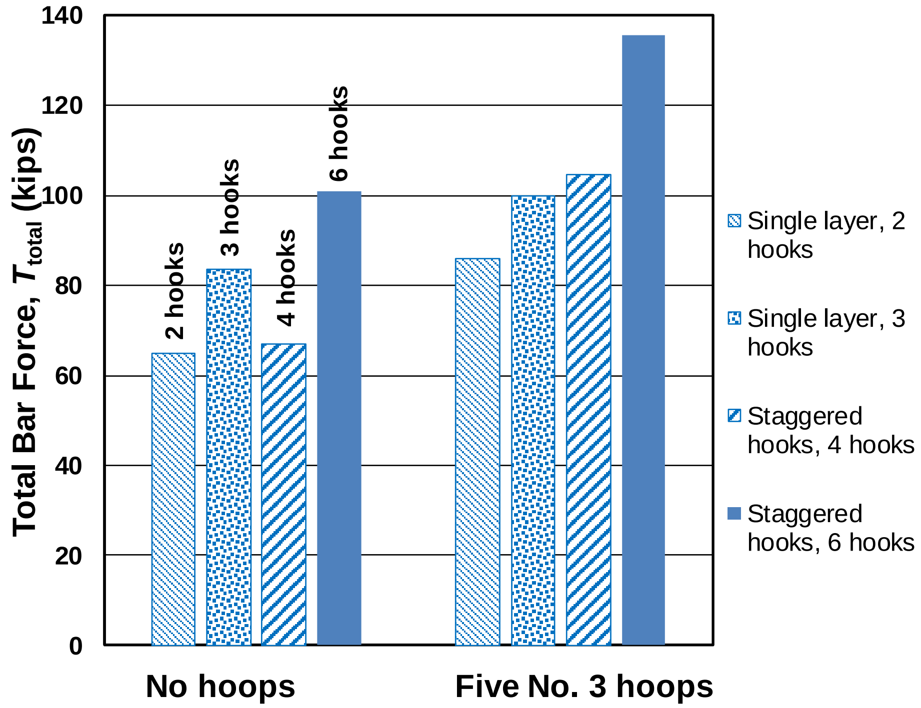


Figure 4.25a Total bar forces at anchorage failure of specimens T_{total} with No. 5 hooked bars including staggered-hook specimens without and with five No. 3 hoops

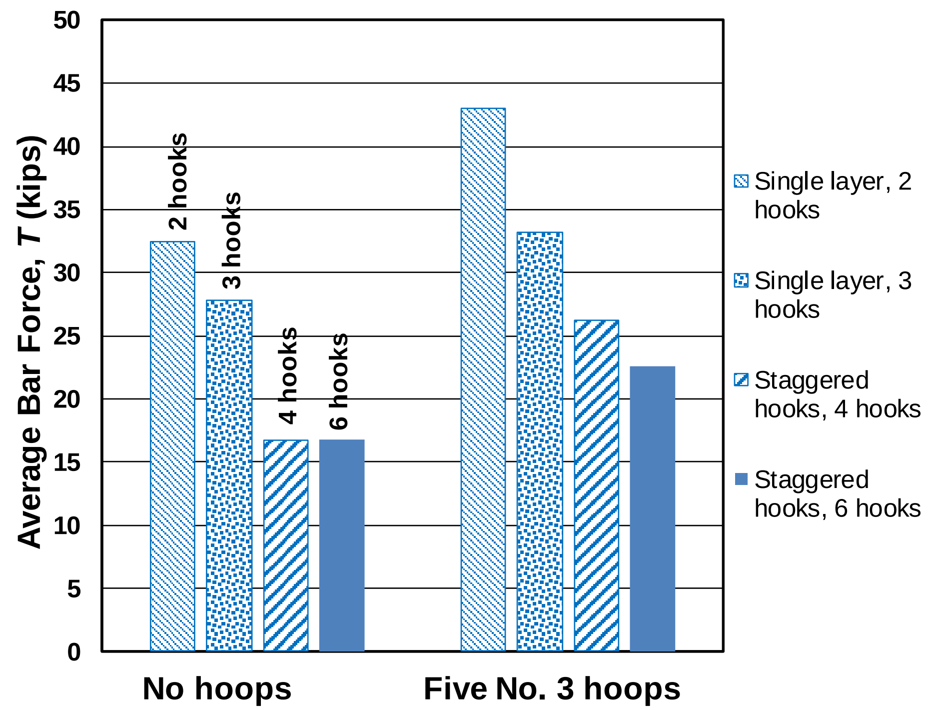


Figure 4.25b Average bar forces at anchorage failure T of specimens with No. 5 hooked bars without and with five No. 3 hoops

Figure 4.26 shows the average bar force at failure for the staggered-hook specimens with four and six hooked bars with different levels of confining reinforcement, no hoops and two, five, and six No. 3 hoops. For specimens with two No. 3 hoops, both hoops are effective in increasing the anchorage strength of the hooked bars; for specimens with five hoops three are effective; and for specimens with six hoops, four are effective. The average bar force increased with increasing confining reinforcement within the joint region with the exception of the specimen containing six hooked bars and six No. 3 hoops, which had an average bar force slightly less than the specimen containing six hooked bars with five No. 3 hoops. This drop may be the result of natural variability in the test specimens. The maximum incremental increase in the average bar force occurred between the specimens with no confinement and those with two No. 3 hoops as confining reinforcement, which is approximately proportional to the increase in the amount of effective confining reinforcement.

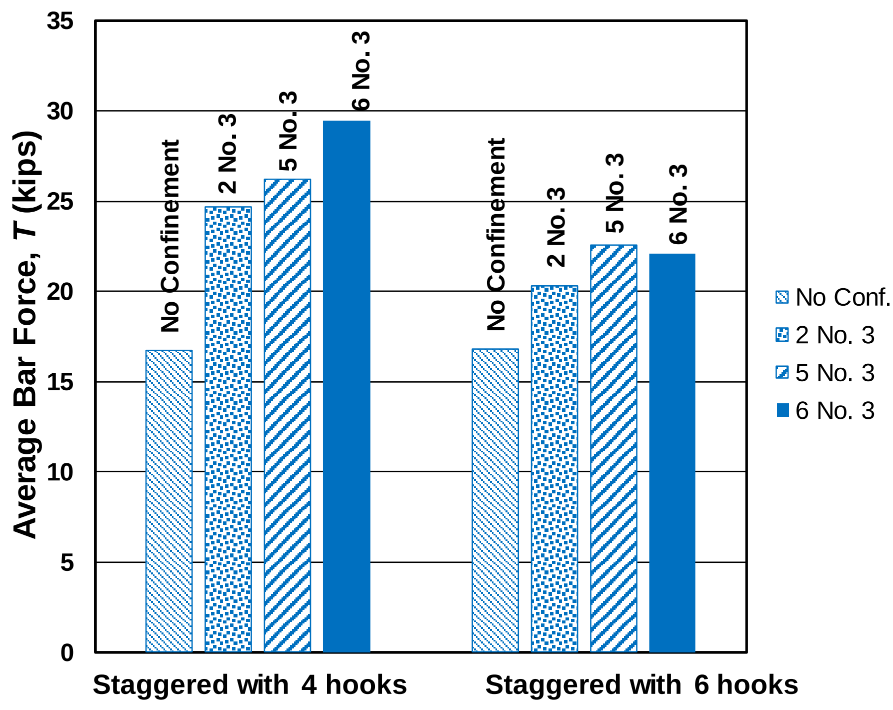


Figure 4.26 Average bar forces at anchorage failure *T* of staggered-hook specimens with No. 5 hooked bars with different levels of confining reinforcement

The group of specimens containing No. 11 hooked bars included two with two hooked bars and five with two pairs of staggered hooks cast from the same batch of concrete. The nominal embedment length for the hooked bars in the upper layer was 16 in.; the tails of hooked bars in the lower layer were located $1d_b$ clear from the hooked bars in the first layer, resulting in a nominal embedment length of 13.2 in. The nominal horizontal center-to-center spacing between bars c_{ch} was $10.7d_b$ (15.1 in.). The nominal vertical center-to-center spacing between staggered hooked bars c_{cv} was $2d_b$ (2.8 in.). The staggered hooked bars were closely spaced in the vertical direction only. Concrete compressive strengths ranged from 4,890 to 5,140 psi.

Confining reinforcement within the joint region consisted of no hoops and two, six, seven, or eight No. 3 hoops. Specimens with two hoops as confining reinforcement had the hoops spaced at 8-in. intervals from the center of the straight portion of the hooked bars or the center of the straight portion of the upper layer of the hooked bars in specimens with staggered hooks. Specimens with six hoops as confining reinforcement had the first hoop centered $1.5d_b$ from the center of the straight portion of the hooked bars or the center of the straight portion of the lower layer of the hooked bars in specimens with staggered hooks and the other hoops spaced at $3d_b$ (center-to-center) from the first hoop. The specimen with seven hoops had the first hoop centered between the center of the straight portions of the hooked bars in the two layers, the second hoop centered $1.5d_b$ from the center of the straight portion of the hooked bars of the lower layer, and the other hoops spaced at $3d_b$ (center-to-center) from the second hoop. The Specimen with eight hoops as confining reinforcement had the first and second hoops located similar to those of the specimens with seven hoops and the other hoops spaced at $2.3d_b$ (center-to-center) from the second hoop (see Section 2.3.3). For No. 11 hooked bars, confining reinforcement is considered to be effective in increasing the anchorage strength when located within a range of $10d_b$ of the top of the hooked bars of all layers. Thus, specimens with No. 11 staggered hooked bars with two hoops as confining reinforcement have both hoops effective, those with six hoops have three hoops effective, those with seven hoops have four hoops effective, and those with eight hoops have five hoops effective.

Table 4.9 presents the test parameters for the specimens and ratios of T/T_h for two values of T_h: T_h^{b} calculated using the descriptive equations for widely-spaced hooked bars without and with confining reinforcement, Eq. (4.5) and (4.8), respectively; and T_h^{c} calculated using the descriptive equations for closely-spaced hooked bars without and with confining reinforcement, Eq. (4.9) and (4.10), respectively.

Table 4.9 Test parameters for specimens with No. 11 hooked bars

Specimen[a]	**Hook**	**Bend Angle**	ℓ_{eh} **in.**	f_{cm} **psi**	**Hook Bar Type**	b **in.**	c_{ch} **in.**	N_h	$A_{tr,l}$ **in.**^{2}	T **lb**	T/T_h[b]	T/T_h[c]	**Failure Type**[d]
11-5-90-0-i-2.5-2-16	A B	90°	16.3 15.8	4890	A1035 Grade 120	21.5	15.3	2	-	89396	1.04	1.04	SS SS
11-5-90-6#3-i-2.5-2-16	A B	90°	15.5 15.3	5030	A1035 Grade 120	21.5	15.0	2	0.11	115623	1.09	1.09	SS SS
(2s) 11-5-90-0-i-2.5-2-16	A B C D	90°	16.0 16.3 13.3 13.5	5030	A1035 Grade 120	21.5	15.0	4	-	47490	0.6	1.01	SS SS SS SS
(2s) 11-5-90-2#3-i-2.5-2-16	A B C D	90°	15.9 16.0 13.3 13.3	5140	A1035 Grade 120	21.5	15.3	4	0.11	57998	0.67	1.00	SS SS SS SS
(2s) 11-5-90-6#3-i-2.5-2-16	A B C D	90°	15.5 15.5 12.3 12.8	5030	A1035 Grade 120	21.5	15.0	4	0.11	62177	0.72	0.95	SS SS SS SS
(2s) 11-5-90-7#3-i-2.5-2-16	A B C D	90°	15.5 15.5 13.0 13.0	5140	A1035 Grade 120	21.5	14.9	4	0.11	67432	0.73	0.96	SS SS SS SS
(2s) 11-5-90-8#3-i-2.5-2-16	A B C D	90°	15.9 15.9 13.3 13.3	5140	A1035 Grade 120	21.5	15.3	4	0.11	70505	0.72	0.95	SS SS SS SS

[a]Notation described in Section 2.1 and Appendix A
[b] Calculated anchorage strength is based on Eq. (4.5) and (4.8)
[c] Calculated anchorage strength is based on Eq. (4.9) and (4.10), specimens with intermediate amount of confining reinforcement involved linear interpolation for spacing effect using Eq. (4.11).
[d]Failure type described in Section 3.3

Figures 4.27a and b show, respectively, the total and average bar force carried by the specimens at failure, T_{total} and T, for specimens with No. 11 hooked bars without confining reinforcement and with six No. 3 hoops (specimens with the same amount of effective confining reinforcement within the joint region). For the specimens without confining reinforcement, the total bar force T_{total} for the staggered-hook specimen was only 7% higher than the companion two-hook specimen, resulting in an average bar force T for the staggered-hook specimen just above one-half of the average bar strength for the companion two-hook specimen. As stated earlier, the reason behind this reduction in average anchorage strength is the limited amount of concrete to resist the forces in the closely-spaced hooks. The specimens with six No. 3 hoops as confining reinforcement developed higher anchorage strength than specimens without confining reinforcement; the total bar force for the staggered-hook specimen was only 8% higher than the companion two-hook specimen.

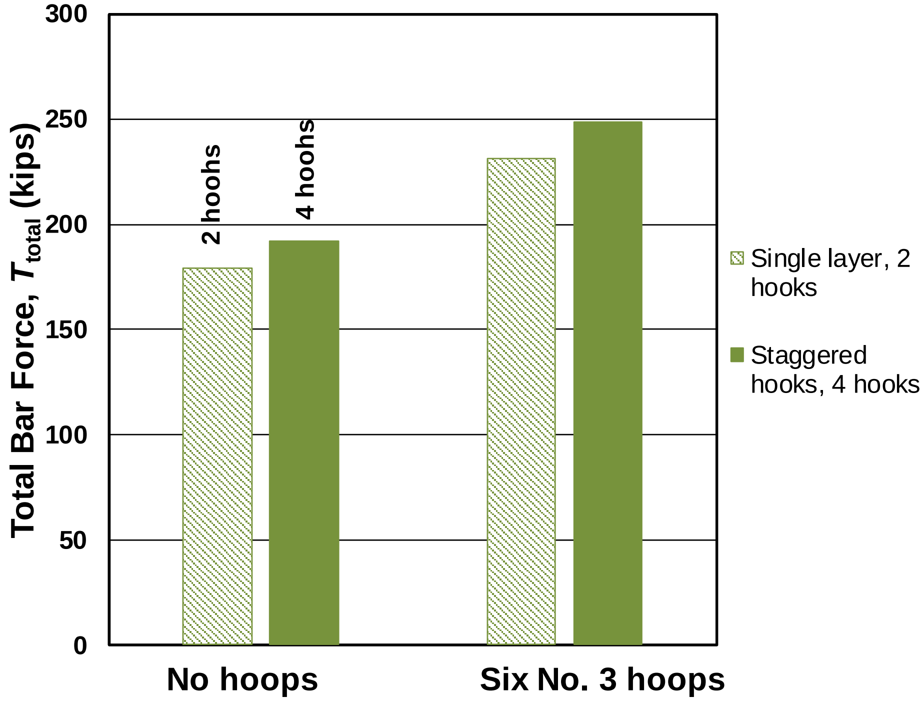


Figure 4.27a Total bar forces at anchorage failure T_{total} of specimens with No. 11 hooked bars, including staggered-hook specimens without and with six No. 3 hoops

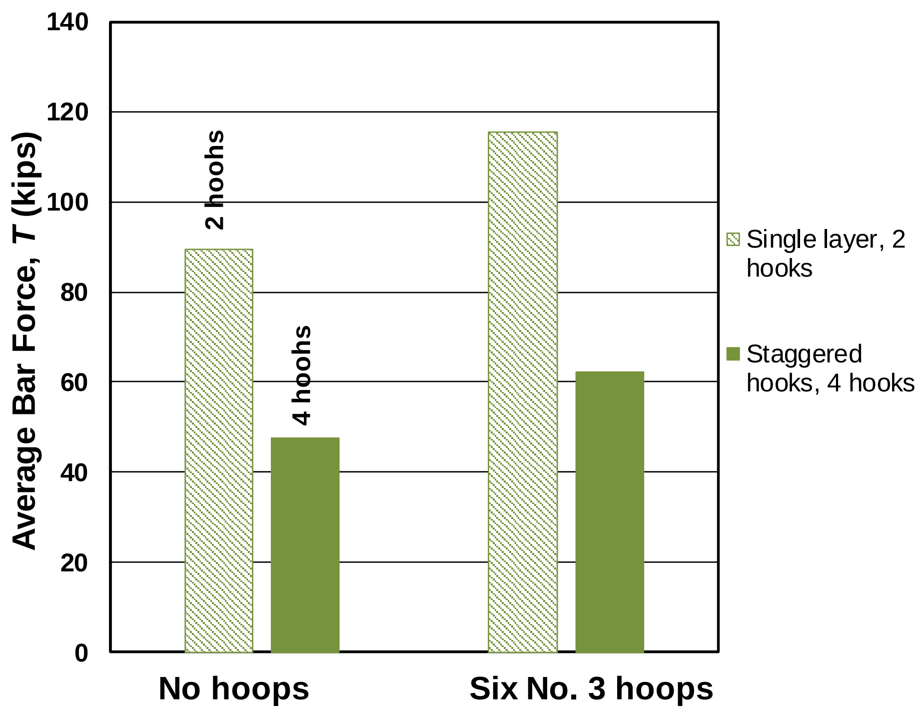


Figure 4.27b Average bar forces at anchorage failure T of specimens with No. 11 hooked bars, including staggered-hook specimens without and with six No. 3 hoops

Figure 4.28 shows the average bar force at failure for staggered-hook specimens with No. 11 hooked bars with no hoops and with two, six, seven, and eight No. 3 hoops. The specimens with two, six, seven, and eight No. 3 hoops have, respectively, two, three, four, and five hoops effective in increasing the anchorage strength of the hooked bars. The average bar force increased with increasing the effective confining reinforcement within the joint region, with the maximum incremental increase occurring between no confinement and two No. 3 hoops as confining reinforcement, which is, as observed for No. 5 staggered hooked bars, proportional to the increase in the effective amount of confining reinforcement within the joint region.

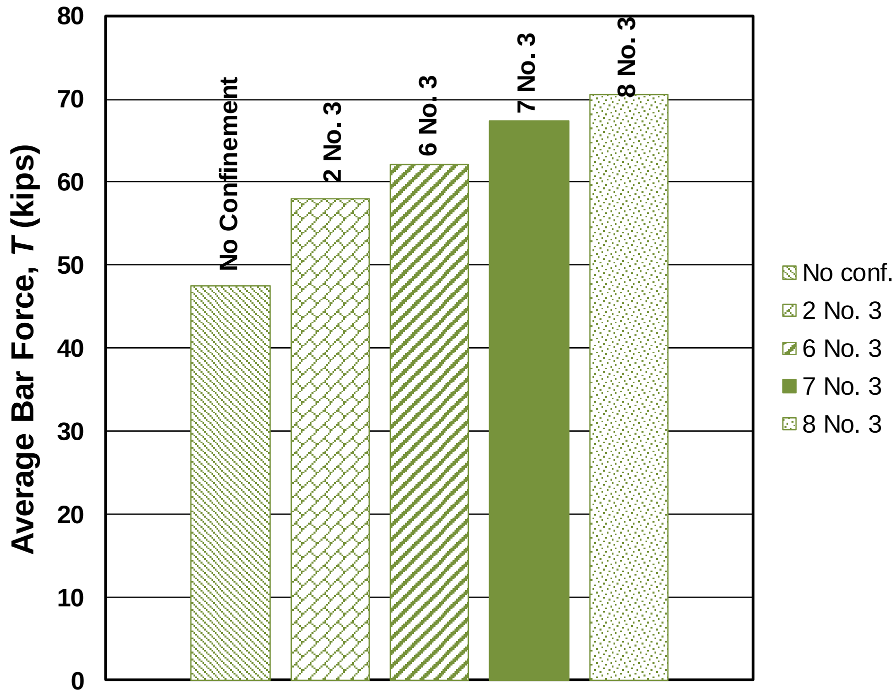


Figure 4.28 Average bar forces at anchorage failure T of staggered-hook specimens with No. 11 hooked bars with different levels of confining reinforcement

Figures 4.29 and 4.30 show the test-to-calculated ratios of average bar force at failure T/T_h, respectively, for specimens without confining reinforcement and with No. 3 hoops spaced at $3d_b$ as confining reinforcement, including the staggered-hook specimens, plotted versus the center-to-center spacing between hooked bars, expressed in multiples of bar diameter c_{ch}/d_b. The staggered-hook specimens included in this analysis are those in Tables 4.8 and 4.9 and the other specimens are from this study and others from the previous studies (Marques and Jirsa 1975, Hamad et al.

1993, Ramirez and Russell 2008, Lee and Park 2010). The calculated average bar forces T_h are based on the descriptive equations for widely-spaced hooked bars [Eq. (4.5) and (4.8)]. The center-to-center spacing between hooked bars is based on the smallest value, which equals the horizontal spacing for the specimens with the hooked bars in a single layer and the vertical spacing (which was less than the horizontal spacing) for the specimens with staggered hooks. The trend lines are those for the closely-spaced hooked bars shown in Figures 4.20 and 4.22 and are not based on the staggered-hook specimens. As shown in Figures 4.29 and 4.30, however, the results for staggered-hook specimens fall along the trend lines for closely-spaced hooked bars, indicating that the anchorage strengths of staggered hooked bars can be represented by the relationship obtained for closely-spaced hooked bars in a single layer. The ratios of test-to-calculated average bar force T/T_h for staggered-hook specimens with T_h calculated using the descriptive equations for closely-spaced hooked bars [Eq. (4.9) and (4.10)] are presented in Tables 4.8 and 4.9. The staggered-hook specimens with No. 5 and No. 11 hooked bars have average of ratios of test-to-calculated bar force of 1.10 and 0.97, respectively.

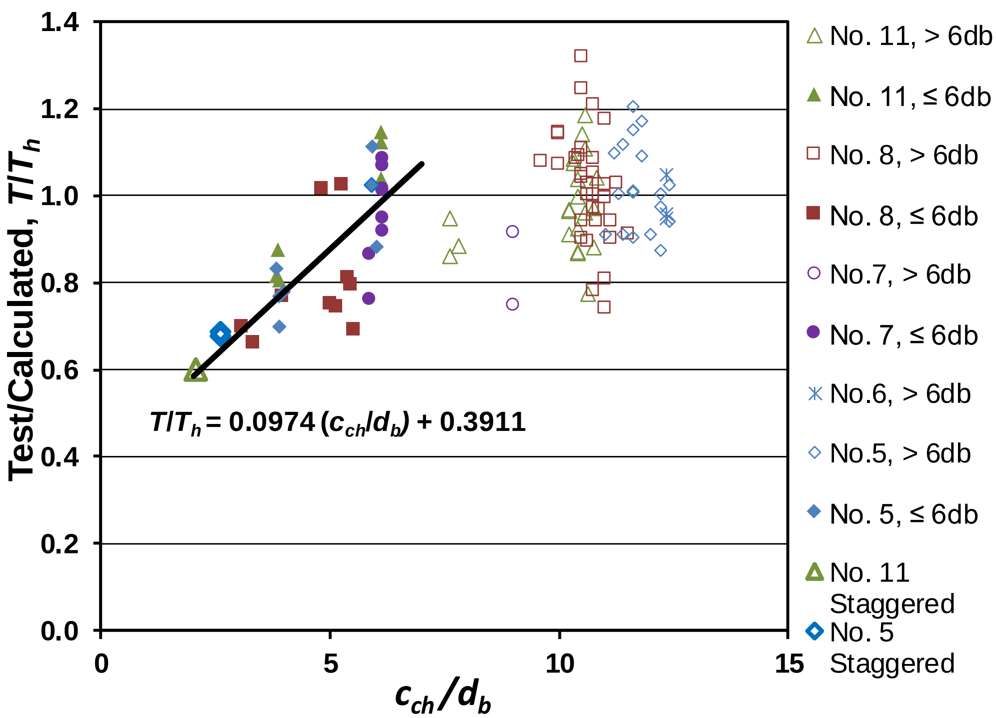


Figure 4.29 Ratio of test-to-calculated bar force at failure T/T_h for specimens without confining reinforcement including staggered-hook specimens versus c_{ch}/d_b, with T_h calculated using Eq. (4.5), c_{ch} is center-to-center spacing

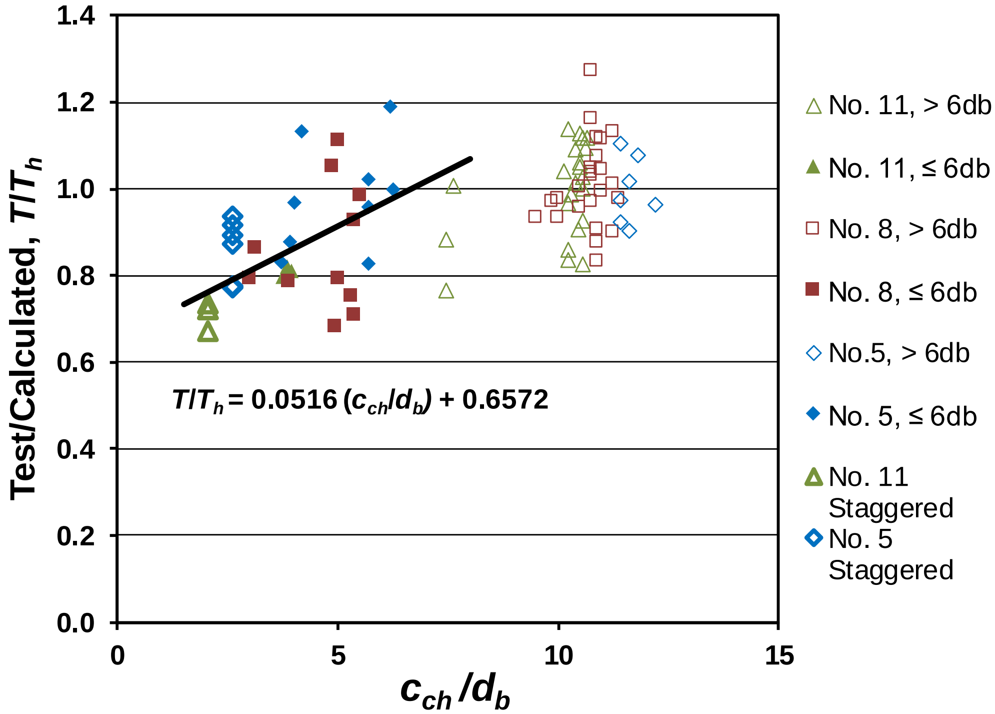


Figure 4.30 Ratio of test-to-calculated bar force at failure T/T_h for specimens with No. 3 hoops spaced at $3d_b$ as confining reinforcement including staggered-hook specimens versus c_{ch}/d_b, with T_h calculated using Eq. (4.8), c_{ch} is center-to-center spacing

4.4.3 Ratio of Beam Effective Depth to Embedment Length

The effect of the ratio of beam effective depth to embedment length on the anchorage strength of hooked bars was investigated using a group of seven specimens contained two widely-spaced hooked bars and cast from the same batch of concrete. All hooked bars had a nominal embedment length l_{eh} of 10 in. Of the seven specimens, three had the distance between the centerline of the hooked bars and bearing member h_{cl} equal to 10.0 in. (see Figure 4.31), and four (referred to as deep-beam specimens) had h_{cl} equal to 19.5 in. More details are provided in Section 2.3.5. The hooked bars were No. 8 with a 90° bend angle. The specimens had a nominal concrete side cover of 2.5 in. and a nominal tail cover of 2 in. The column width was 17 in. The concrete compressive strength was 5,920 psi. Different levels of confining reinforcement were investigated, no confinement, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$. For the specimens with No. 3 hoops spaced at $3d_b$, two configurations of confinement were investigated; hoops along the whole depth of the joint (nine hoops), and hoops extending only to the end of the tail of the hooked bars (five hoops), shown in Figure 2.6.

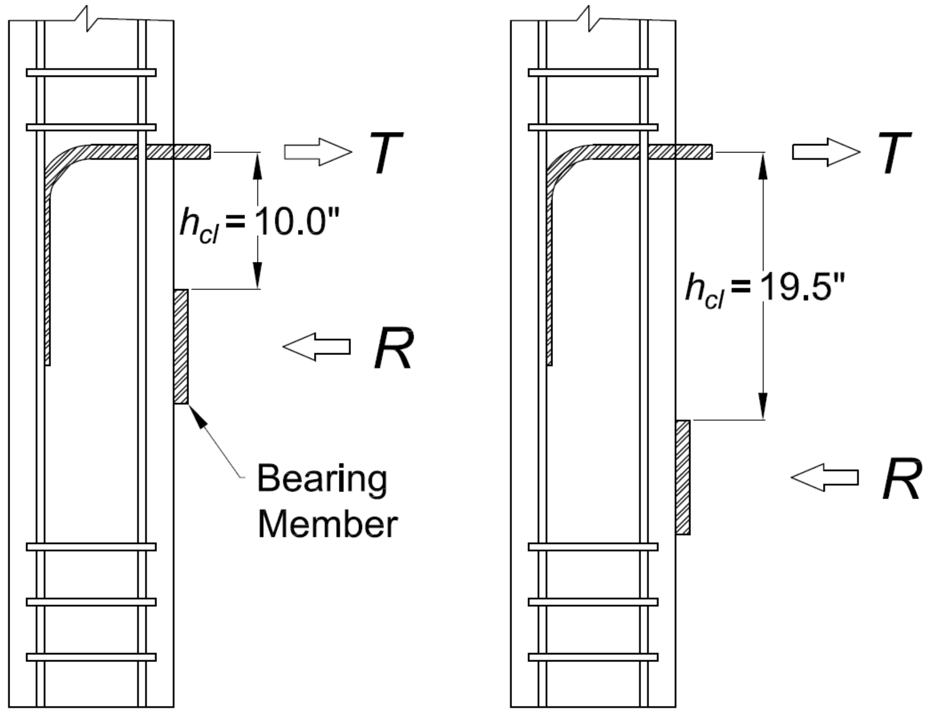


Figure 4.31 Location of bearing member for specimens with different beam effective depth, confining reinforcement within the joint region is not drawn for clarity

The cracking progression for specimens tested in this study was discussed in Section 3.2. At failure, most of the specimens exhibited diagonal cracks on the side faces of the columns initiating from the horizontal crack that appears along the straight portion of the hooked bars up to approximately the location of the bend, growing towards the front face above and below the hook location, Figure 3.1. The diagonal cracks below the hook reached down to the center or even the bottom edge of the bearing member. In deep-beam specimens, particularly those without confining reinforcement, however, these cracks did not reach the bearing member, but rather crossed the column to the front face above the bearing member, as shown in Figure 4.32a, indicating that the bearing member was located out of the anchorage failure zone. The deep-beam specimens with confining reinforcement within the joint region exhibited distributed cracking, as shown in Figure 4.32b, including cracks down to and below the bearing member. Table 4.10 presents the test parameters for the deep-beam specimens (h_{cl} = 19.5 in.) and the companion specimens (h_{cl} = 10.0 in.) with No. 8 hooked bars. T_h is calculated using Eq. (4.9) for hooked bars without confining reinforcement and Eq. (4.10) for hooked bars with confining reinforcement.

(a) (b)

Figure 4.32 Cracking at failure for deep-beam specimens (a) without confining reinforcement, specimen (2d) 8-5-90-0-i-2.5-2-10 (b) with confining reinforcement, specimen (2d) 8-5-90-5#3-i-2.5-2-10

Table 4.10 Test parameters for deep-beam specimens and the companion two-hook specimens containing No. 8 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	Hook Bar Type	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	T lb	T/T_h[b]	Failure Type[c]
8-5-90-0-i-2.5-2-10[d,e]	A B	90°	10.0 10.0	5920	A615 Grade 80	17.0	11.3	2	-	47681	1.03	SS/SB SS
8-5-90-2#3-i-2.5-2-10[d,e]	A B	90°	10.0 10.3	5920	A615 Grade 80	17.0	11.3	2	0.11	56203	1.06	FP/SS FP/SS
8-5-90-5#3-i-2.5-2-10[d,e]	A B	90°	10.0 9.3	5920	A1035 Grade 120	17.0	11.3	2	0.11	70356	1.13	FP/SS FP/SS
(2d) 8-5-90-0-i-2.5-2-10[d,e]	A B	90°	10.3 10.0	5920	A615 Grade 80	17.0	11.0	2	-	32373	0.69	SS SS
(2d) 8-5-90-2#3-i-2.5-2-10[d,e]	A B	90°	10.0 10.3	5920	A615 Grade 80	17.0	11.1	2	0.11	45580	0.86	SS SS
(2d) 8-5-90-5#3-i-2.5-2-10[d,e]	A B	90°	9.9 10.0	5920	A615 Grade 80	17.0	11.3	2	0.11	54735	0.86	FB/SS FB/SS
(2d) 8-5-90-9#3-i-2.5-2-10[d,e]	A B	90°	10.3 10.0	5920	A1035 Grade 120	17.0	11.3	2	0.11	54761	0.85	FB/SS FB/SS

[a]Notation described in Section 2.1 and Appendix A
[b]Calculated anchorage strength is based on Eq. (4.9) and (4.10)
[c]Failure type described in Section 3.3
[d]Specimens had ASTM A1035 Grade 120 longitudinal reinforcement
[e]Specimen had strain gauges

Figure 4.33 shows the average bar forces at failure T for the specimens in Table 4.10. As shown in the figure, the deep-beam specimens were consistently weaker than the companion specimens; the average bar force at failure was 32% less without confining reinforcement, 19% less with two No. 3 hoops as confining reinforcement, and 22% less with No. 3 hoops spaced at $3d_b$. This would be a result of practically no support provided by the bearing member that located out of the anchorage failure zone. The anchorage strength of hooked bars in the deep-beam specimens increased as the amount of confining reinforcement increased from no confinement to five No. 3 hoops, but did not increase further for the specimen with nine No. 3 hoops. This behavior is expected since the additional confining reinforcement was located outside the region previously established as effective for confining reinforcement. The deep-beam specimens with confining reinforcement had test-to-calculated ratios that were 25%, on average, greater than deep-beam specimens without confining reinforcement, indicating that confining reinforcement can reduce the adverse effect of anchoring hooked bars in deep-beam-column joints.

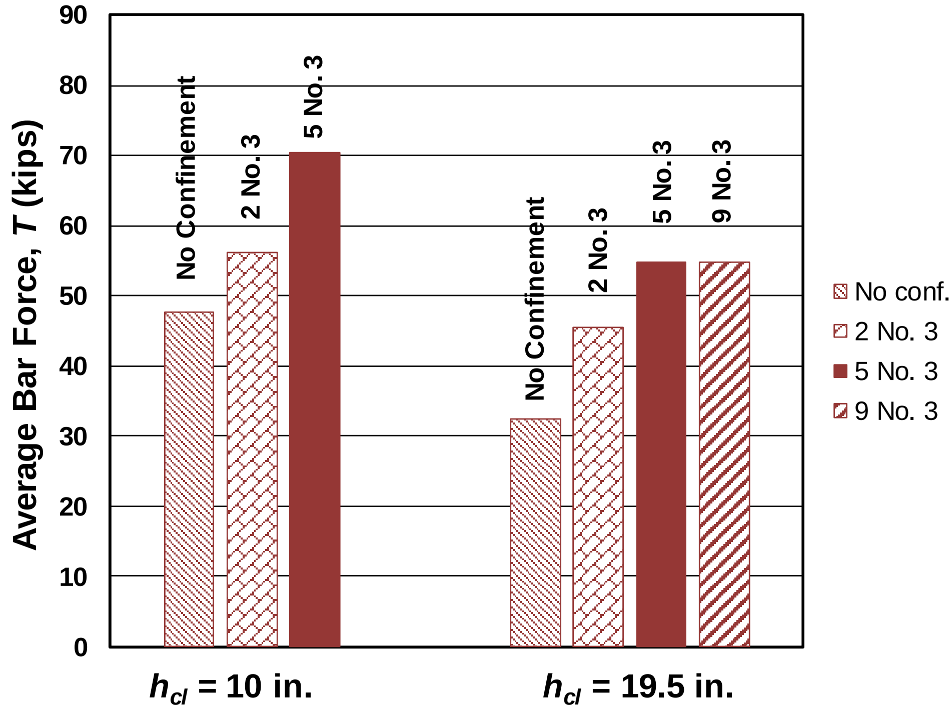


Figure 4.33 Average bar forces at failure T of deep-beam specimens (h_{cl} = 19.5 in.) and companion specimens (h_{cl} = 10.0 in.) with two No. 8 hooked bars and different levels of confining reinforcement

In addition to the specimens containing No. 8 bars, four specimens containing two widely-spaced No. 11 hooked bars were also fabricated with a 10 in. embedment length (deep-beam specimens) with h_{cl} equal to 19.5 in. The concrete compressive strength was 14,050 psi. Three levels of confining reinforcement within the joint region were used: no confinement, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$ (six hoops). The test parameters for these specimens are presented in Table 4.11. The calculated anchorage strength T_h is based on Eq. (4.9) for hooked bars without confining reinforcement and Eq. (4.10) for hooked bars with confining reinforcement. All specimens had a ratio of test-to-calculated strength T/T_h below 1.0, ranging from 0.77 to 0.91, although the three specimens with confining reinforcement averaged 11% higher T/T_h ratios than the specimen without confining reinforcement. The four specimens were similar in behavior to the deep-beam specimens with No. 8 hooked bars, indicating that confining reinforcement can lessen the effect of anchoring hooked bars in deep-beam-column joints.

Table 4.11 Test parameters for deep-beam specimens with No. 11 hooked bars

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	Hook Bar Type	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	T lb	T/T_h[b]	Failure Type[c]
(2d) 11-15-90-0-i-2.5-2-10[d]	A B	90°	9.5 9.5	14050	A615 Grade 80	21.5	15.0	2	-	51481	0.77	FP FP
(2d) 11-15-90-2#3-i-2.5-2-10[d]	A B	90°	10.0 10.0	14050	A615 Grade 80	21.5	14.8	2	0.11	63940	0.82	FP FP
(2d) 11-15-90-6#3-i-2.5-2-10a[d]	A B	90°	9.5 10.0	14050	A615 Grade 80	21.5	14.8	2	0.11	82681	0.91	FP FP
(2d) 11-15-90-6#3-i-2.5-2-10b[d]	A B	90°	9.5 9.8	14050	A615 Grade 80	21.5	14.4	2	0.11	75579	0.83	FP FP

[a]Notation described in Section 2.1 and Appendix A
[b] Calculated anchorage strength is based on Eq. (4.9) and (4.10)
[c]Failure type described in Section 3.3
[d]Specimens had ASTM A1035 Grade 120 longitudinal reinforcement

As discussed previously, the deep-beam specimens exhibited reductions in anchorage strength compared to specimens with lower values of h_{cl}. Thus, it would be desirable to establish a threshold on the ratio of beam depth d to embedment length ℓ_{eh} for the use of the descriptive equation and, eventually, design provisions. The specimens involved in this analysis had a beam simulated by the hooked bars and a bearing member. As shown in Figure 4.34, in this representation, the beam depth would be the sum of the distance from the center of the hooked bars to the top edge of the bearing member h_{cl} and the height of the bearing member (8$^3/_8$ in.). This approach, however, overestimates the value of d because cracking patterns and member failure modes indicate that the compressive force in the simulated beam-column joint is concentrated at the top of the bearing member. Alternatively, the portion of the bearing member subjected to compression can be represented by treating the top edge of the bearing member as the neutral axis of the beam and the nonlinear concrete stress distribution, typically represented using the equivalent rectangular stress block with the extreme compressive fiber located at a distance c below this point, as shown in Figure 4.34. The distance c is calculated by:

$$c = a/\beta_1$$

where $\beta_1 = 0.85 - \frac{0.05(f_{cm} - 400)}{1000} \geq 0.65$; c is the effective depth of neutral axis; a is the depth of the equivalent rectangular compressive stress block equal to the total force in the hooked bars at failure divided by $0.85 f_{cm} \times b$; b is the width of the column; and β_1 is a factor relating a and c, as described in Section 22.2.2.4.3 of ACI 318-14. Thus, following this approach, the effective value of d, d_{eff}, is the sum of the distance from the center of the hooked bars to the top edge of the bearing member h_{cl} and the distance c.

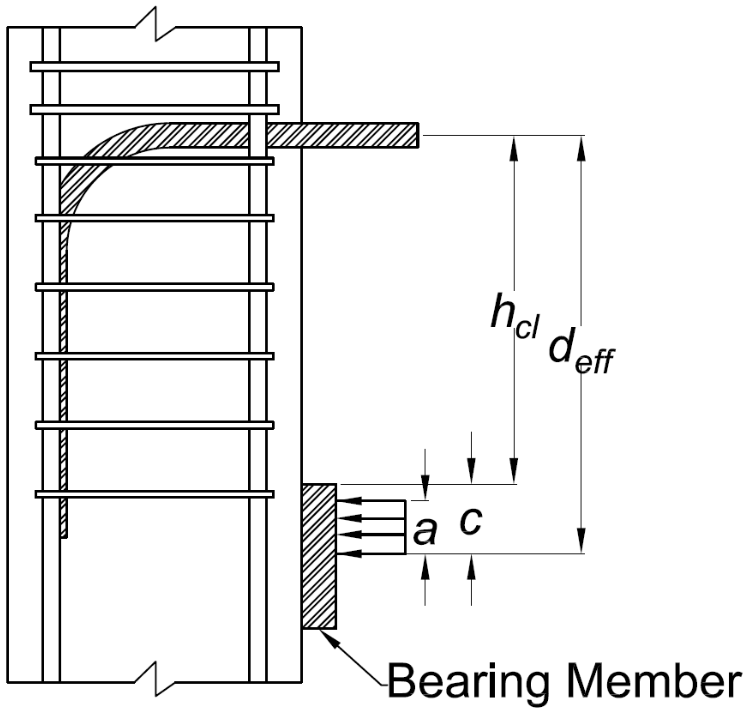


Figure 4.34 Beam effective depth d_{eff}

Figures 4.35 and 4.36 show the ratios of test-to-calculated bar force T/T_h for specimens containing two widely-spaced hooked bars without and with confining reinforcement, respectively, plotted versus the ratio d_{eff}/ℓ_{eh}. Only specimens tested in this investigation and in prior work at the University of Kansas are used in this analysis. All specimens with d_{eff}/ℓ_{eh} above 1.5 exhibited low anchorage strengths. The ratios of test-to-calculated bar force T/T_h are 0.69 and 0.77 for the hooked bars without confining reinforcement and range from 0.82 to 1.01 for the hooked bars with confining reinforcement. Even though only a small number of deep-beam specimens were tested, the analysis shows that d_{eff}/ℓ_{eh} = 1.5 can be considered as a threshold for deep beam-column joints. This matches the observations by Shao et al. (2016) for beam-column joints containing headed bars. The value of 1.5 also matches the recommendations provided in Commentary Section R25.4.4.2 of ACI 318-14, which states a concrete breakout failure can be precluded by "providing reinforcement in the form of hoops and ties to establish a load path in accordance with strut-and-tie modeling principles." This approach appears appropriate to estimate the anchorage strength of hooked bars in beam-column joints with large ratio of d_{eff}/ℓ_{eh}, as will be shown in Chapter 5.

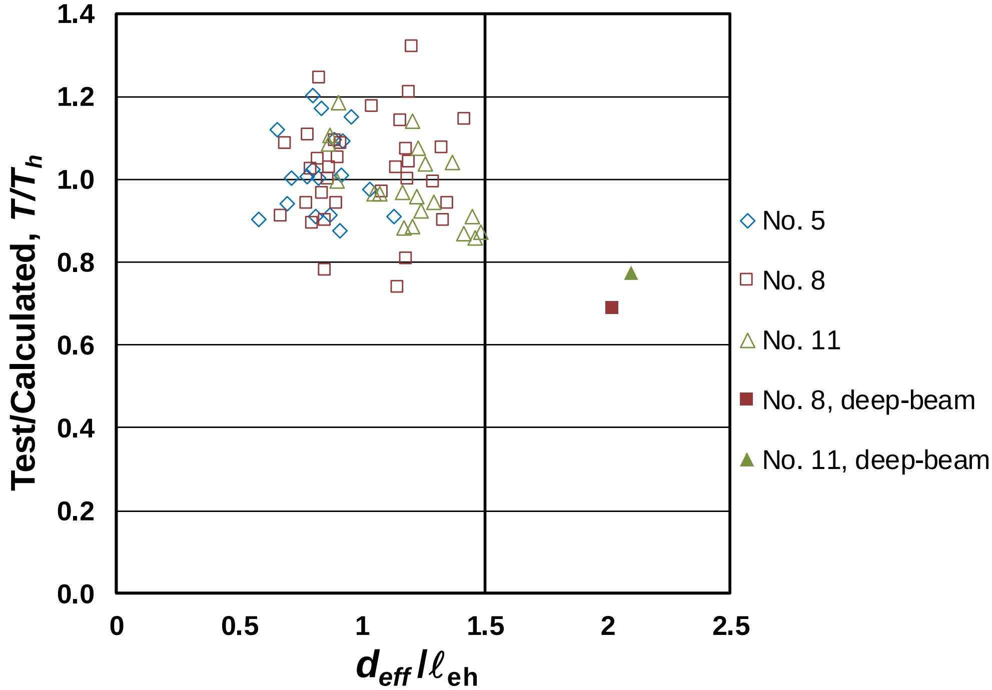


Figure 4.35 Ratio of test-to-calculated bar force at failure T/T_h for specimens containing two widely-spaced hooked bars without confining reinforcement versus d_{eff}/ℓ_{eh}, with T_h calculated using Eq. (4.9)

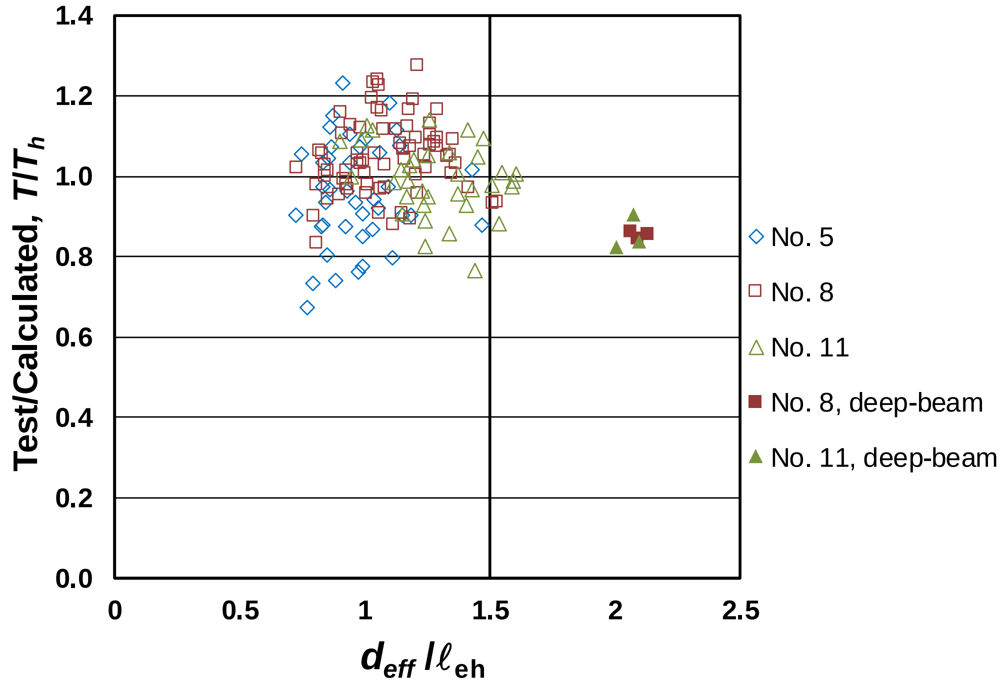


Figure 4.36 Ratio of test-to-calculated bar force at failure T/T_h for specimens containing two widely-spaced hooked bars with confining reinforcement versus d_{eff}/ℓ_{eh}, with T_h calculated using Eq. (4.10)

4.4.4 Hook Location

4.4.4.1 Hooked Bars Location with Respect to Member Depth

The effect of hooked bar location with respect to member depth was investigated using three groups of specimens containing hooked bars not embedded to the far side of the column; 33 specimens contained two, three, or four (No. 5, No. 8, and No. 11) hooked bars with a 90° bend angle. The specimens had a nominal side cover of 2.5 in. and nominal tail covers ranging from 6 to 18 in. Eleven specimens, Group 1, contained two, three, or four No. 5 hooked bars embedded to the mid-depth of the column with a nominal embedment length and tail cover of either 6 or 7 in. The concrete compressive strengths ranged from 5,880 to 6,690 psi, and the center-to-center spacing between the hooked bars ranged from 2 to $5^3/_4$ in. Fourteen specimens, Group 2, contained two, three, or four No. 8 hooked bars embedded to the mid-depth of the column with a nominal embedment length and tail cover of 9 in. The concrete compressive strengths ranged from 7,440 to 7,510 psi, and the center-to-center spacing between the hooked bars ranged from 3 to 11 in. Eight specimens, Group 3, contained two or three No. 11 hooked bars embedded to the mid-depth of the column with a nominal embedment length and tail cover of 13 or 18 in. The concrete compressive strengths ranged from 5,280 to 5,330 psi, and the nominal center-to-center spacing between the hooked bars was 7.5 in. In Groups 1 and 3, containing No. 5 or No. 11 hooked bars, three levels of confining reinforcement were investigated, no confinement, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$ (5 hoops for No. 5 hooked bars and 6 hoops for No. 11 hooked bars). In Group 2, containing No. 8 hooked bars, two levels of confining reinforcement were investigated, no confinement and No. 3 hoops spaced at $3d_b$ (5 hoops). The test parameters for the specimens used in this analysis are presented in Appendix B. An analysis of a portion of these test results by Sperry et al. (2015a) showed that hooked bars embedded to the mid-depth of the column exhibit lower anchorage strengths than hooked bars anchored to the far side of the joint, thought to result from reduced confinement provided by the column compression zone when the column is under bending.

Of the 33 specimens tested in this portion of the study, four with hooked bars embedded to the mid-depth of the column were cast from the same batch of concrete as four with hooked bars embedded to the far side of the column (with 2-in. nominal tail cover). Of these eight specimens, four contained two No. 8 hooked bars with a 9-in. nominal embedment length (two had 2-in. tail cover and two had 9-in. tail cover) and four contained four No. 5 hooked bars with a 6-in. nominal embedment length (two had 2-in. tail cover and two had 6-in. tail cover). Two levels of confining reinforcement were investigated, no confinement and No. 3 hoops spaced at $3d_b$ (5 No. 3 hoops). The test parameters of the eight specimens are presented in Table 4.12; T_h is calculated using Eq. (4.9) for hooked bars without confining reinforcement and Eq. (4.10) for hooked bars with confining reinforcement. The specimens containing No. 8 hooked bars embedded to the mid-depth of the column had almost the same average bar forces at failure T as the companion specimens with 2-in. tail cover for both levels of confining reinforcement. The specimen containing four No. 5 hooked bars embedded to the mid-depth of the column without confining reinforcement had an average bar force at failure that was 17% lower than that of the companion specimen with a 2-in. tail cover, while the specimen with four No. 5 hooked bars embedded to the mid-depth of the column with five No. 3 hoops as confining reinforcement had an average bar force that was 10% higher than that of the companion specimen with a 2-in. tail cover. The results of this small group indicate that the location of hooked bars with respect to the member depth does not have a significant effect on the anchorage strength of hooked bars.

Table 4.12 Test parameters for specimens with hooked bars embedded to the mid-depth of the column and the companion specimens with 2-in. tail cover

Specimen[a]	**Hook**	**Bend Angle**	ℓ_{eh} **in.**	f_{cm} **psi**	**Hook Bar Type**	b **in.**	c_{ch} **in.**	N_h	$A_{tr,l}$ **in.**^{2}	T **lb**	T/T_h[b]	**Failure Type**[c]
8-8-90-0-i-2.5-9-9	A B	90°	9.3 9.0	7710	A615 Grade 80	17.0	11.0	2	-	37679	0.83	FB FB
8-8-90-0-i-2.5-2-9	A B	90°	9.5 9.5	7710	A615 Grade 80	17.0	11.0	2	-	35090	0.74	FB FB
8-8-90-5#3-i-2.5-9-9	A B	90°	9.0 9.3	7710	A615 Grade 80	17.0	11.0	2	0.11	63298	1.0	FB FB
8-8-90-5#3-i-2.5-2-9[d]	A B	90°	8.6 9.0	7710	A615 Grade 80	17.0	10.8	2	0.11	64397	1.04	FB FB
(4@6) 5-8-90-0-i-2.5-6-6[d]	A B C D	90°	6.3 6.3 6.3 6.3	6690	A1035 Grade 120	16.9	3.8 3.8 3.8	4	-	16051	0.72	FP/SS FP/SS FP/SS FP/SS
(4@6) 5-8-90-0-i-2.5-2-6	A B C D	90°	6.0 6.0 5.8 6.0	6690	A1035 Grade 120	16.9	3.8 3.8 3.8	4	-	19303	0.9	FP FP FP FP
(4@6) 5-8-90-5#3-i-2.5-6-6[d]	A B C D	90°	6.8 6.0 6.5 6.3	6690	A1035 Grade 120	16.9	3.8 3.8 3.5	4	0.11	31152	1.07	FP FP FP FP
(4@6) 5-8-90-5#3-i-2.5-2-6[d]	A B C D	90°	6.0 6.0 6.0 6.0	6690	A1035 Grade 120	16.9	4.0 4.0 3.8	4	0.11	28321	1.01	FP FP FP FP

[a]Notation described in Section 2.1 and Appendix A
[b]Calculated anchorage strength is based on Eq. (4.9) or (4.10) depending on the presence of confining reinforcement
[c]Failure type described in Section 3.3
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement

In addition to the specimens containing hooked bars embedded to the mid-depth of the column tested in this study, 26 specimens containing four $^3/_4$-in. (19-mm) hooked bars not embedded to the far side of the column with a 90° bend angle were tested by Joh et al. (1995) and Joh and Shibata (1996). Test parameters of these specimens are presented in Appendix B. Twenty four specimens contained hooked bars embedded to the mid-depth of the column with a nominal embedment length and tail cover of 7.8 in.; the other two specimens contained hooked bars embedded either $^3/_4$ or $^1/_4$ of the column depth, corresponding to a nominal embedment length of 12.6 or 7.8 in. and a tail cover 3.1 or 11.8 in. Concrete compressive strengths ranged from 4,270 to 9,960 psi, and the center-to center spacing between hooked bars ranged from $2.5d_b$ to $3.5d_b$. The specimens had different levels of confining reinforcement in the form of hoops with lateral reinforcement ratios (the total area of the confining reinforcement within the joint region divided by the area of the joint cross-section normal to the plane of the hooked bars) ranging from 0.2 to 0.8, corresponding to 4 to 16 hoops (6-mm in diameter) within the joint region. The test results for these 26 specimens are evaluated next in conjunction with test results from this study.

Figures 4.37 and 4.38 show the ratios of test-to-calculated bar force at failure T/T_h for the two-hook specimens (widely-spaced hooks), deep-beam specimens, and all of the specimens with hooked bars embedded to the mid-depth of the column without and with confining reinforcement plotted versus the ratio of effective beam depth to embedment length d_{eff}/ℓ_{eh}, where d_{eff} approximates the effective depth of the beam, as defined in Section 4.4.3. Specimens with hooked bars embedded to the mid-depth of the column are represented by solid symbols. The calculated anchorage strength T_h is based on Eq. (4.9) for hooked bars without confining reinforcement within the joint region and Eq. (4.10) for hooked bars with confining reinforcement within the joint region. For closely-spaced hooked bars confined with an intermediate amount of confining reinforcement, less than that used to develop spacing term in Eq. (4.10), T_h is modified for spacing between hooked bars by linearly interpolating values of the spacing terms in Eq. (4.9) or (4.10) using Eq. (4.11). The effective depth of the specimens with hooked bars anchored at the mid-depth of the column is calculated as described in Section 4.4.3 for the deep-beam specimens. As shown in Figures 4.37 and 4.38, most specimens with hooked bars embedded to the mid-depth of the column with d_{eff}/ℓ_{eh} greater than 1.5 (the threshold previously established for deep-beam specimens) have values of T/T_h less than 1.0. These specimens contained No. 11 hooked bars without and with confining reinforcement and $^3/_4$-in. hooked bars with confining reinforcement. For these specimens, the average ratios of T/T_h are 0.80 for No. 11 hooked bars without confining reinforcement, 0.86 for No. 11 hooked bars with confining reinforcement, and 0.88 for the $^3/_4$-in. hooked bars with confining reinforcement. The specimens with hooked bars embedded to the mid-depth of the column with d_{eff}/ℓ_{eh} less than 1.5 have average ratios of T/T_h of 0.94 for No. 5 hooked bars without confining reinforcement, 1.09 for No. 5 hooked bars with confining reinforcement, 0.74 for No. 8 hooked bars without confining reinforcement, 0.87 for No. 8 hooked bars with confining reinforcement, and 1.0 for No. 11 hooked bars with confining reinforcement. The 14 specimens that contained No. 8 hooked bars, seven without and seven with confining reinforcement, had low anchorage strength. These 14 specimens were cast from the same batch of concrete along with two companion specimens, one without and one with five No. 3 hoops as confining reinforcement, containing No. 8 hooked bars embedded to the far side of the column with a nominal tail cover of 2 in. (Specimens 8-8-90-0-i-2.5-2-9 and 8-8-90-5#3-i-2.5-2-9, Table 4.12). These specimens have T/T_h of 0.74 and 1.04, respectively, with an average of 0.89, suggesting that the whole group may have been weak.

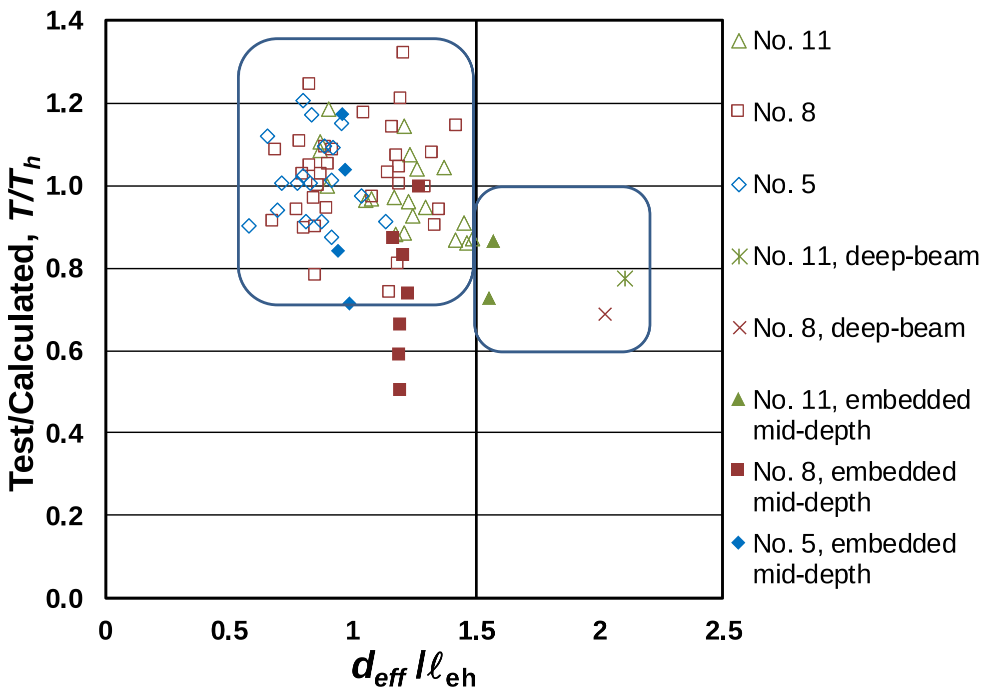


Figure 4.37 Ratio of test-to-calculated bar force at failure T/T_h for specimens without confining reinforcement including specimens with hooked bars not embedded to the far side of the column versus d_{eff}/ℓ_{eh} with T_h calculated using Eq. (4.9)

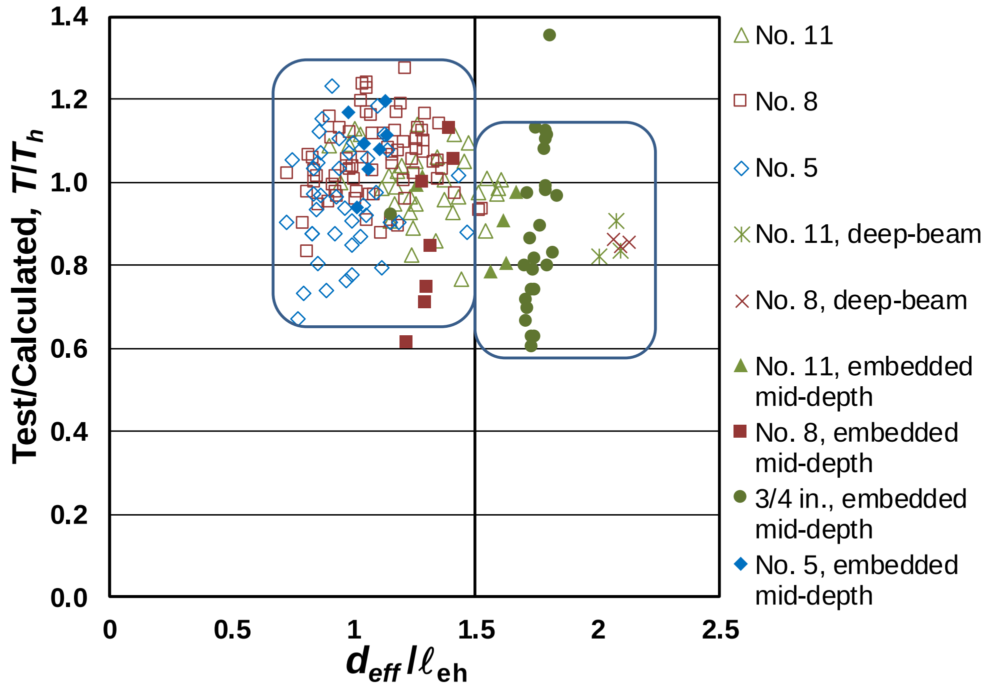


Figure 4.38 Ratio of test-to-calculated bar force at failure T/T_h for specimens with confining reinforcement including specimens with hooked bars not embedded to the far side of the column versus d_{eff}/ℓ_{eh} with T_h calculated using Eq. (4.10)

4.4.4.2 Hooked Bars Location with Respect to Column Core

In addition to the specimens with hooked bars not embedded to the far side of the member, the effect of the hook location was investigated by Sperry et al. (2015a) using specimens with hooked bars placed outside the column core. Thirteen specimens with two hooked bars placed outside the column core were cast together with 13 two-hook specimens with hooked bars placed inside the column core from the same batch of concrete. The specimens contained No. 8 or No. 11 hooked bars with 90° or 180° bend angles embedded to the far side of the column with a nominal tail cover of 2 in. Two levels of confining reinforcement were investigated, no confinement and No. 3 hoops spaced at $3d_b$ (5 No. 3 hoops for No. 8 hooked bars and six No. 3 hoops for No. 11 hooked bars). The nominal concrete compressive strengths were 5,000, 8,000, and 12,000 psi, with actual strengths ranging from 5,270 to 12,370 psi. The specimens had a nominal concrete side cover of 2.5 in., except for two specimens with No. 8 hooked bars without confining reinforcement that had 3.5 and 4 in. nominal concrete side cover. The test parameters of the thirteen two-hook specimens with hooked bars placed outside the column core and the companion two-hook specimens with hooked bars placed inside the column core are presented in Table 4.13; T_h is calculated using Eq. (4.9) for hooked bars without confining reinforcement and Eq. (4.10) for hooked bars with confining reinforcement.

Figure 4.39 shows the ratio of the average bar force at failure for the specimen with hooked bars placed outside the column core to the average bar force at failure for the specimen with hooked bars placed inside the column core ($T_{\text{outside}}/T_{\text{inside}}$) plotted versus the concrete compressive strength. The ratio $T_{\text{outside}}/T_{\text{inside}}$ ranges from 0.66 to 1.03 with an average of 0.85, indicating that placing hooked bars outside a column core provides, on average, about 15% less anchorage strength than placing hooked bars inside a column core.

Table 4.13 Test parameters for the thirteen specimens with hooked bars placed outside the column core and the companion two-hook specimens with hooked bars placed inside the column core

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	f_{cm} psi	Hook Bar Type	b in.	c_{so} in.	c_{ch} in.	$A_{tr,l}$ in.[2]	T lb	T_{inside} / $T_{outside}$	T/T_h[b]	Failure Type[c]
8-8-90-0-o-2.5-2-8	A B	90°	8.6 8.3	8740	A1035 Grade 120	17	2.8 2.5	10.0	-	33015	0.89	0.76	SB/TK SB/TK
8-8-90-0-i-2.5-2-8	A B	90°	8.0 8.0	8780	A1035 Grade 120	17	2.8 2.8	10.5	-	36821		0.90	FP/SS FP/SS
8-8-90-0-o-3.5-2-8	A B	90°	7.6 8.0	8810	A1035 Grade 120	19	3.5 3.6	10.8	-	35875	0.85	0.90	FP/SS SS/FP
8-8-90-0-i-3.5-2-8	A B	90°	8.5 8.0	8780	A1035 Grade 120	19	3.6 3.8	11.0	-	42034		0.99	FP/SS FP/SS
8-8-90-0-o-4-2-8	A B	90°	8.1 8.3	8630	A1035 Grade 120	20	4.5 3.8	10.8	-	37511	1.00	0.90	SS/FP SS
8-8-90-0-i-4-2-8	A B	90°	7.6 8.0	8740	A1035 Grade 120	20	4.5 3.9	10.5	-	37431		0.94	FP/SS FP/SS
8-5-90-5#3-o-2.5-2-10a	A B	90°	10.3 10.5	5270	A1035 Grade 120	17	2.6 2.6	10.9	0.11	54257	0.66	0.84	SS SB
8-5-90-5#3-i-2.5-2-10a	A B	90°	- 10.5	5270	A1035 Grade 120	17	 2.5	10.8	0.11	82800		1.27	- FP/SS
8-5-90-5#3-o-2.5-2-10b	A B	90°	10.5 10.5	5440	A1035 Grade 120	17	2.5 2.6	10.9	0.11	65592	0.94	1.00	FP/SB SB/FP
8-5-90-5#3-i-2.5-2-10b	A B	90°	10.3 10.5	5440	A1035 Grade 120	17	2.8 2.6	10.9	0.11	69715		1.07	FP/SS FP
8-5-90-5#3-o-2.5-2-10c	A B	90°	11.3 10.5	5650	A1035 Grade 120	17	2.6 2.5	10.9	0.11	57700	0.84	0.85	SS/FP SS/FP
8-5-90-5#3-i-2.5-2-10c	A B	90°	10.5 10.5	5650	A1035 Grade 120	17	2.5 2.5	11.0	0.11	68837		1.04	FP/SS FP/SS

[a]Notation described in Section 2.1 and Appendix A
[b]Calculated anchorage strength is based on Eq. (4.9) or (4.10) depending on the presence of confining reinforcement
[c]Failure type described in Section 3.3

Table 4.13 Cont. Test parameters for the thirteen specimens with hooked bars placed outside the column core and the companion two-hook specimens with hooked bars placed inside the column core

Specimen[a]	**Hook**	**Bend Angle**	ℓ_{eh} **in.**	f_{cm} **psi**	**Hook Bar Type**	b **in.**	c_{so} **in.**	c_{ch} **in.**	$A_{tr,l}$ **in.**^{2}	T **lb**	T_{inside} / $T_{outside}$	T/T_h[b]	**Failure Type**[c]
11-8-90-0-o-2.5-2-17	A B	90°	16.8 16.4	9460	A1035 Grade 120	21.5	2.5 2.4	15.2	-	107209	0.81	0.99	SB/FB SB/TK
11-8-90-0-i-2.5-2-17	A B	90°	17.3 18.0	9460	A1035 Grade 120	21.5	2.5 2.5	14.8	-	132055		1.14	FP/TK FB/TK
11-12-180-0-o-2.5-2-17	A B	180°	16.9 17.3	11800	A1035 Grade 120	21.5	2.5 2.6	14.8	-	83493	0.78	0.70	SS/FP SB
11-12-180-0-i-2.5-2-17	A B	180°	16.6 16.6	11880	A1035 Grade 120	21.5	3.0 2.5	14.7	-	107461		0.92	SB/FP SS
11-12-90-0-o-2.5-2-17	A B	90°	17.1 16.6	11800	A1035 Grade 120	21.5	2.5 2.5	15.2	-	105402	0.88	0.90	TK/FB TK/FP
11-12-90-0-i-2.5-2-17	A B	90°	16.1 16.9	11880	A1035 Grade 120	21.5	2.5 2.6	14.7	-	119700		1.04	SB SB/FP
11-8-90-6#3-o-2.5-2-22	A B	90°	21.5 22.3	9120	A1035 Grade 120	21.5	2.5 2.6	14.9	0.11	170249	0.92	1.02	SB SB/FB
11-8-90-6#3-i-2.5-2-22	A B	90°	21.3 21.5	9420	A1035 Grade 120	21.5	2.5 2.6	14.9	0.11	184569		1.12	No Failure SS
11-8-90-6#3-o-2.5-2-16	A B	90°	15.9 16.5	9420	A1035 Grade 120	21.5	2.5 2.6	15.0	0.11	136753	1.03	1.07	SB/FB SB/FB
11-8-90-6#3-i-2.5-2-16	A B	90°	15.5 16.4	9120	A1035 Grade 120	21.5	2.5 2.5	14.8	0.11	132986		1.06	FP/SS FP/SS
11-12-180-6#3-o-2.5-2-17	A B	180°	16.6 16.4	11800	A1035 Grade 120	21.5	2.5 2.8	14.9	0.11	113121	0.76	0.82	SB FB/SS
11-12-180-6#3-i-2.5-2-17	A B	180°	16.8 16.8	12370	A1035 Grade 120	21.5	2.5 2.8	14.8	0.11	148678		1.05	FP/SS SB/FB
11-12-90-6#3-o-2.5-2-17	A B	90°	15.6 17.3	11800	A1035 Grade 120	21.5	2.5 2.4	15.2	0.11	115878	0.71	0.84	FB/SS SB/FB
11-12-90-6#3-i-2.5-2-17	A B	90°	17.1 16.5	12370	A1035 Grade 120	21.5	2.6 3.0	14.4	0.11	161648		1.14	FB/SB SP/SS

[a]Notation described in Section 2.1 and Appendix A
[b]Calculated anchorage strength is based on Eq. (4.9) or (4.10) depending on the presence of confining reinforcement
[c]Failure type described in Section 3.3

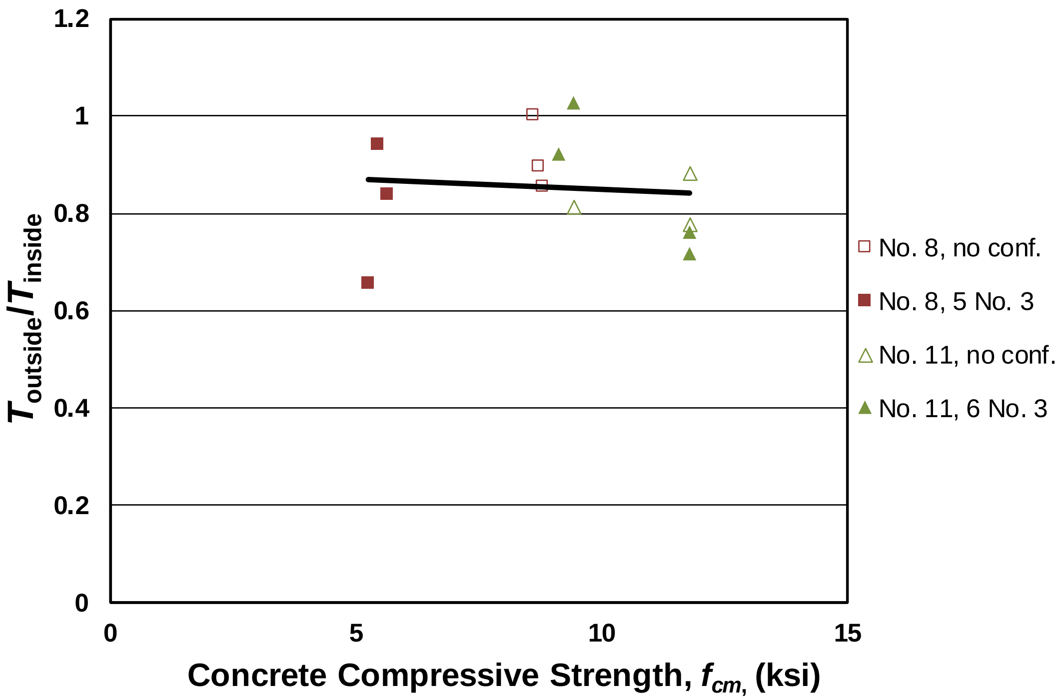
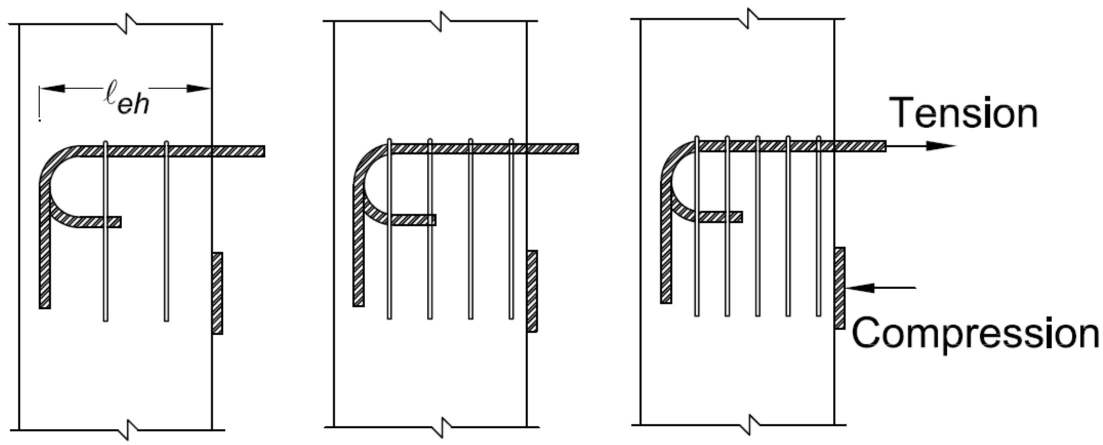


Figure 4.39 Ratio of the average bar force at failure for the specimen with hooked bars placed outside the column core to the average bar force at failure for the specimen with hooked bars placed inside the column core ($T_{outside}/T_{inside}$) plotted versus concrete compressive strength

4.4.5 Orientation of Confining Reinforcement

The effect of the orientation of confining reinforcement with respect to the straight portion of hooked bars on anchorage strength was investigated by Sperry et al. (2015a, 2015b, 2017b) using twelve specimens cast from the same batch of concrete. Each specimen contained two No. 8 hooked bars with a 90° or 180° bend angle embedded to the far side of the column with a nominal tail cover of 2 in. and a nominal concrete side cover of 2.5 in. Of the twelve specimens, two had no confining reinforcement, four had confining reinforcement in the form of hoops parallel to the straight portion of the bar, and six had hoops perpendicular to the straight portion of the bar (as shown in Figure 4.40). Of the specimens with parallel confining reinforcement, two specimens contained two No. 3 hoops and two specimens contained five No. 3 hoops. Of the specimens with perpendicular confining reinforcement, two specimens contained two No. 3 hoops, two specimens contained four No. 3 hoops, and two specimens contained five No. 3 hoops. The nominal concrete compressive strength was 12,000 psi, with an actual strength ranging from 11,800 to 12,010 psi.

The embedment lengths ranged from 9.4 to 12.8 in. The test parameters for these specimens are presented in Table 4.14.



(a) (b) (c)

Figure 4.40 Details of specimens containing hooked bars with 90° and 180° confined with (a) two perpendicular hoops (b) four perpendicular hoops (c) five perpendicular hoops. Column longitudinal bars and confining reinforcement outside the joint are not shown for clarity

Table 4.14 Test parameters for specimens with confining reinforcement perpendicular to the straight portion of hooked bars, confining reinforcement parallel to the straight portion of hooked bars, and with no confining reinforcement (Sperry et al. 2015a, 2015b, 2017b)

Specimen[a]	Hook	Bend Angle	Hoops Orientation	ℓ_{eh} in.	f_{cm} psi	Hook Bar Type	b in.	$A_{tr,l}$ in.^{2}	T Lb	T/T_h[b]	T/T_h[c]	Failure Type[d]
8-12-90-0-i-2.5-2-12.5	A B	90°	-	12.9 12.8	11850	A1035 Grade 120	17	-	66937	0.90	-	FB/SB FB/SB
8-12-180-0-i-2.5-2-12.5	A B	180°	-	12.8 12.5	11850	A1035 Grade 120	17	-	75208	1.03	-	FB/SB FP
8-12-90-2#3-i-2.5-2-11	A B	90°	Para	10.5 11.3	12010	A1035 Grade 120	17	0.11	68683	1.01	-	FP FP
8-12-180-2#3-i-2.5-2-11	A B	180°	Para	11.1 10.4	12010	A1035 Grade 120	17	0.11	64655	0.96	-	FP FB
8-12-90-2#3vr-i-2.5-2-11	A B	90°	Perp	10.9 10.4	12010	A1035 Grade 120	17	0.11	52673	0.72	0.79	FP/SS FP
8-12-180-2#3vr-i-2.5-2-11	A B	180°	Perp	10.9 10.9	12010	A1035 Grade 120	17	0.11	65780	0.89	0.96	SS/FP FB/SB
8-12-90-5#3-i-2.5-2-10	A B	90°	Para	9.0 9.9	11800	A1035 Grade 120	17	0.11	64530	0.91	-	FB/SS SS/FP
8-12-180-5#3-i-2.5-2-10	A B	180°	Para	9.9 9.6	11800	A1035 Grade 120	17	0.11	64107	0.88	-	FP/SS FP
8-12-180-4#3vr-i-2.5-2-10	A B	180°	Perp	10.5 10.0	11850	A1035 Grade 120	17	0.2	69188	0.84	0.98	FP FP
8-12-90-4#3vr-i-2.5-2-10	A B	90°	Perp	10.6 10.3	11850	A1035 Grade 120	17	0.2	59241	0.71	0.83	FP/SS FP
8-12-90-5#3vr-i-2.5-2-10	A B	90°	Perp	10.3 10.2	11800	A1035 Grade 120	17	0.11	60219	0.68	0.82	FP FP
8-12-180-5#3vr-i-2.5-2-10	A B	180°	Perp	11.1 10.5	11800	A1035 Grade 120	17	0.11	67780	0.74	0.88	FP FB

[a]Notation described in Section 2.1 and Appendix A
[b]Calculated anchorage strength is based on Eq. (4.9) or (4.10) depending on the presence of confining reinforcement
[c]Calculated anchorage strength is based on Eq. (4.13)
[d]Failure type described in Section 3.3

The anchorage strength of the hooked bars with perpendicular hoops was similar to that of hooked bars with parallel hoops. Looking at comparable specimens, T for the specimen containing hooked bars with a 180° bend angle confined by two perpendicular hoops was 2% greater than T for the companion specimen with parallel reinforcement. T for the specimen containing hooked bars with a 180° bend angle confined by four perpendicular hoops was 8% greater than T for the companion specimen with parallel hoops. T for the specimen containing hooked bars with a 180° bend angle confined by five perpendicular hoops was 6% greater than T for the companion specimen with parallel hoops. T for the specimen containing hooked bars with a 90° bend angle confined by two perpendicular hoops was 23% lower than T for the companion specimen with parallel hoops. T for the specimen containing hooked bars with a 90° bend angle confined by four perpendicular hoops was 8% lower than T for the companion specimen with parallel hoops, and T

for the specimen containing hooked bars with a 90° bend angle was 6% lower than T for the companion specimen with parallel hoops.

Sperry et al. (2015a, 2015b, 2017b) found that all of the hoops perpendicular to the straight portion of a hooked bar along the embedded length were effective in increasing anchorage strength, but that the contribution of each was less than that of hoops parallel and within 8 or $10d_b$ of the top of the straight portion of the hooked bar (as shown in Figure 4.41) (specimens containing two parallel hoops had one hoop effective in increasing the anchorage strength of hooked bars; specimens with five parallel hoops had three hoops effective; specimens with two, four, or five perpendicular hoops have all hoops effective). The ratios of test-to-calculated average bar force T/T_h for the specimens in this group (tested by Sperry et al. 2015a, 2015b, 2017b) are presented in Table 4.14. The calculated average bar force T_h is based on Eq. (4.9) for hooked bars without confining reinforcement and Eq. (4.10) for hooked bars with parallel confining reinforcement. A_{th} is the total cross-sectional area of confining reinforcement parallel to the straight portion of the bar within $8d_b$ of the top of the hooked bars (applies to No. 8 bars) or the total cross-sectional area of confining reinforcement provided perpendicular to the straight portion of the bars along the embedment length, as shown in Figure 4.41, and n is the number of hooked bars. The two specimens without confining reinforcement have ratios T/T_h of 0.90 and 1.03, with an average of 0.97; the four specimens with parallel confining reinforcement have T/T_h ratios ranging from 0.88 to 1.01, with an average of 0.94; the six specimens with perpendicular confining reinforcement have T/T_h ratios ranging from 0.68 to 0.89, with an average of 0.76.

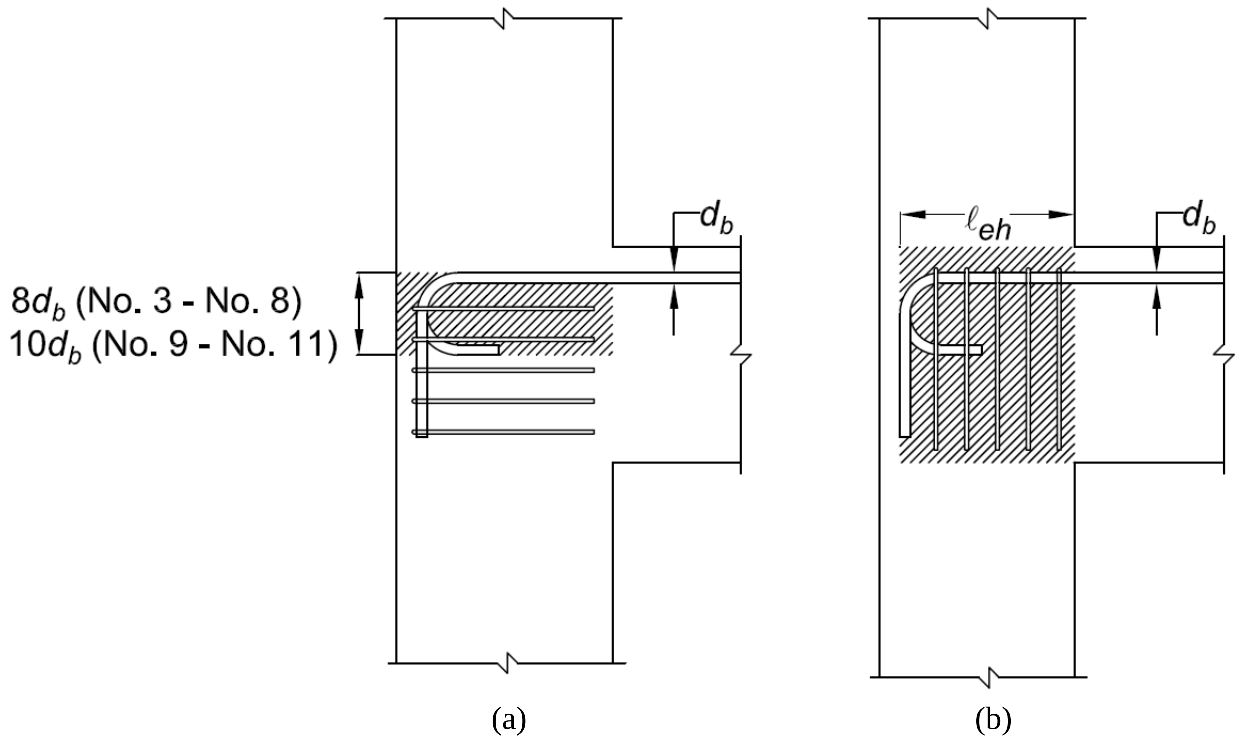


Figure 4.41 Effective confining reinforcement for hooked bars with hoops oriented (a) parallel and (b) perpendicular to the straight portion of the hooked bars

To develop an expression for the contribution of perpendicular confining reinforcement T_{svr}, test results for the comparable specimens (specimens with equivalent amount of total perpendicular and parallel hoops within the joint region) in Table 4.14 are used:

$$T_{svr} = \mathrm{A}_1 \left(\frac{A_{th}}{n} \right)^{1.0175} d_b^{0.73} \tag{4.12}$$

The powers of term A_{th}/n and the bar diameter d_b in Eq. (4.12) are retained from Eq. (4.10) because of the small database. The anchorage strength of hooked bars with perpendicular confining reinforcement (as explained earlier) is similar to that of hooked bars with parallel confining reinforcement. The concrete contribution T_c is the same for the comparable specimens. Thus, the confinement contribution T_{svr} for perpendicular hoops is also similar to the confinement contribution T_s for parallel hoops. Since the effective amount of perpendicular confining reinforcement is double of that for parallel confining reinforcement, the contribution of a single leg of perpendicular confining reinforcement is about half of that for parallel confining reinforcement. Doing so, the value of A_1 is 27,525, giving

$$T_h = 294 f_{cm}^{0.295} \ell_{eh}^{1.0845} d_b^{0.47} + 27525 \left(\frac{A_{th}}{n} \right)^{1.0175} d_b^{0.73} \tag{4.13}$$

As shown in Table 4.14, based on Eq. (4.13), the specimens with hooked bars with a 180° bend angle and perpendicular confining reinforcement have anchorage strengths that are the same or higher than the companion specimens confined by parallel reinforcement. In contrast, the hooked bars with a 90° bend angle and perpendicular confining reinforcement have lower anchorage strengths than the companion specimens confined by parallel reinforcement. Looking at specific specimens, the ratio of test-to-calculated bar force T/T_h for the specimen with hooked bars with a 180° bend angle confined by two perpendicular hoops equals T/T_h for the companion specimen with parallel reinforcement. T/T_h for the specimens with 180° hooked bars confined by four and five perpendicular hoops is, respectively 11% greater and the same as T/T_h for the specimen with five parallel hoops. For specimens containing hooked bars with a 90° bend angle, T/T_h for the specimen with hooked bars confined by two perpendicular hoops is 22% lower than T/T_h for the specimen with parallel hoops, while for the specimens with hooked bars confined by four and five perpendicular hoops, T/T_h is, respectively, 9% and 10% lower than T/T_h for the specimen with five parallel hoops. The average value of T/T_h for all specimens with perpendicular confining reinforcement is 0.88, with a maximum value of 0.98 and a minimum value of 0.79. Considering that these twelve specimens, as a group, exhibit low anchorage strength compared to specimens used to develop the descriptive equation in Section 4.3.2, a higher value of T/T_h for specimens with perpendicular confining reinforcement would be expected using a larger set of specimens.

4.4.6 Confining Reinforcement above the Hook

The effect of the amount of confining reinforcement above the joint region on the anchorage strength of hooked bars is investigated in this section. Specimens included in this analysis were two-hook specimens tested in this and previous studies at the University of Kansas (Peckover and Darwin 2013, Searle et al. 2014, Sperry et al. 2015a, 2015b). Similar to the previous analysis, the effect of confining reinforcement above the joint region will be evaluated separately for specimens without confining reinforcement within the joint region and specimens with different levels of confining reinforcement within the joint region.

Figure 4.42a shows the ratio of test-to-calculated average bar force at failure T/T_h for specimens without confining reinforcement within the joint region plotted versus the term $(A_{th}/n)_{above}$. The calculated average bar force is based on the descriptive equation for hooked bars without confining reinforcement [Eq. (4.9)]. As explained earlier for confining reinforcement within the joint region, A_{th} is the total cross-sectional area of confining reinforcement parallel to the straight portion of the hooked bars within $8d_b$ of the top of the hooked bars for No. 3 through No. 8 bars or within $10d_b$ for No. 9 though No. 11 bars (the dimensions of a standard 180° hooked bar). To be consistent, A_{th} for confining reinforcement above the joint region is also limited to the dimensions of a standard 180° hooked bar, and n is the number of hooked bars. Seventy two specimens contained two hooked bars (No. 5, 8, and 11) with 90° and 180° bend angles. The average bar forces ranged from 19,200 to 213,300 lb, corresponding to average bar stresses ranging from 33,000 to 136,730 psi. The specimens had embedment lengths ℓ_{eh} ranging from 4.9 to 26 in. and concrete compressive strengths ranging from 4,550 to 16,510 psi. The amount of confining reinforcement above the joint per hooked bar, $(A_{th}/n)_{above}$, ranged from 0.09 to 1.0 in., with the minimum value for specimens with No. 5 hooked bars and the maximum value for specimens with No. 8 and No. 11 hooked bars. The values of $(A_{th}/n)_{above}$ can also be expressed as the ratio of the area of the confining reinforcement provided above the joint region to the area of hooked bars being developed $(A_{th}/A_{hs})_{above}$, which ranged from 0.25 to 1.29, with the minimum value for specimens with No. 11 hooked bars and the maximum value for specimens with No. 8 hooked bars. The ratio $(A_{th}/A_{hs})_{above}$ is of interest because A_{th}/A_{hs} for the confining reinforcement *within* the joint will be used as a design parameter, as described in Section 5.3. The values shown in Figure 4.42a are plotted versus $(A_{th}/A_{hs})_{above}$ in Figure 4.42b. The nearly horizontal slope of the trend lines indicate that the amount of confining reinforcement above the joint region does not affect the anchorage strength of hooked bars within beam-column joints.

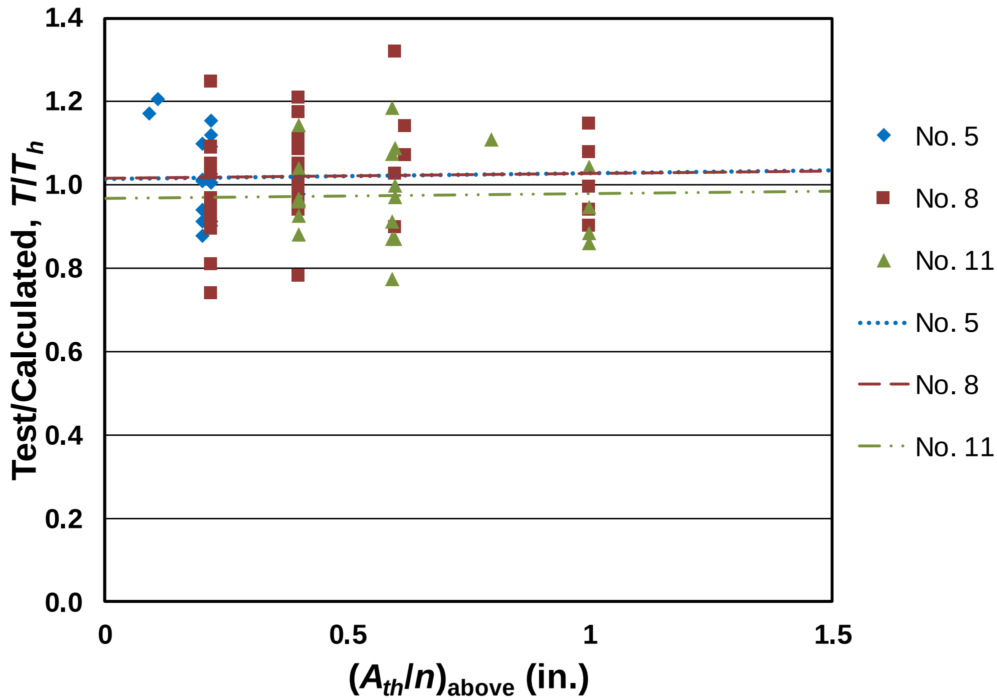


Figure 4.42a Ratio of test-to-calculated bar force at failure T/T_h for two-hook specimens without confining reinforcement per hooked bar versus $(A_{th}/n)_{\text{above}}$, with T_h calculated using Eq. (4.9)

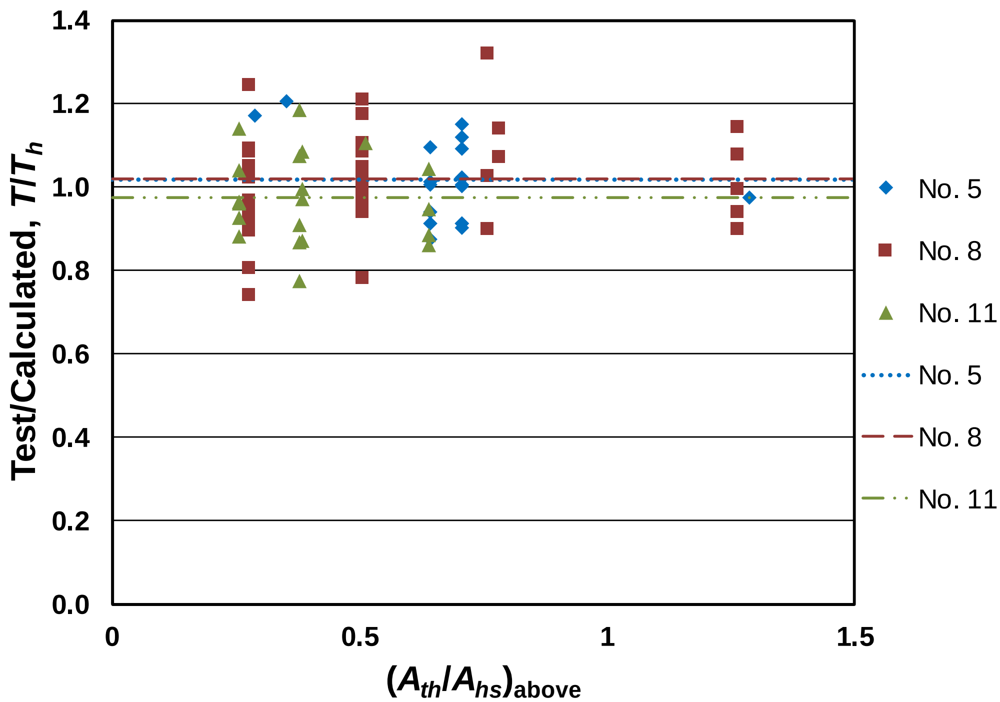


Figure 4.42b Ratio of test-to-calculated bar force at failure T/T_h for two-hook specimens without confining reinforcement versus $(A_{th}/A_{hs})_{\text{above}}$, with T_h calculated using Eq. (4.9)

Figures 4.43a and b show the ratio of test-to-calculated average bar force at failure T/T_h for specimens with confining reinforcement within the joint region plotted versus the term $(A_{th}/n)_{\text{above}}$ and $(A_{th}/A_{hs})_{\text{above}}$, respectively. The calculated average bar force is based on the descriptive equation for hooked bars with confining reinforcement [Eq. (4.10)]. One hundred forty nine specimens contained two hooked bars (No. 5, 8, and 11) with 90° and 180° bend angles, and with different levels of confining reinforcement within the joint region. The average bar force at failure ranged from 18,700 to 209,600 lb, corresponding to average bar stresses ranging from 40,990 to 138,810 psi. The specimens had embedment lengths ranging from 3.75 to 23.5 in. and concrete compressive strengths ranging from 4,300 to 16,480 psi. The amount of confining reinforcement above the joint per hooked bar, $(A_{th}/n)_{\text{above}}$, ranged from 0.2 to 1.0 in. The ratio of the area of the confining reinforcement provided above the joint region to the area of hooked bars being developed $(A_{th}/A_{hs})_{\text{above}}$ ranged from 0.25 to 1.29. The trend lines in Figures 4.43a and b have slight negative slopes indicating not that an increase in the amount of confining reinforcement above the joint would result in lower anchorage strength, but rather, that the amount of confining reinforcement above the joint has no effect on the anchorage strength of hooked bars. Even with confining reinforcement above the joint less than that within the joint region, the specimens did not exhibit a loss in anchorage strength, as shown in Figure 4.44.

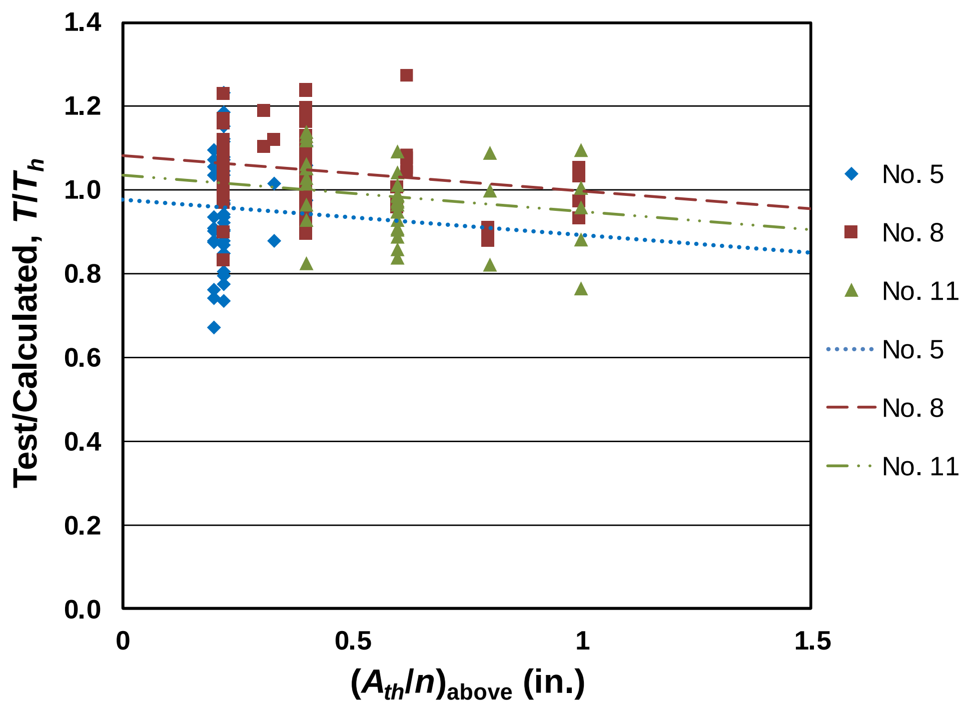


Figure 4.43a Ratio of test-to-calculated bar force at failure T/T_h for two-hook specimens with confining reinforcement per hooked bar versus $(A_{th}/n)_{above}$, with T_h calculated using Eq. (4.10)

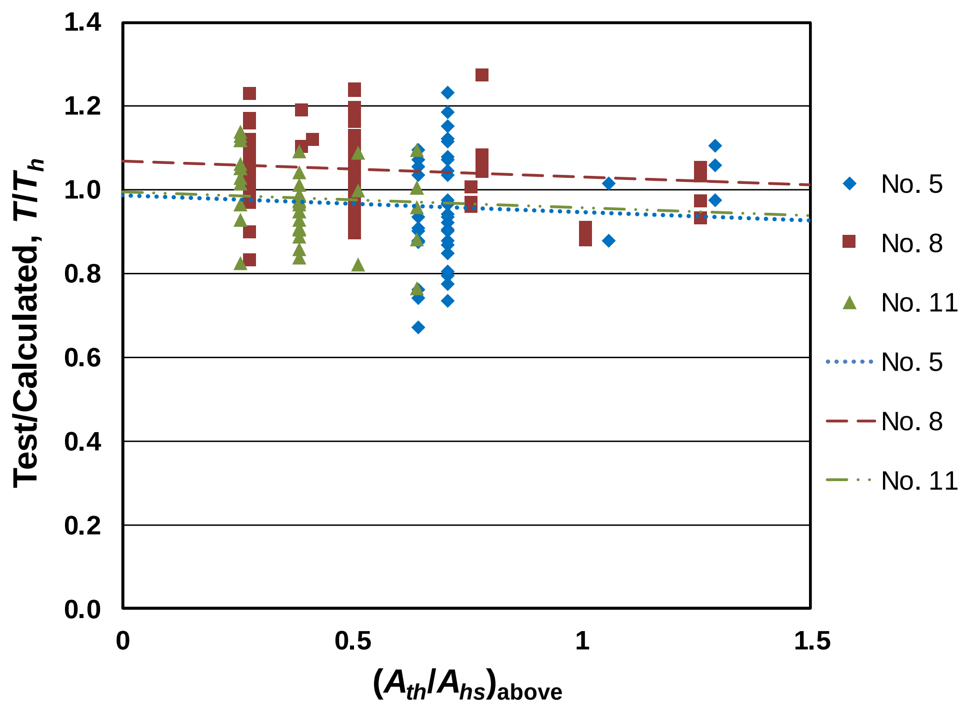


Figure 4.43b Ratio of test-to-calculated bar force at failure T/T_h for two-hook specimens with confining reinforcement versus $(A_{th}/A_{hs})_{above}$, with T_h calculated using Eq. (4.10)

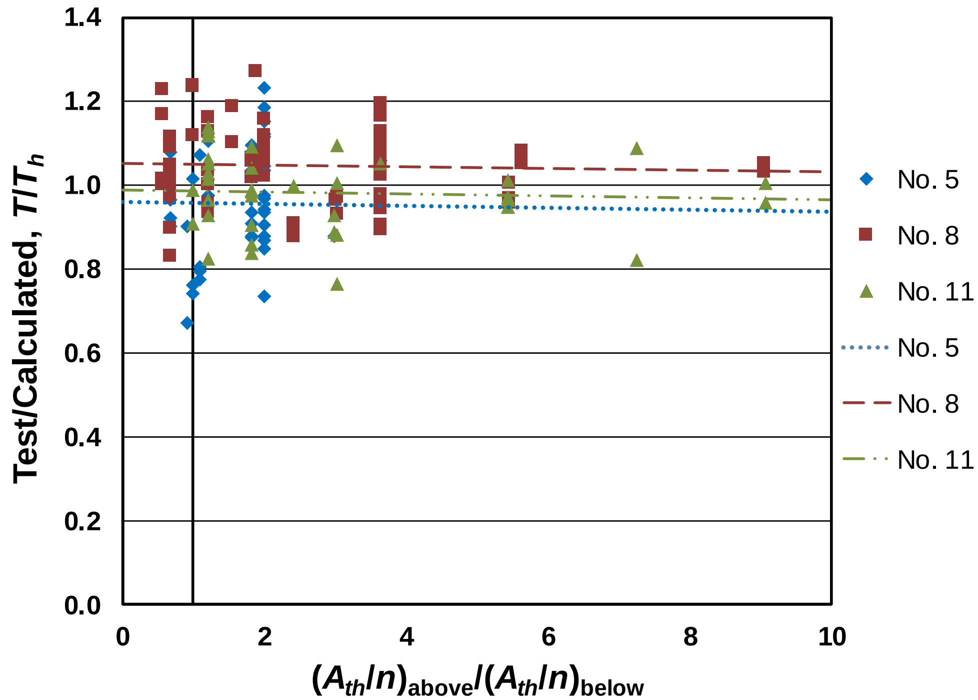


Figure 4.44 Ratio of test-to-calculated bar force at failure T/T_h for two-hook specimens with confining reinforcement versus $(A_{th}/n)_{\text{above}}/(A_{th}/n)_{\text{below}}$, with T_h calculated based on Eq. (4.10)

4.5 COMPARISON OF DESCRIPTIVE EQUATIONS WITH OTHER SPECIMEN TYPES

4.5.1 Monolithic Beam-Column Joints

Hamad and Jumaa (2008) tested 12 monolithic exterior beam-column joints, of which six contained uncoated reinforcing bars and six contained galvanized hooked bars. Only the specimens with uncoated hooked bars are discussed in this section. Each specimen consisted of two cantilever beams connected to a single column, as shown in Figure 1.10 in Section 1.2.2. The tension reinforcement in the beams consisted of two No. 5, No. 8, or No. 10 hooked bars with a 90° bend angle. Of the six specimens with uncoated hooked bars, three had hooked bars anchored inside the column core (that is inside the column longitudinal reinforcement – identified by the suffix C in the specimen identification) and three had hooked bars anchored outside the column core (identified by the suffix U). No confining reinforcement was provided within the joint region. The column depth was 13.8 in. The embedment lengths were 5.9, 7.9, and 9.9 in. for No. 5, No. 8, and No. 10 hooked bars, respectively. The center-to-center spacing between hooked bars ranged from 4.9 to 11d_b for hooked bars inside the column core and from 6.5 to 14.1d_b for hooked bars outside the column core. Only one specimen contained closely-spaced hooked bars ($c_{ch} \leq 6d_b$). The ratio of beam depth to embedment length was 1.75, 1.3, and 1.0, respectively, for specimens containing No. 5, No. 8, and No. 10 hooked bars. Concrete compressive strengths ranged from 7,650 to 9,770 psi. The test parameters of the specimens are presented in Table 4.15. The table also presents the ratio of test-to-calculated bar force at failure T/T_h with T_h calculated using the descriptive equation for hooked bars without confining reinforcement, Eq. (4.9).

The specimen containing No. 5 hooked bars inside the column core (Specimen B16H-C) developed a plastic hinge within the beam (that is, the specimen did not fail in anchorage). Two of the specimens with hooked bars placed outside the column core (B-25H-U and B32H-U) had values of T/T_h that are about 17% lower than the specimens with hooked bars placed inside the column core (B25H-C and B32H-C). The value of T/T_h for the third specimen with hooked bars placed outside the column core, B16H-U, is 24% lower that its companion specimen, B16H-C, which failed by yielding. These observations are similar to those of the simulated beam-column joint specimens described in Section 4.4.4.2, where hooked bars placed outside the column core exhibited 15% lower anchorage strength than hooked bars placed inside the column core. Regardless of the location of the hooked bars, the ratio of test-to-calculated bar force T/T_h increased as the ratio of beam depth to embedment length d/ℓ_{eh} decreased, which matches the observation in Section 4.4.3 that hooked bars in simulated beam-column joints exhibited less anchorage strength with d/ℓ_{eh} greater than 1.5.

Table 4.15 Test parameters for monolithic beam-column specimens comparing hooked bars placed inside and outside the column core (Hamad and Jumaa 2008)[a]

Specimen	Bend Angle	Hook Location	ℓ_{eh} in.	f_{cm} psi	b in.	c_{so} in.	c_{ch}/d_b in.	N_h	d_b in.	d/ℓ_{eh}	T lb	T/T_h[c]	Failure Type[b]
B16H-C	90°	Inside	5.9	7650	11.8	2.2	11.0	2	0.63	1.75	27480	1.21	Bar Yield
B25H-C	90°	Inside	7.9	7650	11.8	2.2	7.5	2	1.0	1.3	46100	1.20	SS
B32H-C	90°	Inside	9.8	7650	11.8	2.2	4.9	2	1.27	1.0	67800	1.42	SS
B16H-U	90°	Outside	5.9	9770	11.8	1.2	14.1	2	0.63	1.75	21850	0.90	SS
B25H-U	90°	Outside	7.9	9770	11.8	1.2	8.5	2	1.0	1.3	42980	1.04	SS
B32H-U	90°	Outside	9.8	9770	11.8	1.2	6.5	2	1.27	1.0	69250	1.17	SS

[a]Values are converted from SI, 1 in. = 25.4 mm, 1 psi = 0.0069 MPa, and 1 lb = 0.0045 kN
[b]SS = Side Splitting failure mode
[c]Calculated anchorage strength is based on Eq. (4.9)

4.5.2 Hooks Anchored in Walls

Johnson and Jirsa (1981) tested 30 exterior beam-wall joints containing hooked bars with a short embedment lengths. The specimens were walls with beams represented by hooked bars and a bearing member. Twenty-six specimens contained one No. 4, No. 7, No. 9, or No. 11 hooked bar with a 90° bend angle placed in a 24×52 in. wall, and four specimens contained three No. 7 or No. 11 hooked bars with a 90° bend angle placed in a 72×52 in. wall. The center-to-center spacing between the multiple hooked bars was 11 or 22 in. The straight portion of the hooked bars ranged from zero to 3 in., corresponding to embedment lengths ℓ_{eh} ranging from 2 to 7 in., none of which satisfies the Code requirement for the minimum development length (maximum of $8d_b$ and 6in.). The tail cover was 1.5 in. No confining reinforcement was provided within the joint region. Johnson and Jirsa also investigated the effect of the internal moment arm of the beams, the distance from the center of the hooked bars to the center of the bearing member (8 to 18 in.) corresponding to ratio of effective beam depth to embedment length d_{eff}/ℓ_{eh} (see Section 4.4.3) ranging from 1.3 to 3.6. Concrete side cover ranged from $11^1/_4$ to 25 in., and concrete compressive strengths ranged from 2,500 to 5,450 psi.

As part of the current study, three multiple-hook specimens were tested containing three No. 5 hooked bars with a 90° bend angle placed in $18^3/_8$×54 in. columns, simulating beam-wall joints, with a nominal concrete side cover of 2.5 in. The hooked bars were embedded to the far side of the member with a nominal tail cover of 2 in., inside the column core, and a center-to-center spacing of $10d_b$. Three levels of confining reinforcement were investigated, no confinement, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$. Concrete compressive strengths ranged from 5,880 to 5,950 psi.

The test parameters of the beam-wall specimens containing single hook tested by Johnson and Jirsa (1981) are presented in Table 4.16. The test parameters of the beam-wall specimens containing three hooked bars tested by Johnson and Jirsa (1981) and the three-hook beam-column specimens tested in the current study are presented in Table 4.17. In both tables, the calculated average bar force T_h is based on Eq. (4.9) for hooked bars without confining reinforcement and Eq. (4.10) for hooked bars with confining reinforcement.

Table 4.16 Test parameters for beam-wall specimens with a single hook tested by Johnson and Jirsa (1981)

Specimen	f_{cm} psi	ℓ_{eh} in.	d_b in.	A_h in.^{2}	Lever Arm in.	d_{eff}/ℓ_{eh}	T kips	f_s ksi	T_h kips	T/T_h[a]
4-3.5-8-M	4500	2.0	0.5	0.2	8.0	3.1	4.4	22	5.38	0.82
4-5-11-M	4500	3.5	0.5	0.2	11.0	2.7	12	60	9.88	1.22
4-5-14-M	4500	3.5	0.5	0.2	14.0	3.5	9.8	49	9.88	0.99
7-5-8-L	2500	3.5	0.875	0.60	8.0	2.1	13	21.7	10.8	1.20
7-5-8-M	4600	3.5	0.875	0.60	8.0	1.9	16.5	27.5	12.9	1.28
7-5-8-H	5450	3.5	0.875	0.60	8.0	1.9	19.5	32.5	13.6	1.43
7-5-8-M	3640	3.5	0.875	0.60	8.0	2.0	14.7	24.5	12.1	1.22
7-5-14-L	2500	3.5	0.875	0.60	14.0	3.6	8.5	14.2	10.8	0.79
7-5-14-M	4100	3.5	0.875	0.60	14.0	3.6	11.2	18.7	12.5	0.90
7-5-14-H	5450	3.5	0.875	0.60	14.0	3.5	11.9	19.8	13.6	0.88
7-5-14-M	3640	3.5	0.875	0.60	14.0	3.6	11.3	18.8	12.1	0.94
7-7-8-M	4480	5.5	0.875	0.60	8.0	1.3	32	53.3	20.9	1.53
7-7-11-M	4480	5.5	0.875	0.60	11.0	1.8	27	45	20.9	1.29
7-7-14-M	5450	5.5	0.875	0.60	14.0	2.3	22	36.7	22.2	0.99
9-7-11-M	4500	5.5	1.128	1.0	11.0	1.9	30.8	30.8	23.6	1.30
9-7-14-M	5450	5.5	1.128	1.0	14.0	2.3	24.8	24.8	25.0	0.99
9-7-18-M	4570	5.5	1.128	1.0	18.0	3.1	22.3	22.3	23.7	0.94
7-8-11-M	5400	6.5	0.875	0.60	11.0	1.6	34.8	58	26.5	1.31
7-8-14-M	4100	6.5	0.875	0.60	14.0	2.0	26.5	44.2	24.5	1.08
9-8-14-M	5400	6.5	1.128	1.0	14.0	2.0	30.7	30.7	29.9	1.03
11-8.5-11-L	2400	7.0	1.41	1.56	11.0	1.8	37	23.7	28.3	1.31
11-8.5-11-M	4800	7.0	1.41	1.56	11.0	1.6	51.5	33.0	34.8	1.48
11-8.5-11-H	5450	7.0	1.41	1.56	11.0	1.6	54.8	35.1	36.1	1.52
11-8.5-14-L	2400	7.0	1.41	1.56	14.0	2.1	31	19.9	28.3	1.09
11-8.5-14-M	4750	7.0	1.41	1.56	14.0	1.9	39	25	34.6	1.13
11-8.5-14-H	5450	7.0	1.41	1.56	14.0	1.9	45.4	29.1	36.1	1.26

[a] Calculated anchorage strength is based on Eq. (4.9) or (4.10) depending on the presence of confining reinforcement

Table 4.17 Test parameters for beam-wall specimens with tested by Johnson and Jirsa (1981) and three-hook beam-column specimens tested in the current study

Specimen	f_{cm} psi	ℓ_{eh} in.	d_b in.	A_h in.^{2}	Lever Arm in.	d_{eff}/ℓ_{eh}	spacing in.	T kips	f_s ksi	T_h kips	T/T_h[c]
7-7-11-M[a]	3800	5.5	0.875	0.60	24	1.9	11	24	40	20.0	1.20
7-7-11-L[a]	3000	5.5	0.875	0.60	22.7	1.9	22	22.7	37.8	18.6	1.22
11-8.5-11-M[a]	3800	7.0	1.41	1.56	38	1.6	11	38	24.4	32.4	1.17
11-8.5-11-L[a]	3000	7.0	1.41	1.56	40	1.7	22	40	25.6	30.3	1.32
(3@10) 5-5-90-0-i-2.5-2-7[b]	5880	6.7	0.625	0.31	9.4	0.9	5.6	21	67.7	23.9	0.88
(3@10) 5-5-90-2#3-i-2.5-2-7[b]	5950	7.0	0.625	0.31	9.4	1.0	5.6	31.3	101.0	27.8	1.13
(3@10) 5-5-90-5#3-i-2.5-2-7[b]	5950	6.9	0.625	0.31	9.4	1.0	5.6	31.7	102.3	33.2	0.96

[a] Tested by Johnson and Jirsa (1981)
[b] Tested as part of the current study at the University of Kansas
[c] Calculated anchorage strength is based on Eq. (4.9) or (4.10) depending on the presence of confining reinforcement

Figure 4.45 shows the measured average bar force at failure T for the beam-wall specimens containing single hooked bars (No. 4, No. 7, No. 9 and No. 11) and three hooked bars (No. 7 and

No. 11) tested by Johnson and Jirsa (1981) and the three-hook specimens containing three No. 5 hooked bars with 10d_b center-to-center spacing tested in the current study plotted versus calculated bar force T_h; the calculated bar force is based on Eq. (4.9) for hooked bars without confining reinforcement and Eq. (4.10) for hooked bars with confining reinforcement. Most of the specimens fall above the equality line showing that the descriptive equations conservatively predict the anchorage strength. Specimens with a single hooked bar have ratios of test-to-calculated bar force T/T_h ranging from 0.79 to 1.53 with an average of 1.15; specimens with multiple hooked bars have T/T_h ratios ranging from 0.88 to 1.32 with an average of 1.13. This indicates that the confinement provided by the high concrete side cover (beam-wall specimens) results in anchorage strength of similar or superior to that of hooks anchored inside the column core (beam-column specimens).

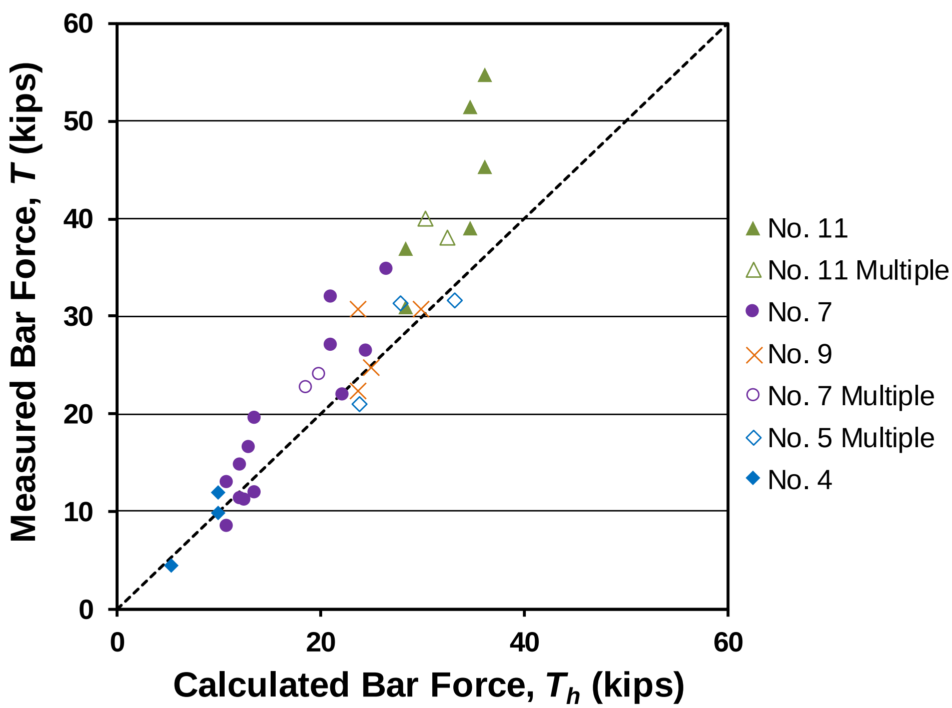


Figure 4.45 Measured bar force at failure versus calculated bar force beam- wall specimens including Multiple-hook specimens with No. 5 at 10d_b, with T_h calculated using Eq. (4.9) and (4.10)

The beam-wall specimens tested by Johnson and Jirsa (1981) had a beam depth (the distance from the center of the hooked bars to the center of the bearing member) ranging from 8 to 18 in., corresponding to ratio of effective beam depth to embedment length d_{eff}/ℓ_{eh} (see Section

4.4.3) ranging from 1.3 to 3.6. Figure 4.46 shows the ratio of test-to-calculated average bar force at failure T/T_h plotted versus the ratio of effective beam depth to embedment length d_{eff}/ℓ_{eh}. The ratio of test-to-calculated bar force consistently decreases as d_{eff}/ℓ_{eh} increases. For values of d_{eff}/ℓ_{eh} above 3.0, the anchorage strengths are less than predicted by the descriptive equations. This analysis shows that hooked bars anchored in walls with shallow embedment exhibit a qualitative effect of d_{eff}/ℓ_{eh} similar to beam-column joint specimens, although the threshold for hooked bars in walls is double that of hooked bars in beam-column joints (d_{eff}/ℓ_{eh} of 1.5). A similar relationship was observed by Shao et al. (2016) for headed bars anchored with shallow embedment and high concrete side cover. With the high concrete side cover in beam-wall joints, the hooked bars exhibited a full concrete cone failure "pullout cone". With the relatively small concrete side cover, the concrete cone is limited, providing less concrete to contribute to anchorage strength.

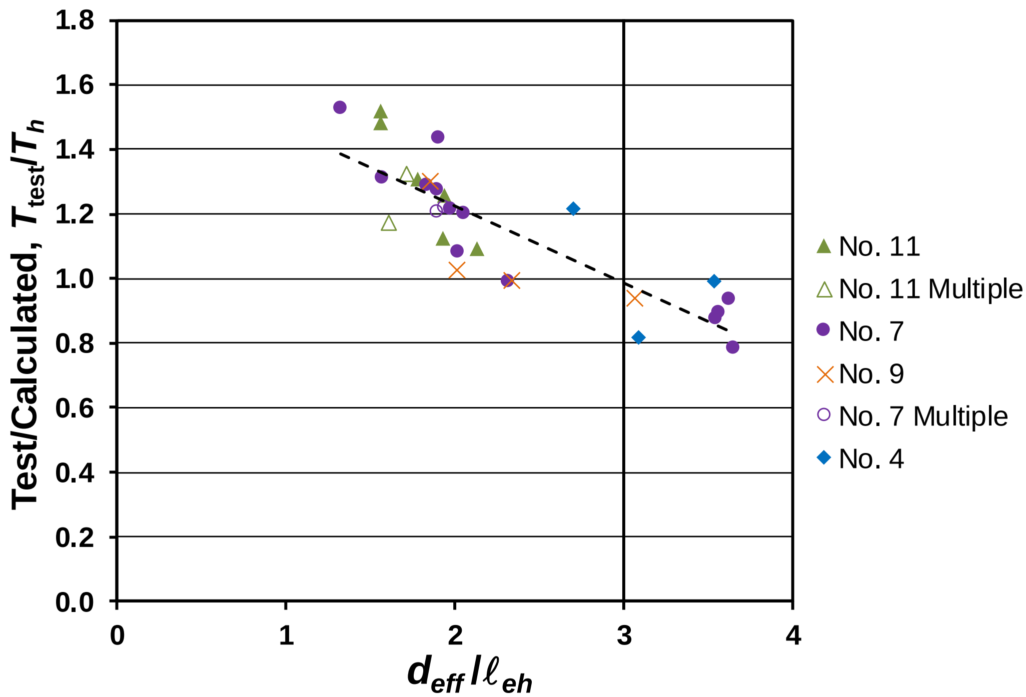


Figure 4.46 Ratio of test-to-calculated bar force at failure T/T_h for beam-wall specimens, with T_h calculated using Eq. (4.9) and (4.10)

4.6 SPECIMENS NOT USED TO DEVELOP DESCRIPTIVE EQUATIONS

Beam-column joint specimens not used to develop the descriptive equations are evaluated in this section. They consisted of 12 specimens with two or three hooked bars tested as part of this study with a column longitudinal reinforcement ratio ρ_{col} greater than 4%, not common in practice, and 29 specimens with two hooked bars with ρ_{col} less than 4%, of which 23 specimens were tested by other researchers (Marques and Jirsa 1975, Pinc et al. 1977, Hamad et al. 1993, Ramirez and Russell 2008, Lee and Park 2010) and six were tested in this study. Of the 29 specimens with two hooked bars, 13 contained two closely-spaced hooked bars (c_{ch} < $6d_b$) without confining reinforcement (11 tested by other researchers and two from this study), eight contained two closely-spaced hooked bars with confining reinforcement (four tested by other researchers and four from this study), and eight contained two widely-spaced hooked bars with confining reinforcement (tested by other researchers). Specimens with two closely-spaced hooked bars (tested by other researchers) had two No. 11 hooked bars with 90° and 180° bend angle without and with confining reinforcement; these specimens were initially included in the analysis but they had high ratios of test-to-calculated bar for force at failure T/T_h compared to specimens with closely-spaced hooked bars tested in the current study. The high values of T/T_h result from the high confinement inherent in these tests. The No. 11 hooked bars with a 180° bend angle had the tail extension within the compression zone of the beam with a concrete cover to the bearing member of not more than 0.5 in., while the No. 11 hooked bars with a 90° bend angle had most of the tail extension within the compression zone of the beam. The majority of the specimens containing two closely-spaced hooked bars were tested by other researchers, as discussed earlier. To be consistent, the small number of specimens (six) containing two closely-spaced hooked bars (c_{ch} < $6d_b$) tested in the current study were also not used to develop the descriptive equations. Specimens containing widely-spaced hooked bars with confining reinforcement (tested by other researchers) were not used because they represent a small number of specimens compared to the database developed in this study and because of the inherent variability in the contribution of the confining reinforcement to the anchorage strength of hooked bars and differences in specimen design.

4.6.1 Specimens with Column Longitudinal Reinforcement Ratio > 4.0%

Figure 4.47 shows the ratio of test-to-calculated average bar force at failure T/T_h for nine two-hook and three three-hook specimens plotted versus the column reinforcement ratio ρ_{col}. The calculated average bar force is based on Eq. (4.9) for hooked bars without confining reinforcement and Eq. (4.10) for hooked bars with confining reinforcement. Of the nine two-hook specimens, two contained No. 5 hooked bars with a 90° bend angle without confining reinforcement and seven contained No. 8 hooked bars with 90° or 180° bend angles and three levels of confining reinforcement, no confinement, two No. 3 hoops, and No. 3 hoops spaced at $3d_b$ (five No. 3 hoops). The three-hook specimens contained No. 8 hooked bars with a 180° bend angles and the same three levels of confining reinforcement investigated with the two-hook specimens. Test parameters of the specimens are presented in Table 4.18. As shown in Figure 4.47, the ratio of test-to-calculated bar force increased as the column reinforcement ratio ρ_{col} increased. Most specimens had a test-to-calculated ratio greater than 1.0, indicating that a high longitudinal reinforcement ratio contributes to the anchorage strength of hooked bars within a joint and justifying the exclusion of these specimens from the analysis.

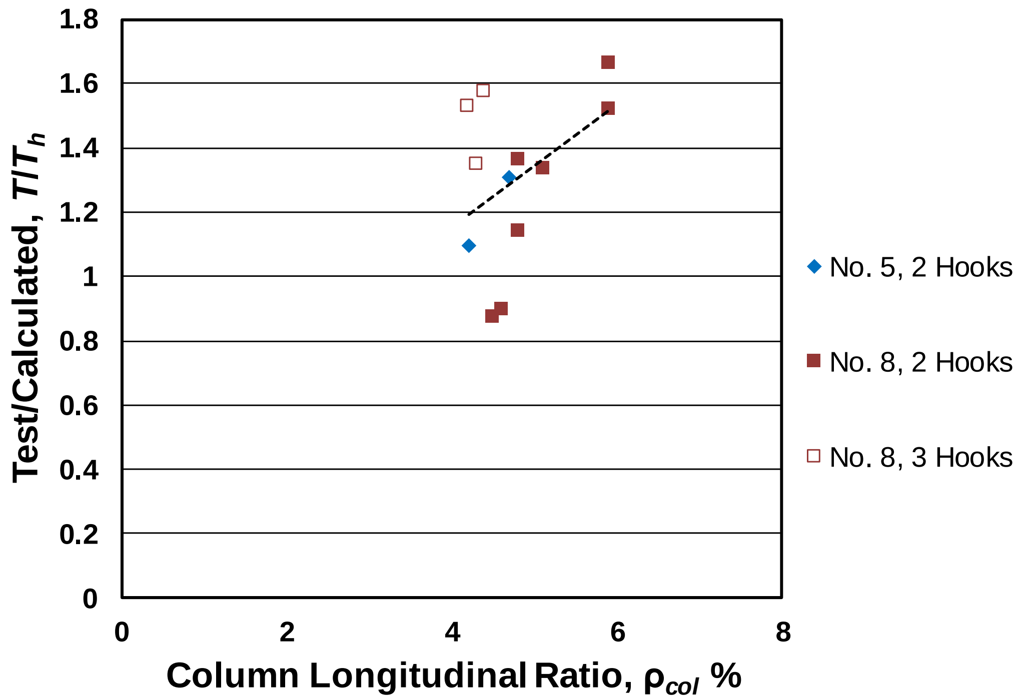


Figure 4.47 Ratio of test-to-calculated bar force at failure T/T_h for specimens with high column longitudinal ratio versus ρ_{col}, with T_h calculated using Eq. (4.9) or (4.10)

Table 4.18 Test parameters for specimens with high column longitudinal reinforcement ratio

Specimen[a]	Hook	ℓ_{eh} in.	f_{cm} psi	b in.	c_{ch} in.	N_h	$A_{tr,l}$ in.^{2}	T lb	T/T_h	ρ_{col}	Failure Type[b]
(2@4) 5-8-90-0-i-2.5-2-6[c]	A B	5.8 6.0	6950	8.1	2.5	2	-	22353	1.31	0.047	FP FP
(2@6) 5-8-90-0-i-2.5-2-6[c]	A B	6.0 6.0	6950	9.4	3.8	2	-	23951	1.09	0.042	FP/SS FP/SS
(2@3) 8-5-180-0-i-2.5-2-10[c,d]	A B	10.3 10.0	5260	9.0	3.0	2	-	51825	1.66	0.059	FP FP
(2@5) 8-5-180-0-i-2.5-2-10[c,d]	A B	10.0 10.0	5260	11.0	5.1	2	-	53165	1.33	0.051	FP FP
(2@3) 8-5-180-2#3-i-2.5-2-10[c,d]	A B	10.3 10.3	5400	9.0	3.0	2	0.11	57651	1.50	0.059	FP FP
(2@5) 8-5-180-2#3-i-2.5-2-10[c,d]	A B	10.3 9.8	5400	11.0	5.0	2	0.11	61885	1.36	0.048	FB FB
(2@5) 8-5-180-5#3-i-2.5-2-10[c,d]	A B	10.0 10.3	5540	11.0	5.0	2	0.11	66644	1.13	0.048	FB FB
8-15-90-2#3-i-2.5-2-6[c]	A B	6.1 6.1	15800	17	10.9	2	0.11	37569	0.90	0.046	FP FP
8-15-90-5#3-i-2.5-2-6[c]	A B	6.5 6.1	15800	17	10.8	2	0.11	48499	0.88	0.045	FP FP
(3@3) 8-5-180-0-i-2.5-2-10[c,d]	A B C	9.8 10.0 9.8	5260	12.0	3.0 3.0 -	3	-	47249	1.57	0.044	FP FP FP
(3@3) 8-5-180-2#3-i-2.5-2-10[c,d]	A B C	10.5 10.3 10.0	5400	12.0	3.0 3.0 -	3	0.11	54576	1.42	0.042	FP FP FP
(3@3) 8-5-180-5#3-i-2.5-2-10[c,d]	A B C	10.1 9.9 9.8	5540	12.0	3.0 3.0 -	3	0.11	58877	1.34	0.043	FP FP FP

[a]Notation described in Section 2.1 and Appendix A
[b]Failure type described in Section 3.3
[c]Specimen had column longitudinal reinforcement ratio > 4.0%
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement

4.6.2 Specimens with Column Longitudinal Reinforcement Ratio < 4.0%

Figure 4.48 shows the measured average bar force at failure T plotted versus the calculated average bar force based on Eq. (4.9) for hooked bars without confining reinforcement and Eq. (4.10) for hooked bars with confining reinforcement for the 29 two-hook specimens with two hooked bars with ρ_{col} less than 4%, not used to develop the descriptive equations. The test parameters and sources of the specimens are presented in Table 4.19. The specimens included 13 without confining reinforcement containing No. 8, No. 9, and No. 11 closely-spaced hooked bars with 90° or 180° bend angles, eight with confining reinforcement containing No. 8 and No. 11 closely-spaced hooked bars with 90° bend angle, and eight with confining reinforcement containing No. 6, 7, and 11 widely-spaced hooked bars with 90° or 180° bend angles. In Figure 4.48, specimens without confining reinforcement are denoted with hollow symbols and specimens with confining reinforcement are denoted with solid symbols. All specimens without confining reinforcement had test-to-calculated ratios greater than 1.0 (1.05 to 1.77, with an average of 1.39). Specimens with confining reinforcement had ratios of test-to-calculated ranging from 0.67 to 1.41 with an average of 1.03. This analysis shows that the descriptive equation accurately represents the anchorage strength of hooked bars with confining reinforcement and is conservative for specimens without confining reinforcement tested in this group of specimens.

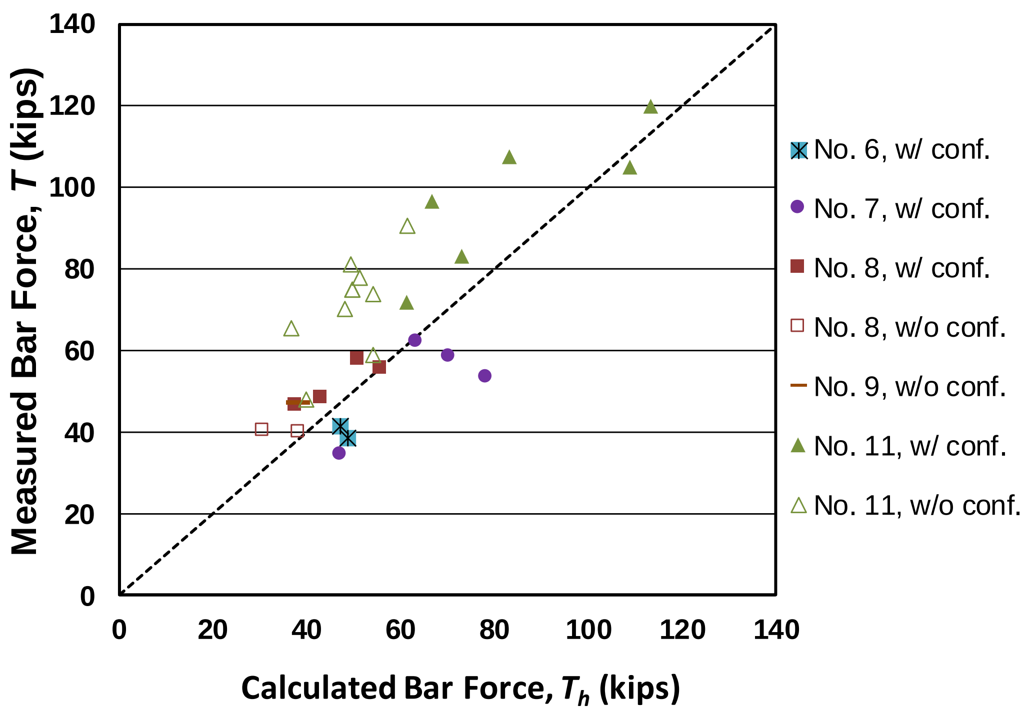


Figure 4.48 Measured bar force at failure T versus calculated bar force for two-hook specimens with $\rho_{col.}$ < 4% not used to develop the descriptive equations, with T_h calculated using Eq. (4.9) and (4.10)

Table 4.19 Test parameters for two-hook specimens with column longitudinal reinforcement ratio < 4% not used to develop descriptive equations

Specimen[a]	**Hook**	**Hook Location**	ℓ_{eh} **in.**	f_{cm} **psi**	b **in.**	c_h **in.**	N_h	$A_{tr,l}$ **in.**^{2}	T **lb**	T/T_h	**Source**
(2@3) 8-5-90-0-i-2.5-2-10[c]	A B	Inside[b]	10.4 10.6	4490	9	2.0	2	-	40313	1.31	Current Investigation
(2@5) 8-5-90-0-i-2.5-2-10[c]	A B	Inside	10.1 10.1	4490	11	4.1	2	-	40052	1.05	Current Investigation
9-12	-	Inside	10.0	4700	12	4.0	2	-	47000	1.23	Pinc et al. (1977)
J 11 - 180 -15 -1 - H	-	Inside	13.1	4400	12	3.4	2	-	70200	1.45	Marques and Jirsa (1975)
J 11- 90 -12 -1 - H	-	Inside	10.1	4600	12	3.4	2	-	65520	1.78	Marques and Jirsa (1975)
J 11- 90 -15 -1 - H	-	Inside	13.1	4900	12	3.4	2	-	74880	1.50	Marques and Jirsa (1975)
J 11- 90 -15 -1 - L	-	Inside	13.1	4750	12	3.4	2	-	81120	1.64	Marques and Jirsa (1975)
11-15	-	Inside	13.1	5400	12	3.4	2	-	78000	1.52	Pinc et al. (1977)
11-18	-	Inside	16.1	4700	12	3.4	2	-	90480	1.47	Pinc et al. (1977)
11-90-U	-	Inside	13.0	2570	12	3.2	2	-	48048	1.20	Hamad et al. (1993)
11-90-U*	-	Inside	13.0	5400	12	3.2	2	-	75005	1.50	Hamad et al. (1993)
11-180-U-HS	-	Inside	13.0	7200	12	3.2	2	-	58843	1.08	Hamad et al. (1993)
11-90-U-HS	-	Inside	13.0	7200	12	3.2	2	-	73788	1.36	Hamad et al. (1993)

[a]Notation described in Section 2.1 and Appendix A
[b]Inside or outside the column core
[c]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement

Figure 4.19 Cont. Test parameters for two-hook specimens with column longitudinal reinforcement ratio < 4% not used to develop descriptive equations

Specimen[a]	Hook	Hook Location	ℓ_{eh} in.	f_{cm} psi	b in.	c_h in.	N_h	$A_{tr,l}$ in.^{2}	T lb	T/T_h	Source
III-13	-	Inside	6.5	13980	15	8.5	2	0.11	41300	0.88	Ramirez and Russell (2008)
III-15	-	Inside	6.5	16350	15	8.5	2	0.11	38500	0.79	Ramirez and Russell (2008)
7-180-U-T4	-	Inside	10.0	3900	12	4.3	2	0.11	34620	0.74	Hamad et al. (1993)
J 7- 90 -15 -3a - H	-	Outside	13.0	3750	12	4.5	2	0.11	58800	0.85	Marques and Jirsa (1975)
H3	-	Inside	15.0	4453	14.64	7.8	2	0.11	53761	0.69	Lee and Park (2010)
J 7- 90 -15 -3 - H	-	Outside	13.0	4650	12	4.5	2	0.11	62400	1.00	Marques and Jirsa (1975)
(2@3) 8-5-90-2#3-i-2.5-2-10[d]	A B	Inside	10.0 10.5	4760	9	2.3	2	0.11	46810	1.24	Current Investigation
(2@5) 8-5-90-2#3-i-2.5-2-10[d]	A B	Inside	9.6 10.0	4760	11	3.9	2	0.11	48515	1.13	Current Investigation
(2@3) 8-5-90-5#3-i-2.5-2-10[c]	A B	Inside	10.0 10.5	4805	9	2.0	2	0.11	57922	1.14	Current Investigation
(2@5) 8-5-90-5#3-i-2.5-2-10[c]	A B	Inside	9.9 9.5	4805	11	4.3	2	0.11	55960	1.01	Current Investigation
III-14	-	Inside	12.5	13980	15	7.2	2	0.11	105000	0.96	Ramirez and Russell (2008)
III-16	-	Inside	12.5	16500	15	7.2	2	0.11	120000	1.06	Ramirez and Russell (2008)
11-90-U-T6	-	Inside	13.0	3700	12	3.2	2	0.11	71807	1.17	Hamad et al. (1993)
J 11- 90 -15 -3a - L	-	Outside	13.1	5000	12	3.4	2	0.11	107640	1.29	Marques and Jirsa (1975)
11-90-U-T4	-	Inside	13.0	4230	12	3.2	2	0.11	83195	1.14	Hamad et al. (1993)
J 11- 90 -15 -3 - L	-	Outside	13.1	4850	12	3.4	2	0.11	96720	1.44	Marques and Jirsa (1975)

[a]Notation described in Section 2.1 and Appendix A
[b]Inside or outside the column core
[c]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement

CHAPTER 5: DESIGN PROVISIONS

5.1 GENERAL

In Chapter 4, descriptive equations were developed to characterize the anchorage strength of hooked bars based on a statistical analysis of test results for simulated beam-column joint specimens with different levels and orientations of confining reinforcement and different spacing between hooked bars. The goal of this chapter is to use the descriptive equations to develop code provisions for the development length of reinforcing bars terminated in standard hooks that are easy to apply and conservative; the code provisions incorporate the effects of bar size, concrete compressive strength, embedment length, amount and orientation of confining reinforcement within the joint region, spacing between hooked bars, ratio of beam depth to embedment length, and hooked bar location (inside or outside the column core). To do so, the descriptive equations are initially simplified by rounding the powers of the parameters. The simplified equations are then solved for development length, incorporating provisions for confining reinforcement, spacing between bars, and bar location and a strength reduction factor. The final version of the design provisions are compared with test results for specimens from this study as well as specimens from other studies (Marques and Jirsa 1975, Pinc et al. 1977, Johnson and Jirsa 1981, Hamad et al. 1993, Joh et al. 1995, Joh and Shibata 1996, Ramirez and Russell 2008, Hamad and Jumaa 2008, Lee and Park 2010, Peckover and Darwin 2013, Searle et al. 2014, and Sperry et al. 2015a, 2015b, 2017a).

5.2 SIMPLIFIED DESCRIPTIVE EQUATIONS

5.2.1 Widely-Spaced Hooked Bars Without and With Parallel Confining Reinforcement

Equation (4.8) was developed to characterize the anchorage strength of two widely-spaced hooked bars ($c_{ch} \geq 6d_b$) without and with confining reinforcement oriented parallel to the straight portion of the bar within the joint region

$$T_h = 294 f_{cm}^{0.295} \ell_{eh}^{1.0845} d_b^{0.47} + 55050 \left(\frac{A_{th}}{n} \right)^{1.0175} d_b^{0.73} \tag{4.8}$$

where T_h is the anchorage strength of hooked bars (lb) without confining reinforcement and with confining reinforcement provided parallel to the straight potion of the hooked bars, f_{cm} is the concrete compressive strength (psi), ℓ_{eh} is the embedment length (in.), d_b is the bar diameter (in.), A_{th} is the total cross-sectional area of all parallel confining reinforcement located within $8d_b$ of the top (or bottom) of the hooked bars for No. 3 through No. 8 hooked bars or within $10d_b$ for No. 9 though No. 11 hooked bars (in.^{2}), and n is the number of hooked bars being developed.

To provide an equation suitable for use in design, several steps are taken to simplify Eq. (4.8). First, the power of embedment length ℓ_{eh} (1.085) is rounded to 1.0, the power of concrete compressive strength f_{cm} (0.295) is set to 0.25, the powers of bar diameter d_b (0.47 and 0.73) are rounded to 0.5 and 0.75 in the first and second terms, respectively, and the power of the term A_{th}/n is set to 1.0. The biggest change is in the power of f_{cm} from 0.295 to 0.25. This is justified based on observations by Zuo and Darwin (2000), the basis of the equation developed by ACI Committee 408, and Shao et al. (2016) that f_{cm} to the 0.24 power gives the best match with data for spliced straight and headed deformed bars, respectively, and that the more practical representation, $f_{cm}^{0.25}$, provides nearly as good a match for splice and headed-bar anchorage strength and, as will be shown in this chapter, with hooked bar anchorage strength. Ultimately, the goal is to have a consistent approach to development length that covers spliced straight, hooked, and headed deformed bars.

Using the simplifications, the descriptive equation, Eq. (4.8), becomes

$$T_h = \mathrm{A}_1 f_{cm}^{0.25} \ell_{eh} d_b^{0.5} + \mathrm{A}_2 \frac{A_{th}}{n} d_b^{0.75} \tag{5.1}$$

The variables are defined after Eq. (4.8).

The value of the coefficient A_1 is selected so that the two-hook beam-column joint specimens without confining reinforcement (the specimens used to develop the descriptive equation in Chapter 4) have a mean value of test-to-calculated bar force of 1.0. With the coefficient A_1 fixed, the value of the coefficient A_2 is selected so that the two-hook beam-column joint specimens with confining reinforcement (the specimens used to develop the descriptive equation in Chapter 4) have a mean value of test-to-calculated bar force of 1.0. Based on this A_1 = 539, A_2 = 57,500, and the simplified descriptive equation becomes

$$T_h = 539 f_{cm}^{0.25} \ell_{eh} d_b^{0.5} + 57{,}500 \frac{A_{th}}{n} d_b^{0.75} \tag{5.2}$$

Figures 5.1 and 5.2 show the ratio of average bar force at failure T to the calculated bar force T_h based on Eq. (5.2) plotted versus the concrete compressive strength for hooked bars without and with confining reinforcement within the joint region, respectively. The plots include test results from this study and those from previous work (Marques and Jirsa 1975, Hamad et al. 1993, Ramirez and Russell 2008, Lee and Park 2010). The trend lines (from dummy variable analysis with the data separated based on the bar size) for both plots have a slight positive slope indicating that the simplified equation predicts a progressively safer anchorage strength as the concrete compressive strength increases. This behavior would be expected since the power of the concrete compressive strength was decreased from 0.295 in the descriptive equation, Eq. (4.8), to 0.25 in the simplified descriptive equation, Eq. (5.2). The order of hooked bars of different sizes listed in the legend corresponds to the order of trend lines in the plot, this is true for all plots in this chapter. In Figures 5.1 and 5.2, the order of the trend lines is not a function of bar diameter, indicating that the simplified descriptive equation properly captures the effect of bar diameter. The statistical parameters for Eq. (5.2) (maximum, minimum, mean, standard deviation, coefficient of variation, and number of specimens for different bar sizes) are summarized in Tables 5.1a for hooked bars without confining reinforcement and Table 5.1b for hooked bars with confining reinforcement. Specimens without confining reinforcement have a mean value of T/T_h of 1.0 with a maximum value of 1.30 and a minimum value of 0.72; the standard deviation and the coefficient of variation are 0.12. Specimens with confining reinforcement have a mean value of T/T_h of 1.0 with a maximum value of 1.25 and a minimum value of 0.66; the standard deviation and the coefficient of variation are 0.116.

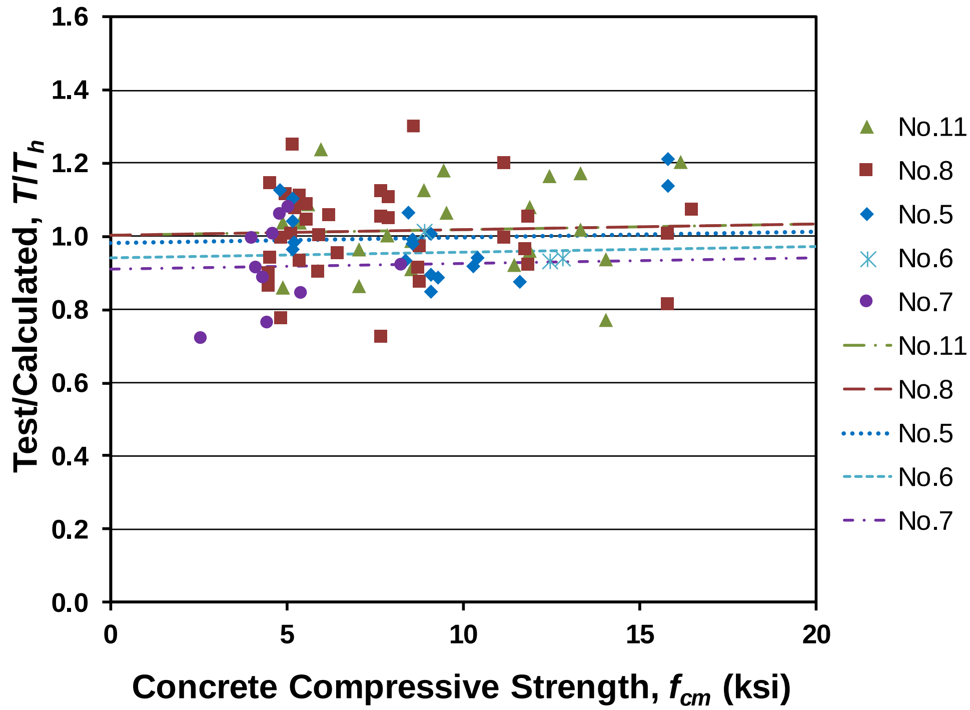


Figure 5.1 Ratio of test-to-calculated bar force T/T_h at failure versus concrete compressive strength f_{cm} for two-hook specimens without confining reinforcement, with T_h based on Eq. (5.2)

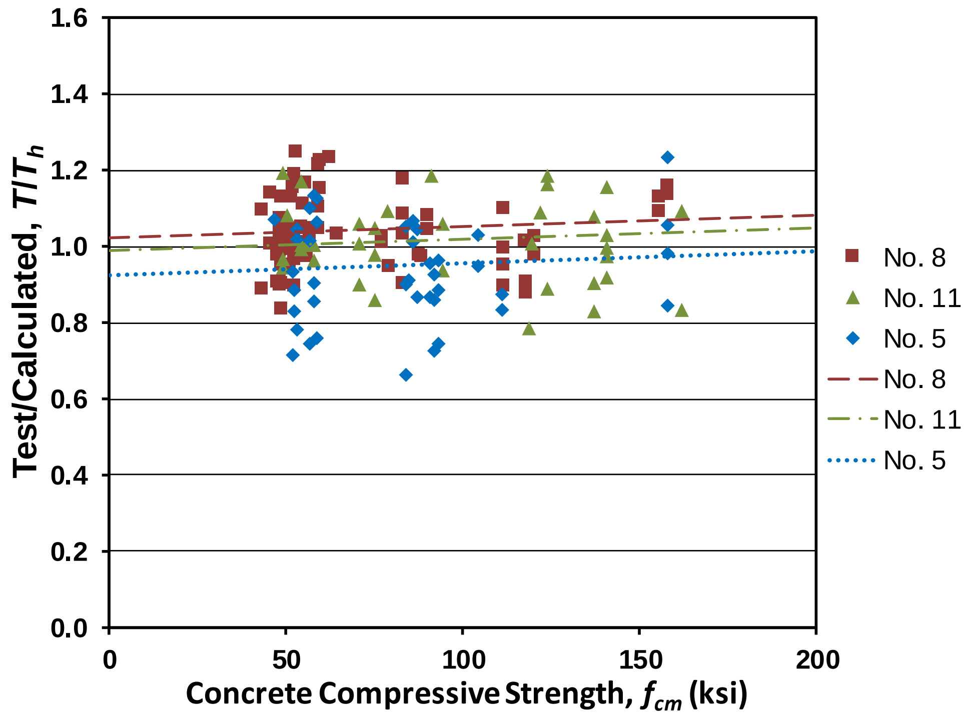


Figure 5.2 Ratio of test-to-calculated bar force T/T_h at failure versus concrete compressive strength f_{cm} for two-hook specimens with confining reinforcement, with T_h based on Eq. (5.2)

Table 5.1a Statistical parameters of T/T_h for hooked-bar beam-column joint specimens without confining reinforcement, with T_h based on Eq. (5.2)

	All	No. 5	No. 6	No. 7	No. 8	No. 11
Max.	1.30	1.21	1.01	1.08	1.30	1.24
Min.	0.72	0.85	0.93	0.72	0.73	0.77
Mean	1.00	0.99	0.96	0.92	1.02	1.02
STD	0.120	0.102	0.045	0.120	0.125	0.123
COV	0.120	0.102	0.047	0.131	0.123	0.121
Number of Specimens	88	18	3	10	33	24

Table 5.1b Statistical parameters of T/T_h for hooked-bar beam-column joint specimens with confining reinforcement, with T_h based on Eq. (5.2)

	All	No. 5	No. 8	No. 11
Max.	1.25	1.24	1.25	1.18
Min.	0.66	0.66	0.84	0.78
Mean	1.00	0.93	1.04	1.01
STD	0.116	0.131	0.095	0.106
COV	0.116	0.140	0.092	0.105
Number of Specimens	149	41	70	38

5.2.2 Widely-Spaced Hooked Bars with Perpendicular Confining Reinforcement

Equation (4.13) was developed to characterize the anchorage strength of hooked bars with confining reinforcement oriented perpendicular to the straight portion of the bar (hoops spaced along the lead embedment portion of the hooked bars).

$$T_h = 294 f_{cm}^{0.295} \ell_{eh}^{1.0845} d_b^{0.47} + 27525 \left(\frac{A_{th}}{n} \right)^{1.0175} d_b^{0.73} \tag{4.13}$$

where A_{th} is the total cross-sectional area of all confining reinforcement perpendicular to straight portion of the hooked bars being developed (in.^{2}). As explained in Section 4.4.5, Eq. (4.13) was developed based on test results from twelve specimens; six specimens contained perpendicular confining reinforcement, four specimens contained parallel confining reinforcement, and two contained no confining reinforcement. Hooked bars in comparable specimens within this group (specimens with the same amount of total confining reinforcement within the joint region) have similar anchorage strengths. Because the effective amount of perpendicular confining reinforcement (for specimens in this group) was double that of parallel confining reinforcement, the contribution of the perpendicular confining reinforcement is approximately one-half of the contribution of parallel confining reinforcement. Equation (4.13) is simplified in a similar manner to Eq. (4.8) to obtain Eq. (5.2), giving

$$T_h = 539 f_{cm}^{0.25} \ell_{eh} d_b^{0.5} + 28750 \frac{A_{th}}{n} d_b^{0.75} \tag{5.3}$$

5.2.3 Closely-Spaced Hooked Bars

Figures 5.3 and 5.4 show, respectively, the test-to-calculated ratios of bar force at failure T/T_h for specimens with two or more hooks without confining reinforcement and with No. 3 hoops spaced at $3d_b$ as confining reinforcement plotted versus center-to-center spacing between hooked bars expressed in terms of bar diameter c_{ch}/d_b. The calculated bar force T_h is based on the simplified descriptive equation, Eq. (5.2). Figure 5.3 compares T/T_h for 108 specimens without confining reinforcement containing hooked bars with 90° or 180° bend angles. Of the 108 specimens, 77 specimens had two hooked bars with $c_{ch}/d_b > 6$, 11 specimens had two hooked bars with $c_{ch}/d_b = 6$, and 20 specimens had three or four hooked bars $c_{ch}/d_b \leq 6$. As demonstrated in Chapter 4, the anchorage strength of closely-spaced hooked bars decreases with decreasing c_{ch}/d_b. The trend line in Figure 5.3 suggests no reduction in anchorage strength of hooked bars without confining reinforcement with center-to-center spacing greater than approximately $6d_b$. Figure 5.4 compares T/T_h for 76 specimens with No. 3 hoops spaced at $3d_b$ as confining reinforcement containing hooked bars with 90° or 180° bend angles. Of the 76 specimens, 53 specimens had two hooked bars with $c_{ch}/d_b > 6$ and 23 specimens had three or four hooked bars with $c_{ch} \leq 6d_b$. As for hooked bars without confining reinforcement, anchorage strength of closely-spaced hooked bars ($c_{ch} \leq 6d_b$) with confining reinforcement decreases with decreasing c_{ch}/d_b. At a given c_{ch}/d_b, specimens with confining reinforcement exhibit less reduction in anchorage strength of hooked bars. The trend line in Figure 5.4 suggests no reduction in anchorage strength of hooked bars with No. 3 hoops spaced at $3d_b$ as confining reinforcement with center-to-center spacing greater than approximately $7.5d_b$. Specimens with a column longitudinal reinforcement ratio of greater than 4% and specimens with two hooked bars with $c_{ch} < 6d_b$ are not included in this analysis, but are discussed in Section 5.4.3.

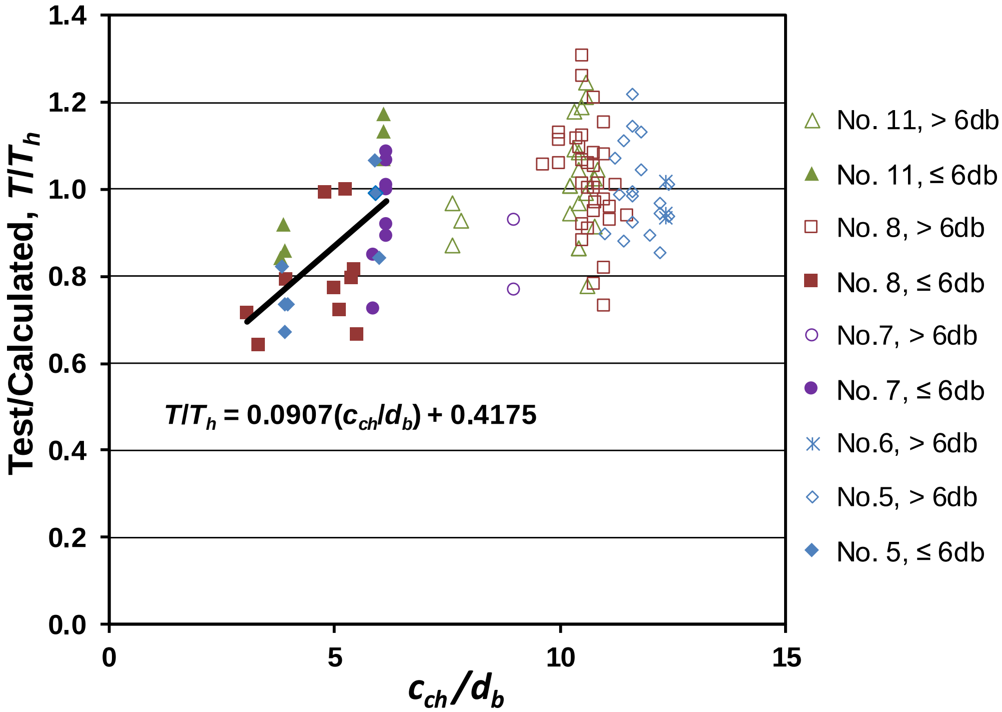


Figure 5.3 Ratio of test-to-calculated bar force T/T_h at failure for specimens without confining reinforcement versus c_{ch}/d_b, with T_h based on Eq. (5.2). c_{ch} is center-to-center spacing

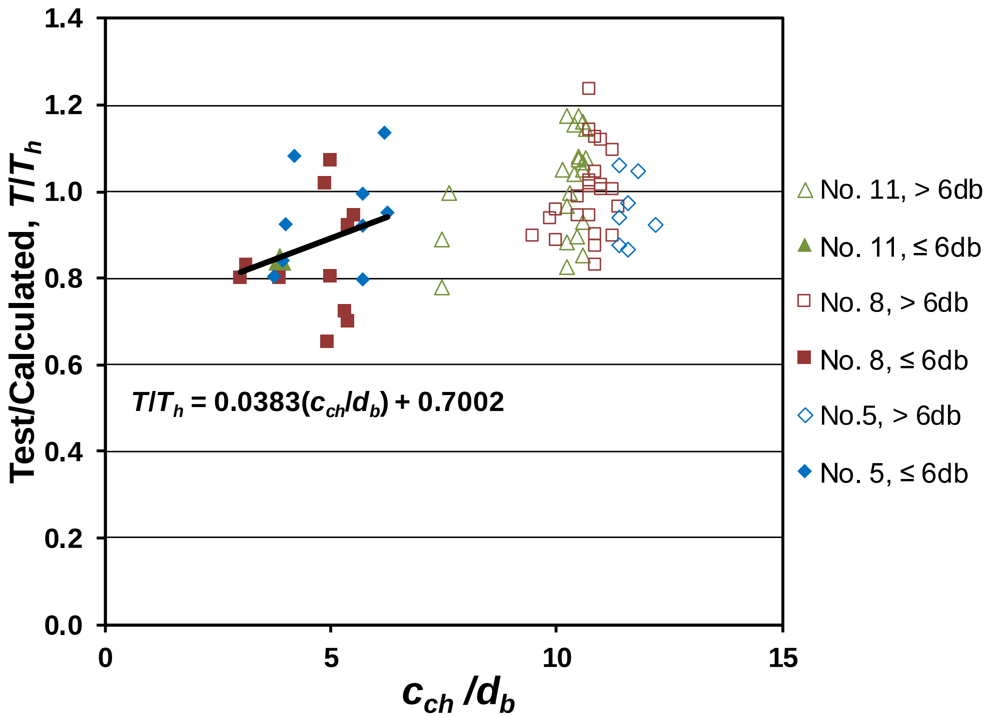


Figure 5.4 Ratio of test-to-calculated bar force T/T_h at failure for specimens with No. 3 hoops spaced at $3d_b$ as confining reinforcement versus c_{ch}/d_b, with T_h based on Eq. (5.2). c_{ch} is center-to-center spacing

As done for the descriptive equation in Section 4.4.1, the trend line for the closely-spaced bars without confining reinforcement shown in Figure 5.3 is used to modify the simplified descriptive equation, Eq. (5.3) to account for spacing between hooked bars. In a similar manner, the trend line for the closely-spaced hooked bars with No. 3 hoops as confining reinforcement shown in Figure 5.4 is used to modify the simplified descriptive equation to account for the spacing between hooked bars. The modified equations are presented in Eq. (5.4) and (5.5).

$$T_c = \left(539\, f_{cm}^{0.25} \ell_{eh}\, d_b^{0.5}\right)\left(0.0907 \frac{c_{ch}}{d_b} + 0.4175\right) \tag{5.4}$$

with spacing term, $\left(0.0907 \frac{c_{ch}}{d_b} + 0.4175\right) \leq 1.0$

$$T_h = \left(539\, f_{cm}^{0.25} \ell_{eh} d_b^{0.5} + 57500 \frac{A_{th}}{n} d_b^{0.75}\right)\left(0.0383 \frac{c_{ch}}{d_b} + 0.7002\right) \tag{5.5}$$

with spacing term, $\left(0.0383 \frac{c_{ch}}{d_b} + 0.7002\right) \leq 1.0$

where c_{ch} is the center-to-center spacing between hooked bars (in.)

In cases where closely-spaced hooked bars are confined with an intermediate amount of confining reinforcement within the joint rejoin (between no confining reinforcement such as specimens used to develop Eq. 5.4 and 5 No. 3 hoops such as specimens used to develop Eq. 5.5), the calculated anchorage strength T_h can be modified for spacing between hooked bars by interpolating between values of the spacing terms in Eq. (5.4) and (5.5) using Eq. (4.11).

$$\beta_{w/i} = \beta_{w/o} + f_1\left(\beta_w - \beta_{w/o}\right) \tag{4.11}$$

in which $f_1 = \left(\frac{A_{th}}{n} \Big/ \left(\frac{A_{th}}{n}\right)_{\max}\right) \leq 1.0$

where $\beta_{w/i}$ is the value of the spacing term for hooked bars with an intermediate amount of confining reinforcement, $\beta_{w/o}$ is the value of the spacing term for hooked bars without confining reinforcement in Eq. (5.4), β_w is the value of the spacing term for hooked bars with No. 3 hoops in Eq. (5.5). In f_1, the value of the effective confining reinforcement per hooked bar $(A_{th}/n)_{\max}$ is set to 0.22 (the maximum value of A_{th}/n used in the derivation of the spacing term for hooked bars with No. 3 hoops as confining reinforcement).

Figures 5.5 and 5.6 show the test-to-calculated ratios of average bar force T/T_h for specimens with two or more hooks, respectively, without confining reinforcement and with No. 3 hoops spaced at $3d_b$ as confining reinforcement plotted versus center-to-center spacing between hooked bars in terms of bar diameter, c_{ch}/d_b. The calculated bar force T_h is based on Eq. (5.4) and (5.5). The nearly horizontal trend lines with mean values close to 1.0 indicate that the modified equations accurately account for the effect of spacing between hooked bars.

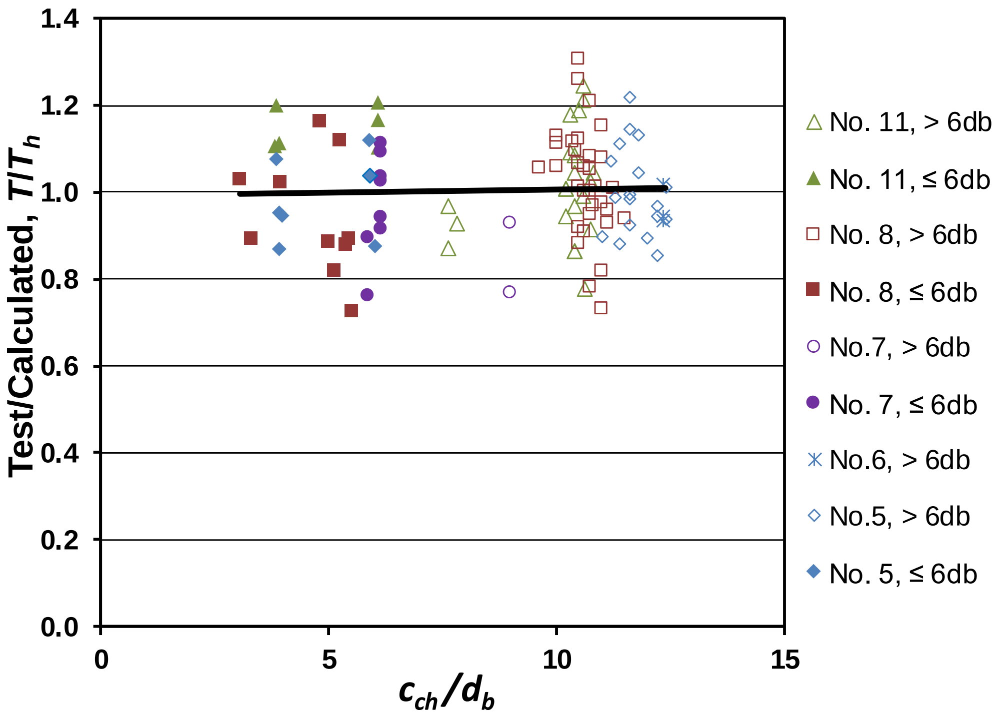


Figure 5.5 Ratio of test-to-calculated bar force T/T_h at failure for specimens without confining reinforcement versus c_{ch}/d_b, with T_h based on Eq. (5.4), c_{ch} is center-to-center spacing

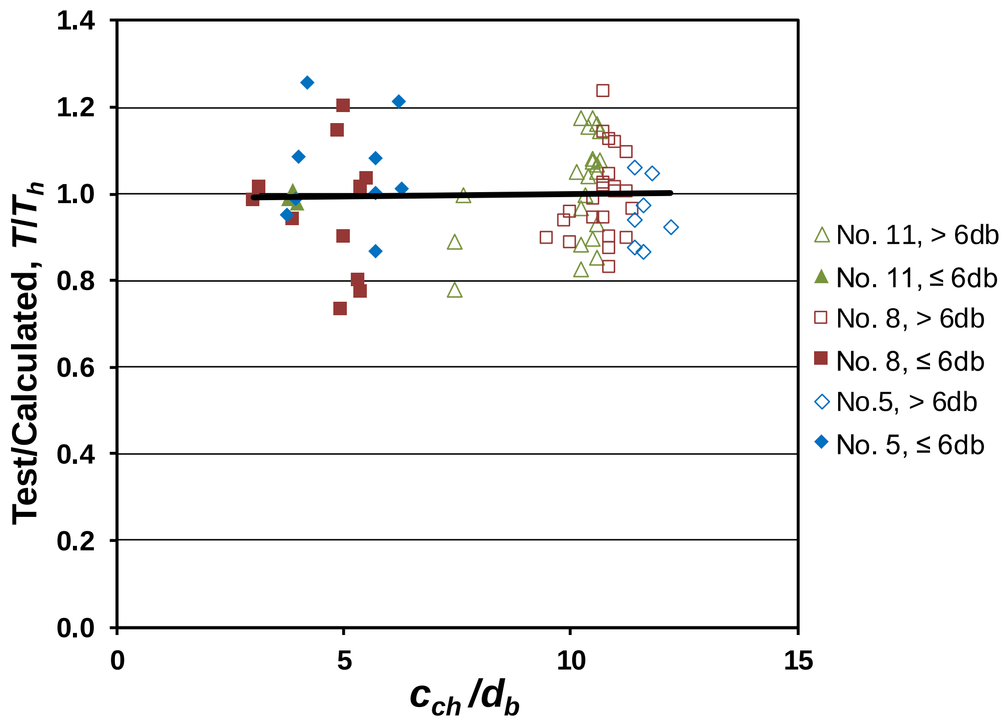


Figure 5.6 Ratio of test-to-calculated bar force T/T_h at failure for specimens with No. 3 hoops spaced at $3d_b$ as confining reinforcement versus c_{ch}/d_b, with T_h based on Eq. (5.5), c_{ch} is center-to-center spacing

5.3 DESIGN EQUATION

5.3.1 Development Length Equation

In practice, designers must calculate the minimum required development length to achieve a desired bar stress (typically the yield stress); therefore, the simplified descriptive equations for two widely-spaced hooked bars [Eq. (5.2) and (5.3)] are solved for the embedment length ℓ_{eh}. Substituting $T_h = A_b f_s = \pi f_s d_b^2/4$, the resulting equation is

$$\ell_{eh} = 0.00146 \frac{f_s \psi_r}{f_{cm}^{0.25}} d_b^{1.5} \qquad (5.6)$$

where f_s is the stress in the hooked bars at anchorage failure (psi), f_{cm} is the measured concrete compressive strength (psi), d_b is the diameter of the hooked bars (in.), and ψ_r is a modification factor for the contribution of confining reinforcement:

$$\psi_r = 1.0 - \left(\frac{57{,}500}{f_s} \frac{A_{th}}{A_{hs}} d_b^{0.75} \right)$$ for parallel confining reinforcement

$$\psi_r = 1.0 - \left(\frac{28{,}750}{f_s} \frac{A_{th}}{A_{hs}} d_b^{0.75} \right)$$ for perpendicular confining reinforcement

where A_{hs} is the total cross-sectional area of hooked bars being developed (in.^{2}). For confining reinforcement parallel to the straight portion of the hooked bar, A_{th} is the total cross-sectional area of all confining reinforcement located within $8d_b$ of the top of the bars for No. 3 through No. 8 hooked bars or within $10d_b$ for No. 9 though No. 11 hooked bars (in.^{2}). For confining reinforcement perpendicular to the straight portion of the hooked bar, A_{th} is the total cross-sectional area of all confining reinforcement along the development length (in.^{2}). For hooked bars without confining reinforcement, $\psi_r = 1.0$.

The modification factor for the contribution of the confining reinforcement ψ_r decreases as the value of A_{th}/A_{hs} increases. The two-hook beam-column joint specimens used to develop the descriptive equations had values of A_{th}/A_{hs} that ranged from 0.35 to 1.06 for specimens containing No. 5 hooked bars, 0.14 to 0.51 for specimens containing No. 8 hooked bars, and 0.07 to 0.38 for specimens containing No. 11 hooked bars. All but two specimens containing No. 11 hooked bars confined by parallel hoops had A_{th}/A_{hs} below 0.21. Figure 5.7 shows the measured bar force at failure T plotted versus the calculated bar force T_h for specimens with confining reinforcement with the calculated bar force based on Eq. (5.2); specimens with A_{th}/A_{hs} above 0.21 are denoted with solid symbols and specimens with A_{th}/A_{hs} below 0.21 are denoted with open symbols. The statistical parameters of Eq. (5.2) are presented in Table 5.1b. As shown in Figure 5.7, the simplified descriptive equation slightly overestimates the anchorage strength of small hooked bars (No. 5) with A_{th}/A_{hs} above 0.21. Of all specimens with A_{th}/A_{hs} above 0.21, 58% have ratios of test-to-calculated average bar force T/T_h below 1.0; while of specimens with A_{th}/A_{hs} below 0.21, 47% have ratios of test-to-calculated average bar force T/T_h below 1.0. Based on this observation and the values of A_{th}/A_{hs} used in the tests, an upper limit of 0.2 is set on A_{th}/A_{hs} for the purposes of calculating ψ_r. A_{th}/A_{hs} ranged from 0.28 to 0.56 in the tests with hooked bars with perpendicular confining reinforcement. For design, the upper limit on A_{th}/A_{hs} is set to 0.4 because based on the approach proposed in the this study, the contribution of perpendicular confining reinforcement is one-half of that for parallel confining reinforcement, as described in Section 4.4.5.

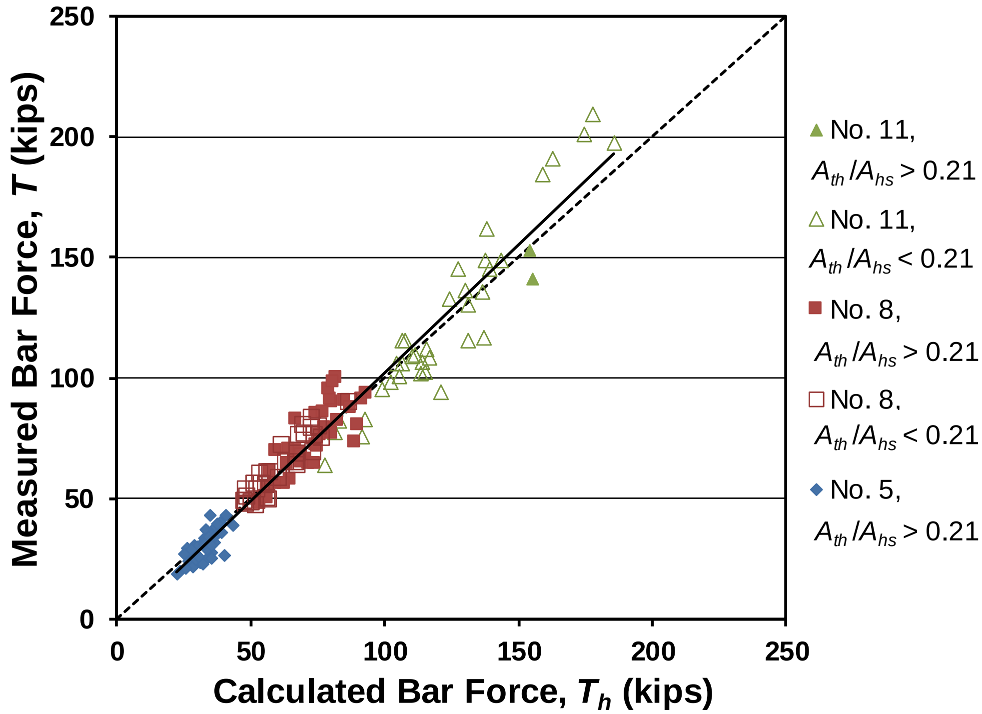


Figure 5.7 Measured bar force at failure T versus calculated bar force T_h for two-hook specimens with confining reinforcement, with T_h based on Eq. (5.2) without limit on A_{th}/A_{hs}

To evaluate this upper limit on A_{th}/A_{hs}, the test results for two-hook specimens with parallel confining reinforcement are compared with the calculated bar force based on Eq. (5.2) using $A_{th}/A_{hs} \leq 0.2$, Figure 5.8. The upper limit on A_{th}/A_{hs} was introduced to Eq. (5.2) by sitting the term $A_{th}/n \leq 0.2A_b$. As in Figure 5.7, specimens with A_{th}/A_{hs} above 0.21 are denoted with solid symbols and specimens with A_{th}/A_{hs} below 0.21 are denoted with open symbols. With the limit on A_{th}/A_{hs}, of the specimens with A_{th}/A_{hs} above 0.21, 23% have ratios of test-to-calculated average bar force T/T_h below 1.0. The mean value of test-to-calculated bar force is 1.07 with a maximum value of 1.47 and a minimum value of 0.75. The statistical parameters (maximum, minimum, mean, standard deviation, and coefficient of variation) for the ratio of test-to-calculated average bar force T/T_h, with T_h based on Eq. (5.2) with the upper limit ($A_{th}/A_{hs} \leq 0.2$) are presented in Table 5.2 for different bar sizes. The mean value of T/T_h for No. 5 hooked bars is 1.06 demonstrating that with the use of the upper limit on A_{th}/A_{hs} the descriptive equation no longer overestimates the anchorage strength of small hooked bars (No. 5) with A_{th}/A_{hs} above 0.21.

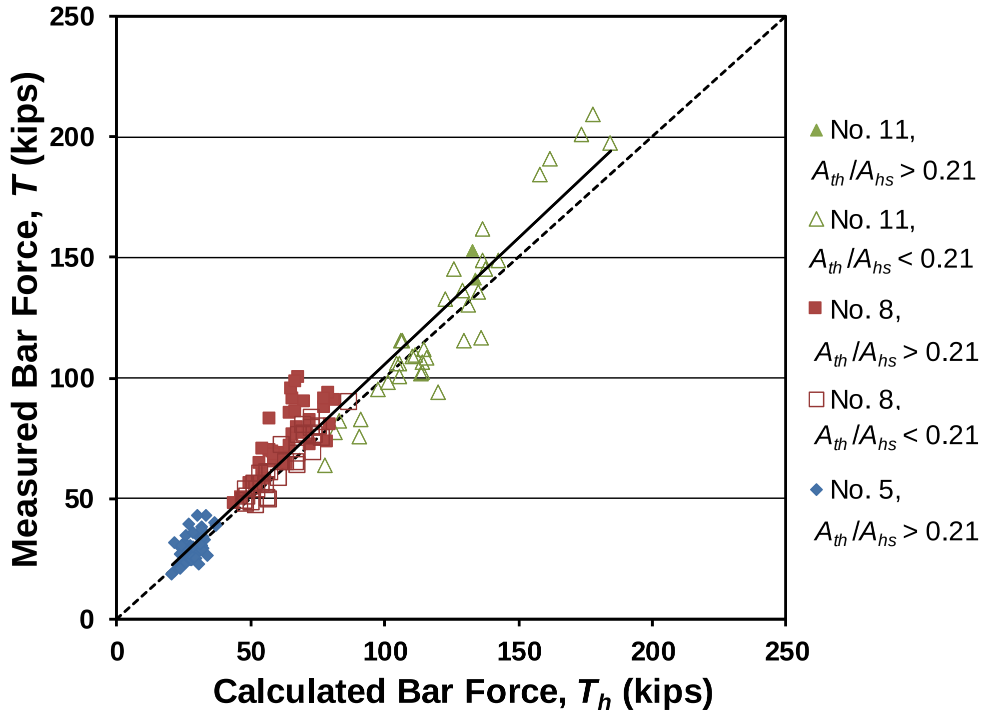


Figure 5.8 Measured bar force at failure T versus calculated bar force T_h for two-hook specimens with confining reinforcement, with T_h based on Eq. (5.2) using $A_{th}/A_{hs} \leq 0.2$ ($A_{th}/n \leq 0.2A_b$)

Table 5.2 Statistical parameters of T/T_h for hooked-bar beam-column joint specimens with confining reinforcement, with T_h based on Eq. (5.2) using $A_{th}/A_{hs} \leq 0.2$ ($A_{th}/n \leq 0.2A_b$)

	All	**No. 5**	**No. 8**	**No. 11**
Max.	1.47	1.47	1.47	1.18
Min.	0.75	0.75	0.82	0.78
Mean	1.07	1.06	1.11	1.01
STD	0.147	0.182	0.132	0.107
COV	0.137	0.172	0.119	0.106

5.3.2 Modification Factors

Equation (5.6) applies for hooked bars with center-to-center spacing not less than $6d_b$ (widely-spaced hooked bars) placed inside a column core with concrete side cover to the hooked bars not less than 2.5 in. In practice, hooked bars are commonly used with a center-to-center spacing as close as $2d_b$ (closely-spaced hooked bars) in beam-column joints and many other applications. For this reason, the equation will be modified so that development length will be calculated for closely-spaced hooked bars and modified to account for wider spacing between hooked bars.

5.3.2.1 Confinement and Spacing Factor

The trend line in Figure 5.3 for closely-spaced hooked bars without confining reinforcement indicates that hooked bars spaced at $2d_b$ (center-to-center) develop about 40% less anchorage strength than that developed by hooked bars spaced at $6d_b$ or greater. Based on this observation, Eq. (5.6) is multiplied by 1.0/0.60 to obtain an expression for the embedment length of hooked bars spaced at $2d_b$ into which a modification factor ψ_m is introduced that decreases from 1.0 at a spacing of $2d_b$ to 0.6 at a spacing of $6d_b$, giving

$$\ell_{eh} = 0.00242 \frac{f_s \psi_r \psi_m}{f_{cm}^{0.25}} d_b^{1.5} \tag{5.7}$$

where $\psi_m = \frac{1}{10}\left(12 - \frac{c_{ch}}{d_b}\right) \geq 0.6$ for hooked bars without confining reinforcement.

For hooked bars with confining reinforcement, spacing has less of an effect on the anchorage strength, as shown in Figures 5.3 and 5.4. Hooked bars with confining reinforcement spaced at $2d_b$ developed about 23% less anchorage strength than that developed by hooked bars spaced at $6d_b$ or greater. Since the embedment length expression in Eq. (5.7) is already 66% greater than values needed for hooked bars spaced at $6d_b$ (as a result of multiplying by 1.0/0.6), ψ_m must equal 0.6 for hooked bars with confining reinforcement spaced at $6d_b$; following this ψ_m is approximated so that it decreases from 0.75 at a spacing of $2d_b$ to 0.6 at a spacing of $6d_b$, giving

$\psi_m = \frac{1}{32}\left(26 - \frac{c_{ch}}{d_b}\right) \geq 0.6$ for hooked bars with confining reinforcement within the joint rejoin.

For additional simplicity in design, the modification factors (ψ_r,ψ_m) in Eq. (5.7) can be combined into a single modification factor ψ_{cs} incorporating the effects of confining reinforcement and spacing, resulting in Eq. (5.8). When calculating ψ_{cs}, the center-to-center spacing between hooked bars c_{ch} is limited to a maximum of $6d_b$ and A_{th}/A_{hs} is limited to a maximum of 0.2 for confining reinforcement parallel to ℓ_{eh} and 0.4 with confining reinforcement perpendicular to ℓ_{eh}.

$$\ell_{eh} = 0.00242 \frac{f_s \psi_{cs}}{f_{cm}^{0.25}} d_b^{1.5} \tag{5.8}$$

where

$\psi_{cs} = \psi_m = \frac{1}{10}\left(12 - \frac{c_{ch}}{d_b}\right)$ for hooked bars without confining reinforcement

$$\psi_{cs} = \psi_m \psi_r = \frac{1}{32}\left(26 - \frac{c_{ch}}{d_b}\right)\left(1 - \frac{57,500}{f_y}\frac{A_{th}}{A_{hs}} d_b^{0.75}\right) \text{ for parallel confining reinforcement}$$

$$\psi_{cs} = \psi_m \psi_r = \frac{1}{32}\left(26 - \frac{c_{ch}}{d_b}\right)\left(1 - \frac{28,750}{f_y}\frac{A_{th}}{A_{hs}} d_b^{0.75}\right) \text{ for perpendicular confining reinforcement}$$

As a final simplification, $d_b^{0.75}$ is set to 1.0 in the expression for ψ_{cs} for hooked bars with confining reinforcement. Table 5.3 shows the resulting values for hooked bars without and with confining reinforcement at 60,000 and 120,000 psi yield strength and $2d_b$ and $6d_b$ center-to-center spacing. This simplification is slightly conservative for hooked bars larger than No. 8 (for No. 11 hooked bars with 60,000 psi yield strength and $2d_b$ spacing. $\psi_{cs} = 0.56$ compared to 0.6 in the table, giving a 7% longer embedment length than required without simplification). The simplification, however, is slightly unconservative for hooked bars smaller than No. 8 (for No. 5 hooked bars with 60,000 psi yield strength and $2d_b$ spacing $\psi_{cs} = 0.65$ versus 0.6 from the table, giving an 8% shorter embedment length than required without simplification). A comparison of test results versus the simplified equation presented in Section 5.4, however, verifies that this simplification produces safe designs.

Table 5.3 Modification factor $\psi_{cs}$for confining reinforcement and spacing[1]

Confinement level	Yield strength	c_{ch}	
		$2d_b$	**$\geq 6d_b$**
No confining reinforcement	-	1.0	0.6
$\frac{A_{th}}{A_{hs}} \geq 0.2$ [2] or $\frac{A_{th}}{A_{hs}} \geq 0.4$ [3]	60,000	0.6	0.5
	120,000	0.66	0.55

[1] ψ_{cs} may be linearly interpolated for spacing or yield strengths not listed
[2] Confining reinforcement parallel to straight portion of bar
[2] Confining reinforcement perpendicular to straight portion of bar

5.3.2.2 Hooked Bar Location Factor

As discussed in Section 4.4.4.2, for a given embedment length, hooked bars placed outside the column core develop less anchorage strength than those placed inside the column core. The specimens containing hooked bars outside the column core simulate hooked bars terminated at the end of a beam without confinement (such as a cantilever beam). The reduction in anchorage strength is conservatively accounted for by a 0.8 factor. For design, the 0.8 factor is converted to a modification factor ψ_o = 1.25 in the embedment length equation, resulting in

$$\ell_{eh} = 0.00242 \frac{f_s \psi_{cs} \psi_o}{f_{cm}^{0.25}} d_b^{1.5} \tag{5.9}$$

ψ_o is taken as 1.0 for hooked bars terminating inside a column core with concrete side cover on the hooked bars of at least 2.5 in., otherwise, ψ_o is taken as 1.25.

Hooked bars anchored in walls, discussed in Section 4.5.2, with relatively wide concrete side covers exhibited an anchorage strength similar or superior to that of hooked bars anchorage inside the column core (beam-column joint specimens). Based this observation and the observation that hooked bars exhibit less anchorage strength at center-to-center spacing of less than $6d_b$, the modification factor ψ_o in Eq. 5.9 is taken as 1.0 for hooked bars terminating in a supporting member with concrete side cover on the hooked bars not less than $6d_b$, otherwise, ψ_o is taken as 1.25.

5.3.3 Reliability-Based Strength Reduction (ϕ) Factor

Equation (5.9) was developed based on the simplified descriptive equations, Eq. (5.2) and (5.3), using a modification factor to represent the effect of confining reinforcement, and adding modification factors for spacing between hooked bars and hooked bar location. To develop a design expression, a strength-reduction factor (ϕ) is needed to ensure an adequately low probability of failure. Reliability concepts are applied to account for the variability in loading, member dimensions, material properties, and the descriptive equations.

This section presents the calculation of a reliability-based ϕ-factor for the design equation following the approach used by Darwin et al. (1998), Zuo and Darwin (1998), and Sperry et al. (2015b). The approach is briefly described next.

5.3.3.1 Overall Approach

A structural member will not fail until the applied load Q exceeds the member resistance R; but Q and R have a random and uncertain nature. To account for the uncertainty in Q and R, structural members are designed for a certain reliability level using load factors (γ-factors) and strength reduction factors (ϕ-factors). These factors account for the uncertainties in predicted load and strength of the member by increasing the loads used for proportioning a member and reducing the usable level of strength for resisting those loads. To determine the degree of reduction needed, data on the mean and variation of critical parameters is applied using Monte Carlo analysis. Monte Carlo analysis is a widely used technique in structural reliability, particularly for complex problems with many random variables. The technique is used to determine the approximate probability of failure of an occurrence that is a result of multiple independent random variables.

Equation (5.9) can be converted to predict an anchorage strength for hooked bars T_h, substituting $T = A_b f_s$, giving

$$T_h = A_b f_s = 324 \frac{\ell_{eh} f_{cm}^{0.25} d_b^{0.5}}{\psi_{cs} \psi_o} \tag{5.10}$$

with ψ_{cs} based on Table 5.3.

In design, the bar force on the left side of Eq. (5.10) is already increased by a factor corresponding to the reciprocal of the strength-reduction factor ϕ for the main loading (in most cases of a reinforcing bar terminated in a standard hook in tension, a ϕ factor of 0.9 corresponding to bending, is used). This increase occurs before the calculation of the development length of the hooked bars. So as to not double-count strength-reduction factors, the overall strength-reduction factor against anchorage failure ϕ_b is applied to $\phi A_b f_s$ [Eq. (5.11)]. Based on this, the effective strength-reduction factor that corresponds to $A_b f_s$ is $\phi_d = \phi_b/\phi$.

$$\phi A_b f_s = \phi_b 324 \frac{\ell_{eh} f_{cm}^{0.25} d_b^{0.5}}{\psi_{cs} \psi_o} \tag{5.11}$$

The overall strength-reduction against anchorage failure of hooked bars ϕ_b can be calculated using the reliability index β [Eq. (5.12)]; as the selected value of β increases the reliability of the member increases. For reinforced concrete beams and columns subjected to typical loads, $\beta \approx 3.0$ (Ellingwood et al. 1980). Hooked bars exhibit a brittle and sudden anchorage failure; therefore it is desired the probability of an anchorage failure be less than that of a flexural failure (which is typically ductile). Therefore, in this calculation β is selected to be 3.5, giving a probability of anchorage failure of about 1/5 that of flexural failure.

$$\beta = \frac{\ln\left(\bar{r}/\phi_c \bar{q}\right)}{\sqrt{V_r^2 + V_q^2}} \tag{5.12}$$

where r is the ratio of random member resistance R to nominal member resistance R_n, given by

$$r = \frac{R}{R_n} = \frac{X_1 R_p}{R_n} \tag{5.13}$$

in which X_1 is the test-to-predicted load capacity random variable. R_p is the predicted capacity random variable (dependent on material and geometric properties of the member, which are also random variables). ϕ_c is the strength reduction factor for loading under consideration ($\phi_b = \phi_c$). $\bar{r}$ and V_r are the mean and coefficient of variation of r. $\bar{q}$ is the mean value of the loading random variables q which is given by

$$q = \frac{X_2 + X_3\left(\dfrac{Q_L}{Q_D}\right)_n}{\gamma_D + \gamma_L\left(\dfrac{Q_L}{Q_D}\right)_n} \tag{5.14}$$

in which X_2 and X_3 are the actual-to-nominal dead and live load random variables. $(Q_L/Q_D)_n$ is the nominal ratio of live load to dead load. γ_D and γ_L are, respectively, the load factors for dead and live load.

$$V_{\phi q} = \frac{\left\{\left[\overline{X_2} V_{Q_D}\right]^2 + \left[\overline{X_3}\left(\dfrac{Q_L}{Q_D}\right)_n V_{Q_L}\right]^2\right\}^{1/2}}{\overline{X_2} + \overline{X_3}\left(\dfrac{Q_L}{Q_D}\right)_n} \tag{5.15}$$

in which V_{QD} and V_{QL} are the coefficient of variation of random variables representing of dead load and live load effects. $\overline{X_2}$ and $\overline{X_3}$ are the mean values of X_2 and X_3.

Equation (5.13) is solved for ϕ_c, giving

$$\phi_c = \phi_b = \frac{\bar{r}}{\bar{q}} e^{-\beta\sqrt{V_r^2 + V_{\phi q}^2}} \tag{5.16}$$

The mean values of $\bar{r}$ and $\bar{q}$ and coefficient of variations V_r and $V_{\phi q}$ are calculated next.

5.3.3.2 Loading Random Variables ($\bar{q}$ and $V_{\phi q}$)

In Eq. (5.14), the loading random variable q is a function of the random variables X_2 and X_3, the ratio of nominal live to dead load $(Q_L/Q_D)_n$, and the load factors for dead and live load (γ_D and γ_L). The values of $(Q_L/Q_D)_n$ were set to 0.5, 1.0, and 1.5; these values are typical of those used when evaluating the reliability of reinforced concrete structures (Darwin et al. 1998). The values of γ_D and γ_L are 1.2 and 1.6, respectively.

For reinforced concrete structures, $\overline{X_2} = \overline{Q_D}/Q_{Dn} = 1.03$, V_{QD} = 0.093 (Ellingwood et al. 1980). The value of $\overline{X_3} = \overline{Q_L}/Q_{Ln}$ is a function of the mean and nominal live loads, which, in turn, are functions of the tributary area A_T and the influence area A_I (Ellingwood et al. 1980). The value of the mean live load can be obtained from Eq. (5.17).

$$\overline{Q_L} = \left(0.25 + \frac{15}{\sqrt{A_I}}\right) L_o \tag{5.17}$$

where L_o is the basic unreduced live load, psf

Following ASCE 7-10, the nominal live load Q_{Ln} can be obtained from Eq. (5.18).

$$Q_{Ln} = \left(0.25 + \frac{15}{\sqrt{K_{LL} A_T}}\right) L_o \tag{5.18}$$

where K_{LL} is the live load element factor, 2 for interior beams.

For reinforced concrete structures, the values of A_T and A_I are typically selected to be 400 ft^2 and 800 ft^2, respectively. Substituting these values into Eq. (5.17) and (5.18) results in $\overline{X_3} = \overline{Q_L}/Q_{Ln} = 1.0$. V_{QL} = 0.25 (Ellingwood et al. 1980).

5.3.3.3 Resistance Random Variables ($\bar{r}$ and V_r)

The ratio of random-to-nominal resistance r is calculated using Eq. (5.13). X_1 is calculated based a comparison of test results with the value calculated using the descriptive equations for hooked bar anchorage strength, Eq. (4.8) and (4.12); X_1 is a normal random variable with a mean equal to the mean of test-to-calculated ratio T/T_h of hooked bars without and with confining reinforcement of Eq. (4.8), X_1 = 1.0. The coefficient of variation V_{X_1} equals to the effective coefficient of variation, V_m, of test-to-calculated ratio T/T_h that is associated with the descriptive equation.

Variations in other test parameters – measured loads, member geometry and material priorities – also affect the total coefficient of variation $V_{T/C}$. The total coefficient of variation can be obtained from Eq. (5.19) (Grant et al. 1978).

$$V_{T/C} = \left(V_m^2 + V_{ts}^2\right)^{1/2} \tag{5.19}$$

Solving Eq. (5.19) for V_m gives

$$V_m = \left(V_{T/C}^2 - V_{ts}^2\right)^{1/2} \tag{5.20}$$

For reinforced concrete structures, Grant et al. (1978) found that $V_{ts} \approx 0.07$. From Tables 4.2 and 4.3 in Section 4.3, $V_{T/C}$ equals 0.115 and 0.112 for hooked bars without and with confinement, respectively. Substituting values of V_{ts} and $V_{T/C}$ into Eq. (5.20) gives $V_m = 0.091$ for hooked bars without confining reinforcement and $V_m = 0.087$ for hooked bars with confining reinforcement.

Values of the predicted capacity random variable R_p are determined for hypothetical beam-column joints using the Monte Carlo method. R_p is obtained using Eq. (4.8) and (4.12). The expression for concrete compressive strength is based on values for coefficient of variation for laboratory cured cylinders from Nowak et al. (2012); geometric properties of the members are based on tolerances for construction specified in ACI 117-14. These values were used by Sperry et al. (2015b) in a similar analysis.

The nominal strength R_n is obtained using Eq. (5.10) with the nominal dimensions of the beam-column joint and the specified concrete compressive strength.

The values of $\bar{r}$ and V_r are determined using Monte Carlo simulation of a selected set of hypothetical beam-column joints. For each beam-column joint and simulation, values are chosen for the random variables (X_1,….X_i); the random variables are represented by a normal distribution function. This is done by using a random number generator producing numbers ranging from 0 to 1.0 for each variable. Then, the random number is used to obtain the standard normal random variable z ($-\infty < z < \infty$). For variable i, $X_i = \overline{X_i} + z\sigma_{X_i}$. The values of X_i are used to obtain r from Eq. (5.13) for the simulation. The result of 10,000 simulations for each beam-column joint are combined to obtain $\bar{r}$ and V_r for the population. The hypothetical members used in the calculations consist of 2,160 beam-column joints in five groups of 432 each: beam-column joints containing hooked bars without confinement, one No. 3 hoop as parallel confinement, two No. 3 hoops as parallel confinement, No. 3 hoops spaced at $3d_b$ as parallel confinement, and No. 3 hoops spaced at $3d_b$ as perpendicular confinement. The hooked bar sizes were No. 6, 8, 9, or 11 with nominal yield strengths ranging from 60,000 to 120,000 psi. Nominal concrete compressive strengths ranged from 4,000 to 15,000 psi. The beam-column joints contained 2, 3, 4, 6 or 8 hooked bars with center-to-center spacing ranging from 2.1 to 11.6d_b. Appendix D presents the properties of the beam-column joints used in the analysis.

5.3.3.4 Strength Reduction Factor

The overall strength-reduction factor against anchorage failure ϕ_b is obtained from Eq. (5.16); the values of $\bar{r}$ and V_r are obtained using the results of the Monte Carlo simulation; the values of $\overline{q}$ and $V_{\phi q}$ are obtained using the load factors and live-to-dead load ratios. The value of the effective strength-reduction factor ϕ_d is then calculated from $\phi_d = \phi_b/\phi$. Table 5.4 presents the results of the Monte Carlo simulations for each of the five groups used in the Monte Carlo simulation.

Table 5.4 Strength reduction factor using Eq. (5.10)

	No Confinement			**1 No. 3 Parallel**			**2 No. 3 Parallel**		
r	1.08			1.03			1		
V_r	0.133			0.145			0.132		
$(Q_D/Q_L)_n$	0.5	1.0	1.5	0.5	1.0	1.5	0.5	1	1.5
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	0.785	0.775	0.757	0.724	0.717	0.702	0.729	0.719	0.703
ϕ_d	0.872	0.861	0.841	0.804	0.796	0.780	0.81	0.799	0.781

Table 5.4 Cont. Strength reduction factor using Eq. (5.10)

	No. 3 at 3d_b Parallel			**No. 3 at 3d_b Perpendicular**		
R	1.03			1.09		
V_r	0.126			0.146		
$(Q_D/Q_L)_n$	0.5	1.0	1.5	0.5	1.0	1.5
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	0.759	0.747	0.729	0.760	0.752	0.737
ϕ_d	0.843	0.830	0.811	0.844	0.836	0.819

As presented in Table 5.4, with a ratio of live-to-dead load of 1.0 ϕ_d equals 0.861 for hooked bars without confinement, 0.796 for hooked bars with 1 No. 3 hoop as parallel confinement, 0.799 with 2 No. 3 hoops as parallel confinement, 0.830 with No. 3 hoops spaced at 3d_b as parallel confinement, and 0.836 with No. 3 hoops spaced at 3d_b as perpendicular confinement. The proposed strength-reduction factor, $\phi_d = 0.82$, is set equal to the average values of ϕ_d with ratios of dead-to-live loads of 1.0. This value is slightly greater than the strength-reduction factor (ϕ_d = 0.81) for widely-spaced hooked bars found by Sperry at el. (2015b).

5.3.4 Final Design Equation

The design equation is developed by incorporating the strength-reduction factor ($\phi_d = 0.82$) calculated based on the reliability analysis in the previous section into the embedment length equation, Eq. (5.9), giving Eq. (5.21a). The multiplier in Eq. (5.21a) is then rounded to 0.003, equivalent to $\phi_d = 0.81$, for ease in calculation, giving Eq. (5.21b).

$$\ell_{eh} = 0.00295 \frac{f_s \psi_{cs} \psi_o}{f_{cm}^{0.25}} d_b^{1.5} \tag{5.21a}$$

$$\ell_{eh} = 0.003 \frac{f_s \psi_{cs} \psi_o}{f_{cm}^{0.25}} d_b^{1.5} \tag{5.21b}$$

Eq. (5.21b) is modified for the use in design by replacing the embedment length ℓ_{eh} with the development length ℓ_{dh}, the stress at hooked bars at anchorage failure f_s with specified yield strength of the hooked bars f_y, and the measured concrete compressive strength f_{cm} with the specified concrete compressive strength f_c'. In addition, modification factors for coated hooked bars $\psi_e = 1.2$ and lightweight concrete $\lambda = 0.75$ are retained from the current code provisions. With these changes, the design equation becomes

$$\ell_{dh} = 0.003 \frac{f_y \psi_e \psi_{cs} \psi_o}{\lambda f_c'^{0.25}} d_b^{1.5} \tag{5.22}$$

with ψ_{cs} given in Table 5.3 (repeated below) as a function of hooked bar specified yield strength, minimum center-to-center spacing between hooked bars, and the ratio A_{th}/A_{hs}; the values of ψ_{cs} can be linearly interpolated for intermediate values of f_y, c_{ch}, A_{th}/A_{hs}. ψ_o is 1.0 for hooked bars terminating inside a column core with concrete side cover on the hooked bars not less than 2.5 in. or terminating in a supporting member with concrete side cover on the hooked bars not less than $6d_b$; otherwise, ψ_o is 1.25.

Table 5.3 Modification factor ψ_{cs} for confining reinforcement and spacing[1]

Confinement level	Yield strength	c_{ch}	
		2d_b	**≥ 6d_b**
No confining reinforcement	-	1.0	0.6
$\frac{A_{th}}{A_{hs}} \geq 0.2$ [2] or $\frac{A_{th}}{A_{hs}} \geq 0.4$ [3]	60,000	0.6	0.5
	120,000	0.66	0.55

[1] ψ_{cs} may be linearly interpolated for spacing or yield strengths not listed
[2] Confining reinforcement parallel to straight portion of bar
[2] Confining reinforcement perpendicular to straight portion of bar

5.4 COMPARISON OF DESIGN EQUATION WITH RESULTS FROM BEAM-COLUMN JOINT SPECIMENS

In this section, strengths calculated based on the design equation are compared with test results for specimens used to develop the descriptive equations and modification factors. To do so, Eq. (5.22) is converted to calculate anchorage strength of hooked bars T_h.

$$T_h = \frac{\ell_{eh} f_{cm}^{0.25} A_b}{0.003\psi_{cs}\psi_o d_b^{1.5}} \tag{5.23}$$

where ℓ_{eh} is the embedment length (in.), f_{cm} is the concrete compressive strength (psi), A_b is the hooked bar cross-sectional area (in.^{2}), d_b is the nominal bar diameter (in.), and ψ_{cs} and ψ_o are as defined following Eq. (5.22).

5.4.1 Specimens Used to Develop the Descriptive Equations

Anchorage strength calculated using the design equations is first compared with the test results used to develop the design equation, including the specimens containing widely-spaced hooked bars without and with parallel confining reinforcement, widely-spaced hooked bars with perpendicular confining reinforcement, closely-spaced hooked bars, staggered hooked bars, and hooked bars located outside the column core.

5.4.1.1 Widely-Spaced Hooked Bars Without and With Parallel Confining Reinforcement

Figures 5.9 and 5.10 show the ratio of test-to-calculated average bar force T/T_h plotted versus concrete compressive strength for specimens containing widely-spaced hooked bars without confining reinforcement within the joint region and with confining reinforcement provided parallel to the straight portion of the hooked bars (horizontal hoops), respectively. The calculated bar force T_h is based on Eq. (5.23). Figure 5.9 includes test results of 87 two-hook specimens without confining reinforcement used to develop the descriptive equation, containing No. 5, 6, 7, 8, and 11 hooked bars with 90° and 180° bend angles. As for trend lines in Figure 5.1 that show the relation between T/T_h (with T_h based on the simplified descriptive equation) and concrete compressive strength, the trend lines in Figures 5.9 have a slightly upward slope indicating that the design equation becomes more conservative as the concrete compressive strength increases. Table 5.5 presents the maximum, minimum, mean, standard deviation, coefficient of variation, and number of specimens with T/T_h below 1.0 for the different bar sizes. The mean value of T/T_h is 1.24 with a maximum of 1.61 and a minimum of 0.90. The coefficient of variation, 0.117, is higher than that of the descriptive equation, 0.115 (presented in Table 4.2). Only four specimens out of the 87 (4.6%) have a ratio of test-to-calculated bar force below 1.0.

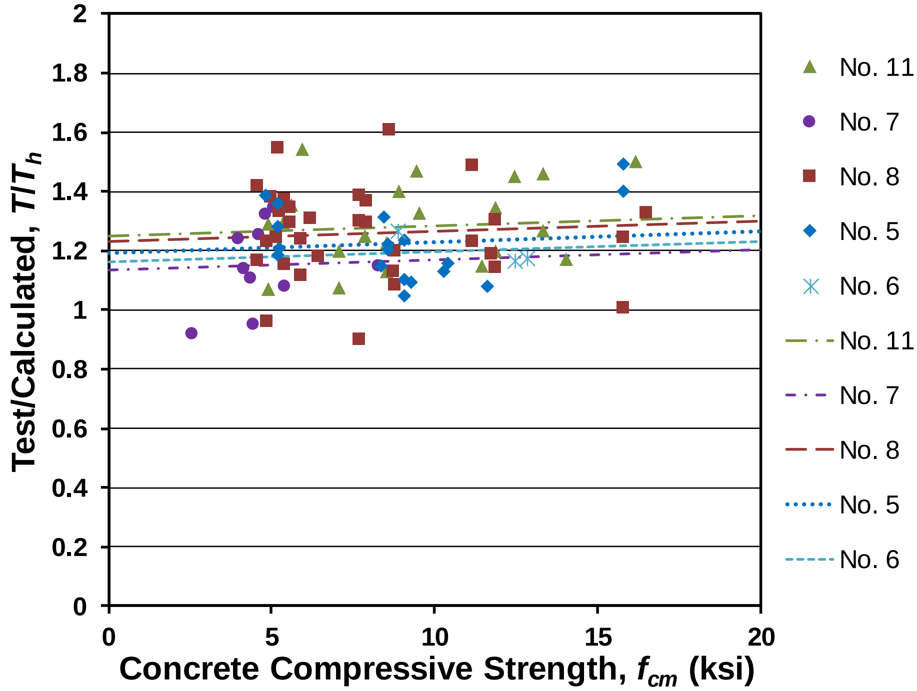


Figure 5.9 Ratio of test-to-calculated bar force at failure T/T_h versus concrete compressive strength f_{cm} for two-hook specimens without confining reinforcement, with T_h based on Eq. (5.23)

Table 5.5 Statistical parameters of T/T_h for widely-spaced hooked bars without confining reinforcement, with T_h based on Eq. (5.23)

	All	No. 5	No. 6	No. 7	No. 8	No. 11
Max.	1.61	1.49	1.26	1.35	1.61	1.54
Min.	0.90	1.05	1.16	0.92	0.90	1.07
Mean	1.24	1.23	1.20	1.15	1.26	1.28
STD	0.145	0.125	0.056	0.144	0.154	0.142
COV	0.117	0.102	0.047	0.125	0.122	0.111
Number of Specimens	87	18	3	10	33	23
No. with T/T_h < 1.0	4	0	0	2	2	0

Figure 5.10 includes test results of 146 two-hook specimens with confining reinforcement used to develop the descriptive equation, containing No. 5, 8, and 11 hooked bars with 90° and 180° bend angles. The trend lines in Figure 5.10 also have a slightly upward slope similar to those in Figure 5.2 indicating that the design equation becomes more conservative as the concrete compressive strength increases. Table 5.6 presents the maximum, minimum, mean, standard deviation, coefficient of variation, and number of specimens with T/T_h below 1.0 for the different bar sizes. The mean value of T/T_h is 1.34 with a maximum of 1.92 and a minimum of 0.85. As for

the specimens without confining reinforcement, the coefficient of variation, 0.153, is higher than that for the descriptive equation, 0.112 (presented in Table 4.3). Only three specimens out of 146 (2.0%) have a ratio of test-to-calculated bar force below 1.0. The calculated anchorage strengths for specimens included in Figures 5.9 and 5.10 are shown in Appendix C.

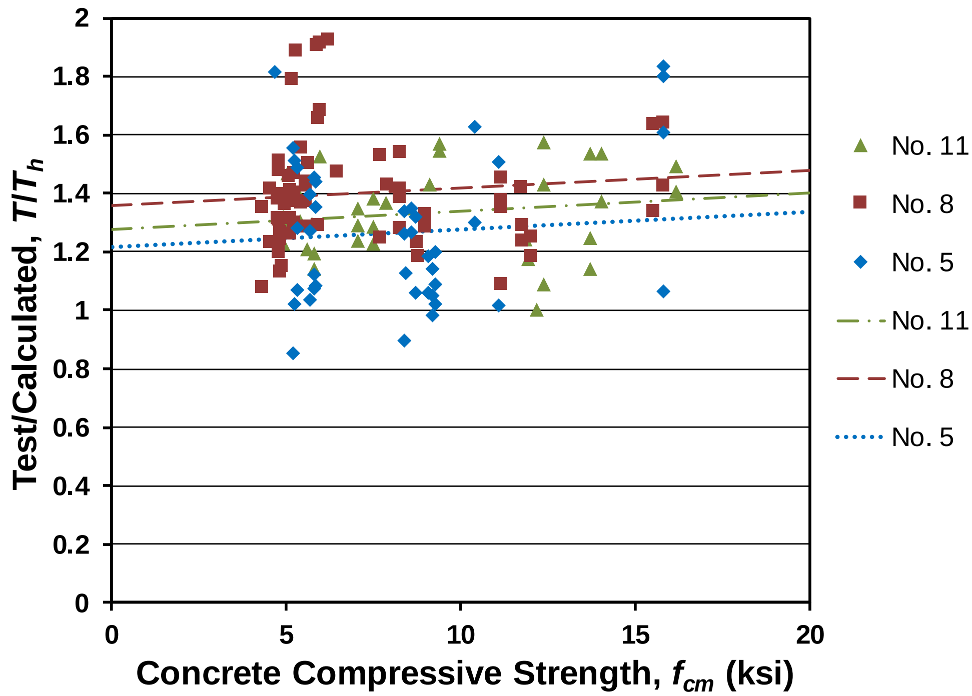


Figure 5.10 Ratio of test-to-calculated bar force T/T_h at failure versus concrete compressive strength f_{cm} for two-hook specimens with confining reinforcement, with T_h based on Eq. (5.23) and Table 5.3

Table 5.6 Statistical parameters of T/T_h for widely-spaced hooked bars with confining reinforcement, with T_h based on Eq. (5.23)

	All	**No. 5**	**No. 8**	**No. 11**
Max.	1.92	1.83	1.92	1.57
Min.	0.85	0.85	1.08	1.00
Mean	1.34	1.27	1.40	1.33
STD	0.205	0.251	0.187	0.146
COV	0.153	0.198	0.134	0.110
Number of Specimens	146	41	70	35
No. with $T/T_h < 1.0$	3	3	0	0

5.4.1.2 Closely-Spaced Hooked Bars

Figure 5.11 compares the measured failure load T with the calculated failure load T_h for both widely and closely-spaced hooked bars without confining reinforcement within the joint region. The specimens with widely-spaced hooked bars are represented by open symbols and those with closely-spaced hooked bars by solid symbols. Figure 5.12 shows the same for the specimens with confining reinforcement provided parallel to the straight portion of the hooked bars. The calculated bar forces T_h are based on Eq. (5.23). The broken lines represent the equality line for which the calculated failure loads equal the measured failure loads. The solid lines are the trend lines for the widely-spaced hooked bars. Figure 5.11 includes test results of 107 specimens without confining reinforcement within the joint region containing No. 5, 6, 7, 8, and 11 hooked bars with 90° and 180° bend angles. Of the 107 specimens, 31 specimens contained two, three, or four closely-spaced hooked bars ($c_{ch} \leq 6d_b$). Two of the 31 specimens with closely-spaced hooked bars without confining reinforcement fall below the equality line, T/T_h < 1.0. The values of the maximum, minimum, mean, standard deviation, coefficient of variation, and number of specimens with T/T_h below 1.0 for the different bar sizes for the closely-spaced hooked bars are presented in Table 5.7. The mean value of test-to-calculated bar force for closely-spaced hooked bars is 1.24 with a maximum value of 1.55 and a minimum value of 0.89. The coefficient of variation for all specimens in the table is 0.134.

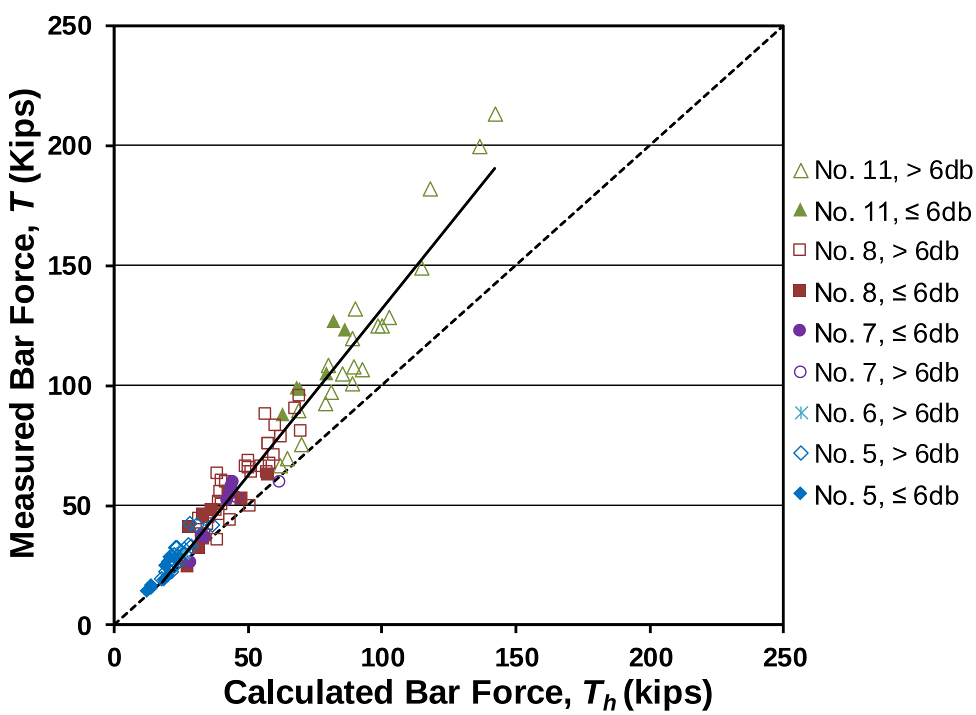


Figure 5.11 Measured bar force at failure T versus calculated bar force for two-hook specimens without confining reinforcement, with T_h based on Eq. (5.23)

Table 5.7 Statistical parameters of T/T_h for closely-spaced hooked bars without confining reinforcement, with T_h based on Eq. (5.23)

	All	**No. 5**	**No. 7**	**No. 8**	**No. 11**
Max.	1.55	1.37	1.35	1.47	1.55
Min.	0.89	1.03	0.92	0.89	1.33
Mean	1.24	1.21	1.18	1.18	1.43
STD	0.167	0.117	0.143	0.181	0.072
COV	0.134	0.097	0.121	0.153	0.050
Number of Specimens	31	7	8	10	6
No. with T/T_h < 1.0	2	0	1	1	0

Figure 5.12 includes test results of 180 specimens with confining reinforcement containing No. 5, 8, and 11 hooked bars with 90° and 180° bend angles. Of the 180 specimens, 34 specimens contained three or four closely-spaced hooked bars. Three of the 34 specimens with closely-spaced bars fall below the equality line, $T/T_h < 1.0$. The values of the maximum, minimum, mean, standard deviation, coefficient of variation, and number of specimens with T/T_h below 1.0 for the different bar sizes for the closely-spaced hooked bars are presented in Table 5.8. The mean value of test-to-calculated bar force for closely-spaced hooked bars is 1.25 with a maximum value of 1.80 and a minimum value of 0.91. The coefficient of variation for all specimens in the table is 0.167.

Overall, 12 specimens (4.1%) containing closely and widely-spaced hooked bars without and with confining reinforcement have test-to-calculated ratios below 1.0. The calculated values of anchorage strength T_h and T/T_h for the specimens included in Figures 5.9 through 5.12 are shown in Appendix C.

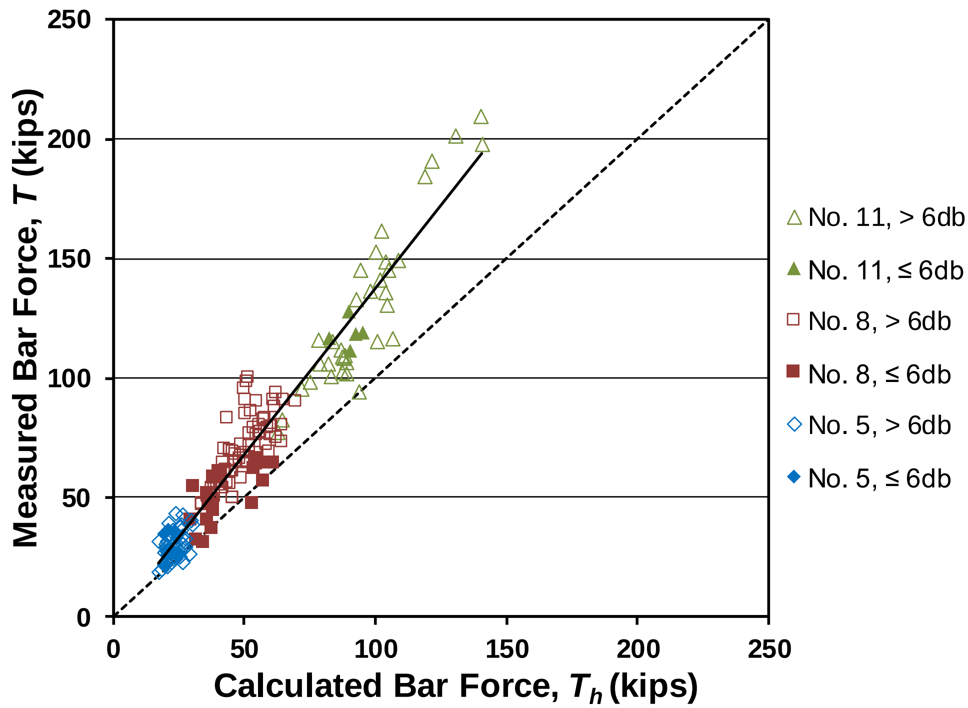


Figure 5.12 Measured bar force at failure T versus calculated bar force for two-hook specimens with horizontal confining reinforcement, with T_h based on Eq. (5.23)

Table 5.8 Statistical parameters of T/T_h for closely-spaced hooked bars with confining reinforcement, with T_h based on Eq. (5.23)

	All	**No. 5**	**No. 8**	**No. 11**
Max.	1.80	1.80	1.52	1.42
Min.	0.91	1.05	0.91	1.23
Mean	1.25	1.35	1.21	1.32
STD	0.209	0.249	0.176	0.092
COV	0.167	0.184	0.145	0.07
Number of Specimens	34	11	18	5
No. with $T/T_h < 1.0$	3	0	3	0

5.4.1.3 Staggered-Hooked Bars

Figure 5.13 shows the measured failure load T plotted versus the calculated failure load T_h for 13 specimens containing staggered-hooked bars without confining reinforcement within the joint region and with confining reinforcement provided parallel to the straight portion of the hooked bars. The calculated bar force T_h is based on Eq. (5.23). Of the 13 staggered-specimens, eight contained either four or six No. 5 hooked bars and five specimens contained four No. 11 hooked bars, all with a 90° bend angle. The specimens had a vertical clear spacing between hooked bars of 1 in. and 1d_b for No. 5 and No. 11 hooked bars, respectively, corresponding to c_{ch}/d_b of 2.6 and 2.0. The values of calculated bar force T_h based on the Eq. (5.23) and T/T_h are presented in Table 5.9. All specimens fall above the equality line with a mean value of test-to-calculated bar force of 1.25, a maximum value of 1.49, and a minimum value of 1.0.

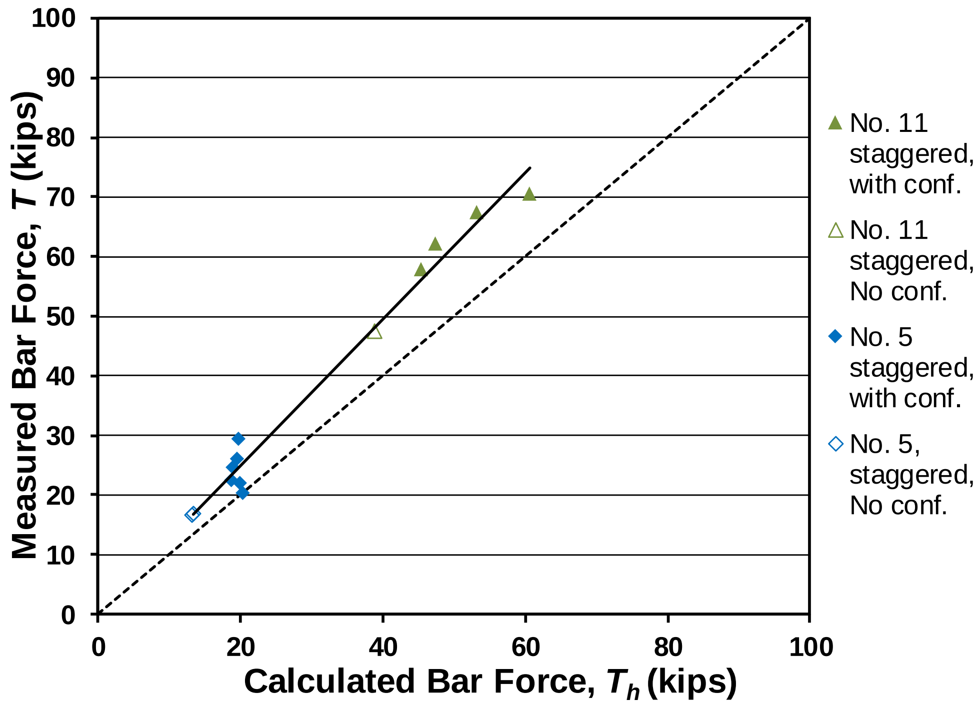


Figure 5.13 Measured bar force at failure T versus calculated bar force T_h for staggered-hook specimens without and with confining reinforcement, with T_h based on Eq. (5.23)

Table 5.9 Test parameters for staggered-hook specimens without and with confining reinforcement and comparisons with the design equation, Eq. (5.23)

Specimen[a]	$\ell_{eh,avg}$ in.	f_{cm} psi	N_h	A_{th}/A_{hs}	c_{ch}/d_b	T lb	T_h[b] lb	T/T_h[*]
(2s) 5-5-90-0-i-2.5-2-8	7.2	4660	4	-	2.6	16727	13272	1.26
(3s) 5-5-90-0-i-2.5-2-8	7.3	4830	6	-	2.6	16804	13487	1.25
(2s) 5-5-90-2#3-i-2.5-2-8	6.6	4860	4	0.11	2.6	24730	18967	1.30
(3s) 5-5-90-2#3-i-2.5-2-8	6.9	4860	6	0.07	2.6	20283	20398	1.00
(2s) 5-5-90-5#3-i-2.5-2-8	6.9	4660	4	0.53	2.6	26180	19511	1.34
(3s) 5-5-90-5#3-i-2.5-2-8	6.4	4860	6	0.35	2.6	22598	18818	1.20
(2s) 5-5-90-6#3-i-2.5-2-8	7.1	4660	4	0.71	2.6	29528	19793	1.49
(3s) 5-5-90-6#3-i-2.5-2-8	6.8	4860	6	0.47	2.6	22081	19905	1.11
(2s) 11-5-90-0-i-2.5-2-16	14.8	5030	4	-	2.0	47490	38830	1.22
(2s) 11-5-90-2#3-i-2.5-2-16	14.6	5140	4	0.07	2.0	57998	45354	1.28
(2s) 11-5-90-6#3-i-2.5-2-16	14.0	5030	4	0.11	2.0	62177	47297	1.31
(2s) 11-5-90-7#3-i-2.5-2-16	14.3	5140	4	0.14	2.0	67432	53299	1.27
(2s) 11-5-90-8#3-i-2.5-2-16	14.6	5140	4	0.18	2.0	70505	60575	1.16

[a]Notation described in Section 2.1 and Appendix A
[b]Calculated anchorage strength is based on Eq. (5.23)

5.4.1.4 Hooked Bars with Perpendicular Confining Reinforcement

The ratio of test-to-calculated bar force T/T_h for specimens with perpendicular confining reinforcement and the companion specimens (in the same batch of concrete) with parallel confining reinforcement and with no confinement are presented in Table 5.10. T_h is based on Eq. (5.23), in which the value of the confinement and spacing factor ψ_{cs} is calculated using Table 5.3 as a function of hooked bar stress, center-to-center spacing between hooked bars, and the ratio A_{th}/A_{hs}. A_{th} is the total cross-sectional area of confining reinforcement parallel to the straight portion of the hooked bars within $8d_b$ of the top of the hooked bars with parallel hoops, since No. 8 bars were used in the tests, and the total cross-sectional area of confining reinforcement provided along a length equal to the development length for hooked bars with perpendicular hoops. A_{hs} is the total cross-sectional area of hooked bars being developed. Specimens with parallel confining reinforcement had values of A_{th}/A_{hs} ranging from 0.14 to 0.42. Specimens with perpendicular confining reinforcement had values of A_{th}/A_{hs} ranging from 0.28 to 0.70. When calculating T_h using Eq. (5.23), based on the discussion in Section 5.3.1, A_{th}/A_{hs} is limited to 0.2 for parallel confining reinforcement and 0.4 for perpendicular confining reinforcement. Specimens without confining reinforcement have a mean value of T/T_h of 1.22 with minimum and maximum values between 1.14 and 1.30. Specimens with parallel confining reinforcement have a mean value of T/T_h of 1.24 with minimum and maximum values between 1.18 and 1.29. Specimens with perpendicular confining reinforcement have a mean value of T/T_h of 1.13 with minimum and maximum values between 0.96 and 1.29. The mean value of specimens with perpendicular confining reinforcement would expected to be higher using a larger set of specimens.

Table 5.10 Test parameters for two-hook specimens contained perpendicular confining reinforcement, parallel confining reinforcement, and without confining reinforcement and comparisons with the design equation, Eq. (5.23)

Specimen[a]	Hoop Orientation	$\ell_{eh,avg}$ in.	f_{cm} Psi	A_{th}/A_{hs}	T lb	$T_h{}^b$ lb	T/T_h
8-12-90-0-i-2.5-2-12.5	-	12.8	11850	-	66937	58670	1.14
8-12-180-0-i-2.5-2-12.5	-	12.6	11850	-	75208	57812	1.30
8-12-90-2#3-i-2.5-2-11	Para	10.9	12010	0.14	68683	54906	1.25
8-12-180-2#3-i-2.5-2-11	Para	10.8	12010	0.14	64655	54571	1.18
8-12-90-2#3vr-i-2.5-2-11	Perp	10.6	12010	0.28	52673	54822	0.96
8-12-180-2#3vr-i-2.5-2-11	Perp	10.9	12010	0.28	65780	55120	1.19
8-12-90-5#3-i-2.5-2-10	Para	9.4	11800	0.42	64530	59997	1.29
8-12-180-5#3-i-2.5-2-10	Para	9.8	11800	0.42	64107	51697	1.24
8-12-180-4#3vr-i-2.5-2-10	Perp	10.3	11850	0.56	69188	53847	1.29
8-12-90-4#3vr-i-2.5-2-10	Perp	10.4	11850	0.56	59241	55961	1.06
8-12-90-5#3vr-i-2.5-2-10	Perp	10.2	11800	0.70	60219	54618	1.10
8-12-180-5#3vr-i-2.5-2-10	Perp	10.8	11800	0.70	67780	56903	1.19

[a]Notation described in Section 2.1 and Appendix A
[b]Calculated anchorage strength based on Eq. (5.23)

5.4.1.5 Hooked Bars Placed Outside the Column Core

Figure 5.14 compares the measured failure load T with the calculated failure load T_h for 37 two-hook specimens containing hooked bars outside the column core without and with confining reinforcement within the joint region. The specimens contained No. 5. No. 8 or No. 11 hooked bars with 90° or 180° bend angles with different levels of confining reinforcement within the joint region. Of the 37 specimens, 13 were tested together with 13 specimens with hooked bars placed inside the column core from the same batch of concrete (discussed in Section 4.4.4.2). The calculated bar force T_h is based on Eq. (5.23) with ψ_o = 1.25. The broken line represents the equality line for which the calculated failure loads equal the measured failure loads. The solid line is the trend line for specimens. The values of calculated bar force T_h based on the Eq. (5.23) and T/T_h are presented in Table 5.11. All specimens containing hooked bars outside the column core, but one, fall above the equality line. The Specimens have an average ratio of test-to-calculated bar force T/T_h of 1.42 with a maximum value of 1.81 and a minimum value of 0.85.

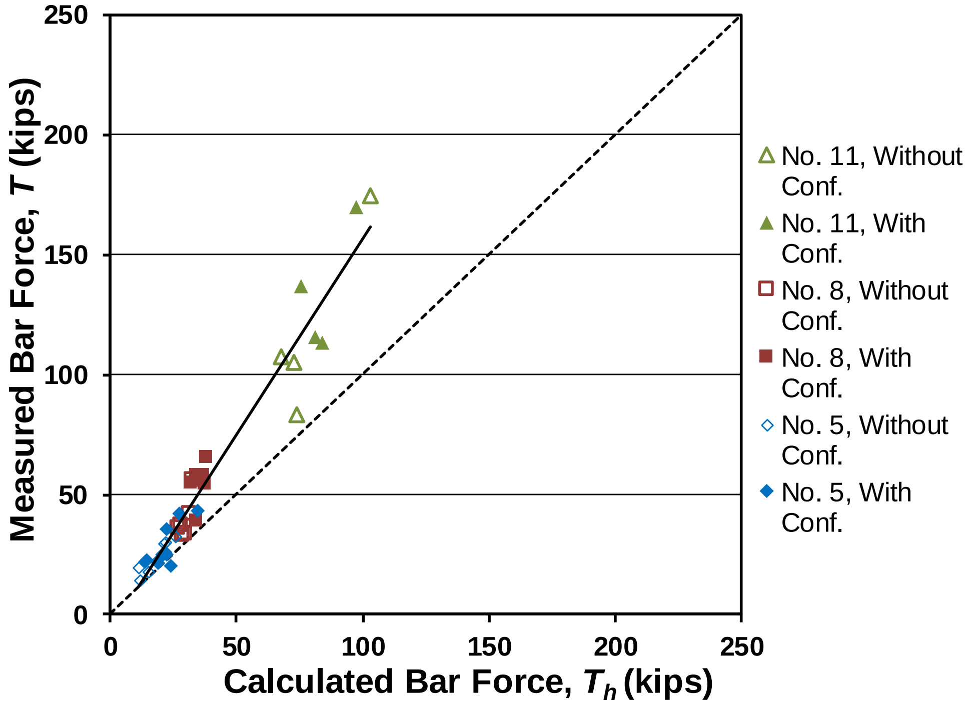


Figure 5.14 Measured bar force at failure T versus calculated bar force T_h for two-hook specimens containing hooked bars outside the column core without and with confining reinforcement, with T_h based on Eq. (5.23)

Table 5.11 Test parameters for two-hook specimens contained hooked bars outside column core and comparisons with the design equation, Eq. (5.23)

Specimen	$\ell_{eh,avg}$ in.	f_{cm} psi	d_b in.	T lb	A_{th}/A_{hs}	T_h[b] lb	T/T_h*
5-5-90-0-o-1.5-2-5	5.0	4930	0.63	14070	-	11683	1.20
5-5-90-0-o-2.5-2-5	4.8	4930	0.63	19285	-	11099	1.74
5-5-90-0-o-1.5-2-6.5	6.2	5650	0.63	17815	-	14989	1.19
5-5-90-0-o-1.5-2-8	7.9	5650	0.63	22760	-	19038	1.23
5-5-90-0-o-2.5-2-8	9.0	5780	0.63	26100	-	21882	1.39
5-5-180-0-o-1.5-2-9.5	9.4	4420	0.63	29485	-	21457	1.37
5-5-180-0-o-2.5-2-9.5	9.5	4520	0.63	30130	-	21720	1.39
5-5-180-0-o-1.5-2-11.25	11.3	4520	0.63	32400	-	25721	1.26
5-5-180-2#3-o-2.5-2-9.5	9.2	4420	0.63	35500	0.35	22513	1.76
5-5-180-2#3-o-1.5-2-11.25	11.6	4420	0.63	43050	0.35	34851	1.24
5-5-180-2#3-o-1.5-2-9.5	8.8	4520	0.63	20300	0.35	23792	0.85
5-5-180-2#3-o-2.5-2-11.25	11.3	4520	0.63	42325	0.35	27374	1.55
5-5-90-5#3-o-1.5-2-5	5.0	5205	0.63	21780	1.06	13955	1.58
5-5-90-5#3-o-2.5-2-5	5.2	4930	0.63	22530	1.06	14139	1.59
5-5-90-5#3-o-1.5-2-8	7.9	5650	0.63	25110	1.06	22073	1.14
5-5-90-5#3-o-2.5-2-8	7.5	5650	0.63	24910	1.06	20666	1.38
5-5-90-5#3-o-1.5-2-6.5	6.5	5780	0.63	21710	1.06	18652	1.16
8-5-90-0-o-2.5-2-10a	10.4	5270	1.00	42315	-	31037	1.36
8-5-90-0-o-2.5-2-10b	9.8	5440	1.00	33650	-	29400	1.14
8-5-90-0-o-2.5-2-10c	10.6	5650	1.00	55975	-	32343	1.73
8-8-90-0-o-2.5-2-8	8.4	8740	1.00	33015	-	28644	1.15
8-8-90-0-o-3.5-2-8	7.8	8810	1.00	35870	-	26575	1.35
8-8-90-0-o-4-2-8	8.2	8630	1.00	37510	-	27708	1.35
8-5-90-5#3-o-2.5-2-10a	10.4	5270	1.00	54255	0.42	37185	1.46
8-5-90-5#3-o-2.5-2-10b	10.5	5440	1.00	65590	0.42	37843	1.73
8-5-90-5#3-o-2.5-2-10c	10.9	5650	1.00	57700	0.42	36988	1.56
8-8-90-5#3-o-2.5-2-8	8.5	8630	1.00	57980	0.42	33764	1.72
8-8-90-5#3-o-3.5-2-8	7.9	8810	1.00	54955	0.42	31641	1.74
8-8-90-5#3-o-4-2-8	8.3	8740	1.00	39070	0.42	34210	1.14
11-8-90-0-o-2.5-2-25	25.2	9460	1.41	174700	-	102866	1.70
11-8-90-0-o-2.5-2-17	16.6	9460	1.41	107200	-	67641	1.58
11-12-180-0-o-2.5-2-17	17.1	11800	1.41	83500	-	73642	1.13
11-12-90-0-o-2.5-2-17	16.9	11800	1.41	105400	-	72833	1.45
11-8-90-6#3-o-2.5-2-22	21.9	9120	1.41	170200	0.21	97457	1.75
11-8-90-6#3-o-2.5-2-16	16.2	9420	1.41	136800	0.21	75777	1.81
11-12-180-6#3-o-2.5-2-17	16.5	11800	1.41	113100	0.21	83782	1.35
11-12-90-6#3-o-2.5-2-17	16.4	11800	1.41	115900	0.21	81234	1.43

[a]Notation described in Section 2.1 and Appendix A
[b]Calculated anchorage strength based on Eq. (5.23)

5.4.2 Specimens with Large Ratio of Beam Effective Depth to Embedment Length, d/ℓ_{eh} > 1.5

As discussed in Sections 4.4.3 and 4.4.4.1, beam-column specimens with a ratio of effective beam depth to embedment length d_{eff}/ℓ_{eh} greater than 1.5, referred to as deep-beam specimens, exhibited low anchorage strengths when compared to specimens with d_{eff}/ℓ_{eh} less than 1.5. For design, the ratio of d_{eff}/ℓ_{eh} can be considered equivalent to the ratio of beam depth to the development length d/ℓ_{dh}. Figure 5.15 compares the measured failure load T with the calculated failure load T_h for deep-beam specimens without and with confining reinforcement within the joint region. The calculated bar force T_h is based on Eq. (5.23). The broken line is the equality line for which the calculated failure loads equal the measured failure loads. The solid line is the trend for the data. The values of calculated bar force T_h based on the Eq. (5.23) and T/T_h are presented in Table 5.12. The figure includes test results of 39 specimens evaluated in this study, and by Joh et al. (1995) and Joh and Shibata (1996). Of the 39 specimens, eight specimens contained No. 11 and No. 8 hooked bars embedded to the far side of the column with a nominal tail cover of 2 in. and 31 specimens contained No. 11 and ¾ in. diameter (No. 6) hooked bars embedded to mid-depth of the column with a nominal tail cover ranging from 7.8 to 13 in. These tests were not used to develop the descriptive equations, with the exception of four specimens containing No. 11 hooked bars embedded to the far side of the column with a nominal concrete compressive strength of 15,000 psi; the four specimens were used to develop the descriptive equations because the available number of specimens containing No. 11 hooked bars with high concrete compressive strength is relatively small (six), and using these specimens produces more conservative descriptive equations.

Twenty out of 39 (51%) specimens fall below the equality line. The specimens have a mean value of T/T_h equal to 1.0, compared with values of 1.24 for specimens without confining reinforcement and 1.34 for specimens with confining reinforcement with d_{eff}/ℓ_{eh} less than 1.5, a minimum value of 0.57, and a maximum value of 1.52. This analysis indicates that using the design equation [Eq. (5.22)] with hooked bars for beam-column joints with a ratio of beam depth to development length d/ℓ_{dh} greater than 1.5 will result in unconservative designs and that members with d/ℓ_{dh} greater than 1.5 must be designed to account for the difference in behavior compared to that observed for beam-column joints with lower ratios of effective depth d to development length ℓ_{dh}. This observation indicates that a Code change is needed in Section 15.4.4 for the development of reinforcing bars terminating in joints, as discussed next and as will be presented in Section 5.6.

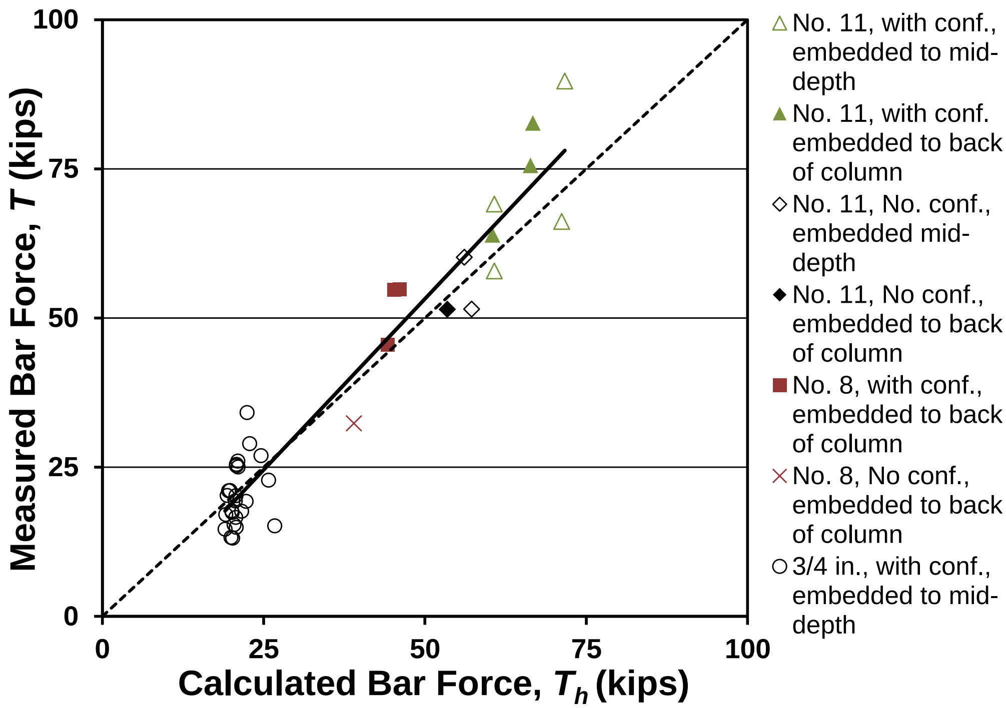


Figure 5.15 Measured bar force at failure T versus calculated bar force T_h for specimens containing hooked bars with d_{eff}/ℓ_{eh} > 1.5 without and with confining reinforcement, with T_h based on Eq. (5.23)

Table 5.12 Test parameters for specimens containing hooked bars with d_{eff}/ℓ_{eh} > 1.5 and comparisons with the design equation, Eq. (5.23)

Specimen[a]	$\ell_{eh,avg}$ in.	f_{cm} psi	c_{th} in.	N_h	A_v[b] in.^{2}	d_{eff}/ℓ_{eh}	T lb	T_h[c] lb	T/T_h[c]	$T_{h\text{-}st}$[d] lb	$T/T_{h\text{-}st}$[d]	Source
(2@5.35) 11-5-90-0-i-2.5-13-13	13.9	5330	12.0	2	-	1.57	60593	56106	1.08	-	-	Current
(2@5.35) 11-5-90-2#3-i-2.5-13-13	13.8	5330	12.1	2	0.44	1.61	69123	60731	1.14	16217	4.26	Current
(2@5.35) 11-5-90-6#3-i-2.5-13-13	13.9	5280	12.0	2	0.66	1.66	89748	71650	1.25	24326	3.69	Current
(3@5.35) 11-5-90-0-i-2.5-13-13	13.8	5330	12.2	3	-	1.55	51506	57226	0.90	-	-	Current
(3@5.35) 11-5-90-2#3-i-2.5-13-13	13.9	5330	12.0	3	0.44	1.56	57900	60759	0.95	10811	5.36	Current
(3@5.35) 11-5-90-6#3-i-2.5-13-13	13.6	5280	12.5	3	0.66	1.62	66200	71200	0.93	16217	4.08	Current
11-15-90-0-i-2.5-2-10	9.5	14050	2.5	2	-	2.1	51481	53538	0.96	-	-	Current
11-15-90-2#3-i-2.5-2-10	10.0	14050	2.0	2	0.44	2.0	63940	60467	1.06	16217	3.94	Current

[a]Notation described in Section 2.1 and Appendix A
[b]Cross-sectional area of confining reinforcement within the shaded region
[c]Calculated anchorage strength based on Eq. (5.23)
[d]Calculated anchorage strength based on strut and tie model, with f_{yt} = 68.8, 47.5, and 49.0 ksi for specimens from current study, Joh et al. (1995) and Joh and Shibata (1996), respectively.

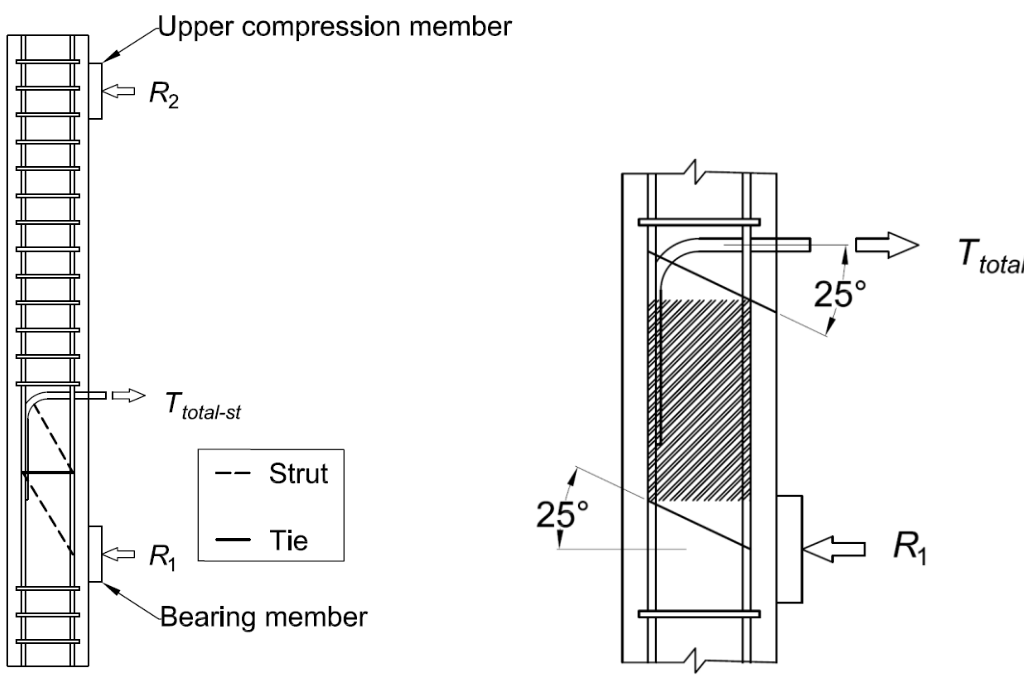
Figure 5.12 Cont. Test parameters for specimens containing hooked bars with d_{eff}/ℓ_{eh} > 1.5 and comparisons with the design equation, Eq. (5.23)

Specimen[a]	$\ell_{eh,avg}$ in.	f_{cm} psi	c_{th} in.	N_h	A_v[b] in.^{2}	d_{eff}/ℓ_{eh}	T lb	T_h[c] lb	T/T_h[c]	$T_{h\text{-}st}$[d] lb	$T/T_{h\text{-}st}$[d]	Source
11-15-90-6#3-i-2.5-2-10a	9.8	14050	2.3	2	0.66	2.1	82681	66709	1.24	24326	3.40	Current
11-15-90-6#3-i-2.5-2-10b	9.6	14050	2.4	2	0.66	2.1	75579	66369	1.14	24326	3.11	Current
(2d) 8-5-90-0-i-2.5-2-10	10.1	5920	2.0	2	-	2.02	32370	38982	0.83	-	-	Current
(2d) 8-5-90-2#3-i-2.5-2-10	10.1	5920	2.0	2	0.44	2.06	45580	44207	1.03	16217	2.81	Current
(2d) 8-5-90-5#3-i-2.5-2-10	9.9	5920	2.1	2	0.88	2.13	54730	45213	1.21	32434	1.69	Current
(2d) 8-5-90-9#3-i-2.5-2-10	10.1	5920	2.3	2	1.10	2.09	54760	46063	1.18	40543	1.35	Current
LA 3-2	7.8	5192	7.8	4	0.27	1.76	20231	20717	0.98	3435	5.89	Joh, (1995)
LA 4-1	7.8	5049	7.8	4	0.27	1.73	13230	19935	0.66	3435	3.85	Joh, (1995)
LA 4-2	7.8	5049	7.8	4	0.27	1.74	17640	21574	0.82	3435	5.13	Joh, (1995)
LA 5-1	7.8	5049	7.8	4	0.27	1.72	16593	20685	0.80	3435	4.83	Joh, (1995)
LA 5-2	7.8	5049	7.8	4	0.27	1.70	14939	20736	0.72	3435	4.35	Joh, (1995)
LA 7-1	7.8	4651	7.8	4	0.54	1.74	15159	26712	0.57	6871	2.21	Joh, (1995)
LA 7-2	7.8	4495	7.8	4	1.08	1.79	22822	25770	0.89	13741	1.66	Joh, (1995)
LA 8-1	7.8	5405	7.8	4	0.27	1.79	25247	20772	1.22	3435	7.35	Joh, (1995)
LA 8-2	7.8	5661	7.8	4	0.27	1.78	25027	21020	1.19	3435	7.29	Joh, (1995)
LA 10-1	7.8	6927	7.8	4	0.27	1.73	19294	22296	0.87	3435	5.62	Joh, (1995)
LA 10-2	7.8	10724	7.8	4	0.27	1.72	26956	24591	1.10	3435	7.85	Joh, (1995)
LA 1-1	7.8	4480	7.8	4	0.27	1.72	13120	20180	0.65	3435	3.82	Joh, (1995)
LA 8-1	7.8	5405	7.8	4	0.27	1.79	25468	20765	1.23	3544	7.19	Joh, (1996)
LA 8-2	7.8	5661	7.8	4	0.27	1.79	26019	20990	1.24	3544	7.34	Joh, (1996)
LA 8-3	7.8	4338	7.8	4	0.27	1.78	21113	19781	1.07	3544	5.96	Joh, (1996)
LA 8-4	7.8	4153	7.8	4	0.27	1.79	21058	19569	1.08	3544	5.94	Joh, (1996)
LA 8-5	7.8	3698	7.8	4	0.27	1.81	17089	19121	0.89	3544	4.82	Joh, (1996)
LA 8-6	7.8	3968	7.8	4	0.27	1.83	20286	19369	1.05	3544	5.72	Joh, (1996)
LA 8-7	7.8	7737	7.8	4	0.27	1.80	34178	22426	1.52	3544	7.23	Joh, (1996)
LA 8-8	7.8	8065	7.8	4	0.27	1.74	28941	22833	1.27	3544	6.13	Joh, (1996)
LA 5-1	7.8	4473	7.8	4	0.27	1.74	17695	20035	0.88	3544	4.99	Joh, (1996)
LA 5-2	7.8	4757	7.8	4	0.27	1.71	15380	20416	0.75	3544	4.34	Joh, (1996)
LA 5-3	7.8	5041	7.8	4	0.27	1.72	19349	20592	0.94	3544	5.46	Joh, (1996)
LA 5-4	7.8	4544	7.8	4	0.27	1.70	17420	20122	0.87	3544	4.92	Joh, (1996)
LA 5-5	7.8	3564	7.8	4	0.27	1.70	14608	19016	0.77	3544	4.12	Joh, (1996)

[a]Notation described in Section 2.1 and Appendix A
[b]Cross-sectional area of confining reinforcement within the shaded region
[c]Calculated anchorage strength based on Eq. (5.23)
[d]Calculated anchorage strength based on strut and tie model, with f_{yt} = 68.8, 47.5, and 49.0 ksi for specimens from current study, Joh et al. (1995) and Joh and Shibata (1996), respectively.

An approach for beam-column joints with d/ℓ_{dh} greater than 1.5 is suggested by Section R25.4.4.2 of the Commentary of ACI 318R-14, which, in addressing a similar case for headed bars, recommends "providing reinforcement in the form of hoops and ties to establish a load path in accordance with strut-and-tie modeling principles." To evaluate this approach, the measured anchorage strengths for the deep-beam specimens with confining reinforcement presented in Table 5.12 are compared with the calculated strength obtained using a strut-and-tie model.

A schematic diagram of the simulated beam-column joint specimens included in this analysis is shown in Figure 5.16a. The hooked bars and the bearing member simulate the tension reinforcement and the compression zone of the virtual beam. The upper compression member prevents the specimens from rotating during the test. For the purpose of this investigation, the specimens are structurally analyzed as simply-supported members, where the bearing member R_1 and the upper compression member R_2 are the supports and the force of the hooked bars T_{total} is the applied load. With this assumption, the fraction of the load in the hooked bars, corresponding to the ratio of the distance between the hooked bars and the bearing member to the distance from the hooked bars to the upper compression member, transfers to the bearing member through the joint. For specimens included in this analysis, about 70% of the total load applied to the hooks is transfered to the bearing member.



(a) (b)

Figure 5.16 Strut-and-tie model (a) Load path (b) Region of confining reinforcement considered to calculate the strength of the tie

The specimens contained different quantities of confining reinforcement within the joint region. The specimens tested in this study had either two, five, six, or nine No. 3 hoops provided parallel to the straight portion of the hooked bars within the joint region. The specimens tested by Joh et al. (1995) and Joh and Shibata (1996) had four 0.24-in. (6-mm) diameter hoops parallel to the straight portion of the hooked bars within the joint region, except for two specimens that had eight or sixteen 0.24-in. (6-mm) diameter hoops. Specimens containing No. 8 hooked bars tested in this study had strain gauges mounted on the confining reinforcement, as discussed in Section 3.5.6. The strain gauge results show that hoops located under the bearing member, Figure 5.16a, exhibited very low strains throughout the test.

The load path shown in Figure 5.16a assumes that the load transfers from the hooked bars to the bearing member through a diagonal strut from the hooks to a tie located at the middle of the joint and through another diagonal strut to the bearing member. For the specimens included in this analysis, the strength of the tie controls the strength of the specimens. For simplicity, the strength of the tie ($F_{nt} = A_v f_{yt}$) is calculated using confining reinforcement located within the shaded region of the joint as shown in Figure 5.16b. The shaded region includes the portion of the column below the hooked bars at which a straight line with a 25° angle (the minimum angle allowed by the strut-and-tie model), starting from the center point in the bend in the hooked bars, intersects the column longitudinal reinforcement to a similar point above the bearing member. A strength reduction factor $\phi = 0.75$ is applied to F_{nt}. Using the load path in Figure 5.16a, the force in the tie equal to the force at the bearing member. The calculated force at the hooked bars $T_{h\text{-}st}$ can be found using the simply-supported assumption where, for specimens included in this analysis, about 70% of the force in the hooked bars transfers to the bearing member. The values of $T_{h\text{-}st}$ obtained following this approach are given in Table 5.12. As shown in the table, the specimens have a mean value of test-to-calculated bar force $T/T_{h\text{-}st}$ of 4.79 with a maximum value of 7.85 and a minimum value of 1.35. The standard deviation is 1.72 and the coefficient of variation is 0.36. As demonstrated by this analysis and earlier by others (Park and Kuchma 2007, Tuchscherer, Birrcher, and Byrak 2011), strut-and-tie models provide over-conservative designs with a high range of scatter. Using a strut-and-tie model, however, does provide an approach for beam-column joints with $d/\ell_{dh} > 1.5$.

5.4.3 Other Beam-Column Specimens Not Used in Equation Development

The test results for the beam-column joint specimens not used in the derivation of the descriptive and design equations are compared with anchorage strengths calculated using the design equation. These specimens were compared with the descriptive equations in Section 4.6. They consisted of 12 specimens tested as part of this study with two or more hooked bars anchored in a column with a longitudinal reinforcement ratio ρ_{col} greater than 4%, not common in practical application, and 29 specimens with two hooked bars with ρ_{col} less than 4%, of which 23 specimens were tested by other researchers (Marques and Jirsa 1975, Pinc et al. 1977, Hamad et al. 1993, Ramirez and Russell 2008, Lee and Park 2010) and six were tested in this study. Of the 29 specimens with two hooked bars, 13 contained two closely-spaced hooked bars without confining reinforcement (11 tested by other researchers and two from this study), eight contained two closely-spaced hooked bars with confining reinforcement (four tested by other researchers and four from this study), and eight contained two widely-spaced hooked bars with confining reinforcement (tested by other researchers). As discussed in Section 4.6, specimens with two closely-spaced hooked bars (tested by other researchers) had two No. 11 hooked bars with a 90° or 180° bend angle without or with confining reinforcement. These specimens were initially included in the analysis but they had high ratios of test-to-calculated bar for force at failure T/T_h compared to specimens with closely-spaced hooked bars tested in the current study. The high values of T/T_h result from the high confinement inherent in these tests. The No. 11 hooked bars with the 180° bend angle had the tail extension within the compression zone of the beam with a concrete cover to the bearing member of 0.5 in. or less, while the No. 11 hooked bars with a 90° bend angle had most of the tail extension within the compression zone of the beam. ,As discussed earlier, the majority of the specimens containing two closely-spaced hooked bars were tested by other researchers. To be consistent, the small number of specimens (six) containing two closely-spaced hooked bars (c_{ch} < $6d_b$) tested in the current study were also not used to develop the descriptive equations. Specimens containing widely-spaced hooked bars with confining reinforcement (tested by other researchers) were not used because they represent a small number of specimens compared to the database developed in this study and because of the inherent variability in the contribution of the confining reinforcement to the anchorage strength of hooked bars and differences in specimen design.

5.4.3.1 Specimens with Column Longitudinal ratio > 4.0%

Figure 5.17 shows the ratio of test-to-calculated average bar force T/T_h for nine two-hook and three three-hook specimens plotted versus column reinforcement ratio ρ_{col}. The calculated bar force is based on the design equation, Eq. (5.23). The values of calculated bar force T_h and T/T_h are presented in Table 5.13. The specimens contained No. 5 and No. 8 hooked bars with 90° and 180° bend angles and three levels of confining reinforcement, no confinement, 2 No. 3 hoops, or No. 3 hoops spaced at $3d_b$. All specimens have a test-to-calculated ratio greater than 1.0, with nine out the twelve specimens with T/T_h above 1.5. T/T_h increases as the column longitudinal reinforcement ratio increases. The specimens have a mean value of test-to-calculated bar force of 1.58 with a maximum value of 2.05 and a minimum value of 1.09.

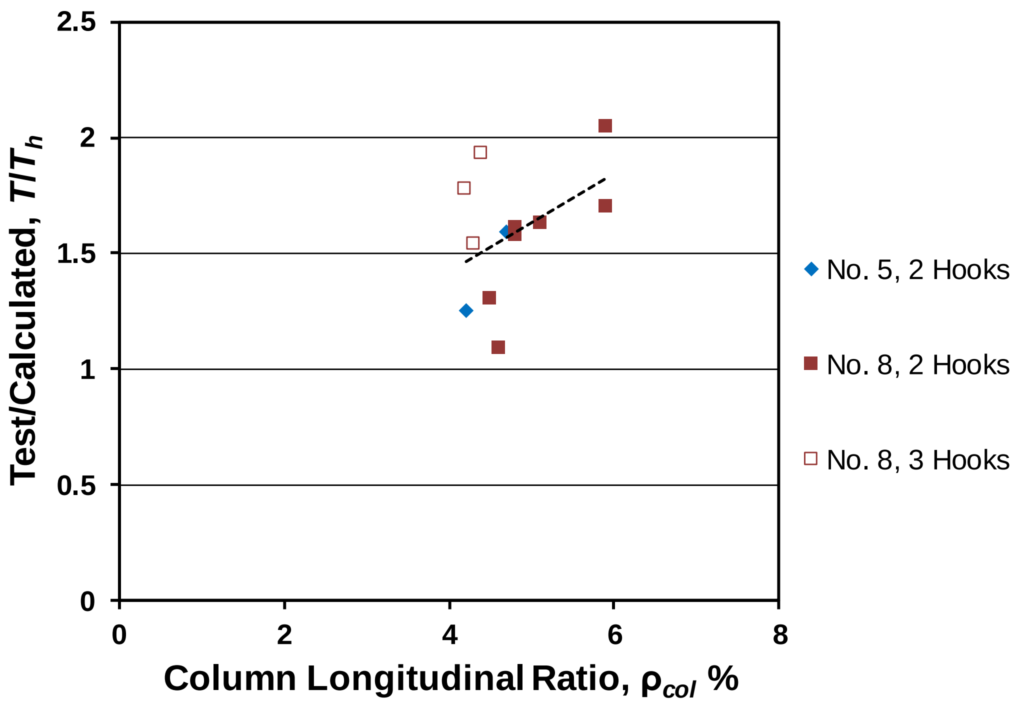


Figure 5.17 Ratio of test-to-calculated bar force at failure T/T_h for specimens with high column longitudinal ratio versus ρ_{col}, with T_h based on Eq. (5.23)

Table 5.13 Test parameters for specimens with high column longitudinal reinforcement ratio and comparisons with the design equation, Eq. (5.23)

Specimen[a]	ℓ_{eh} in.	f_{cm} psi	N_h	d_b in.	A_{th}/A_{hs}	c_{ch}/d_b	T lb	T_h[b] lb	T/T_h[b]	ρ_{col}
(2@4) 5-8-90-0-i-2.5-2-6[c]	5.9	6950	2	0.63	-	4.0	22350	14029	1.59	0.047
(2@6) 5-8-90-0-i-2.5-2-6[c]	6.0	6950	2	0.63	-	6.0	23950	19103	1.25	0.042
(2@3) 8-5-180-0-i-2.5-2-10[c,d]	10.1	5260	2	1.0	-	3.0	51825	25307	2.05	0.059
(2@5) 8-5-180-0-i-2.5-2-10[c,d]	10.0	5260	2	1.0	-	5.0	53165	32620	1.63	0.051
(2@3) 8-5-180-2#3-i-2.5-2-10[c,d]	10.3	5400	2	1.0	0.14	3.0	57651	33907	1.70	0.059
(2@5) 8-5-180-2#3-i-2.5-2-10[c,d]	10.0	5400	2	1.0	0.14	5.0	61885	38304	1.62	0.048
(2@5) 8-5-180-5#3-i-2.5-2-10[c,d]	10.1	5540	2	1.0	0.42	5.0	66644	42105	1.58	0.048
8-15-90-2#3-i-2.5-2-6[c]	6.1	15800	2	1.0	0.14	10.8	37569	34389	1.09	0.046
8-15-90-5#3-i-2.5-2-6[c]	6.3	15800	2	1.0	0.42	10.8	48499	37187	1.30	0.045
(3@3) 8-5-180-0-i-2.5-2-10[c,d]	9.8	5260	3	1.0	-	3.0	47249	24503	1.93	0.044
(3@3) 8-5-180-2#3-i-2.5-2-10[c,d]	10.3	5400	3	1.0	0.09	3.0	54576	30720	1.78	0.042
(3@3) 8-5-180-5#3-i-2.5-2-10[c,d]	9.9	5540	3	1.0	0.28	3.0	58877	38255	1.54	0.043

[a]Notation described in Section 2.1 and Appendix A
[b]Calculated anchorage strength based on Eq. (5.23)
[c]Specimen had column longitudinal reinforcement ratio > 4.0%
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement

5.4.3.2 Specimens with Column Longitudinal ratio < 4.0%

Figure 5.18 shows the measured failure load T plotted versus the calculated failure load T_h for the beam-column specimens with column longitudinal reinforcement ratio < 4% not used to develop the descriptive and design equations, tested in this study and by others (Marques and Jirsa 1975, Pinc et al. 1977, Hamad et al. 1993, Ramirez and Russell 2008, Lee and Park 2010). The calculated bar force T_h is based on Eq. (5.23). The broken line represents cases in which the calculated failure loads equal the measured failure loads. Figure 5.18 includes 13 specimens without confining reinforcement containing No. 8, No. 9, or No. 11 hooked bars with 90° or 180° bend angles, denoted with hollow symbols, and 16 specimens with confining reinforcement containing No. 6, 7, 8, and 11 hooked bars with 90° or 180° bend angles, denoted with solid symbols. The calculated bar force T_h and ratio T/T_h for the specimens are presented in Table 5.12. All specimens without confining reinforcement fall above the equity line with a mean value of test-to-calculated bar force T/T_h of 1.74, a maximum value of 2.18, and a minimum value of 1.27. The high values of T/T_h, as discussed earlier, result from the high confinement inherent in these tests. Specimens with confining reinforcement, however, have a mean value of T/T_h of 1.36, a maximum value of 1.86, and a minimum value of 0.9; two of the specimens fall below the equity line. The high range of scatter in the specimens with confining reinforcement results from the inherent variability in the contribution of the confining reinforcement to the anchorage strength of hooked bars and differences in specimen design.

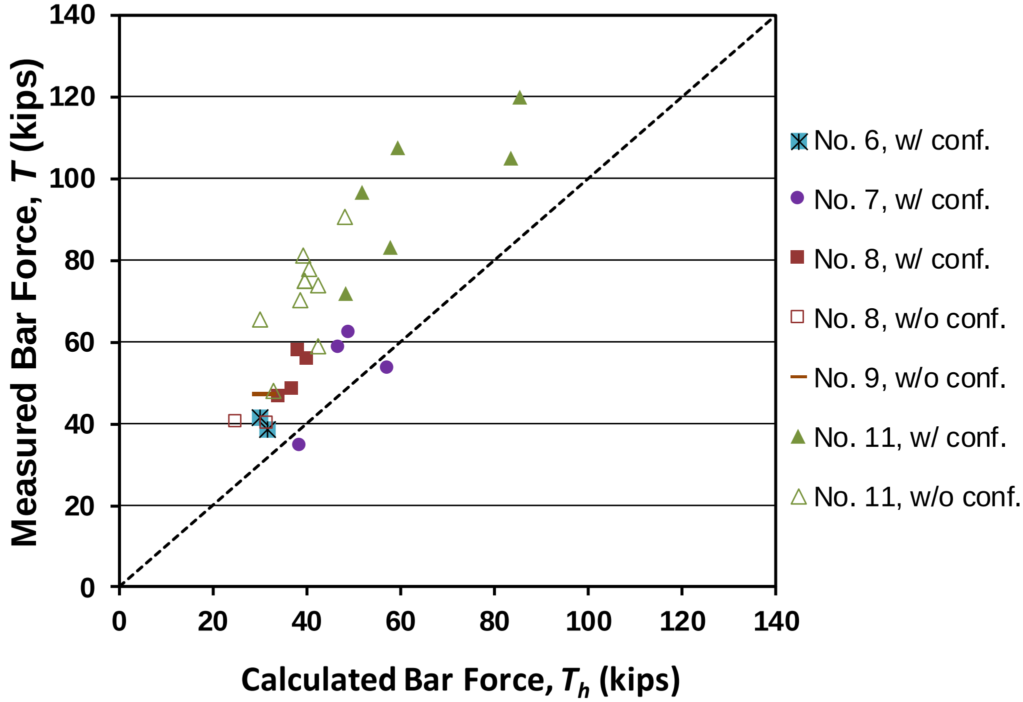


Figure 5.18 Measured bar force at failure versus calculated bar force for two-hook specimens with $\rho_{col.}$ < 4% not used in equation development, with T_h based on Eq. (5.23)

Table 5.14 Test parameters for two-hook specimens with column longitudinal reinforcement ratio < 4% excluded from equation development and comparisons with the design equation, Eq. (5.23)

Specimen[a]	Hook Location	ℓ_{eh} in.	f_{cm} psi	N_h	d_b in.	A_{th}/A_{hs}	c_{ch}/d_b	T lb	T_h[b] lb	T/T_h[b]	Source
(2@3) 8-5-90-0-i-2.5-2-10[d]	Inside	10.5	4490	2	1.0	-	3.0	40313	25149	1.60	Current Investigation
(2@5) 8-5-90-0-i-2.5-2-10[d]	Inside	10.1	4490	2	1.0	-	5.1	40100	31555	1.27	Current Investigation
9-12	Inside	10.0	4700	2	1.13	-	4.5	47000	30929	1.52	Pinc et al. (1977)
J 11 - 180 -15 -1 - H	Inside	13.1	4400	2	1.41	-	3.4	70200	38546	1.82	Marques and Jirsa (1975)
J 11- 90 -12 -1 - H	Inside	10.1	4600	2	1.41	-	3.4	65520	30017	2.18	Marques and Jirsa (1975)
J 11- 90 -15 -1 - H	Inside	13.1	4900	2	1.41	-	3.4	74880	39598	1.89	Marques and Jirsa (1975)
J 11- 90 -15 -1 - L	Inside	13.1	4750	2	1.41	-	3.4	81120	39291	2.06	Marques and Jirsa (1975)

[a]Notation described in Section 2.1 and Appendix A
[b]Calculated anchorage strength based on Eq. (5.23)
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement

Figure 5.14 Cont. Test parameters for two-hook specimens with column longitudinal reinforcement ratio < 4% excluded from equation development and comparisons with the design equation, Eq. (5.23)

Specimen[a]	Hook Location	ℓ_{eh} in.	f_{cm} psi	N_h	d_b in.	A_{th}/A_{hs}	c_{ch}/d_b	T lb	T_h[b] lb	T/T_h[b]	Source
11-15	Inside	13.1	5400	2	1.41	-	3.4	78000	40571	1.92	Pinc et al. (1977)
11-18	Inside	16.1	4700	2	1.41	-	3.4	90480	48196	1.88	Pinc et al. (1977)
11-90-U	Inside	13.0	2570	2	1.41	-	3.2	48048	32888	1.46	Hamad et al. (1993)
11-90-U*	Inside	13.0	5400	2	1.41	-	3.2	75005	39596	1.89	Hamad et al. (1993)
11-180-U-HS	Inside	13.0	7200	2	1.41	-	3.2	58843	42549	1.38	Hamad et al. (1993)
11-90-U-HS	Inside	13.0	7200	2	1.41	-	3.2	73788	42549	1.73	Hamad et al. (1993)
III-13	Inside	6.5	13980	2	0.75	0.75	12.3	41300	30227	1.37	Ramirez and Russell (2008)
III-15	Inside	6.5	16350	2	0.75	0.75	12.3	38500	31753	1.21	Ramirez and Russell (2008)
7-180-U-T4	Inside	10.0	3900	2	0.88	0.36	5.8	34620	38510	0.90	Hamad et al. (1993)
J 7- 90 -15 -3a - H	Outside	13.0	3750	2	0.88	0.66	6.1	58800	46775	1.26	Marques and Jirsa (1975)
H3	Inside	15.0	4453	2	0.88	0.55	9.9	53761	57090	0.94	Lee and Park (2010)
J 7- 90 -15 -3 - H	Outside	13.0	4650	2	0.88	0.36	6.1	62400	48899	1.28	Marques and Jirsa (1975)
(2@3) 8-5-90-2#3-i-2.5-2-10[d]	Inside	10.3	4760	2	1.0	0.14	3.2	46810	33903	1.38	Current Investigation
(2@5) 8-5-90-2#3-i-2.5-2-10[d]	Inside	9.8	4760	2	1.0	0.14	4.9	48515	36877	1.32	Current Investigation
(2@3) 8-5-90-5#3-i-2.5-2-10[d]	Inside	10.3	4805	2	1.0	0.42	3.0	57922	38234	1.51	Current Investigation
(2@5) 8-5-90-5#3-i-2.5-2-10[d]	Inside	9.7	4805	2	1.0	0.42	5.2	55960	40217	1.39	Current Investigation
III-14	Inside	12.5	13980	2	1.41	0.21	6.1	105000	83448	1.26	Ramirez and Russell (2008)
III-16	Inside	12.5	16500	2	1.41	0.21	6.1	120000	85623	1.40	Ramirez and Russell (2008)
11-90-U-T6	Inside	13.0	3700	2	1.41	0.14	3.2	71807	48506	1.48	Hamad et al. (1993)
J 11- 90 -15 -3a - L	Outside	13.1	5000	2	1.41	0.21	3.4	107640	59542	1.81	Marques and Jirsa (1975)
11-90-U-T4	Inside	13.0	4230	2	1.41	0.21	3.2	83195	57932	1.44	Hamad et al. (1993)
J 11- 90 -15 -3 - L	Outside	13.1	4850	2	1.41	0.14	3.4	96720	51916	1.86	Marques and Jirsa (1975)

[a]Notation described in Section 2.1 and Appendix A
[b]Calculated anchorage strength based on Eq. (5.23)
[d]Specimen had ASTM A1035 Grade 120 longitudinal reinforcement

5.5 COMPARISON OF DESIGN EQUATION WITH RESULTS FOR SPECIMENS OTHER THAN SIMULATED BEAM-COLUMN JOINTS

5.5.1 Monolithic Beam-Column Joints

The anchorage strengths of hooked bars T in monolithic exterior beam-column joints tested by Hamad and Jumaa (2008) are compared with the strengths T_h calculated using the design equation, Eq. (5.23), in this section. Each specimen consisted of two cantilever beams connected to a single column (see Section 1.2.2). The beam tension reinforcement consisted of two No. 5, No. 8, or No. 10 hooked bars with a 90° bend angle. The hooked bars were placed inside and outside the column core. No confining reinforcement was provided within the joint region. The calculated bar force T_h and the ratio T/T_h for the specimens are presented in Table 5.15. Specimens containing No. 5, No. 8, and No. 10 hooked bars had a ratios of beam effective depth to embedment length of 1.75, 1.3, and 1.0, respectively. Specimen B16H-C containing No. 5 hooked bars inside the column core developed a plastic hinge within the beam (that is, the specimen did not fail in anchorage). All specimens have a ratio of test-to-calculated bar force with the calculated based the design equation, Eq. (5.23) above 1.0, with a mean value of 1.55, a maximum value of 1.79, and a minimum value of 1.33. For hooked bars, both inside and outside the column core, the ratio of test-to-calculated average bar force T/T_h increases as the ratio of beam effective depth to embedment length d/ℓ_{eh} decreases, matching the observations for hooked bars in simulated beam-column joints where hooked bars exhibited lower anchorage strength with d/ℓ_{eh} greater than 1.5

Table 5.15 Test parameters for monolithic beam-column specimens tested by Hamad and Jumaa (2008) and comparisons with the design equation, Eq. (5.23)[a]. No specimens contained confining reinforcement within the joint

Specimen	Hook Location	$\ell_{eh,avg}$ in.	f_{cm} psi	N_h	d_b in.	d/ℓ_{eh}	T lb	T_h[b] lb	T/T_h[b]
B16H-C[c]	Inside	5.9	7650	2	0.63	1.75	27480	19252	1.42
B25H-C	Inside	7.9	7650	2	1.0	1.3	46100	32322	1.43
B32H-C	Inside	9.8	7650	2	1.27	1.0	67800	38384	1.77
B16H-U	Outside	5.9	9770	2	0.63	1.75	21850	16372	1.33
B25H-U	Outside	7.9	9770	2	1.0	1.3	42980	27487	1.56
B32H-U	Outside	9.8	9770	2	1.27	1.0	69250	38594	1.79

[a]Values are converted from metric, 1 in. = 25.4 mm, 1 psi = 0.0069 MPa, and 1 lb = 0.0045 kN
[b]Calculated anchorage strength based on Eq. (5.23)
[c]Specimen developed a plastic hinge within the beam (not an anchorage failure)

5.5.2 Hooks Anchored in Walls

As discussed in Section 4.5.2, confinement provided by a high concrete side cover, such as for hooked bars in walls, can provide confinement similar to that provided by the column core. In this section, the anchorage strengths of hooked bars T in the beam-wall specimens tested by Johnson and Jirsa (1981) and specimens containing three hooked bars with large spacing between the bars that were tested in this study are compared with the strength T_h calculated using the design equation, Eq. (5.23). The specimens consisted of 26 beam-wall specimens (Johnson and Jirsa 1981) containing one No. 4, No. 7, No. 9, or No. 11 hooked bar with a 90° bend angle placed in a 24 × 52 in. wall, four beam-wall specimens containing three No. 7 or No. 11 hooked bars with a 90° bend angle placed in a 72 × 52 in. wall, and three multiple-hook specimens tested in this study containing three No. 5 hooked bars with a 90° bend angle placed in a $18^3/_8$×54 in. column. Beam-wall specimens containing one hooked bar had a ratio of effective beam depth to embedment length d_{eff}/ℓ_{eh} ranging from 1.3 to 3.6; beam-wall specimens containing three hooked bars had d_{eff}/ℓ_{eh} ranging from 1.6 to 1.9; and beam-column specimens containing three hooked bars had d_{eff}/ℓ_{eh} ranging from 0.9 to 1.0. As discussed in Section 4.5.2, the ratio of test-to-calculated bar force T/T_h, with T_h based on the descriptive equation, consistently decreased as d_{eff}/ℓ_{eh} increased; beyond a value of d_{eff}/ℓ_{eh} of approximately 3.0, the hooked bars had anchorage strengths less than that predicted by the descriptive equation. Figure 5.19 compares the measured failure load T with the calculated failure load T_h based on Eq. (5.23) for the specimens. The values of T_h and T/T_h are presented in Tables 5.16 and 5.17. The beam-wall specimens containing one hooked bar with a ratio of effective beam depth to embedment length d_{eff}/ℓ_{eh} less than 3.0 fall above the equality line with a mean value of test-to-calculated bar force T/T_h of 1.41, a maximum value of 1.76, and a minimum value of 1.13; the beam-wall specimens containing one hooked bar with d_{eff}/ℓ_{eh} greater than 3.0 have a mean value of T/T_h of 0.97 with maximum value of 1.08 and a minimum value of 0.84; the beam-wall specimens and beam-column specimens containing three hooked bars with d_{eff}/ℓ_{eh} less than 3.0 have a mean value of T/T_h of 1.36 with a maximum value of 1.50 and a minimum value of 1.03. This analysis suggests that d/ℓ_{dh} = 3.0 could be considered a threshold for the use of the design equation in hooked bars terminated in walls. Because the comparisons are limited and for simplicity on the Code, however, a recommendation for such a provision will not be made at this time.

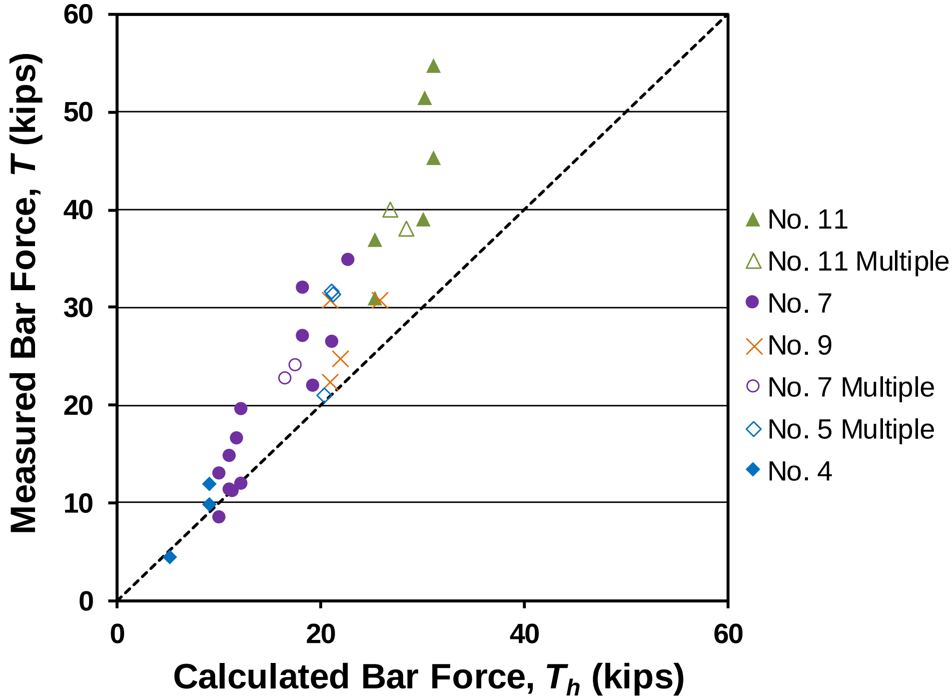


Figure 5.19 Measured bar force at failure versus calculated bar force beam- wall specimens tested by Johnson and Jirsa 1981 and multiple-hook specimens tested in this study, with T_h based on Eq. (5.23)

Table 5.16 Test parameters for beam-wall specimens with one hook tested by Johnson and Jirsa (1981) and comparisons with the design equation, Eq. (5.23)

Specimen	f_{cm} psi	ℓ_{eh} in.	d_b in.	d_{eff}/ℓ_{eh}	T lb	T_h[a] lb	T/T_h[a]
4-3.5-8-M	4500	2.0	0.5	3.1	4400	5148	0.85
4-5-11-M	4500	3.5	0.5	2.7	12000	9010	1.33
4-5-14-M	4500	3.5	0.5	3.5	9800	9010	1.09
7-5-8-L	2500	3.5	0.875	2.1	13000	10080	1.29
7-5-8-M	4600	3.5	0.875	1.9	16500	11740	1.41
7-5-8-H	5450	3.5	0.875	1.9	19500	12248	1.59
7-5-8-M	3640	3.5	0.875	2.0	14700	11072	1.33
7-5-14-L	2500	3.5	0.875	3.6	8500	10080	0.84
7-5-14-M	4100	3.5	0.875	3.6	11200	11407	0.98
7-5-14-H	5450	3.5	0.875	3.5	11900	12248	0.97
7-5-14-M	3640	3.5	0.875	3.6	11300	11072	1.02
7-7-8-M	4480	5.5	0.875	1.3	32000	18327	1.75
7-7-11-M	4480	5.5	0.875	1.8	27000	18327	1.47
7-7-14-M	5450	5.5	0.875	2.3	22000	19247	1.14
9-7-11-M	4500	5.5	1.128	1.9	30800	20891	1.47
9-7-14-M	5450	5.5	1.128	2.3	24800	21916	1.13
9-7-18-M	4570	5.5	1.128	3.1	22300	20972	1.06
7-8-11-M	5400	6.5	0.875	1.6	34800	22694	1.53
7-8-14-M	4100	6.5	0.875	2.0	26500	21184	1.25
9-8-14-M	5400	6.5	1.128	2.0	30700	25841	1.19
11-8.5-11-L	2400	7.0	1.41	1.8	37000	25363	1.46
11-8.5-11-M	4800	7.0	1.41	1.6	51500	30162	1.71
11-8.5-11-H	5450	7.0	1.41	1.6	54800	31135	1.76
11-8.5-14-L	2400	7.0	1.41	2.1	31000	25363	1.22
11-8.5-14-M	4750	7.0	1.41	1.9	39000	30084	1.30
11-8.5-14-H	5450	7.0	1.41	1.9	45400	31135	1.46

[a]Calculated anchorage strength based on Eq. (5.23)

Table 5.17 Test parameters for beam-wall specimens with three hooks tested by Johnson and Jirsa 1981 and multiple-hook specimens tested in this study and comparisons with the design equation, Eq. (5.23)

Specimen	f_{cm} psi	ℓ_{eh} in.	d_b in.	d_{eff}/ℓ_{eh}	spacing in.	T lb	T_h[a] lb	T/T_h[a]	Source
7-7-11-M	3800	5.5	0.875	1.9	11	24000	17588	1.36	Johnson and Jirsa 1981
7-7-11-L	3000	5.5	0.875	1.9	22	22700	16578	1.37	Johnson and Jirsa 1981
11-8.5-11-M	3800	7.0	1.41	1.6	11	38000	28451	1.34	Johnson and Jirsa 1981
11-8.5-11-L	3000	7.0	1.41	1.7	22	40000	26819	1.49	Johnson and Jirsa 1981
(3@10) 5-5-90-0-i-2.5-2-7	5880	6.7	0.625	0.9	5.6	21034	20348	1.03	Current investigation
(3@10) 5-5-90-2#3-i-2.5-2-7	5950	7.0	0.625	1.0	5.6	31296	21277	1.47	Current investigation
(3@10) 5-5-90-5#3-i-2.5-2-7	5950	6.9	0.625	1.0	5.6	31684	21063	1.51	Current investigation

[a]Calculated anchorage strength based on Eq. (5.23)

5.6 PROPOSED CODE PROVISIONS

This section presents proposed design provisions for the development of hooked bars in tension for incorporation in the ACI 318-14 Code.

2.2—Notation

A_{th} = total cross-sectional area of all confining reinforcement parallel to ℓ_{dh} for hooked bars being developed and located within $8d_b$ of the top (bottom) of the bars in the direction of the hook for No. 3 through No. 8 hooked bars or within $10d_b$ of the top (bottom) of the bars in the direction of the hook for No. 9 through No. 11 hooked bars; or total cross-sectional area of all confining reinforcement perpendicular to ℓ_{dh}, in.^{2}

A_{hs} = total cross-sectional area of hooked bars being developed, in.^{2}

c_{ch} = minimum center-to-center spacing of hooked bars being developed, in.

d_b = nominal diameter of bar, in.

f_c' = Specified compressive strength of concrete (psi)

f_y = Specified yield strength of hooked bar (psi)

ℓ_{dh} = development length in tension of hooked deformed bar, measured from the critical section

ψ_{cs} = factor used to modify development length based on confining reinforcement and bar spacing

ψ_e = factor used to modify development length based on reinforcement coating

ψ_o = factor used to modify development length based on bar placement within member

15.4.4 Development of longitudinal reinforcement terminating in the joint shall be in accordance with **25.4**. If the effective depth ***d*** of any beam framing into the joint and generating shear exceeds **1.5** times the reinforcement anchorage length, analysis and design of the joint shall be based on the strut-and-tie method in accordance with **Chapter 23**.

25.4.1.4 The value of f_c' used to calculate development length shall not exceed 10,000 psi, except as permitted in 25.4.3.1(a)

Replace **25.4.3** with:

25.4.3 *Development of standard hooks in tension*

25.4.3.1 Development length ℓ_{dh} for deformed bars in tension terminating in a standard hook shall be the greatest of (a) through (c).

(a) $\left(0.003\dfrac{f_y\psi_e\psi_{cs}\psi_o}{\lambda f_c'^{0.25}}\right)d_b^{1.5}$ with ψ_e, ψ_{cs}, ψ_o, and λ given in 25.4.3.2; the value of f_c' is permitted to exceed 10,000 psi, but shall not exceed 16,000 psi

(b) $8d_b$

(c) 6 in.

25.4.3.2 For the calculation of ℓ_{dh}, modification factors ψ_e, ψ_o, and λ shall be in accordance with Table 25.4.3.2a and modification factor ψ_{cs} shall be in accordance with Table 25.4.3.2b. Factor ψ_{cs} shall be permitted to be taken as 1.0. At discontinuous ends of members, 25.4.3.3 shall apply.

Table 25.4.3.2a—Modification factors for development of hooked bars in tension

Modification Factor	Condition	Value of Factor
Lightweight λ	Lightweight concrete	0.75
	Normalweight concrete	1.0
Epoxy ψ_e	Epoxy-coated or zinc and epoxy dual-coated reinforcement	1.2
	Uncoated or zinc-coated (galvanized) reinforcement	1.0
Placement ψ_o[1]	For No. 11 bar and smaller hooks (1) terminating inside a column core with side cover (normal to plane of hook) ≥ 2.5 in., or (2) terminating in a supporting member with side cover (normal to plane of hook) ≥ $6d_b$	1.0
	Other	1.25

[1]d_b is the nominal diameter of the hooked bar

Table 25.4.3.2b—Modification factor ψ_{cs} for confining reinforcement and spacing[1]

Bar size and confinement level	f_y	c_{ch}	
		$2d_b$	$\geq 6d_b$
For No. 11 bar and smaller hooks with $\frac{A_{th}}{A_{hs}} \geq 0.2$ [2] or $\frac{A_{th}}{A_{hs}} \geq 0.4$ [3]	60,000	0.6	0.5
	120,000	0.66	0.55
For No. 11 bar and smaller hooks with no confining reinforcement	all	1.0	0.6
For No. 14 bar and larger hooks	all	1.0	0.6

[1] ψ_{cs} is permitted to be linearly interpolated for values of A_{th}/A_{hs} between 0 and 0.2, or between 0 and 1.0, and for spacing c_{ch} or yield strength f_y intermediate to those in the table

[2] Confining reinforcement parallel to straight portion of bar

[3] Confining reinforcement perpendicular to straight portion of bar

Modify **25.4.3.3**:

25.4.3.3 For bars being developed by a standard hook at discontinuous ends of members with both side cover and top (or bottom) cover to hook less than 2-1/2 in., (a) through (c) shall be satisfied:

(a) The hook shall be enclosed along ℓ_{dh} within ties or stirrups perpendicular to ℓ_{dh} at $s \leq 3d_b$

(b) The first tie or stirrup shall enclose the bent portion of the hook within $2d_b$ of the outside of the bend

(c) ψ_o shall be taken as 1.25 in calculating ℓ_{dh} in accordance with 25.4.3.1(a)

where d_b is the nominal diameter of the hooked bar.

CHAPTER 6: SUMMARY AND CONCLUSIONS

6.1 SUMMARY

One hundred twenty two simulated beam-column joint specimens, containing No. 5, No. 8 and No. 11 hooked bars with 90° and 180° bend angles, were tested as a continuation of prior research at the University of Kansas (Peckover and Darwin 2013, Searle et al. 2014, and Sperry et al. 2015a, 2015b, 2017a). The specimens were cast in 12 groups using normalweight ready-mix concrete with concrete compressive strengths ranging from 4,490 to 14,050 psi. The hooked bars were fabricated from ASTM A615 Grade 80 and ASTM A1035 Grade 120 steel. The stresses in the hooked bars at anchorage failure ranged from 22,800 to 138,800 psi. The hooked bars were placed inside the column core (that is, inside the column longitudinal reinforcement) with a nominal side cover of 2.5 in. The test parameters also included embedment length (5.5 to 23.5 in.), amount of confining reinforcement within the joint (no confining reinforcement to nine No. 3 hoops), location of the hooked bar with respect to member depth, center-to-center spacing between hooked bars (2 to 11.8d_b), number of hooked bars (2, 3, 4, or 6), arrangement of hooked bars (staggered hooks), and ratio of beam effective depth to embedment length (0.6 to 2.13). Some specimens had strain gauges mounted along the straight portion of the hooked bars and on the confining reinforcement within the joint region. Test results from this study, along with test results from earlier work covering specimens without and with confining reinforcement, concrete compressive strengths between 2,570 and 16,510 psi, and bars stresses at anchorage failure ranging from 22,800 and 144,100 psi, were used to develop descriptive equations for anchorage strength of hooked bars. Factors affecting anchorage strength – spacing between hooked bars, staggering hooks, ratio of beam effective depth to embedment length, hooked bar location (inside or outside the column core and with respect to member depth), orientation of confining reinforcement, and confining reinforcement above the joint region – were evaluated using the descriptive equations. The descriptive equations were used along with a reliability-based strength reduction factor to develop Code provisions for the development length of reinforcing bars terminated with standard hooks.

6.2 CONCLUSIONS

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

1. The provisions in ACI 318-14 for the development length for hooked bars overestimate the contribution of concrete compressive strength and bar size on the anchorage strength.
2. The incorporation of the modification factors based on concrete cover and confining reinforcement in the current Code provisions for development length overestimate the anchorage strength of hooked bars, particularly for large hooked bars and closely-spaced hooked bars.
3. The contribution of concrete compressive strength on the anchorage strength of hooked bars is best represented by the concrete compressive strength to the 0.295 power. Compressive strength to the 0.25 power works well for design.
4. The anchorage strength of hooked bars increases with an increase in the amount of confining reinforcement, even for confining reinforcement below the value required by ACI 318-14 to reduce development length by 20 percent.
5. Hooked bars with a center-to-center spacing below six bar diameters exhibit lower anchorage strengths than hooked bars with wider spacing. The reduction in anchorage strength of closely-spaced hooked bars is a function of the spacing between the hooked bars and amount of confining reinforcement.
6. The straight portion of hooked bars contributes to anchorage strength of hooked bars even at failure.
7. For hooked bars with a bend angle of 90°, at peak load, confining reinforcement provided in form of hoops within the joint region generally exhibit the greatest strain at the hoop closest to the straight portion of the bar, with strains decreasing as the distance from the bar increases. For hooked bars with a bend angle of 180°, at peak load, the hoop adjacent to the tail extension of the hooked bars exhibits the greatest strain; the strains in hoops above and below the hoop with the highest strain decrease as the distance from the hoop with the highest strain increases.
8. The anchorage strength of staggered hooked bars can be represented by considering the minimum spacing between hooked bars.

9. Hooked bars anchored in beam-column joints with a ratio of beam effective depth to embedment length (d/ℓ_{eh}) greater than 1.5 exhibit low anchorage strengths.
10. The amount of confining reinforcement provided above the joint region, within a range of 0.25 to 1.29 times the area of the hooked bars, does not affect the anchorage strength of the hooked bars within the joint region.
11. The proposed provisions for ACI 318 provide conservative criteria for the development length of reinforcing bars anchored with standard hooks for reinforcing steel with yield strengths up to 120,000 psi and concrete with compressive strengths up to 16,000 psi.

6.3 FUTURE WORK

The maximum bar size of hooked bars evaluated in this and previous work is No. 11. In practice, however, larger hooked bars sizes (No. 14 and No. 18) can be used. For these larger bars, the proposed design provisions do not allow for a reduction factor based on the confining reinforcement when calculating the development length. This approach is similar to that provided in the provisions in ACI 318-14 for the development length of No. 14 and No. 18 hooked bars. Because of this lack of data, it is recommended that tests be performed to investigate the anchorage strength of the two large size hooked bars without and with confining reinforcement.

As shown in this study, the anchorage strength of hooked bars decreases as the center-to-center spacing between the bars decreases below six bar diameters. The effect is not recognized by the provisions in ACI 318-14 for development length of hooked bars. The closely-spaced hooked bars tested in this study, however, were either closely-spaced in the horizontal or the vertical direction, but not both. Therefore, it is recommended that the anchorage strength of hooked bars that are closely-spaced in both horizontal and vertical directions be evaluated.

The provisions in ACI 318-14 for the development length of hooked bars allow for the same reduction factor with parallel and perpendicular confining reinforcement for hooked bars with a 90° bend angle. Test results for the limited number of specimens containing hooked bars with perpendicular confining reinforcement described in this report indicate that, bar for bar, the contribution of perpendicular confining reinforcement distributed along the development length is about half of that of parallel confining reinforcement located with 8 to 10 bar diameters of the straight portion of the hooked bar. The tests of specimens containing perpendicular confining reinforcement represent the first of such tests. To expand the understanding of the contribution of perpendicular confining reinforcement to anchorage strength, additional tests are recommended of hooked bar specimens containing perpendicular confining reinforcement.

REFERENCES

AASHTO (2012). *AASHTO LRFD Bridge Design Specifications*, 6^{th} edition, American Association of State Highway and Transportation Officials, 1672 pp.

ACI Committee 117 (2014). *Specification for Tolerances for Concrete Construction and Materials (ACI 117-14) and Commentary*, American Concrete Institute, Farmington Hills, 76 pp.

ACI Committee 318 (1963). *Building Code Requirements for Reinforced Concrete (ACI 318-63)*, American Concrete Institute, Detroit, Michigan, 144 pp.

ACI Committee 318 (1971). *Building Code Requirements for Reinforced Concrete (ACI 318-71)*, American Concrete Institute, Detroit, Michigan, 78 pp.

ACI Committee 318 (1977). *Building Code Requirements for Reinforced Concrete (ACI 318-77)*, American Concrete Institute, Detroit, Michigan.

ACI Committee 318 (1983). *Building Code Requirements for Reinforced Concrete (ACI 318-83)*, American Concrete Institute, Detroit, Michigan, 111 pp.

ACI Committee 318 (1989). *Building Code Requirements for Reinforced Concrete (ACI 318-89) and Commentary (ACI 318R-89),* American Concrete Institute, Detroit, Michigan, 353 pp.

ACI Committee 318 (1995). *Building Code Requirements for Reinforced Concrete (ACI 318-95) and Commentary (ACI 318R-95),* American Concrete Institute, Farmington Hills, Michigan, 369 pp.

ACI Committee 318 (2005). *Building Code Requirements for Reinforced Concrete (ACI 318-05) and Commentary (ACI 318R-05),* American Concrete Institute, Farmington Hills, Michigan, 430 pp.

ACI Committee 318 (2014). *Building Code Requirements for Reinforced Concrete (ACI 318-14) and Commentary (ACI 318R-14),* American Concrete Institute, Farmington Hills, Michigan, 519 pp.

ACI Committee 349 (2006). *Code Requirements for Nuclear Safety Related Concrete Structures (ACI 349-06),* American Concrete Institute, Farmington Hills, Michigan, 157 pp.

ACI Committee 408 (1979). *Suggested Development, Splice, and Standard Hook Provisions for Deformed Bars in Tension (ACI 408.1R-79),* American Concrete Institute, Detroit, Michigan, 3 pp.

ACI Committee 408 (2003). *Bond and Development of Straight Reinforcing Bars in Tension (ACI 408R-3), American Concrete Institute*, Farmington Hills, Michigan, 49 pp.

ASTM A615 (2015). “Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement,” (ASTM A615/A615M-15), ASTM International, West Conshohocken PA., 8 pp.

ASTM A1035 (2014). “Standard Specification for Deformed and Plain Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement,” (ASTM A1035/A1035M-14), ASTM International, West Conshohocken PA., 7 pp

Darwin, D., Idun, E. K., Zuo, J., and Tholen, M. L. (1998). “Reliability-Based Strength Reduction Factor for Bond,” *ACI Structural Journal*, V. 95, No. 4, July-August, pp. 434-443.

Draper, N. R., and Smith, H. (1981). *Applied Regression Analysis*, second edition, Wiley, New York, 709 pp.

Ellingwood, B., Galambos, T. V., MacGregor, J. G., and Cornell, C. A. (1980). “Development of a Probability Based Load Criterion for American National Standard A58,” *NBS Special Publication* 577, U.S. Dept. of Commerce, Washington, D.C., June, 222 pp.

Grant, L. H., Mirza, S. A., and MacGregor, J. G. (1978). “Monte Carlo Study of Strength of Concrete Columns,” ACI Journal, *Proceedings*, V. 75, No. 8, Aug., pp. 348-358.

Hamad, B., Jirsa, J., and D’Abreu de Paulo, N. (1993). “Anchorage Strength of Epoxy-Coated Hooked Bars,” *ACI Structural Journal*, Vol. 90, No. 2, Mar.-Apr., pp. 210-217

Hamad, B. and Jumaa, G. (2008). “Bond Strength oh Hot-dip Galvanized Hooked Bars in High Strength Concrete Structures,” *Construction and Building Materials*, Vol. 22, pp. 2042-2052

Hribar, A. and Vasko, R. (1969). “End Anchorage of High Strength Steel Reinforcing Bars,” *ACI Journal Proceedings*, Vol. 66, No. 11, November, pp. 875-883

Jirsa, J., Lutz, L., and, Gergely, P. (1979). “Rationale for Suggested Development, Splice, and Standard Hook Provisions for Deformed Bars in Tension,” *Concrete International*, Vol. 1, No. 7, July. pp. 47-61

Joh, O., Goto, Y., and Shibata, T. (1995). “Anchorage of Beam Bars with 90-Degree Bend in Reinforced Concrete Beam-Column Joints,” *ACI Special Publication*, Vol. 157, Oct., pp. 97-116

Joh, O. and Shibata, T. (1996). “Anchorage of Beam Bars with 90-Degree Bend in Reinforced Concrete Beam-Column Joints,” *Eleventh World Conference Earthquake Engineering*, No. 1196, Elsvier Science Ltd., 8 pp.

Johnson, L. A., Jirsa, J. O. (1981). “The Influence of Short Embedment and Close Spacing on the Strength of Hooked Bar Anchorages,” *PMFSEL Report No.81-2*, Department of Civil Engineering-Structures Research Laboratory, University of Texas, Austin, Texas, 93 pp.

Lee, J., and Park, H. (2010). "Bending - Applicability Study of Ultra-Bar (SD 600) and Ultra-Bar for Rebar Stirrups and Ties (SD 500 and 600) for Compression Rebar,"[Translated from Korean] Korea Concrete Institute, Aug., 504 pp.

Marques, J. and Jirsa, J. (1975). "A Study of Hooked Bar Anchorage in Beam-Column Joints," ACI Journal, *Proceedings* Vol. 72, No. 5, May, pp. 198-209

Minor, J. and Jirsa, J. (1975). "Behavior of Bent Bar Anchorages," ACI Journal, *Proceedings* Vol. 72, No. 4, Apr., pp. 141-149

Nowak, A. S., Rakoczy, A. M., and Szeliga, E. K. (2012). "Revised Statistical Resistance Models for R/C Structural Components," *ACI Special Publication*, V. 284, Mar., pp. 1-16.

Park, J. and Kuchma, D (2007). "Strut-and-tie Model Analysis for Strength Prediction of Deep Beams," *ACI Structural Journal*, V. 104, No. 6, Nov.-Dec., pp. 657-666.

Peckover, J. and Darwin, D. (2013). "Anchorage of High-Strength Reinforcing Bars with Standard Hooks: Initial Tests," *SL Report* No. 13-1, University of Kansas Center for Research, Inc. Lawrence, KS, 47 pp.

Pinc, R., Watkins, M., and Jirsa, J. (1977). "Strength of Hooked Bars Anchorages in Beam-Column Joints," *Report on a Research Project Sponsored by Reinforced Concrete Research Council*, Project 33, Department of Civil Engineering-Structures Research Laboratory, University of Texas at Austin, 67 pp.

Ramirez, J. and Russell, B. (2008). *Transfer, Development, and Splice Length for Standard/ Reinforcement in High-strength Concrete*, Washington, D.C.: Transportation Research Board, National Research Council, 99-120

Scott, R. (1996). "Intrinsic Mechanism in Reinforced Concrete Beam-Column Connection Behavior," *ACI Structural Journal*, Vol. 93, No. 3, May-June, pp. 336-346

Searle, N., DeRubeis, M., Darwin, D., Matamoros, A., O'Reilly, M., and Feldman, L. (2014). "Anchorage of High-Strength Reinforcing Bars with Standard Hooks," *SM Report* No. 108, University of Kansas Center for Research, Inc. Lawrence, KS, 110 pp.

Shao, Y., Darwin, D., O'Reilly, M., Lequesne, R., Ghimire, K., and Hano, M. (2016) "Anchorage of Conventional and High-Strength Headed Reinforcing Bars," *SM Report* No. 117, University of Kansas Center for Research, Inc. Lawrence, KS, 334 pp.

Soroushian, P., Obaseki, K., Nagi, M., and Rojas, M. (1988). "Pullout Behavior of Hooked Bars in Exterior Beam-Column Connections," *ACI Structural Journal*, Vol. 85, No. 3, May-June, pp. 296-276

Sperry, J., Al-Yasso, S., Searle, N., DeRubeis, M., Darwin, D., Matamoros, A., O'Reilly, M., Feldman, L. Lepage, A., Lequesne, R., and Ajaam, A. (2015a) "Anchorage of High-Strength

Reinforcing Bars with Standard Hooks," *SM Report* No. 111, University of Kansas Center for Research, Inc. Lawrence, KS, 244 pp.

Sperry, J., Darwin, D., O'Reilly, M., and Lequesne, R. (2015b), "Anchorage Strength of Conventional and High-Strength Hooked Bars in Concrete," *SM Report* No. 115, University of Kansas Center for Research, Inc. Lawrence, KS, Dec., 266 pp.

Sperry, J., Yasso, S., Searle, N., DeRubeis, M., Darwin, D., O'Reilly, M., Matamoros, A., Feldman, L., Lepage, A., Lequesne, R., and Ajaam, A. (2017a). "Conventional and High-Strength Hooked Bars-Part 1: Anchorage Tests" *ACI Structural Journal*, Vol. 114, No. 01, Jan.-Feb., pp. 255-265

Sperry, J., Darwin, D., O'Reilly, M., Lequesne, R., Yasso, S., Matamoros, A., Feldman, L., and Lepage, A. (2017b). "Conventional and High-Strength Hooked Bars-Part 2: Data Analysis" *ACI Structural Journal*, Vol. 114, No. 01, Jan.-Feb., pp. 267-276

Thompson, M., Jirsa, J., Breen, J., and Klingner, R. (2002) "Anchorage Behavior of Headed Reinforcement: Literature Review," *Research Report* No. 1855-1, Center for Transportation Research Bureau of Engineering Research, University of Texas at Austin, May, 102 pp.

Tuchscherer, R. G., Birrcher, D., B., and Bayrak, O. (2011). "Strut-and-Tie Model Design Provisions," *PCI Journal*, V. 56, No. 1, Winter, pp. 155-170.

Zuo, J. and Darwin, D. (1998). "Bond Strength of High Relative Rib Area Reinforcing Bars," *SM Report No. 46*, University of Kansas Center for Research, Inc., Lawrence, KS, Jan., 377 pp.

Zuo, J., and Darwin, D. (2000). "Splice Strength of Conventional and High Relative Rib Area Bars in Normal and High-Strength Concrete," *ACI Structural Journal*, V. 97, No. 4, July-Aug., pp. 630-641.

APPENDIX A: NOTATION

a	Depth of equivalent rectangular compressive stress block
A_{cti}	Total area of cross-ties inside the hook region
A_h	Area of hooked bar
A_{hs}	Total cross-sectional area of hooked bars being developed
A_I	Influence area
A_s	Area of longitudinal steel in the column
A_T	Tributary area
A_{th}	Total cross-sectional area of all confining reinforcement parallel to ℓ_{dh} for hooked bars being developed and located within $8d_b$ of the top (bottom) of the bars in the direction of the hook for No. 3 through No. 8 hooked bars or within $10d_b$ of the top (bottom) of the bars in the direction of the hook for No. 9 through No. 11 hooked bars; or total cross-sectional area of all confining reinforcement perpendicular to ℓ_{dh}
$A_{tr,l}$	Area of single leg of confining reinforcement inside hook region
A_v	Cross-sectional area of all confining reinforcement along the effective depth d_{eff}
b	Column width
c	Effective depth of neutral axis from the assumed extreme compression fiber for beam-column and beam-wall joint specimens
c_{ch}	Minimum center-to-center spacing between hooked bars
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
$c_{so,\mathrm{avg}}$	Average clear cover of the hooked bars
c_{th}	Clear cover measured from the tail of the hook to the back of the column
c_v	Vertical clear spacing between hooked bars (see Figures 2.4 and 2.8)
c_{cv}	Vertical center-to-center spacing between hooked bars
d	Distance from the centroid of the tension bar to the extreme compression fiber of the beam
d_b	Nominal diameter of the hooked bar
d_{cto}	Nominal bar diameter of cross-ties outside the hook region
d_{eff}	Effective value of d for beam-column and beam-wall joint specimens
d_s	Nominal bar diameter of confining reinforcing steel outside the hook region
d_{tr}	Nominal bar diameter of confining reinforcement inside 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 of ACI 318-14
f_{su}	Average peak stress on hooked bars at failure
$f_{su,\mathrm{max}}$	Maximum stress on individual hooked bar
f_{ys}	Nominal yield strength of longitudinal reinforcing steel in the column
f_{yt}	Nominal yield strength of confining reinforcement
h	Column depth
h_c	Width of bearing member
h_{cl}	Height measured from the center of the hook to the top of the bearing member
h_{cu}	Height measured from the center of the hook to the bottom of the upper compression member

ℓ_{dh} Development length of hooked bar

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

$\ell_{eh,\text{avg}}$ Average embedment length of hooked bars

L_o Basic unreduced live load

n Number of hooked bars confined by N legs

N Effective number of legs of confining reinforcement in joint region associated to A_{th}

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

q Random loading

Q Total load

Q_D Random variable representing dead load effect

Q_{Dn} Nominal dead load

Q_L Random variable representing live load effect

Q_{Ln} Nominal live load

$(Q_L/Q_D)_n$ Nominal ratio of live tot dead load

R Random variable for resistance

R_n Nominal resistance

R_p predicted capacity random variable

R_r Relative rib area

R_1 Reaction from the bearing member for beam-column and beam-wall joint specimens

s_{cti} Center-to-center spacing of cross-ties in the hook region

s_{tr} Center-to-center spacing of confining reinforcement in the hook region

s_s Center-to-center spacing of stirrups/ties outside the hook region

T Average load on hooked bars at failure

T_c Contribution of concrete to hooked bar anchorage strength

T_h Hooked bar anchorage strength

T_{ind} Load on individual hooked bar at failure

T_{max} Maximum load on individual hooked bar

T_s Contribution of confining steel in joint region to hooked bar anchorage strength

T_{total} Sum of loads on hooked bars at failure

V Coefficient of variation

V_m Coefficient of variation associated with the descriptive equation 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_{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

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

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
β Reliability index
β_w value of the spacing term for hooked bars with No. 3 hoops in Eq. (4.10)
$\beta_{w/i}$ value of the spacing term for hooked bars with an intermediate amount of confining reinforcement
$\beta_{w/o}$ value of the spacing term for hooked bars without confining reinforcement in Eq. (4.9)
γ_D load factor for dead loads
γ_L load factor for live loads
λ Factor for lightweight concrete as defined in ACI 318-14 Section 25.4.3.2
ρ_{col} Column longitudinal steel ratio
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
ϕ_d Effective strength reduction factor for use in development of design equation
σ Standard deviation
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_{cs} Factor for spacing between hooked bars and confinement in hook region
ψ_r Factor for confinement in the hook region
ψ_o Factor for hooked bar location
ψ_m Factor for spacing between hooked bars

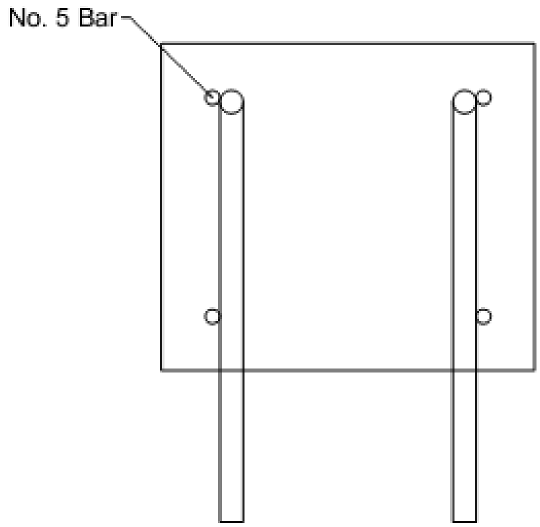
Failure types
FP Front pullout
FB Front blowout
SS Side splitting
SB Side blowout
TK Tail kickout
FL Flexural failure of column
BY Yield or fracture of hooked bars

Specimen identification
(A@B) C-D-E-F#G-H-I-J-Kx(L)
A Number of hooks in the specimen
B Center-to-center spacing between hooks in terms of bar diameter
(A@B = blank, indicates standard 2-hook specimen)
C ASTM in.-lb bar size
D Nominal compressive strength of concrete
E Angle of bend
F Number of bars used as transverse reinforcement within the hook region
G ASTM in.-lb bar size of transverse reinforcement
(if F#G = 0 = no transverse reinforcement)
H Hooked bars placed inside (i) or outside (o) of longitudinal reinforcement
I Nominal value of c_{so}
J Nominal value of c_{th}

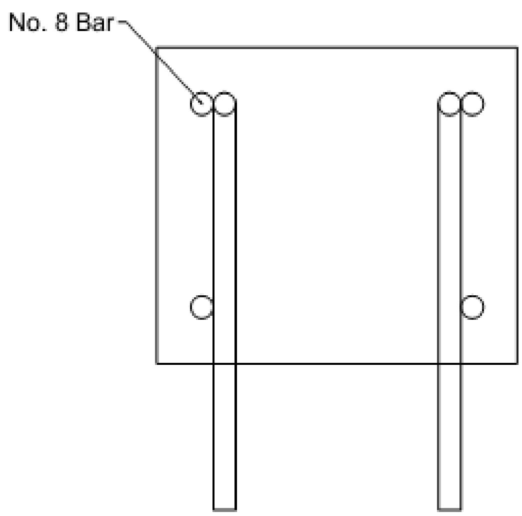
K	Nominal value of ℓ_{eh}
x	Replication in a series, blank (or a), b, c, etc.
L	Replication not in a series

APPENDIX B: COMPREHANSIVE TEST RESULTS

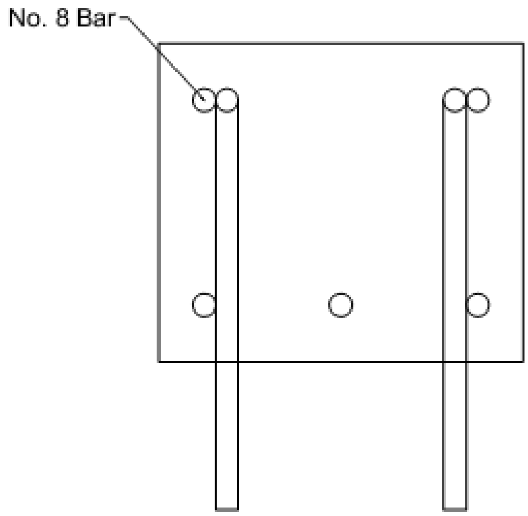
B.1 Longitudinal Column Steel Layout



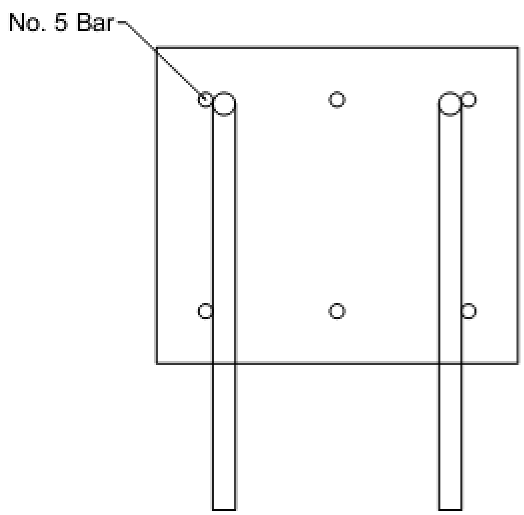
Layout B1: Longitudinal column reinforcement-4 No. 5 bars. Transverse reinforcement not shown.



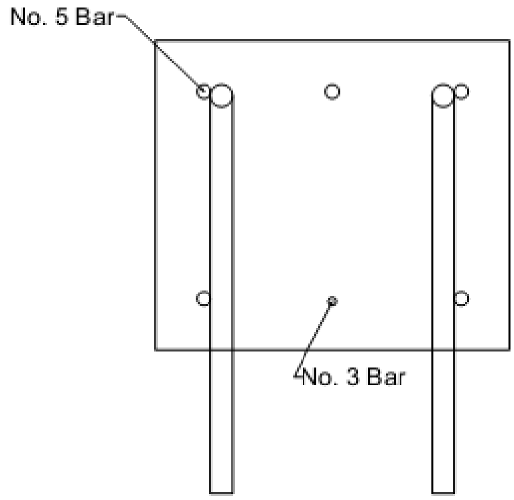
Layout B2: Longitudinal column reinforcement-4 No. 8 bars. Transverse reinforcement not shown.



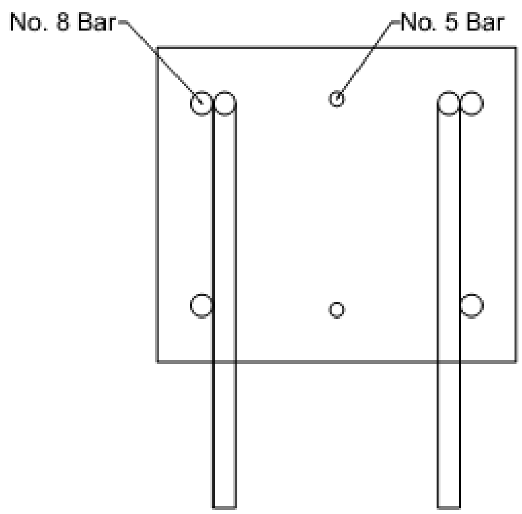
Layout B3: Longitudinal column reinforcement-5 No. 8 bars. Transverse reinforcement not shown.



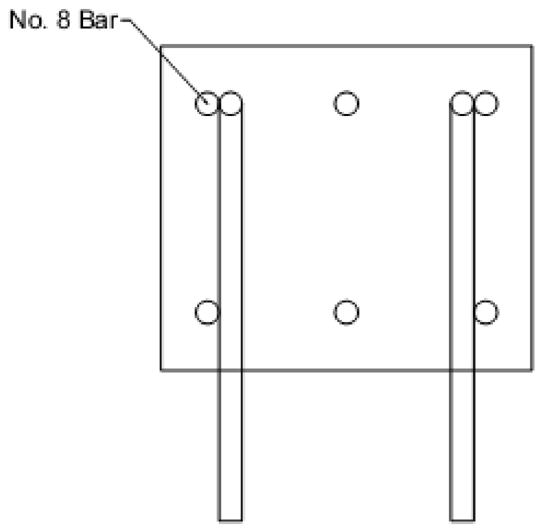
Layout B4: Longitudinal column reinforcement-6 No. 5 bars. Transverse reinforcement not shown.



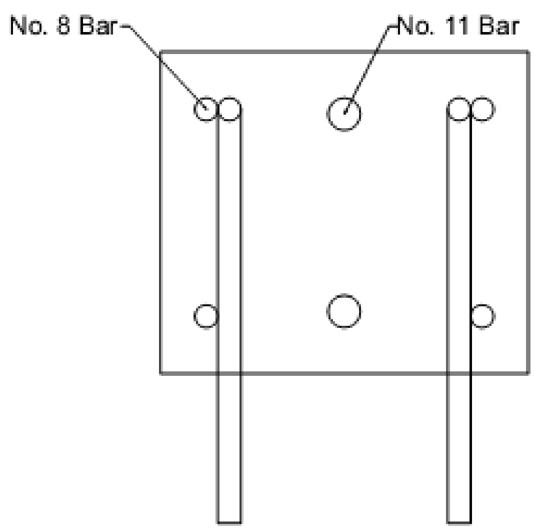
Layout B5: Longitudinal column reinforcement-5 No. 5 bars + 1 No. 3 bar. Transverse reinforcement not shown.



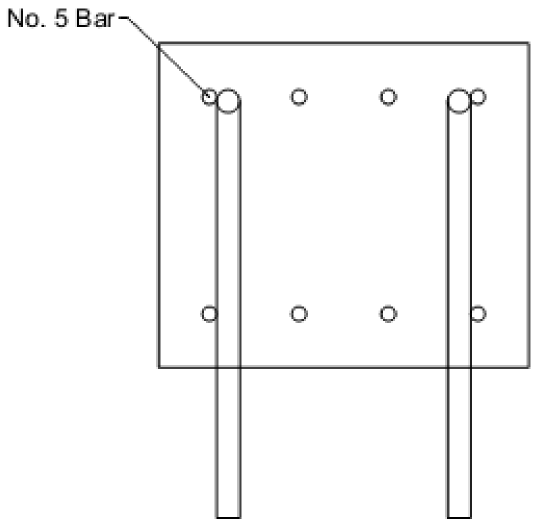
Layout B6: Longitudinal column reinforcement-4 No. 8 bars + 2 No. 5 bars. Transverse reinforcement not shown.



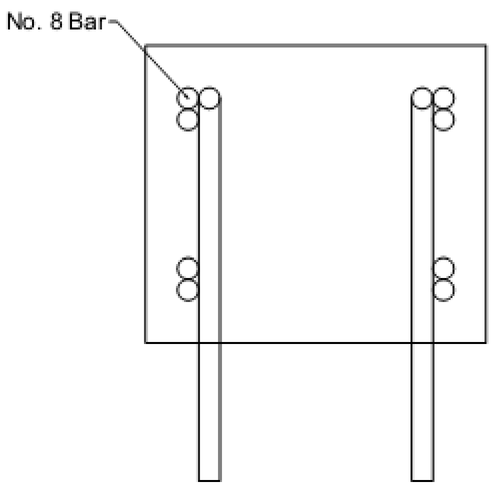
Layout B7: Longitudinal column reinforcement-6 No. 8 bars. Transverse reinforcement not shown.



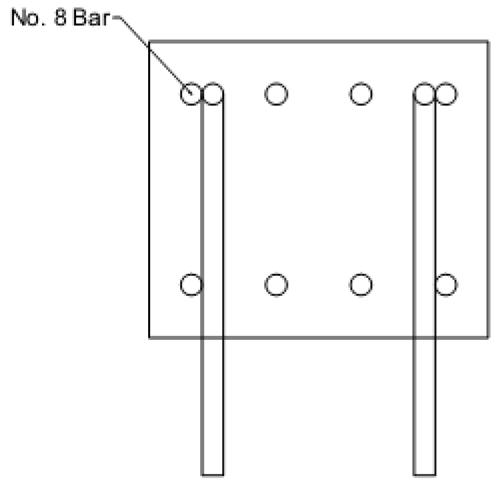
Layout B8: Longitudinal column reinforcement-4 No. 8 bars + 2 No. 11 bars. Transverse reinforcement not shown.



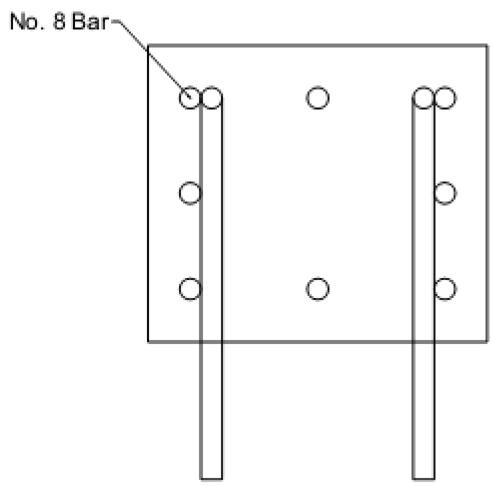
Layout B9: Longitudinal column reinforcement-8 No. 5 bars. Transverse reinforcement not shown.



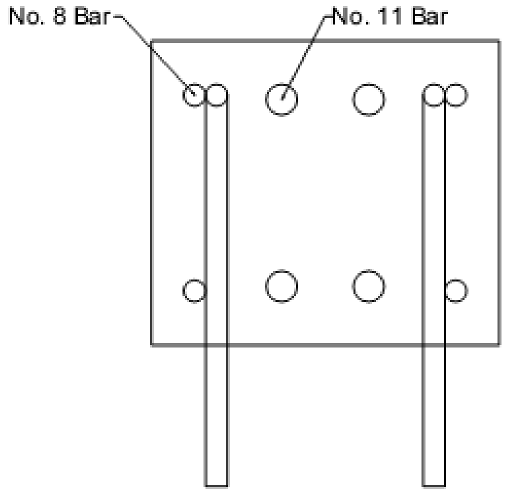
Layout B10: Longitudinal column reinforcement-8 No. 8 bars (four bundles of two bars each). Transverse reinforcement not shown.



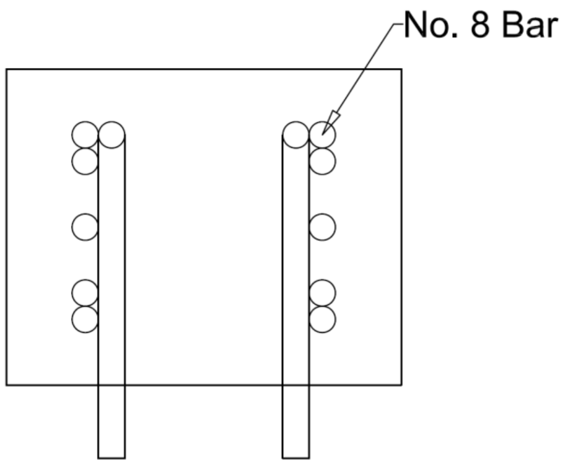
Layout B11: Longitudinal column reinforcement-8 No. 8 bars (distributed across two column faces). Transverse reinforcement not shown.



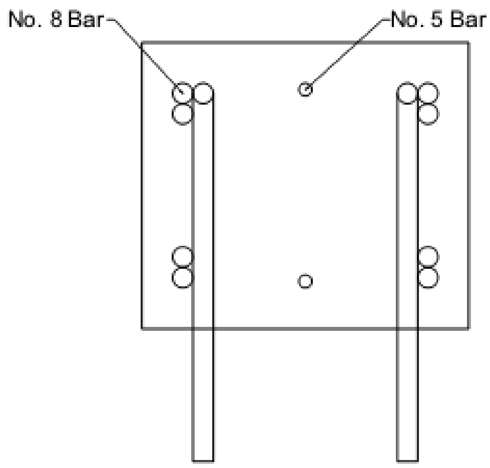
Layout B12: Longitudinal column reinforcement-8 No. 8 bars (distributed across four column faces). Transverse reinforcement not shown.



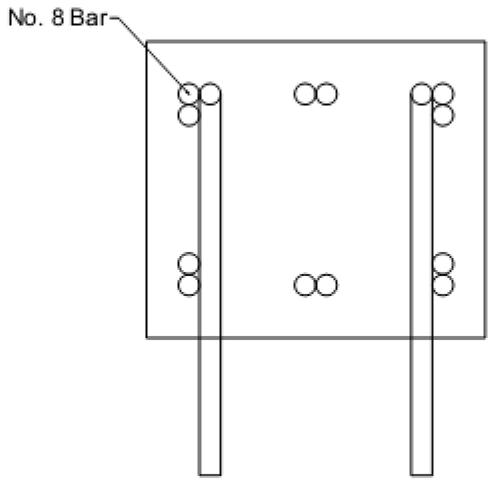
Layout B13: Longitudinal column reinforcement-4 No. 8 bars + 4 No. 11 bars. Transverse reinforcement not shown.



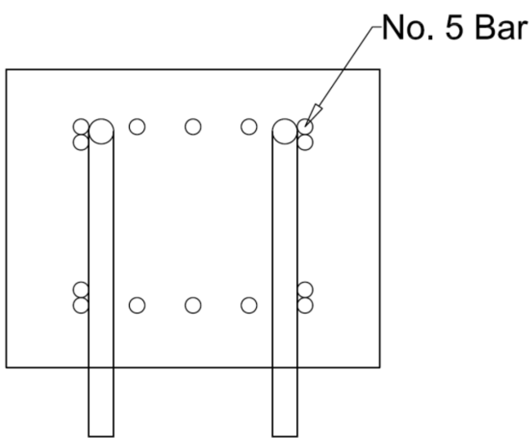
Layout B14: Longitudinal column reinforcement-10 No. 8 bars (four bundles of two bars and two single bars). Transverse reinforcement not shown.



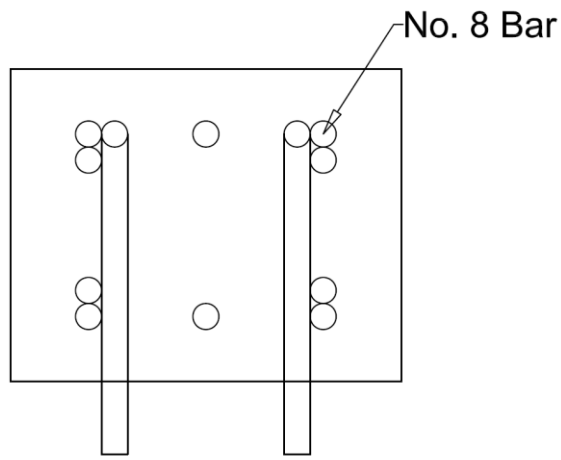
Layout B15: Longitudinal column reinforcement-8 No. 8 bars + 2 No. 5 bars. Transverse reinforcement not shown.



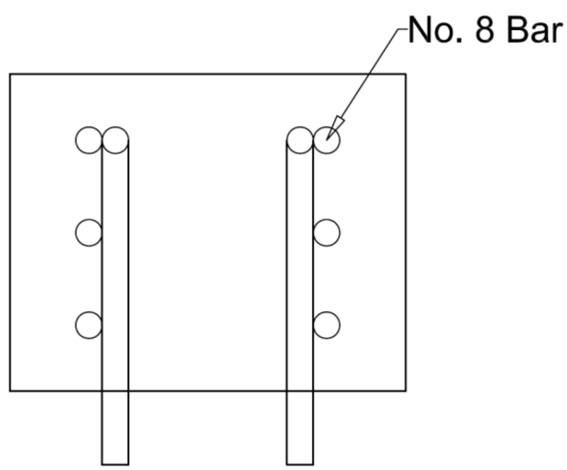
Layout B16: Longitudinal column reinforcement-12 No. 8 bars. Transverse reinforcement not shown.



Layout B17: Longitudinal column reinforcement-14 No. 5 bars (four bundles of two bars and six single bars). Transverse reinforcement not shown.



Layout B18: Longitudinal column reinforcement-10 No. 8 bars (four bundles of two bars and two single bars). Transverse reinforcement not shown.



Layout B19: Longitudinal column reinforcement-6 No. 8 bars. Transverse reinforcement not shown.

B.2 Stress-Strain Curves

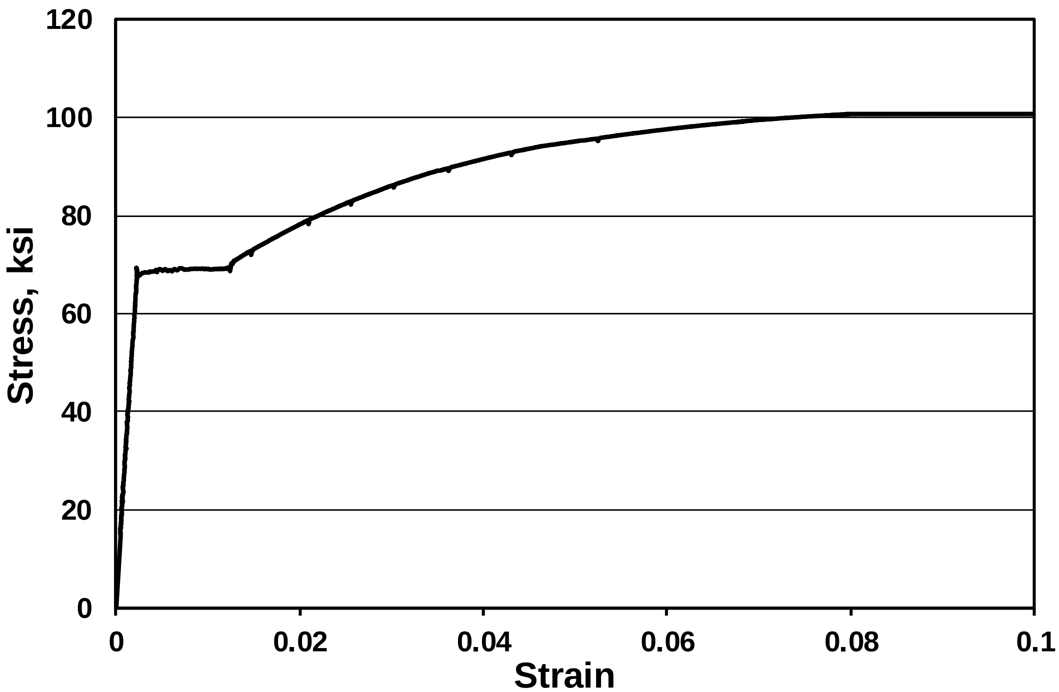


Figure B.20 Stress-strain curve for No. 3 (A615 steel)

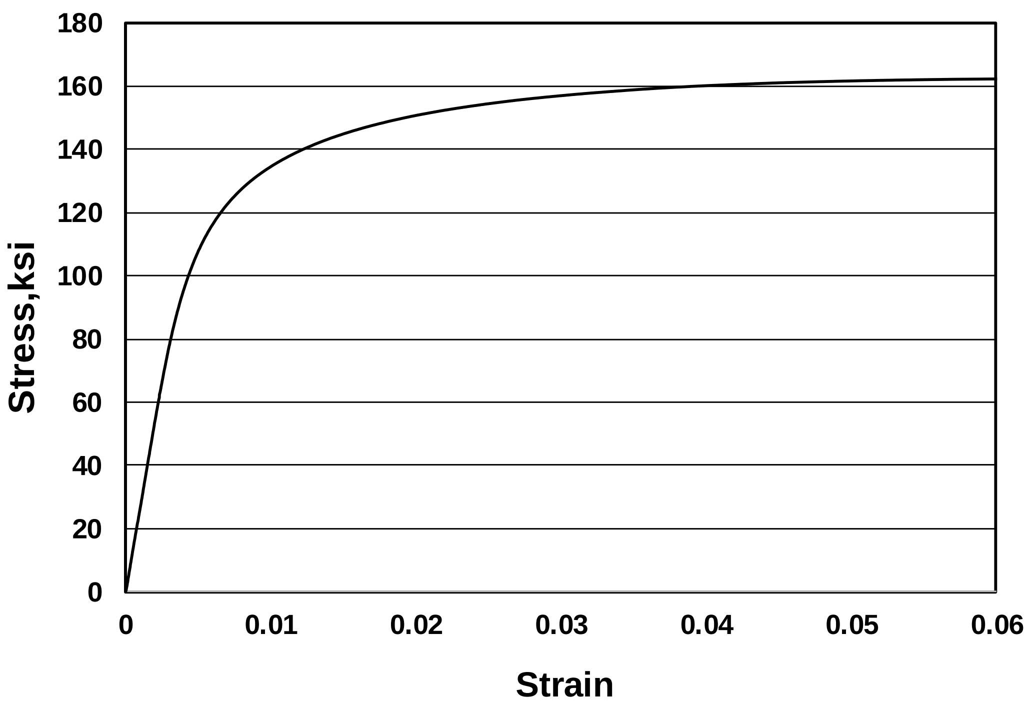


Figure B.21 Stress-strain curve for No. 5 (A1035 steel)

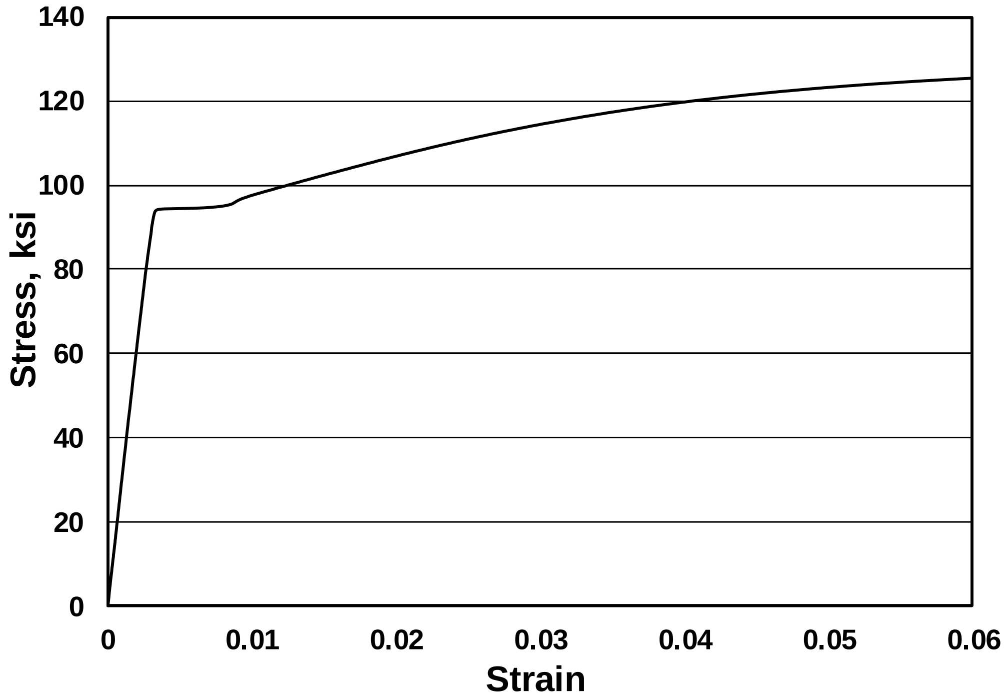


Figure B.22 Stress-strain curve for No. 8 (A615 steel)

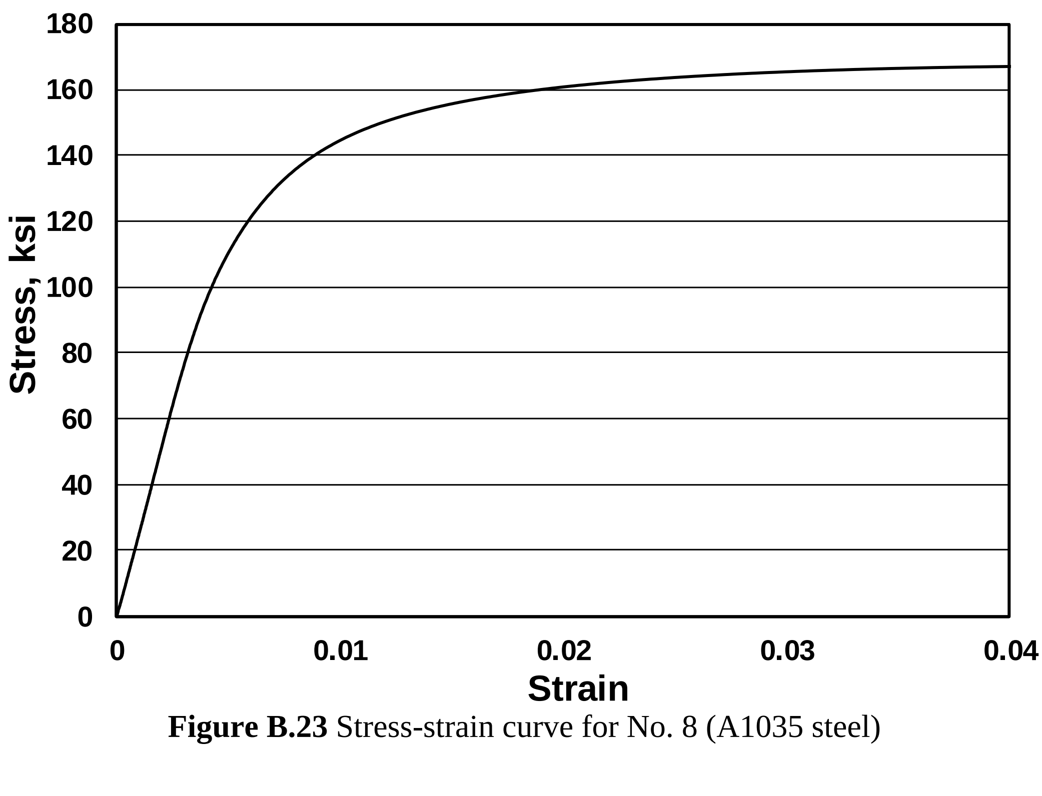


Figure B.23 Stress-strain curve for No. 8 (A1035 steel)

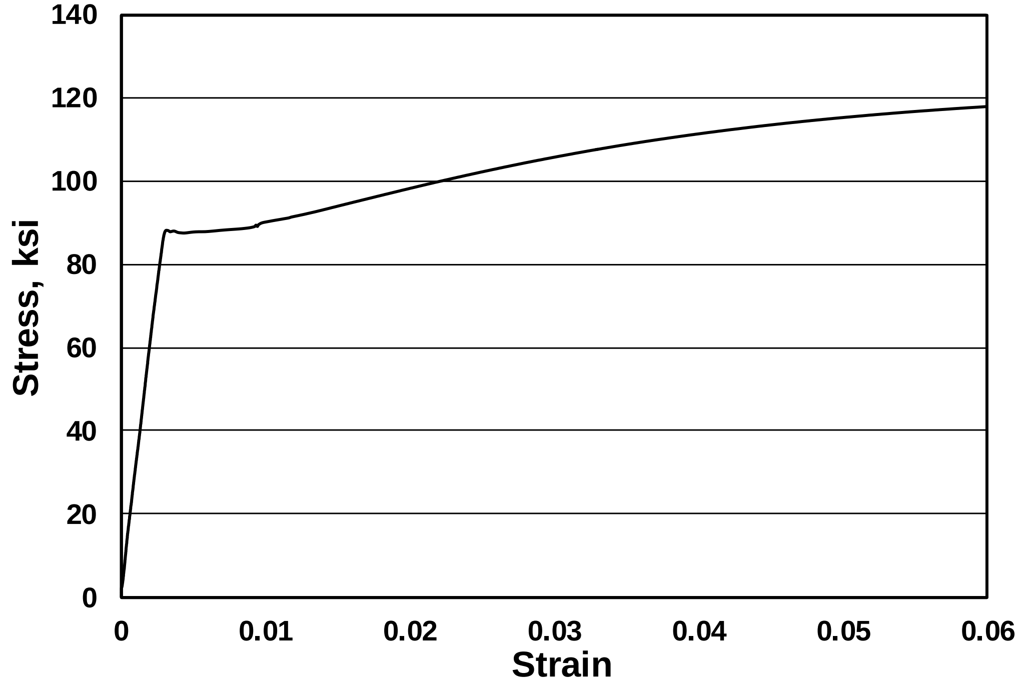


Figure B.24 Stress-strain curve for No. 11 (A615 steel)

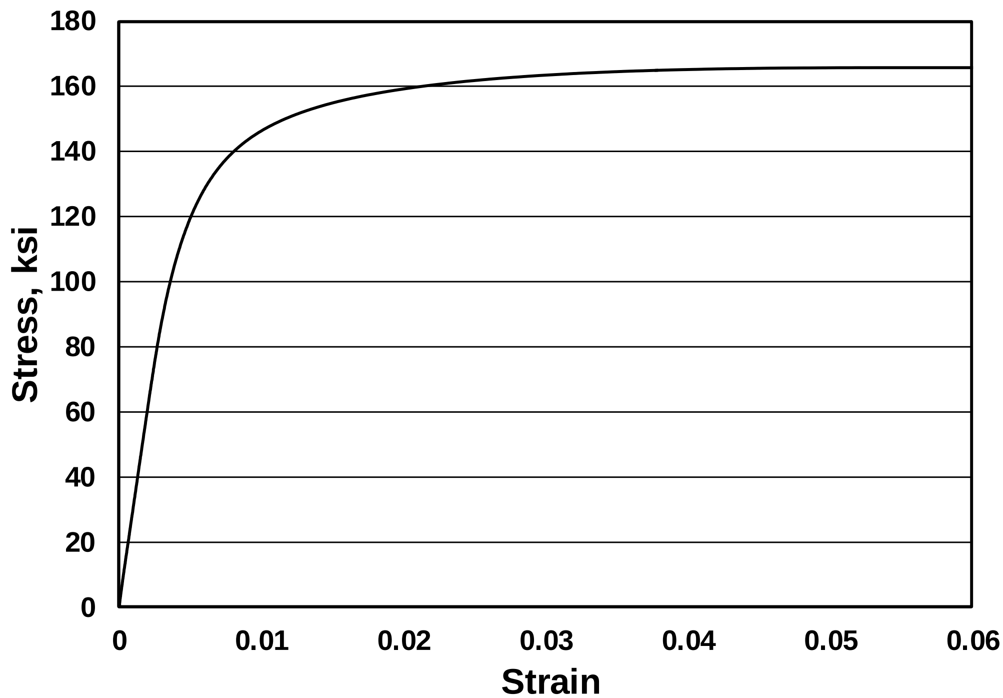


Figure B.25 Stress-strain curve for No. 11 (A1035 steel)

B.3 Comprehensive Test Results

Table B.1 Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
1	5-5-90-0-o-1.5-2-5	A B	90°	-	A615	5.0 5.0	5.0	4930	4	0.625
2	5-5-90-0-o-1.5-2-6.5	A B	90°	-	A1035	6.5 5.9	6.2	5650	6	0.625
3	5-5-90-0-o-1.5-2-8	B	90°	-	A1035	7.9	7.9	5650	6	0.625
4	5-5-90-0-o-2.5-2-5	A B	90°	-	A615	4.8 4.8	4.8	4930	4	0.625
5	5-5-90-0-o-2.5-2-8	A	90°	-	A1035	9.0	9.0	5780	7	0.625
6	5-5-180-0-o-1.5-2-9.5	A B	180°	-	A1035	9.6 9.3	9.4	4420	7	0.625
7	5-5-180-0-o-1.5-2-11.25	A	180°	-	A1035	11.3	11.3	4520	8	0.625
8	5-5-180-0-o-2.5-2-9.5	A B	180°	-	A1035	9.5 9.5	9.5	4520	8	0.625
9	5-5-90-0-i-2.5-2-8	A B	90°	-	A1035	8.1 8.0	8.1	4830	9	0.625
10	(2@9) 5-5-90-0-i-2.5-7-7	A B	90°	-	A1035	6.8 7.0	6.9	5880	11	0.625
11	5-5-90-0-i-2.5-2-10	A B	90°	-	A1035	9.4 9.4	9.4	5230	6	0.625
12	5-5-90-0-i-2.5-2-7	A B	90°	-	A1035	6.9 7.0	6.9	5190	7	0.625
13	5-8-90-0-i-2.5-2-6	A B	90°	-	A615	6.8 6.8	6.8	8450	14	0.625
14	5-8-90-0-i-2.5-2-6(1)	A B	90°	-	A1035	6.1 6.5	6.3	9080	11	0.625
15	5-8-90-0-i-2.5-2-8	A B	90°	-	A1035	8.0 7.5	7.8	8580	15	0.625
16	(2@4) 5-8-90-0-i-2.5-2-6	A B	90°	-	A1035	5.8 6.0	5.9	6950	18	0.625
17	(2@6) 5-8-90-0-i-2.5-2-6	A B	90°	-	A1035	6.0 6.0	6.0	6950	18	0.625
18	5-12-90-0-i-2.5-2-10	A B	90°	-	A1035	10.0 11.0	10.5	10290	14	0.625
19	5-12-90-0-i-2.5-2-5	A B	90°	-	A1035	5.1 4.8	4.9	11600	84	0.625
20	5-15-90-0-i-2.5-2-5.5	A B	90°	-	A1035	6.1 5.8	5.9	15800	62	0.625
21	5-15-90-0-i-2.5-2-7.5	A B	90°	-	A1035	7.3 7.3	7.3	15800	62	0.625
22	5-5-90-0-i-3.5-2-10	A B	90°	-	A1035	10.5 10.4	10.4	5190	7	0.625
23	5-5-90-0-i-3.5-2-7	A B	90°	-	A1035	7.5 7.6	7.6	5190	7	0.625
24	5-8-90-0-i-3.5-2-6	A B	90°	-	A615	6.3 6.4	6.3	8580	15	0.625
25	5-8-90-0-i-3.5-2-6(1)	A B	90°	-	A1035	6.5 6.6	6.6	9300	13	0.625

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	**Axial Load** kips	**Long. Reinf. Layout°**
1	A B	0.077	11.3	7.0	5.25	8.375	1.5 1.8	1.6	2.0 2.0	6.8	2	80	B1
2	A B	0.073	11.0	8.6	5.25	8.375	1.5 1.6	1.6	2.0 2.8	6.6	2	80	B4
3	B	0.073	11.9	10.0	5.25	8.375	1.5	1.5	2.1	6.6	2	80	B1
4	A B	0.077	12.6	6.9	5.25	8.375	2.5 2.5	2.5	2.1 2.1	6.4	2	80	B1
5	A	0.073	12.1	10.8	5.25	8.375	2.6	2.6	1.5	6.6	2	80	B1
6	A B	0.077	10.9	11.6	5.25	8.375	1.6 1.6	1.6	2.1 2.1	6.4	2	80	B1
7	A	0.077	11.4	13.3	5.25	8.375	1.8	1.8	2.3	6.6	2	80	B1
8	A B	0.077	12.9	11.3	5.25	8.375	2.5 2.5	2.5	1.9 1.8	6.6	2	80	B4
9	A B	0.073	13.1	10.3	5.25	8.375	2.5 2.6	2.5	2.1 2.3	6.8	2	30	B2
10	A B	0.073	11.3	14.7	5.25	8.375	2.3 2.6	2.4	8.4 7.3	5.1	2	30	B2
11	A B	0.073	13.1	12.3	5.25	8.375	2.8 2.6	2.7	2.9 2.9	6.4	2	30	B4
12	A B	0.073	13.0	9.6	5.25	8.375	2.5 2.5	2.5	2.8 2.6	6.8	2	30	B1
13	A B	0.073	13.0	8.0	5.25	8.375	2.8 2.6	2.7	1.3 1.3	6.4	2	80	B1
14	A B	0.073	13.3	8.8	5.25	8.375	2.5 2.5	2.5	2.6 2.3	7.0	2	30	B1
15	A B	0.073	13.1	10.0	5.25	8.375	2.5 2.8	2.6	2.0 2.5	6.6	2	80	B1
16	A B	0.073	9.5	8.0	5.25	8.375	2.7 3.7	3.2	2.3 2.0	1.9	2 2	30	B2
17	A B	0.073	9.6	8.0	5.25	8.375	2.6 2.7	2.6	2.0 2.0	3.1	2 2	30	B2
18	A B	0.073	12.8	12.5	5.25	8.375	2.4 2.5	2.4	2.5 1.5	6.6	2	30	B4
19	A B	0.073	13.0	7.3	5.25	8.375	2.6 2.6	2.6	2.1 2.5	6.5	2	30	B1
20	A B	0.073	12.6	7.7	5.25	8.375	2.4 2.4	2.4	1.6 1.9	6.6	2	30	B1
21	A B	0.073	12.9	9.8	5.25	8.375	2.5 2.5	2.5	2.6 2.6	6.6	2	30	B2
22	A B	0.073	14.8	12.3	5.25	8.375	3.5 3.5	3.5	1.8 1.9	6.5	2	30	B4
23	A B	0.073	15.1	8.8	5.25	8.375	3.4 3.5	3.4	1.3 1.1	7.0	2	30	B1
24	A B	0.073	15.0	8.0	5.38	8.375	3.6 3.5	3.6	1.8 1.6	6.6	2	80	B1
25	A B	0.073	15.6	8.6	5.25	8.375	3.8 3.8	3.8	2.1 1.9	6.9	2	30	B1

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
1	A	14139	14029	28137	14069	45609	45382	40122	-	FP/SB
	B	19575	14108			63147			-	FP/SB
2	A	20758	17440	35627	17813	66962	57463	53261	-	FP
	B	18187	18187			58667			-	FP/SB
3	B	23455	23455	23455	23455	75663	75663	67650	-	SB
4	A	19559	19559	38566	19283	63094	62204	38116	-	FP/SB
	B	23982	19007			77362			-	FP/SB
5	A	30340	30340	30340	30340	97870	97870	78198	-	SB
6	A	35211	28603	58973	29486	113585	95117	71707	-	FP
	B	30370	30370			97968			-	FP/SB
7	A	32374	32374	32374	32374	104432	104432	86440	-	FP/SB
8	A	40406	40351	60255	30128	130342	97186	72994	-	FP
	B	24657	19904			79538			-	FP
9	A	32068	31463	64895	32448	103445	104670	64057	-	FP/SB
	B	33433	33433			107847			-	FP/SB
10	A	28176	28014	57960	28980	90891	93484	60249	0.01	FP/SB
	B	33681	29946			108650			0.08	FP/SB
11	A	37404	34303	67166	33583	120656	108333	77484	-	FP/SS
	B	32864	32864			106012			-	FP/SS
12	A	26607	26607	52529	26265	85831	84724	57119	-	FP/SS
	B	26095	25922			84176			0.192	FP/SS
13	A	27578	27102	59140	29570	88961	95387	70913	-	FB/SB
	B	32135	32038			103663			-	SB/FB
14	A	21741	21741	44849	22425	70131	72338	68744	0.296	FP
	B	24995	23109			80630			.330(.030)	FP
15	A	31878	31469	63347	31673	102831	102172	82042	-	SS/FP
	B	35934	31878			115915			-	SS/FP
16	A	23217	23089	44706	22353	74893	72106	55975	-	FP
	B	21747	21617			70152			-	FP
17	A	25504	25052	47902	23951	82272	77261	57166	-	FP/SS
	B	24013	22850			77463			-	FP/SS
18	A	40823	40823	83314	41657	131688	134377	121728	0.191	SB
	B	42491	42491			137066			-	FB/SB/TK
19	A	19389	19389	38441	19220	62546	62001	60775	-	FP/SS
	B	23171	19051			74745			-	FP
20	A	36163	32648	65021	32511	116656	104873	85295	-	FP
	B	32373	32373			104430			-	FB
21	A	42470	42464	84441	42221	137001	136196	104150	-	FB
	B	41977	41977			135410			-	*
22	A	43228	43228	83855	41927	139446	135250	85935	-	SB/FP
	B	41140	40626			132710			-	SB/FP
23	A	27197	27197	53033	26516	87732	85537	62265	-	SS
	B	25884	25836			83498			-	FP/SS
24	A	25129	25129	50950	25475	81060	82178	66825	-	FP/SS
	B	29054	25822			93723			-	FP/SS
25	A	24440	24440	49083	24541	78838	79166	72327	0.152	FP/SS
	B	27541	24643			88842			.178(.150)	FP/SS

*Test terminated prior to failure of second hooked bar

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
1	A B	60	-	-	-	-	0.88	4[1]	2.5 (1.3)	0.375	2.50 (1.3)	-	-	1.27	60
2	A B	60	-	-	-	-	0.88	4[1]	2.5 (1.3)	0.375	2.50 (1.3)	-	-	1.89	60
3	B	60	-	-	-	-	0.88	4[1]	2.5 (1.3)	0.375	2.50 (1.3)	-	-	1.27	60
4	A B	60	-	-	-	-	0.88	4[1]	2.5 (1.3)	0.375	2.50 (1.3)	-	-	1.27	60
5	A	60	-	-	-	-	0.88	4[1]	2.5 (1.3)	0.375	2.50 (1.3)	-	-	1.27	60
6	A B	60	-	-	-	-	0.22	1[1]	4.0 (2.0)	0.375	4.00 (2.0)	-	-	1.27	60
7	A	60	-	-	-	-	0.22	1[1]	4.0 (2.0)	0.375	4.0 (2.0)	-	-	1.27	60
8	A B	60	-	-	-	-	0.22	1[1]	4.0 (2.0)	0.375	4.00 (2.0)	-	-	1.89	60
9	A B	60	-	-	-	-	-	-	-	0.500	3.00 (1.5)	-	-	3.16	60
10	A B	60	-	-	-	-	-	-	-	0.375	4.00 (2.0)	-	-	3.16	60
11	A B	60	-	-	-	-	0.33	3	3.0 (1.5)	0.375	3.00 (1.5)	-	-	1.89	60
12	A B	60	-	-	-	-	0.80	4	2.5 (1.3)	0.500	3.50 (1.8)	-	-	1.27	60
13	A B	60	-	-	-	-	0.80	4	4.0 (2.0)	0.500	4.00 (2.0)	-	-	1.27	60
14	A B	60	-	-	-	-	0.66	6	3.0 (1.7)	0.500	3.00 (1.8)	-	-	1.27	60
15	A B	60	-	-	-	-	0.80	4	4.0 (2.0)	0.500	4.00 (2.0)	-	-	1.27	60
16	A B	60	-	-	-	-	-	-	-	0.375	4.00 (1.5)	-	-	3.16	60
17	A B	60	-	-	-	-	-	-	-	0.375	4.00 (1.5)	-	-	3.16	60
18	A B	60	-	-	-	-	0.66	6	2.5 (2.2)	0.375	5.00 (1.5)	-	-	1.89	60
19	A B	60	-	-	-	-	0.66	6	2.5 (2.2)	0.500	3.00 (1.5)	-	-	1.27	60
20	A B	60	-	-	-	-	-	-	-	0.375	2.50 (1.3)	-	-	1.27	60
21	A B	60	-	-	-	-	-	-	-	0.375	3.50 (1.75)	-	-	3.16	60
22	A B	60	-	-	-	-	0.33	3	3.0 (1.5)	0.375	3.00 (1.5)	-	-	1.89	60
23	A B	60	-	-	-	-	0.80	4	2.5 (1.3)	0.375	3.50 (1.8)	-	-	1.27	60
24	A B	60	-	-	-	-	0.80	4	4.0 (2.0)	0.500	4.00 (2.0)	-	-	1.27	60
25	A B	60	-	-	-	-	0.66	6	3.0 (1.7)	0.500	3.00 (1.8)	-	-	1.27	60

[1] Specimen had full stirrups around the longitudinal bars in the hook region but not around the hooked bars
[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
26	5-8-90-0-i-3.5-2-8	A B	90°	-	A1035	8.6 8.5	8.6	8380	13	0.625
27	5-12-90-0-i-3.5-2-5	A B	90°	-	A1035	5.5 5.4	5.4	10410	15	0.625
28	5-12-90-0-i-3.5-2-10	A B	90°	-	A1035	10.1 10.0	10.1	11600	84	0.625
29	5-8-180-0-i-2.5-2-7	A B	180°	-	A1035	7.4 7.1	7.3	9080	11	0.625
30	5-8-180-0-i-3.5-2-7	A B	180°	-	A1035	7.4 7.3	7.3	9080	11	0.625
31	5-5-90-1#3-i-2.5-2-8	A B	90°	Para	A1035	8.0 7.6	7.8	5310	6	0.625
32	5-5-90-1#3-i-2.5-2-6	A B	90°	Para	A615	4.8 5.5	5.1	5800	9	0.625
33	5-8-90-1#3-i-2.5-2-6	A B	90°	Para	A615	6.0 6.3	6.1	8450	14	0.625
34	5-8-90-1#3-i-2.5-2-6(1)	A B	90°	Para	A1035	6.1 5.6	5.9	9300	13	0.625
35	5-8-90-1#3-i-3.5-2-6	A B	90°	Para	A1035	6.0 6.0	6.0	8710	16	0.625
36	5-8-90-1#3-i-3.5-2-6(1)	A B	90°	Para	A1035	6.3 6.3	6.3	9190	12	0.625
37	5-5-180-1#3-i-2.5-2-8	A B	180°	Para	A1035	8.0 7.8	7.9	5670	7	0.625
38	5-5-180-1#3-i-2.5-2-6	A B	180°	Para	A615	6.0 6.0	6.0	5800	9	0.625
39	5-8-180-1#3-i-2.5-2-7	A B	180°	Para	A1035	7.1 7.3	7.2	9300	13	0.625
40	5-8-180-1#3-i-3.5-2-7	A B	180°	Para	A1035	7.1 6.8	6.9	9190	12	0.625
41	5-5-90-1#4-i-2.5-2-8	A B	90°	Para	A1035	7.4 7.8	7.6	5310	6	0.625
42	5-5-90-1#4-i-2.5-2-6	A B	90°	Para	A615	5.3 5.8	5.5	5860	8	0.625
43	5-8-90-1#4-i-2.5-2-6	A B	90°	Para	A1035	5.9 6.0	6.0	9300	13	0.625
44	5-8-90-1#4-i-3.5-2-6	A B	90°	Para	A1035	6.0 7.0	6.5	9190	12	0.625
45	5-5-180-1#4-i-2.5-2-8	A B	180°	Para	A1035	8.0 8.0	8.0	5310	6	0.625
46	5-5-180-1#4-i-2.5-2-6	A B	180°	Para	A615	6.5 6.0	6.3	5670	7	0.625
47	5-5-180-2#3-o-1.5-2-11.25	A B	180°	Para	A1035	11.6 11.5	11.6	4420	7	0.625
48	5-5-180-2#3-o-1.5-2-9.5	B	180°	Para	A1035	8.8	8.8	4520	8	0.625
49	5-5-180-2#3-o-2.5-2-9.5	A B	180°	Para	A1035	9.1 9.3	9.2	4420	7	0.625
50	5-5-180-2#3-o-2.5-2-11.25	A B	180°	Para	A1035	11.1 11.4	11.3	4520	8	0.625

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°
26	A B	0.060	15.5	10.0	5.25	8.375	3.6 3.5	3.6	1.4 1.5	7.1	2	80	B1
27	A B	0.073	15.5	7.2	5.25	8.375	3.6 3.6	3.6	1.7 1.8	7.0	2	30	B1
28	A B	0.073	15.0	12.1	5.25	8.375	3.5 3.5	3.5	2.5 1.5	6.8	2	30	B4
29	A B	0.073	12.6	9.5	5.25	8.375	2.5 2.6	2.6	2.1 2.4	6.3	2	30	B1
30	A B	0.073	15.4	9.3	5.25	8.375	3.6 3.4	3.5	1.9 2.0	7.1	2	30	B1
31	A B	0.073	13.1	10.4	5.25	8.375	2.5 2.5	2.5	2.4 2.8	6.9	2	80	B1
32	A B	0.060	13.1	8.0	5.25	8.375	2.5 2.5	2.5	3.3 2.5	6.9	2	80	B1
33	A B	0.060	12.9	8.0	5.25	8.375	2.5 2.5	2.5	2.0 1.8	6.6	2	80	B1
34	A B	0.073	13.1	8.3	5.25	8.375	2.6 2.8	2.7	2.1 2.6	6.5	2	30	B1
35	A B	0.060	15.3	8.0	5.25	8.375	3.6 3.6	3.6	2.0 2.0	6.8	2	80	B1
36	A B	0.073	15.3	8.6	5.25	8.375	3.8 3.5	3.6	2.4 2.4	6.8	2	30	B1
37	A B	0.073	13.0	10.3	5.25	8.375	2.6 2.5	2.6	2.3 2.5	6.6	2	80	B1
38	A B	0.060	13.1	8.0	5.25	8.375	2.6 2.6	2.6	2.0 2.0	6.6	2	80	B1
39	A B	0.073	12.8	9.5	5.25	8.375	2.5 2.5	2.5	2.4 2.3	6.5	2	30	B1
40	A B	0.073	15.3	9.3	5.25	8.375	3.5 3.5	3.5	2.1 2.5	7.0	2	30	B1
41	A B	0.073	13.1	10.1	9.25	8.375	2.5 2.5	2.5	2.8 2.4	6.9	2	80	B1
42	A B	0.060	12.9	8.0	5.25	8.375	2.5 2.5	2.5	2.8 2.3	6.6	2	80	B1
43	A B	0.073	12.9	8.8	5.25	8.375	2.5 2.8	2.6	2.8 2.8	6.4	2	30	B1
44	A B	0.073	15.1	9.0	5.25	8.375	3.6 3.5	3.6	3.0 2.0	6.8	2	30	B1
45	A B	0.073	12.9	10.0	5.25	8.375	2.5 2.5	2.5	2.0 2.0	6.6	2	80	B1
46	A B	0.060	13.0	8.5	5.25	8.375	2.5 2.6	2.6	2.0 2.5	6.6	2	80	B1
47	A B	0.077	11.0	13.4	5.25	8.375	1.6 1.5	1.6	1.9 1.9	6.6	2	80	B4
48	B	0.08	12.0	11.0	5.25	8.375	1.6	1.6	2.4	6.6	2	80	B1
49	A B	0.077	12.9	11.3	5.25	8.375	2.5 2.5	2.5	2.1 2.0	6.6	2	80	B4
50	A B	0.077	13.1	13.6	5.25	8.375	2.5 2.8	2.6	2.5 2.1	6.6	2	80	B4

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
26	A B	39109 34311	31179 34311	65490	32745	126159 110679	105629	89581	- -	FB/SS SS
27	A B	22045 23158	22040 22201	44241	22121	71114 74702	71357	63404	- -	FP FP
28	A B	46085 46076	46016 44849	90864	45432	148661 148631	146556	123859	- -	BY BY
29	A B	26722 35215	26722 27495	54217	27108	86199 113596	87446	78954	0.194 .146(.016)	FP/SS SB/FP
30	A B	34057 31441	30094 31414	61508	30754	109860 101422	99206	79634	0.251 .237(.021)	SS/FP FP/SS
31	A B	32860 37440	32628 33645	66273	33136	106001 120776	106892	65062	- -	FP SB/FB
32	A B	20038 29285	19968 19863	39830	19915	64639 94469	64242	44607	- -	SS SS/FP
33	A B	26203 27858	26172 26974	53146	26573	84524 89865	85719	64347	- -	FP SS
34	A B	29328 25430	29328 25430	54758	27379	94606 82032	88319	64750	- -	FP/SS FP/SS
35	A B	41369 31173	28996 31173	60169	30084	133448 100558	97046	63996	- -	FP/SS FP/SS
36	A B	28967 26270	25617 26194	51811	25905	93441 84741	83565	68475	0.239 0.158	FP/SS FP/SS
37	A B	36570 39949	36332 36565	72896	36448	117967 128867	117575	67769	- -	SS SS/FP
38	A B	29091 24285	23661 24171	47832	23916	93843 78338	77148	52222	- -	SS/FP FP/SS
39	A B	34198 35367	34198 31621	65819	32909	110316 114087	106159	79216	0.373 .261(.035)	FP/SS FP/SS
40	A B	35824 28925	35733 25266	60999	30500	115563 93305	98386	76007	0.205 0.238	FP FP
41	A B	35739 27537	27537 27537	55074	27537	115288 88829	88829	62980	- -	FP/SS SB
42	A B	21633 26769	21535 21379	42914	21457	69782 86352	69217	48118	- -	SS SS
43	A B	23854 27932	23854 24731	48585	24292	76947 90103	78363	65783	0.25 0.22	FP FP/SS
44	A B	25266 25221	25261 25221	50482	25241	81504 81359	81423	71214	- -	FP/SS FP/SS
45	A B	43142 38421	38421 38421	76842	38421	139167 123938	123938	66624	- -	FP/SS FP
46	A B	25321 22912	23275 22679	45954	22977	81681 73909	74119	53785	- -	FP/SS FP
47	A B	48319 43017	43085 43017	86101	43051	155868 138764	138873	87853	- -	FP/SB FP/SB
48	B	20282	20282	20282	20282	65426	65426	67231	-	FP/SB
49	A B	35466 43930	35466 43930	79396	39698	114406 141710	128058	69807	- -	FP/SB FP
50	A B	43621 42484	42165 42484	84648	42324	140714 137044	136530	86440	- -	FP FP/SB

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
26	A B	60	-	-	-	-	0.80	4	4.0 (2.0)	0.500	4.00 (2.0)	-	-	1.27	60
27	A B	60	-	-	-	-	0.66	6	2.5 (2.2)	0.500	3.00 (1.5)	-	-	1.27	60
28	A B	60	-	-	-	-	0.11	1	(7.0)	0.375	5.00 (2.5)	-	-	1.89	60
29	A B	60	-	-	-	-	0.22	2	(1.7)	0.500	3.00 (1.8)	-	-	1.27	60
30	A B	60	-	-	-	-	0.22	2	(1.7)	0.500	3.00 (1.8)	-	-	1.27	60
31	A B	60	0.38	0.11	1	5.00	0.44	4	6.0 (1.1)	0.375	4.00 (2.0)	-	-	1.27	60
32	A B	60	0.38	0.11	1	5.00	0.44	4	6.0 (1.1)	0.375	4.00 (2.0)	-	-	1.27	60
33	A B	60	0.38	0.11	1	5.00	0.80	4	6.0 (1.1)	0.500	4.00 (2.0)	-	-	1.27	60
34	A B	60	0.38	0.11	1	5.00	0.66	6	3.0 (1.7)	0.500	3.00 (1.8)	-	-	1.27	60
35	A B	60	0.38	0.11	1	5.00	0.80	4	6.0 (1.1)	0.500	4.00 (2.0)	-	-	1.27	60
36	A B	60	0.38	0.11	1	5.00	0.66	6	3.0 (1.7)	0.500	3.00 (1.8)	-	-	1.27	60
37	A B	60	0.38	0.11	1	2.00	-	-	-	0.375	4.00 (2.0)	-	-	1.27	60
38	A B	60	0.38	0.11	1	2.00	-	-	-	0.375	4.00 (2.0)	-	-	1.27	60
39	A B	60	0.38	0.11	1	3.00	-	-	-	0.375	3.00 (1.8)	-	-	1.27	60
40	A B	60	0.38	0.11	1	3.00	-	-	-	0.375	3.00 (1.8)	-	-	1.27	60
41	A B	60	0.5	0.20	1	5.00	0.44	4	6.0 (1.1)	0.375	4.00 (2.0)	-	-	1.27	60
42	A B	60	0.5	0.20	1	5.00	0.44	4	6.0 (1.1)	0.375	4.00 (2.0)	-	-	1.27	60
43	A B	60	0.5	0.20	1	5.00	0.44	4	6.0 (1.7)	0.500	3.00 (1.8)	-	-	1.27	60
44	A B	60	0.5	0.20	1	5.00	0.44	4	6.0 (1.7)	0.500	3.00 (1.8)	-	-	1.27	60
45	A B	60	0.5	0.20	1	2.00	-	-	-	0.375	4.00 (2.0)	-	-	1.27	60
46	A B	60	0.5	0.20	1	2.00	-	-	-	0.375	4.00 (2.0)	-	-	1.27	60
47	A B	60	0.38	0.11	2	2.00	-	-	-	0.375	4.00 (2.0)	-	-	1.89	60
48	B	60	0.375	0.11	2	2.0	-	-	-	0.375	4.0 (2.0)	-	-	1.27	60
49	A B	60	0.38	0.11	2	2.00	-	-	-	0.375	4.00 (2.0)	-	-	1.89	60
50	A B	60	0.38	0.11	2	2.00	-	-	-	0.375	4.50 (2.3)	-	-	1.89	60

[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars

[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
51	(2@9) 5-5-90-2#3-i-2.5-7-7	A B	90°	Para	A1035	7.0 7.0	7.0	5880	11	0.625
52	5-5-90-2#3-i-2.5-2-8	A B	90°	Para	A1035	8.0 7.5	7.8	5860	8	0.625
53	5-5-90-2#3-i-2.5-2-6	A B	90°	Para	A615	6.0 5.8	5.9	5800	9	0.625
54	5-8-90-2#3-i-2.5-2-6	A B	90°	Para	A1035	6.0 6.0	6.0	8580	15	0.625
55	5-8-90-2#3-i-2.5-2-8	A B	90°	Para	A1035	8.3 8.5	8.4	8380	13	0.625
56	5-12-90-2#3-i-2.5-2-5	A B	90°	Para	A1035	5.8 5.8	5.8	11090	83	0.625
57	5-15-90-2#3-i-2.5-2-6	A B	90°	Para	A1035	6.3 6.5	6.4	15800	61	0.625
58	5-15-90-2#3-i-2.5-2-4	A B	90°	Para	A1035	3.5 4.0	3.8	15800	61	0.625
59	5-5-90-2#3-i-3.5-2-6	A B	90°	Para	A1035	6.0 5.8	5.9	5230	6	0.625
60	5-5-90-2#3-i-3.5-2-8	A B	90°	Para	A1035	7.9 7.5	7.7	5190	7	0.625
61	5-8-90-2#3-i-3.5-2-6	A B	90°	Para	A1035	6.5 6.0	6.3	8580	15	0.625
62	5-8-90-2#3-i-3.5-2-8	A B	90°	Para	A1035	7.1 7.0	7.1	8710	16	0.625
63	5-12-90-2#3-i-3.5-2-5	A B	90°	Para	A1035	5.6 5.3	5.4	10410	15	0.625
64	5-12-90-2#3-i-3.5-2-10	A B	90°	Para	A1035	10.8 10.6	10.7	11090	83	0.625
65	5-5-180-2#3-i-2.5-2-8	A B	180°	Para	A1035	8.0 8.0	8.0	5670	7	0.625
66	5-5-180-2#3-i-2.5-2-6	A B	180°	Para	A615	5.8 5.5	5.6	5860	8	0.625
67	5-8-180-2#3-i-2.5-2-7	A B	180°	Para	A1035	7.0 7.3	7.1	9080	11	0.625
68	5-8-180-2#3-i-3.5-2-7	A B	180°	Para	A1035	6.8 6.9	6.8	9080	11	0.625
69	5-8-90-4#3-i-2.5-2-8	A B	90°	Para	A1035	7.9 7.5	7.7	8380	13	0.625
70	5-8-90-4#3-i-3.5-2-8	A B	90°	Para	A1035	8.6 8.3	8.4	8380	13	0.625
71	5-5-90-5#3-o-1.5-2-5	B	90°	Para	A615	5.0	5.0	5205	5	0.625
72	5-5-90-5#3-o-1.5-2-8	A B	90°	Para	A1035	8.0 7.8	7.9	5650	6	0.625
73	5-5-90-5#3-o-1.5-2-6.5	A B	90°	Para	A1035	6.5 6.5	6.5	5780	7	0.625
74	5-5-90-5#3-o-2.5-2-5	A B	90°	Para	A615	5.2 5.1	5.2	4903	4	0.625
75	5-5-90-5#3-o-2.5-2-8	A	90°	Para	A1035	7.5	7.5	5650	6	0.625

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°
51	A B	0.073	11.5	14.2	5.25	8.375	2.5 2.7	2.6	7.3 7.2	5.1	2	30	B2
52	A B	0.073	12.9	10.0	5.38	8.375	2.5 2.5	2.5	2.0 2.5	6.6	2	80	B1
53	A B	0.060	13.1	8.5	5.25	8.375	2.6 2.6	2.6	2.5 2.8	6.6	2	80	B1
54	A B	0.073	13.0	8.0	5.25	8.375	2.8 2.9	2.8	2.0 2.0	6.1	2	80	B1
55	A B	0.073	12.9	10.0	5.25	8.375	2.6 2.5	2.6	1.8 1.5	6.5	2	80	B5
56	A B	0.073	13.0	8.8	5.25	8.375	2.5 2.8	2.6	3.0 3.0	6.5	2	30	B1
57	A B	0.073	12.6	8.2	5.25	8.375	2.4 2.4	2.4	1.9 1.7	6.6	2	30	B2
58	A B	0.073	13.0	6.1	5.25	8.375	2.5 2.5	2.5	2.6 2.1	6.8	2	30	B9
59	A B	0.073	14.5	8.3	5.25	8.375	3.4 3.4	3.4	2.3 2.5	6.5	2	30	B1
60	A B	0.073	14.9	10.3	5.25	8.375	3.4 3.5	3.4	2.3 2.8	6.8	2	30	B1
61	A B	0.073	14.9	8.0	5.25	8.375	3.5 3.8	3.6	1.5 2.0	6.4	2	80	B1
62	A B	0.060	14.9	10.0	5.25	8.375	3.5 3.5	3.5	2.9 3.0	6.6	2	80	B5
63	A B	0.073	15.1	7.4	5.25	8.375	3.8 3.5	3.6	1.8 2.2	6.6	2	30	B1
64	A B	0.073	15.1	13.0	5.25	8.375	3.5 3.6	3.6	2.3 2.4	6.8	2	30	B4
65	A B	0.073	13.1	10.0	5.25	8.375	2.5 2.5	2.5	2.0 2.0	6.9	2	80	B1
66	A B	0.060	13.1	7.8	5.25	8.375	2.6 2.6	2.6	2.0 2.3	6.6	2	80	B1
67	A B	0.073	12.6	9.3	5.25	8.375	2.5 2.5	2.5	2.3 2.1	6.4	2	30	B1
68	A B	0.073	15.1	9.2	5.25	8.375	3.4 3.5	3.4	2.4 2.3	7.0	2	30	B1
69	A B	0.060	12.6	10.0	5.25	8.375	2.5 2.5	2.5	2.1 2.5	6.4	2	80	B5
70	A B	0.060	15.1	10.0	5.25	8.375	3.5 3.5	3.5	1.4 1.8	6.9	2	80	B5
71	B	0.077	10.8	7.1	5.25	8.375	1.5	1.5	2.0	6.5	2	80	B1
72	A B	0.077	10.7	10.3	5.25	8.375	1.6 1.5	1.5	2.3 2.6	6.4	2	80	B1
73	A B	0.073	10.9	8.5	5.25	8.375	1.6 1.6	1.6	2.0 2.0	6.5	2	80	B4
74	A B	0.077	13.1	7.0	5.38	8.375	2.6 2.6	2.6	1.9 1.9	6.6	2	80	B1
75	A	0.077	13.1	11.7	5.25	8.375	2.6	2.6	2.1	6.5	2	80	B1

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
51	A B	33452 35246	33408 35055	68463	34232	107910 113697	110425	61345	0.018 0.125	FP/SB FP/SB
52	A B	37932 38949	37807 36500	74307	37154	122360 125642	119850	67802	- -	SS/FP SS/FP
53	A B	31846 29191	29697 29191	58888	29444	102730 94164	94980	51134	- -	FP/SS FP/SS
54	A B	33454 30874	30402 30874	61277	30638	107916 99595	98833	63517	- -	FP/SS FP/SS
55	A B	39822 40545	39791 40545	80336	40168	128457 130789	129574	87619	- -	FP/SS FP/SS
56	A B	25201 29393	25120 23576	48696	24348	81295 94816	78542	69203	- -	FP/SS FP
57	A B	42381 42895	42381 42895	85276	42638	136714 138371	137542	91580	- -	FP FB
58	A B	18652 21256	18652 18683	37334	18667	60167 68569	60217	53871	- -	FB FP
59	A B	21341 21262	21146 21040	42186	21093	68842 68586	68042	48557	0.183 -	SS/FP SS/FP
60	A B	43675 45654	43675 45654	89329	44665	140887 147271	144079	63551	- -	FP FP
61	A B	29930 30139	29930 30139	60069	30035	96549 97223	96886	66163	- -	FP FP/SS
62	A B	38022 28596	28716 28596	57312	28656	122652 92246	92439	75329	- -	FP FP
63	A B	27860 28869	27860 28869	56728	28364	89871 93124	91497	63404	- 0.349	FP FP
64	A B	46561 46006	44490 46001	90490	45245	150197 148406	145952	128628	- -	BY BY
65	A B	34036 34483	33674 34483	68157	34078	109795 111236	109930	68845	- -	FP/SS FP/SS
66	A B	26852 26912	26782 26674	53456	26728	86620 86814	86220	49211	- -	FP/SS FP
67	A B	34580 28697	29762 28697	58459	29230	111548 92572	94289	77592	- .369(.081)	FP/SS FP/SS
68	A B	29310 32577	29285 32577	61862	30931	94550 105086	99777	74189	- .329(.028)	FP/SS FP
69	A B	33367 27016	25867 26955	52823	26411	107636 87150	85198	80426	- -	FP/SS FP/SS
70	A B	42471 39278	37810 39150	76960	38480	137003 126704	124130	88273	- -	FP SS/FP
71	B	22060	22060	22060	22060	71000	71000	51500	-	FP/SB
72	A B	25173 30446	25173 25048	50221	25110	81202 98211	81002	84562	- -	FP/SB FP/SB
73	A B	26229 20940	22736 20686	43422	21711	84610 67550	70035	70596	- -	FP/SB FP/SB
74	A B	22279 29466	22230 22829	45058	22529	71868 95050	72675	51578	- -	FP/SB FP/SB
75	A	28429	28429	28429	28429	91706	91706	80536	-	FP

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
51	A B	60	0.38	0.11	2	3.00 (3.0)	-	-	-	0.375	4.00 (2.0)	-	-	3.16	60
52	A B	60	0.38	0.11	2	4.00 (2.0)	-	-	-	0.375	4.00 (2.0)	-	-	1.27	60
53	A B	60	0.38	0.11	2	4.00 (2.0)	-	-	-	0.375	4.00 (2.0)	-	-	1.27	60
54	A B	60	0.38	0.11	2	4.00 (2.0)	-	-	-	0.500	4.00 (2.0)	-	-	1.27	60
55	A B	60	0.38	0.11	2	4.00 (2.0)	-	-	-	0.500	4.00 (2.0)	-	-	1.67	60
56	A B	60	0.38	0.11	2	3.30 (3.0)	0.33	3	3.3 (1.3)	0.500	3.00 (1.5)	-	-	1.27	60
57	A B	60	0.38	0.11	2	3.00 (3.0)	-	-	-	0.375	2.75 (1.4)	-	-	3.16	60
58	A B	60	0.38	0.11	2	3.00 (3.0)	-	-	-	0.375	1.75 (0.9)	-	-	2.51	60
59	A B	60	0.38	0.11	2	3.50 (2.0)	0.11	1	3.5 (1.75)	0.375	3.50 (1.75)	-	-	1.27	60
60	A B	60	0.38	0.11	2	3.50 (2.0)	-	-	-	0.375	4.00 (2.0)	-	-	1.27	60
61	A B	60	0.38	0.11	2	4.00 (2.0)	-	-	-	0.500	4.00 (2.0)	-	-	1.27	60
62	A B	60	0.38	0.11	2	4.00 (2.0)	-	-	-	0.500	4.00 (2.0)	-	-	1.67	60
63	A B	60	0.38	0.11	2	3.33 (3.0)	0.33	3	3.3 (1.3)	0.500	3.00 (1.5)	-	-	1.27	60
64	A B	60	0.38	0.11	2	3.30 (3.0)	-	-	-	0.375	5.00 (2.5)	-	-	1.89	60
65	A B	60	0.38	0.11	2	2.50 (0.75)	-	-	-	0.375	4.00 (2.0)	-	-	1.27	60
66	A B	60	0.38	0.11	2	2.50 (0.75)	-	-	-	0.375	4.00 (2.0)	-	-	1.27	60
67	A B	60	0.38	0.11	2	2.00 (1.4)	-	-	-	0.375	3.00 (1.8)	-	-	1.27	60
68	A B	60	0.38	0.11	2	2.00 (1.4)	-	-	-	0.375	3.00 (1.8)	-	-	1.27	60
69	A B	60	0.38	0.11	4	2.00 (2.5)	-	-	-	0.500	4.00 (2.0)	-	-	1.67	60
70	A B	60	0.38	0.11	4	2.00 (2.5)	-	-	-	0.500	4.00 (2.0)	-	-	1.67	60
71	B	60	0.375	0.11	5	2.00 (1.4)	-	-	-	0.375	2.50 (1.3)	-	-	1.27	60
72	A B	60	0.38	0.11	5	2.50 (1.4)	-	-	-	0.375	2.50 (1.3)	-	-	1.27	60
73	A B	60	0.38	0.11	5	2.50 (1.4)	-	-	-	0.375	2.50 (1.3)	-	-	1.89	60
74	A B	60	0.38	0.11	5	2.00 (1.4)	-	-	-	0.375	2.50 (1.3)	-	-	1.27	60
75	A	60	0.375	0.11	5	2.50 (1.4)	-	-	-	0.375	2.50 (1.3)	-	-	1.27	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
76	5-5-90-5#3-i-2.5-2-8	A B	90°	Para	A1035	7.8 7.8	7.8	4660	7	0.625
77	(2@9) 5-5-90-5#3-i-2.5-7-7	A B	90°	Para	A1035	6.8 7.0	6.9	5950	12	0.625
78	5-5-90-5#3-i-2.5-2-7	A B	90°	Para	A1035	5.6 7.0	6.3	5230	6	0.625
79	(2@4) 5-8-90-5#3-i-2.5-2-6	A B	90°	Para	A1035	6.0 6.0	6.0	6700	22	0.625
80	(2@6) 5-8-90-5#3-i-2.5-2-6	A B	90°	Para	A1035	6.0 6.0	6.0	6700	22	0.625
81	5-12-90-5#3-i-2.5-2-5	A B	90°	Para	A1035	5.1 5.8	5.4	10410	15	0.625
82	5-15-90-5#3-i-2.5-2-4	A B	90°	Para	A1035	3.8 4.1	4.0	15800	62	0.625
83	5-15-90-5#3-i-2.5-2-5	A B	90°	Para	A1035	5.0 5.1	5.1	15800	62	0.625
84	5-5-90-5#3-i-3.5-2-7	A B	90°	Para	A1035	7.5 6.8	7.1	5190	7	0.625
85	5-12-90-5#3-i-3.5-2-5	A B	90°	Para	A1035	5.3 4.8	5.0	11090	83	0.625
86	5-12-90-5#3-i-3.5-2-10	A B	90°	Para	A1035	11.0 11.3	11.1	11090	83	0.625

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°
76	A B	0.073	13.1	10.1	5.25	8.375	2.5 2.9	2.7	2.4 2.3	6.5	2	30	B2
77	A B	0.073	11.5	14.1	5.25	8.375	2.5 2.7	2.6	7.3 7.3	5.1	2	30	B2
78	A B	0.073	13.3	9.3	5.25	8.375	2.8 2.8	2.8	3.6 2.3	6.5	2	30	B1
79	A B	0.073	9.5	8.0	5.25	8.375	2.8 3.0	2.9	2.0 2.0	2.5	2	30	B2
80	A B	0.073	10.8	8.0	5.25	8.375	2.8 3.0	2.9	2.0 2.0	3.8	2	30	B2
81	A B	0.073	13.0	7.3	5.25	8.375	2.6 2.6	2.6	2.1 1.5	6.5	2	30	B1
82	A B	0.073	12.8	6.0	5.25	8.375	2.4 2.5	2.4	2.2 1.9	6.6	2	30	B9
83	A B	0.073	12.8	7.1	5.25	8.375	2.4 2.3	2.4	2.1 1.9	6.8	2	30	B2
84	A B	0.073	15.1	9.5	5.25	8.375	3.4 3.5	3.4	2.0 2.8	7.0	2	30	B1
85	A B	0.073	14.4	7.0	5.25	8.375	3.3 3.3	3.3	2.5 1.5	6.6	2	30	B1
86	A B	0.073	15.1	13.0	5.25	8.375	3.5 3.5	3.5	2.0 1.8	6.9	2	30	B4

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
76	A B	42760 44727	42711 43348	86059	43030	137936 144280	138805	75578	- -	FP/SB FP/SB
77	A B	42205 41295	41678 40229	81907	40954	136145 133210	132109	75759	0.27 0.24	FP/SB FP/SB
78	A B	32080 31340	32080 31313	63393	31696	103484 101095	102246	65216	- -	FP FP/SS
79	A B	40800 41400	40800 41400	82200	41100	131613 133548	132581	70160	- -	No Failure No Failure
80	A B	39300 40300	39300 40300	79600	39800	126774 130000	128387	70160	- -	No Failure No Failure
81	A B	33923 34916	33923 34916	68839	34420	109428 112634	111031	79255	0.292 0.295	FP/SS SS/FP
82	A B	31312 31325	31312 31325	62637	31318	101006 101048	101027	71266	0.603 0.378	FP FP
83	A B	38574 46165	38574 39737	78312	39156	124434 148921	126309	90907	- -	FP BY
84	A B	44301 35206	36844 35206	72050	36025	142906 113568	116210	73328	- -	FP FP
85	A B	31472 31302	31396 29485	60882	30441	101522 100973	98196	75221	- -	FP FP
86	A B	46464 45703	46464 45638	92102	46051	149882 147430	148551	167366	- -	BY BY

Table B.1 Cont. Comprehensive test results and data for specimens containing two No. 5 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
76	A B	60	0.38	0.11	5	1.88 (0.75)	-	-	-	0.500	3.00 (1.5)	-	-	3.16	60
77	A B	60	0.38	0.11	5	1.75 (0.9)	-	-	-	0.380	4.00 (2.0)	-	-	3.16	60
78	A B	60	0.38	0.11	5	1.75 (0.9)	-	-	-	0.500	3.50 (1.75)	-	-	1.27	60
79	A B	60	0.38	0.11	5	1.67 (0.9)	-	-	-	0.380	3.00 91.5)	-	-	3.16	120
80	A B	60	0.38	0.11	5	1.67 (0.9)	-	-	-	0.380	3.00 (1.5)	-	-	3.16	120
81	A B	60	0.38	0.11	5	1.67 (1.3)	-	-	-	0.500	3.00 (1.5)	-	-	1.27	60
82	A B	60	0.38	0.11	5	1.75 (0.9)	-	-	-	0.375	1.75 (0.9)	-	-	2.51	60
83	A B	60	0.38	0.11	5	1.75 (0.9)	-	-	-	0.375	2.25 (1.1)	-	-	3.16	60
84	A B	60	0.38	0.11	5	1.75 (0.9)	-	-	-	0.500	3.50 (1.75)	-	-	1.27	60
85	A B	60	0.38	0.11	5	1.70 (1.3)	-	-	-	0.500	3.00 (1.5)	-	-	1.27	60
86	A B	60	0.38	0.11	5	1.70 (1.3)	-	-	-	0.375	5.00 (2.5)	-	-	1.89	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.2 Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
87	8-5-90-0-o-2.5-2-10a	A B	90°	-	A1035[a]	10.3 10.5	10.4	5270	7	1
88	8-5-90-0-o-2.5-2-10b	A B	90°	-	A1035[a]	9.3 10.3	9.8	5440	8	1
89	8-5-90-0-o-2.5-2-10c	A B	90°	-	A1035[a]	10.8 10.5	10.6	5650	9	1
90	8-8-90-0-o-2.5-2-8	A B	90°	-	A1035[b]	8.6 8.3	8.4	8740	12	1
91	8-8-90-0-o-3.5-2-8	A B	90°	-	A1035[b]	7.6 8.0	7.8	8810	14	1
92	8-8-90-0-o-4-2-8	A B	90°	-	A1035[b]	8.1 8.3	8.2	8630	11	1
93	8-5-90-0-i-2.5-2-16	A B	90°	-	A1035[b]	16.0 16.8	16.4	4980	7	1
94	8-5-90-0-i-2.5-2-9.5	A B	90°	-	A615	9.0 10.3	9.6	5140	8	1
95	8-5-90-0-i-2.5-2-12.5	A B	90°	-	A615	13.3 13.3	13.3	5240	9	1
96	8-5-90-0-i-2.5-2-18	A B	90°	-	A1035[b]	19.5 17.9	18.7	5380	11	1
97	8-5-90-0-i-2.5-2-13	A B	90°	-	A1035[b]	13.3 13.5	13.4	5560	11	1
98	8-5-90-0-i-2.5-2-15(1)	A B	90°	-	A1035[b]	14.5 15.3	14.9	5910	14	1
99	8-5-90-0-i-2.5-2-15	A B	90°	-	A1035[b]	15.3 14.4	14.8	6210	8	1
100	8-5-90-0-i-2.5-2-10	A B	90°	-	A615	10.0 10.0	10.0	5920	12	1
101	(2d) 8-5-90-0-i-2.5-2-10	A B	90°	-	A615	10.3 10.0	10.1	5920	12	1
102	(2@3) 8-5-90-0-i-2.5-2-10	A B	90°	-	A615	10.4 10.6	10.5	4490	10	1
103	(2@5) 8-5-90-0-i-2.5-2-10	A B	90°	-	A615	10.1 10.1	10.1	4490	10	1
104	8-8-90-0-i-2.5-2-8	A B	90°	-	A1035[b]	8.9 8.0	8.4	7910	15	1
105	8-8-90-0-i-2.5-2-10	A B	90°	-	A1035[b]	9.8 9.5	9.6	7700	14	1
106	8-8-90-0-i-2.5-2-8(1)	A B	90°	-	A1035[b]	8.0 8.0	8.0	8780	13	1
107	8-8-90-0-i-2.5-2-9	A B	90°	-	A615	9.5 9.5	9.5	7710	25	1
108	8-8-90-0-i-2.5-9-9	A B	90°	-	A615	9.3 9.0	9.1	7710	25	1
109	(2@3) 8-8-90-0-i-2.5-9-9	A B	90°	-	A615	9.3 9.0	9.1	7510	21	1
110	(2@4) 8-8-90-0-i-2.5-9-9	A B	90°	-	A615	9.9 10.0	9.9	7510	21	1
111	8-12-90-0-i-2.5-2-9	A B	90°	-	A1035[b]	9.0 9.0	9.0	11160	77	1

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

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°
87	A B	0.084	17.1	12.3	10.5	8.375	2.5 2.6	2.6	2.0 1.8	10.0	2	80	B2
88	A B	0.084	17.0	12.5	10.5	8.375	2.5 2.5	2.5	3.3 2.3	10.0	2	80	B2
89	A B	0.084	17.0	12.3	10.5	8.375	2.5 2.5	2.5	1.5 1.8	10.0	2	80	B2
90	A B	0.078	16.3	10.4	10.5	8.375	2.8 2.5	2.6	1.8 2.1	9.0	2	30	B2
91	A B	0.078	18.9	10.0	10.5	8.375	3.5 3.6	3.6	2.4 2.0	9.8	2	30	B2
92	A B	0.078	20.0	10.6	10.5	8.375	4.5 3.8	4.1	2.5 2.4	9.8	2	30	B2
93	A B	0.078	17.0	17.9	10.5	8.375	2.8 2.8	2.8	1.8 1.4	9.5	2	80	B2
94	A B	0.078	16.8	12.0	10.5	8.375	2.8 2.5	2.6	3.0 1.8	9.5	2	80	B2
95	A B	0.078	17.3	14.5	10.5	8.375	2.8 2.8	2.8	1.3 1.3	9.8	2	80	B2
96	A B	0.078	17.5	20.3	10.5	8.375	2.5 2.5	2.5	0.8 2.4	10.5	2	30	B6
97	A B	0.078	16.8	15.3	10.5	8.375	2.5 2.5	2.5	2.0 1.8	9.8	2	30	B2
98	A B	0.073	16.7	17.3	10.5	8.375	2.5 2.6	2.5	2.8 2.0	9.6	2	30	B2
99	A B	0.073	16.6	17.3	10.5	8.375	2.5 2.6	2.6	2.0 2.9	9.5	2	30	B2
100	A B	0.073	17.6	12.3	10.5	8.375	2.5 2.9	2.7	2.3 2.3	10.3	2	57	B17
101	A B	0.073	17.3	12.3	19.5	8.375	2.5 2.8	2.6	2.0 2.3	10.0	2	57	B17
102	A B	0.073	9.0	12.0	10.5	8.375	2.5 2.5	2.5	1.6 1.4	2.0	2	30	B2
103	A B	0.073	10.9	12.0	10.5	8.375	2.5 2.3	2.4	1.9 1.9	4.1	2	30	B2
104	A B	0.078	16.3	10.0	10.5	8.375	2.8 2.9	2.8	1.1 2.0	8.6	2	30	B2
105	A B	0.078	16.6	12.0	10.5	8.375	2.8 2.9	2.8	2.3 2.5	9.0	2	30	B2
106	A B	0.078	17.0	10.8	10.5	8.375	2.8 2.8	2.8	2.8 2.8	9.5	2	30	B2
107	A B	0.073	17.3	11.0	10.5	8.375	2.5 2.8	2.6	1.5 1.5	10.0	2	30	B2
108	A B	0.073	17.5	18.0	10.5	8.375	2.8 2.8	2.8	8.8 9.0	10.0	2	30	B7
109	A B	0.073	9.1	18.0	10.5	8.375	2.5 2.6	2.6	8.8 9.0	2.0	2	30	B7
110	A B	0.073	10.2	18.0	10.5	8.375	2.6 2.5	2.5	8.1 8.0	3.1	2	30	B7
111	A B	0.078	17.0	11.4	10.5	8.375	2.8 2.6	2.7	2.4 2.4	9.6	2	30	B2

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
87	A	40645	38970	84628	42314	51449	53562	53798	-	FP/SS
	B	46612	45658			59003			0.186	SS/FP
88	A	47870	38190	67302	33651	60596	42596	51366	-	FP/SS
	B	30599	29112			38733			-	SS/FP
89	A	62682	57437	111949	55975	79345	70854	57046	-	FP/SS
	B	54558	54512			69061			0.132	SS/FP/TK
90	A	44396	32792	66029	33015	56198	41791	56343	0.153	SB/TK
	B	33238	33238			42073			0.113	SB/TK
91	A	35613	35613	71745	35872	45080	45408	52378	-	FP/SS
	B	44488	36132			56314			-	SS/FP
92	A	37130	35849	75022	37511	47000	47482	54329	0.362	SS/FP
	B	39173	39173			49586			.(0.017)	SS
93	A	83310	83310	166479	83239	105455	105366	82541	-	FP/SB
	B	86063	83169			108940			-	FB/TK
94	A	44627	44627	88971	44485	56489	56311	49289	-	FP
	B	65800	44344			83291			-	SS
95	A	65254	65254	131639	65819	82600	83316	68510	-	SS/B
	B	69872	66385			88446			-	SS
96	A	100169	82023	161763	80881	126796	102381	97907	-	FB/SS/TK
	B	79805	79740			101018			0.153	FB/SS/TK
97	A	73143	65881	131078	65539	92586	82960	71237	-	SS
	B	65197	65197			82527			-	FP/SS
98	A	64532	64532	127534	63767	81686	80718	81681	-	FB/SB
	B	87275	63002			110475			-	SB
99	A	76256	76162	150955	75478	96527	95541	83377	-	SS/FP
	B	80724	74793			102182			-	SB/FP
100	A	47731	47731	95363	47681	60420	60356	54958	-	SS/SB
	B	47658	47631			60327			-	SS
101	A	33147	33147	64746	32373	41958	40979	55645	-	SS
	B	31600	31600			39999			-	SS
102	A	38900	38908	80626	40313	49241	51029	50256	0.2	FP
	B	41700	41718			52785			-	FP
103	A	41853	41853	80104	40052	52979	50699	48150	0.33	FP
	B	38251	38251			48419			0	FB/SS
104	A	54674	45317	90486	45243	69208	57269	53601	-	FP/TK
	B	45169	45169			57176			-	FP/SS
105	A	50000	49985	102911	51455	63291	65134	60328	0.195	FP
	B	52926	52926			66995			0.185	FP
106	A	38047	35988	73642	36821	48161	46609	53544	0.387	FP/SS
	B	37660	37654			47671			0.229	FP/SS
107	A	35543	35543	70199	35100	44991	44430	59583	0.104	FB
	B	34656	34656			43868			0	FB
108	A	38519	38519	75358	37679	48758	47695	57231	0.12	FB
	B	36839	36839			46632			0.29	FB
109	A	34015	33826	61345	30672	43057	38826	56484		FP
	B	27575	27518			34905			-	FP
110	A	32856	32856	68391	34195	41590	43285	61513	0.018	FP
	B	35534	35534			44980			0	FP
111	A	50809	50677	99845	49923	64315	63193	67912	0.219	FP/SS
	B	54796	49168			69362				SS/FP

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
87	A B	60	-	-	-	-	3.10	5	3.5 (1.5)	0.63	3.50 (1.75)	-	-	3.16	60
88	A B	60	-	-	-	-	3.10	5	3.5 (1.5)	0.63	3.50 (1.75)	-	-	3.16	60
89	A B	60	-	-	-	-	3.10	5	3.5 (1.5)	0.63	3.50 (1.75)	-	-	3.16	60
90	A B	60	-	-	-	-	2.00	10	3.0 (2.3)	0.50	1.75 (0.9)	-	-	3.16	60
91	A B	60	-	-	-	-	2.00	10	3.0 (2.3)	0.50	1.75 (0.9)	-	-	3.16	60
92	A B	60	-	-	-	-	2.00	10	3.0 (2.3)	0.50	1.75 (0.9)	-	-	3.16	60
93	A B	60	-	-	-	-	2.00	10	3.0 (1.5)	0.50	3.00 (1.5)	-	-	3.16	60
94	A B	60	-	-	-	-	2.00	10	3.0 (1.5)	0.50	3.00 (1.5)	-	-	3.16	60
95	A B	60	-	-	-	-	2.00	10	3.0 (1.5)	0.50	3.00 (1.5)	-	-	3.16	60
96	A B	60	-	-	-	-	1.10	10	3.0 (1.5)	0.38	3.50 (1.75)	0.375	1	3.78	60
97	A B	60	-	-	-	-	1.00	5	3.0 (1.5)	0.50	3.00 (1.5)	0.375	1	3.16	60
98	A B	60	-	-	-	-	1.10	10	3.0 (1.5)	0.38	3.50 (1.75)	0.375	2	3.16	60
99	A B	60	-	-	-	-	1.10	10	3.0 (1.5)	0.38	3.50 (1.75)	0.375	2	3.16	60
100	A B	60	-	-	-	-	-	-	-	0.50	4.00 (2.0)	-	-	4.34	120
101	A B	60	-	-	-	-	-	-	-	0.50	4.00 (2.0)	-	-	4.34	120
102	A B	60	-	-	-	-	-	-	-	0.38	5.00 (1.5)	-	-	3.16	120
103	A B	60	-	-	-	-	-	-	-	0.38	5.00 (1.5)	-	-	3.16	120
104	A B	60	-	-	-	-	1.60	8	4.0 (2.0)	0.50	1.75 (0.9)	-	-	3.16	60
105	A B	60	-	-	-	-	1.60	8	4.0 (2.5)	0.63	3.50 (1.75)	-	-	3.16	60
106	A B	60	-	-	-	-	1.60	8	4.0 (2.0)	0.50	1.50 (0.9)	-	-	3.16	60
107	A B	60	-	-	-	-	-	-	-	0.38	4.00 (2.5)	-	-	3.16	60
108	A B	60	-	-	-	-	-	-	-	0.38	4.00 (2.5)	-	-	4.74	60
109	A B	60	-	-	-	-	-	-	-	0.38	4.00 (2.5)	-	-	4.74	60
110	A B	60	-	-	-	-	-	-	-	0.38	4.00 (2.5)	-	-	4.74	60
111	A B	60	-	-	-	-	0.88	8	4.0 (2.0)	0.50	4.00 (2.0)	0.375	2	3.16	60

[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
112	8-12-90-0-i-2.5-2-12.5	A B	90°	-	A1035[c]	12.9 12.8	12.8	11850	39	1
113	8-12-90-0-i-2.5-2-12	A B	90°	-	A1035[c]	12.1 12.1	12.1	11760	34	1
114	8-15-90-0-i-2.5-2-8.5	A B	90°	-	A1035[c]	8.8 8.9	8.8	15800	61	1
115	8-15-90-0-i-2.5-2-13	A B	90°	-	A1035[c]	12.8 12.8	12.8	15800	61	1
116	8-5-90-0-i-3.5-2-18	A B	90°	-	A1035[b]	19.0 18.0	18.5	5380	11	1
117	8-5-90-0-i-3.5-2-13	A B	90°	-	A1035[b]	13.4 13.4	13.4	5560	11	1
118	8-5-90-0-i-3.5-2-15(2)	A B	90°	-	A1035[c]	15.6 14.9	15.3	5180	8	1
119	8-5-90-0-i-3.5-2-15(1)	A B	90°	-	A1035[c]	15.4 15.1	15.3	6440	9	1
120	8-8-90-0-i-3.5-2-8(1)	A B	90°	-	A1035[b]	7.8 7.8	7.8	7910	15	1
121	8-8-90-0-i-3.5-2-10	A B	90°	-	A1035[b]	8.8 10.8	9.8	7700	14	1
122	8-8-90-0-i-3.5-2-8(2)	A B	90°	-	A1035[b]	8.5 8.0	8.3	8780	13	1
123	8-12-90-0-i-3.5-2-9	A B	90°	-	A1035[b]	9.0 9.0	9.0	11160	77	1
124	8-8-90-0-i-4-2-8	A B	90°	-	A1035[b]	7.6 8.0	7.8	8740	12	1
125	8-5-180-0-i-2.5-2-11	A B	180°	-	A615	11.0 11.0	11.0	4550	7	1
126	8-5-180-0-i-2.5-2-14	A B	180°	-	A1035[b]	14.0 14.0	14.0	4840	8	1
127	(2@3) 8-5-180-0-i-2.5-2-10	A B	180°	-	A615	10.3 10.0	10.2	5260	15	1
128	(2@5) 8-5-180-0-i-2.5-2-10	A B	180°	-	A615	10.0 10.0	10.0	5260	15	1
129	8-8-180-0-i-2.5-2-11.5	A B	180°	-	A1035[b]	9.3 9.3	9.3	8630	11	1
130	8-12-180-0-i-2.5-2-12.5	A B	180°	-	A1035[c]	12.8 12.5	12.6	11850	39	1
131	8-5-180-0-i-3.5-2-11	A B	180°	-	A615	11.6 11.6	11.6	4550	7	1
132	8-5-180-0-i-3.5-2-14	A B	180°	-	A1035[b]	14.4 13.9	14.1	4840	8	1
133	8-15-180-0-i-2.5-2-13.5	A B	180°	-	A1035[c]	13.8 13.5	13.6	16510	88	1
134	8-5-90-1#3-i-2.5-2-16	A B	90°	Para	A1035[b]	15.6 15.6	15.6	4810	6	1
135	8-5-90-1#3-i-2.5-2-12.5	A B	90°	Para	A1035[b]	12.5 12.5	12.5	5140	8	1
136	8-5-90-1#3-i-2.5-2-9.5	A B	90°	Para	A615	9.0 9.0	9.0	5240	9	1

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

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout[o]
112	A B	0.073	17.4	14.6	10.5	8.375	2.6 2.6	2.6	1.7 1.8	10.1	2	30	B2
113	A B	0.073	16.8	14.0	10.5	8.375	2.5 2.4	2.5	1.9 1.9	9.8	2	30	B2
114	A B	0.073	17.0	10.8	10.5	8.375	2.5 2.5	2.5	2.0 1.9	10.0	2	30	B6
115	A B	0.073	16.8	14.8	10.5	8.375	2.4 2.5	2.4	2.1 2.0	9.9	2	30	B7
116	A B	0.078	18.5	20.4	10.5	8.375	3.8 3.4	3.6	1.4 2.4	9.4	2	30	B6
117	A B	0.078	18.4	15.3	10.5	8.375	3.6 3.4	3.5	1.9 1.9	9.4	2	30	B2
118	A B	0.073	18.5	17.3	10.5	8.375	3.5 3.5	3.5	1.6 2.4	9.5	2	30	B2
119	A B	0.073	18.8	17.1	10.5	8.375	3.3 3.4	3.3	1.8 2.0	10.1	2	30	B2
120	A B	0.078	18.3	10.0	10.5	8.375	3.5 3.8	3.6	2.3 2.3	9.0	2	30	B2
121	A B	0.078	18.5	12.0	10.5	8.375	3.8 3.8	3.8	3.3 1.3	9.0	2	30	B2
122	A B	0.078	19.4	10.6	10.5	8.375	3.6 3.8	3.7	2.1 2.6	10.0	2	30	B2
123	A B	0.078	19.0	11.3	10.5	8.375	3.5 3.8	3.6	2.4 2.1	9.8	2	30	B2
124	A B	0.078	19.9	10.5	10.5	8.375	4.5 3.9	4.2	2.9 2.5	9.5	2	30	B2
125	A B	0.078	17.5	13.0	10.5	8.375	3.0 2.8	2.9	2.0 2.0	9.8	2	80	B2
126	A B	0.078	17.1	16.0	10.5	8.375	2.8 2.6	2.7	2.0 2.0	9.8	2	80	B2
127	A B	0.073	8.9	12.0	10.5	8.375	2.5 2.4	2.4	1.7 2.0	2.0	2	30	B10
128	A B	0.073	11.0	12.0	10.5	8.375	2.4 2.5	2.4	2.0 2.0	4.1	2	30	B10
129	A B	0.078	17.5	13.8	10.5	8.375	3.0 3.0	3.0	4.5 4.5	9.5	2	30	B2
130	A B	0.073	17.1	14.9	10.5	8.375	3.0 2.5	2.8	2.1 2.4	9.6	2	30	B2
131	A B	0.078	19.5	13.0	10.5	8.375	3.8 3.8	3.8	1.4 1.4	10.0	2	80	B2
132	A B	0.078	19.4	16.0	10.5	8.375	3.9 3.8	3.8	1.6 2.1	9.8	2	80	B2
133	A B	0.073	17.0	15.8	10.5	8.375	2.5 2.5	2.5	2.0 2.3	10.0	2	30	B7
134	A B	0.078	17.3	17.9	10.5	8.375	2.8 3.0	2.9	2.3 2.3	9.5	2	80	B2
135	A B	0.078	17.1	14.6	10.5	8.375	2.6 2.8	2.7	2.1 2.1	9.8	2	80	B2
136	A B	0.078	17.1	11.5	10.5	8.375	2.6 2.8	2.7	2.5 2.5	9.8	2	80	B2

[o] Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
112	A	66009	65995	133873	66937	83555	84730	99624	0.295	FB/SB
	B	77378	67878			97947			0.266	FB/SB
113	A	70689	65980	131758	65879	89479	83391	93920	-	SB/FP
	B	65778	65778			83263			0.0119	FB/SS
114	A	43063	43063	87150	43575	54510	55158	79122	-	FP
	B	44087	44087			55807			-	FP
115	A	77232	77232	156239	78120	97762	98885	114756	-	FB/SB
	B	79007	79007			100009			-	FB
116	A	96026	96026	190743	95372	121552	120724	96925	0.181	FP/SS/TK
	B	105140	94717			133089			-	FB/SS
117	A	69449	67892	136199	68099	87910	86202	71237	-	FP/SS
	B	68307	68307			86464			-	SS/FP
118	A	106184	89959	175417	87709	134410	111024	78398	-	SS
	B	85459	85459			108176			-	SS/FP
119	A	71216	70412	141302	70651	90146	89432	87415		SS/FP
	B	79405	70890			100512				SB
120	A	43697	43697	87690	43845	55313	55500	49234	0.144	SS/FP
	B	43993	43993			55687			0.156	SS/FP
121	A	55230	55088	111134	55567	69911	70338	61111	0.195	FP/SS
	B	71880	56046			90987			0.242	SS/FP
122	A	41170	41170	84069	42034	52114	53208	55217	0.133	FP
	B	42930	42899			54341			0.201	FP
123	A	61380	61380	120477	60238	77696	76251	67912		FP
	B	68385	59097			86563			0.434	FP/SS
124	A	37554	37554	74863	37431	47537	47381	52170	-	FP/SS
	B	48708	37309			61656			-	FP
125	A	45587	45587	92286	46143	57705	58409	52999	0.275	SS/FP
	B	50511	46699			63938			-	SS
126	A	49439	49439	98305	49152	62581	62218	69570	0.088	SS
	B	69415	48866			87867			0.096	SS
127	A	47587	47587	103651	51825	60236	65602	52614	0	FP
	B	56064	56064			70967			0.9	FP
128	A	52300	52300	106330	53165	66202	67297	51804		FP
	B	54030	54030			68392				FP
129	A	62777	62777	142967	71484	79465	90485	61379	-	FP/SB
	B	80190	80190			101506			-	FP/SS
130	A	74782	74782	150417	75208	94661	95201	98166	0.193	FB/SB
	B	92250	75635			116772			0.242	FP
131	A	58575	58145	118584	59292	74145	75053	56011	0.372	FP/SS
	B	60519	60439			76606			0.239	SS
132	A	63745	63689	127009	63504	80690	80385	70191	-	SS
	B	78050	63320			98797			-	FB/SS
133	A	90688	90688	179833	89916	114795	113818	125050	-	-
	B	89145	89145			112841			-	FB/SB
134	A	94588	75682	149617	74809	119731	94694	77429	-	FP/SS
	B	73936	73936			93589			-	FP/SS
135	A	73919	64891	129674	64837	93569	82072	64012	-	FP/SS
	B	64783	64783			82004			-	SS/FP
136	A	62525	59716	124467	62233	79145	78776	46535	-	SB
	B	65289	64750			82645			-	FP/SS

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
112	A B	60	-	-	-	-	-	-	-	0.50	2.25 (1.1)	-	-	3.16	60
113	A B	60	-	-	-	-	-	-	-	0.38	4.00 (2.0)	-	-	3.16	60
114	A B	60	-	-	-	-	-	-	-	0.38	4.00 (2.0)	-	-	3.78	60
115	A B	60	-	-	-	-	-	-	-	0.38	5.00 (2.5)	-	-	4.74	60
116	A B	60	-	-	-	-	1.10	10	3.0 (1.5)	0.38	3.50 (1.75)	0.375	1	3.78	60
117	A B	60	-	-	-	-	1.00	5	3.0 (1.5)	0.50	3.00 (1.5)	0.375	1	3.16	60
118	A B	60	-	-	-	-	1.10	10	3.0 (1.5)	0.38	3.50 (1.75)	0.375	2	3.16	60
119	A B	60	-	-	-	-	1.10	10	3.0 (1.5)	0.38	3.50 (1.75)	0.375	2	3.16	60
120	A B	60	-	-	-	-	1.60	8	4.0 (2.0)	0.50	1.75 (0.9)	-	-	3.16	60
121	A B	60	-	-	-	-	1.60	8	4.0 (2.5)	0.63	3.50 (1.75)	-	-	3.16	60
122	A B	60	-	-	-	-	1.60	8	4.0 (2.0)	0.50	1.50 (0.9)	-	-	3.16	60
123	A B	60	-	-	-	-	0.88	8	4.0 (2.0)	0.50	4.00 (2.0)	0.375	2	3.16	60
124	A B	60	-	-	-	-	1.60	8	4.0 (2.0)	0.50	1.75 (0.9)	-	-	3.16	60
125	A B	60	-	-	-	-	0.44	4	3.5 (1.75)	0.50	3.50 (1.75)	-	-	3.16	60
126	A B	60	-	-	-	-	0.44	4	3.5 (1.75)	0.50	3.50 (1.75)	-	-	3.16	60
127	A B	60	-	-	-	-	-	-	-	0.50	4.00 (1.5)	-	-	6.32	120
128	A B	60	-	-	-	-	-	-	-	0.50	4.00 (1.5)	-	-	6.32	120
129	A B	60	-	-	-	-	0.44	4	3.0 (2.0)	0.50	3.00 (1.5)	-	-	3.16	60
130	A B	60	-	-	-	-	-	-	-	0.50	2.25 (1.1)	-	-	3.16	60
131	A B	60	-	-	-	-	0.44	4	3.5 (1.75)	0.50	3.50 (1.75)	-	-	3.16	60
132	A B	60	-	-	-	-	0.44	4	3.5 (1.75)	0.50	3.50 (1.75)	-	-	3.16	60
133	A B	60	-	-	-	-	-	-	-	0.50	4.00 (2.0)	-	-	4.74	60
134	A B	60	0.38	0.11	1	7.50	2.00	10	3.0 (1.5)	0.50	3.00 (1.5)	-	-	3.16	60
135	A B	60	0.38	0.11	1	7.50	2.00	10	3.0 (1.5)	0.50	3.00 (1.5)	-	-	3.16	60
136	A B	60	0.38	0.11	1	7.50	2.00	10	3.0 (1.5)	0.50	3.00 (1.5)	-	-	3.16	60

[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
137	8-5-180-1#3-i-2.5-2-11	A B	180°	Para	A615	11.5 11.5	11.5	4300	6	1
138	8-5-180-1#3-i-2.5-2-14	A B	180°	Para	A1035[b]	14.8 15.0	14.9	4870	9	1
139	8-5-180-1#3-i-3.5-2-11	A B	180°	Para	A615	11.6 10.6	11.1	4550	7	1
140	8-5-180-1#3-i-3.5-2-14	A B	180°	Para	A1035[b]	15.6 14.5	15.1	4840	8	1
141	8-8-180-1#4-i-2.5-2-11.5	A B	180°	Para	A1035[b]	12.0 12.3	12.1	8740	12	1
142	8-5-90-2#3-i-2.5-2-16	A B	90°	Para	A1035[b]	15.0 15.8	15.4	4810	6	1
143	8-5-90-2#3-i-2.5-2-9.5	A B	90°	Para	A615	9.0 9.3	9.1	5140	8	1
144	8-5-90-2#3-i-2.5-2-12.5	A B	90°	Para	A615	12.0 12.0	12.0	5240	9	1
145	8-5-90-2#3-i-2.5-2-8.5	A B	90°	Para	A1035[c]	8.9 9.6	9.3	5240	6	1
146	8-5-90-2#3-i-2.5-2-14	A B	90°	Para	A1035[c]	13.5 14.0	13.8	5450	7	1
147	8-5-90-2#3-i-2.5-2-10	A B	90°	Para	A615	10.0 10.3	10.1	5920	13	1
148	(2d) 8-5-90-2#3-i-2.5-2-10	A B	90°	Para	A615	10.0 10.3	10.1	5920	12	1
149	(2@3) 8-5-90-2#3-i-2.5-2-10	A B	90°	Para	A615	10.0 10.5	10.3	4760	11	1
150	(2@5) 8-5-90-2#3-i-2.5-2-10	A B	90°	Para	A615	9.6 10.0	9.8	4760	11	1
151	8-8-90-2#3-i-2.5-2-8	A B	90°	Para	A1035[b]	8.0 8.5	8.3	7700	14	1
152	8-8-90-2#3-i-2.5-2-10	A B	90°	Para	A1035[b]	9.9 9.5	9.7	8990	17	1
153	8-12-90-2#3-i-2.5-2-9	A B	90°	Para	A1035[b]	9.0 9.0	9.0	11160	77	1
154	8-12-90-2#3-i-2.5-2-11	A B	90°	Para	A1035[c]	10.5 11.3	10.9	12010	42	1
155	8-12-90-2#3vr-i-2.5-2-11	A B	90°	Perp	A1035[c]	10.9 10.4	10.6	12010	42	1
156	8-15-90-2#3-i-2.5-2-6	A B	90°	Para	A1035[c]	5.8 6.4	6.1	15800	61	1
157	8-15-90-2#3-i-2.5-2-11	A B	90°	Para	A1035[c]	11.3 10.8	11.0	15800	61	1
158	8-5-90-2#3-i-3.5-2-17	A B	90°	Para	A1035[b]	17.5 17.0	17.3	5570	12	1
159	8-5-90-2#3-i-3.5-2-13	A B	90°	Para	A1035[b]	13.8 13.5	13.6	5560	11	1
160	8-8-90-2#3-i-3.5-2-8	A B	90°	Para	A1035[b]	8.0 8.1	8.1	8290	16	1
161	8-8-90-2#3-i-3.5-2-10	A B	90°	Para	A1035[b]	8.8 8.8	8.8	8990	17	1

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

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout[o]
137	A B	0.078	17.0	13.0	10.5	8.375	2.5 2.5	2.5	1.5 1.5	10.0	2	80	B2
138	A B	0.078	17.5	16.0	10.5	8.375	2.8 2.9	2.8	1.3 1.0	9.9	2	80	B2
139	A B	0.078	19.3	13.0	10.5	8.375	3.8 3.5	3.6	1.4 2.4	10.0	2	80	B2
140	A B	0.078	19.3	16.5	10.5	8.375	3.6 3.6	3.6	0.9 2.0	10.0	2	80	B2
141	A B	0.078	17.1	14.0	10.5	8.375	2.9 2.8	2.8	2.0 1.8	9.5	2	30	B2
142	A B	0.078	17.1	17.9	10.5	8.375	2.8 2.9	2.8	2.9 2.1	9.5	2	80	B2
143	A B	0.078	17.0	11.6	10.5	8.375	2.5 2.5	2.5	2.6 2.3	10.0	2	80	B2
144	A B	0.078	17.0	14.6	10.5	8.375	2.8 2.8	2.8	2.6 2.6	9.5	2	80	B2
145	A B	0.073	17.1	10.7	10.5	8.375	3.0 3.0	3.0	1.8 1.1	9.1	2	30	B2
146	A B	0.073	17.0	16.1	10.5	8.375	2.8 3.0	2.9	2.6 2.1	9.3	2	30	B2
147	A B	0.073	17.4	12.0	19.5	8.375	2.5 2.6	2.6	2.0 1.8	10.3	2	57	B17
148	A B	0.073	17.4	12.2	19.5	8.375	2.5 2.8	2.6	2.0 2.1	10.1	2	57	B17
149	A B	0.073	9.3	12.0	10.5	8.375	2.5 2.5	2.5	2.0 1.5	2.3	2	30	B2
150	A B	0.073	10.9	12.0	10.5	8.375	2.5 2.5	2.5	2.4 2.0	3.9	2	30	B2
151	A B	0.078	16.9	10.0	10.5	8.375	3.0 2.9	2.9	2.0 1.5	9.0	2	30	B2
152	A B	0.078	16.0	12.0	10.5	8.375	2.8 2.8	2.8	2.1 2.5	8.5	2	30	B2
153	A B	0.078	17.0	11.3	10.5	8.375	2.9 2.6	2.8	2.3 2.3	9.5	2	30	B2
154	A B	0.073	17.0	12.9	10.5	8.375	2.8 2.8	2.8	2.4 1.6	9.5	2	30	B2
155	A B	0.073	16.5	13.0	10.5	8.375	2.5 2.3	2.4	2.1 2.6	9.8	2	30	B2
156	A B	0.073	16.8	8.1	10.5	8.375	2.5 2.4	2.4	2.3 1.8	9.9	2	30	B11
157	A B	0.073	17.0	13.1	10.5	8.375	2.5 2.5	2.5	1.9 2.4	10.0	2	30	B11
158	A B	0.078	18.9	19.3	10.5	8.375	3.3 3.5	3.4	1.8 2.3	10.1	2	30	B2
159	A B	0.078	19.0	15.3	10.5	8.375	3.1 3.6	3.4	1.5 1.8	10.3	2	30	B2
160	A B	0.078	17.9	10.0	10.5	8.375	3.6 3.8	3.7	2.0 1.9	8.5	2	30	B2
161	A B	0.078	17.9	12.0	10.5	8.375	3.6 3.8	3.7	3.3 3.3	8.5	2	30	B2

[o] Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
137	A	57294	48342	99464	49732	72524	62952	53865	0.088	SS/FP
	B	68950	51122			87278			0.341	SS/FP
138	A	67269	67183	138043	69021	85150	87369	74147	-	SS/FP
	B	70909	70860			89758			0.123	FP/SS
139	A	62945	54681	110781	55390	79678	70114	53602	0.434	SS
	B	56154	56100			71082			0.216	SS
140	A	78657	75069	151988	75994	99565	96195	74850	0.232	SS/FP
	B	76919	76919			97366			0.227	SS/FP
141	A	72047	71987	144462	72231	91199	91432	80967	-	FP/SS
	B	72506	72475			91780			.(0.013)	FP/SS
142	A	80014	79629	159258	79629	101284	100796	76166	-	SS/FP
	B	92780	79629			117443			-	FP
143	A	54916	53621	107242	53621	69513	67874	46729	-	FP
	B	53621	53621			67874			-	FP
144	A	74108	67801	144135	72067	93808	91225	62047	-	FP
	B	76334	76334			96625			-	FP/SS
145	A	52863	52862	101122	50561	66915	64001	47828		FP/SS
	B	48439	48260			61315				SS
146	A	76959	76388	153927	76964	97416	97422	72506		SS/FP
	B	77540	77540			98151				FP/SS
147	A	55820	55820	112405	56203	70659	71143	55645		FP/SS
	B	56628	56585			71681			-	FP/SS
148	A	45802	45802	91160	45580	57977	57696	55645		SS
	B	45358	45358			57415			-	SS
149	A	58584	58435	93619	46810	74157	59253	50513		FP
	B	47051	35184			59558			-	FP
150	A	48430	48412	97029	48515	61303	61411	48357	0.23	FB
	B	48617	48617			61541			0.108	FB
151	A	46211	46211	95751	47876	58495	60602	51710	-	FP/SS
	B	55377	49540			70098			-	FP/SS
152	A	60670	60670	122047	61024	76797	77245	65609	0.186	FP
	B	67001	61378			84812			0.152	FB
153	A	61813	61813	122026	61013	78244	77232	67912	0.345	FP/SS
	B	60251	60213			76267			0.361	SS/FP
154	A	68128	68101	137365	68683	86237	86940	85128	0.181	FP
	B	79794	69264			101004			0.165	FP
155	A	50709	50709	105346	52673	64188	66674	83171	-	FP/SS
	B	66830	54637			84595			0.13	FP
156	A	37450	37450	75138	37569	47405	47556	54712	-	FP
	B	37689	37689			47707			-	FP
157	A	99011	83072	166640	83320	125330	105468	98763	-	FB
	B	83603	83567			105827			0.123	FB
158	A	102613	91402	179829	89914	129889	113816	91958	-	SS
	B	88572	88426			112117			-	SS/FP
159	A	81199	81199	160720	80360	102783	101722	72568	-	SS/FP
	B	86858	79522			109946			-	SS/FP
160	A	48324	48324	97545	48773	61169	61738	52435	0.31	FP
	B	49258	49222			62352			.340(.147)	FP
161	A	53960	53960	107770	53885	68304	68209	59260	-	SS
	B	53810	53810			68113			-	FP

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
137	A B	60	0.38	0.11	1	3.50	0.44	4	4.5 (1.1)	0.50	3.50 (1.75)	-	-	3.16	60
138	A B	60	0.38	0.11	1	3.50	0.44	4	4.5 (1.1)	0.50	3.50 (1.75)	-	-	3.16	60
139	A B	60	0.38	0.11	1	3.50	0.44	4	4.5 (1.1)	0.50	3.50 (1.75)	-	-	3.16	60
140	A B	60	0.38	0.11	1	3.50	0.44	4	4.5 (1.1)	0.50	3.50 (1.75)	-	-	3.16	60
141	A B	60	0.5	0.20	1	3.00	0.44	4	3.0 (2.0)	0.50	3.00 (1.5)	-	-	3.16	60
142	A B	60	0.38	0.11	2	3.00 (4.5)	2.00	10	3.0 (1.5)	0.50	3.00 (1.5)	-	-	3.16	60
143	A B	60	0.38	0.11	2	3.00 (4.5)	2.00	10	3.0 (1.5)	0.50	3.00 (1.5)	-	-	3.16	60
144	A B	60	0.38	0.11	2	3.00 (4.5)	2.00	10	3.0 (1.5)	0.50	3.00 (1.5)	-	-	3.16	60
145	A B	60	0.38	0.11	2	7.50 (3.0)	2.00	10	2.5 (1.3)	0.50	3.25 (1.5)	0.5	1	3.16	60
146	A B	60	0.38	0.11	2	6.00 (3.0)	0.88	8	3.0 (1.5)	0.50	3.50 (1.75)	0.5	1	3.16	60
147	A B	60	0.38	0.11	2	8.00	-	-	-	0.50	4.00 (2.0)	-	-	4.34	120
148	A B	60	0.38	0.11	2	8.00	-	-	-	0.50	4.00 (2.0)	-	-	4.34	120
149	A B	60	0.38	0.11	2	8.00 (3.0)	-	-	-	0.38	4.00 (1.5)	-	-	3.16	120
150	A B	60	0.38	0.11	2	8.00 (3.0)	-	-	-	0.38	5.00 (1.5)	-	-	3.16	120
151	A B	60	0.38	0.11	2	7.13 (5.5)	1.20	6	4.0 (4.0)	0.50	1.50 (0.9)	-	-	3.16	60
152	A B	60	0.38	0.11	2	7.13 (5.5)	1.20	6	4.0 (4.0)	0.63	3.50 (0.9)	-	-	3.16	60
153	A B	60	0.38	0.11	2	8.00 (3.5)	0.88	8	4.0 (2.0)	0.50	4.00 (2.0)	0.375	2	3.16	60
154	A B	60	0.38	0.11	2	8.00	-	-	-	0.50	2.00 (1.0)	-	-	3.16	60
155	A B	60	0.38	0.11	2	2.67	-	-	-	0.50	2.00 (1.0)	-	-	3.16	60
156	A B	60	0.38	0.11	2	6.00 (4.5)	-	-	-	0.38	2.75 (1.4)	-	-	6.32	60
157	A B	60	0.38	0.11	2	5.50 (5.0)	-	-	-	0.38	4.00 (2.0)	-	-	6.32	60
158	A B	60	0.38	0.11	2	8.00	0.80	4	4.0 (2.0)	0.50	4.00 (2.0)	0.375	1	3.16	60
159	A B	60	0.38	0.11	2	8.00	0.44	4	4.0 (2.0)	0.50	3.00 (1.5)	-	-	3.16	60
160	A B	60	0.38	0.11	2	7.13 (5.5)	1.20	6	4.0 (4.0)	0.50	1.50 (0.9)	-	-	3.16	60
161	A B	60	0.38	0.11	2	7.13 (5.5)	1.20	6	4.0 (4.0)	0.63	3.50 (0.9)	-	-	3.16	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
162	8-12-90-2#3-i-3.5-2-9	A B	90°	Para	A1035[b]	9.0 9.0	9.0	11160	77	1
163	8-5-180-2#3-i-2.5-2-11	A B	180°	Para	A615	10.8 10.5	10.6	4550	7	1
164	8-5-180-2#3-i-2.5-2-14	A B	180°	Para	A1035[b]	13.5 14.0	13.8	4870	9	1
165	(2@3) 8-5-180-2#3-i-2.5-2-10	A B	180°	Para	A615	10.3 10.3	10.3	5400	16	1
166	(2@5) 8-5-180-2#3-i-2.5-2-10	A B	180°	Para	A615	10.3 9.8	10.0	5400	16	1
167	8-8-180-2#3-i-2.5-2-11.5	A B	180°	Para	A1035[b]	10.5 10.3	10.4	8810	14	1
168	8-12-180-2#3-i-2.5-2-11	A B	180°	Para	A1035[c]	11.1 10.4	10.8	12010	42	1
169	8-12-180-2#3vr-i-2.5-2-11	A B	180°	Perp	A1035[b]	10.9 10.9	10.9	12010	42	1
170	8-5-180-2#3-i-3.5-2-11	A B	180°	Para	A1035[b]	10.1 10.6	10.4	4300	6	1
171	8-5-180-2#3-i-3.5-2-14	A B	180°	Para	A1035[b]	13.5 13.6	13.6	4870	9	1
172	8-15-180-2#3-i-2.5-2-11	A B	180°	Para	A1035[b]	11.1 11.1	11.1	15550	87	1
173	8-8-90-2#4-i-2.5-2-10	A B	90°	Para	A1035[b]	8.5 9.3	8.9	8290	16	1
174	8-8-90-2#4-i-3.5-2-10	A B	90°	Para	A1035[b]	9.0 9.8	9.4	8290	16	1
175	8-5-90-4#3-i-2.5-2-16	B A	90°	Para	A1035[b]	16.0 16.3	16.1	4810	6	1
176	8-5-90-4#3-i-2.5-2-12.5	A B	90°	Para	A1035[b]	11.9 11.9	11.9	4980	7	1
177	8-5-90-4#3-i-2.5-2-9.5	A B	90°	Para	A615	9.5 9.5	9.5	5140	8	1
178	8-5-90-5#3-o-2.5-2-10a	A B	90°	Para	A1035[a]	10.3 10.5	10.4	5270	7	1
179	8-5-90-5#3-o-2.5-2-10b	A B	90°	Para	A1035[a]	10.5 10.5	10.5	5440	8	1
180	8-5-90-5#3-o-2.5-2-10c	A B	90°	Para	A1035[a]	11.3 10.5	10.9	5650	9	1
181	8-8-90-5#3-o-2.5-2-8	A B	90°	Para	A1035[b]	8.3 8.8	8.5	8630	11	1
182	8-8-90-5#3-o-3.5-2-8	A B	90°	Para	A1035[b]	7.8 8.0	7.9	8810	14	1
183	8-8-90-5#3-o-4-2-8	A B	90°	Para	A1035[b]	8.5 8.0	8.3	8740	12	1
184	8-5-90-5#3-i-2.5-2-10b	A B	90°	Para	A1035[a]	10.3 10.5	10.4	5440	8	1
185	8-5-90-5#3-i-2.5-2-10c	A B	90°	Para	A1035[a]	10.5 10.5	10.5	5650	9	1
186	8-5-90-5#3-i-2.5-2-15	A B	90°	Para	A1035[b]	15.3 15.8	15.5	4850	7	1

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

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout[o]
162	A B	0.078	19.3	11.3	10.5	8.375	3.6 4.0	3.8	2.3 2.4	9.6	2	30	B2
163	A B	0.078	16.8	13.0	10.5	8.375	2.8 2.5	2.6	2.3 2.5	9.5	2	80	B2
164	A B	0.078	17.3	16.0	10.5	8.375	2.8 2.8	2.8	2.5 2.0	9.8	2	80	B2
165	A B	0.073	9.0	12.0	10.5	8.375	2.5 2.5	2.5	1.8 1.8	2.0	2	30	B10
166	A B	0.073	11.0	12.0	10.5	8.375	2.5 2.5	2.5	1.8 2.3	4.0	2	30	B10
167	A B	0.078	17.5	12.8	10.5	8.375	2.8 2.8	2.8	2.3 2.5	10.0	2	30	B2
168	A B	0.073	16.8	13.2	10.5	8.375	2.5 2.6	2.6	2.1 2.8	9.6	2	30	B2
169	A B	0.073	17.1	13.3	10.5	8.375	2.8 2.6	2.7	2.4 2.4	9.8	2	30	B2
170	A B	0.078	18.6	13.0	10.5	8.375	3.4 3.5	3.4	2.9 2.4	9.8	2	80	B2
171	A B	0.078	19.1	16.0	10.5	8.375	3.6 3.8	3.7	2.5 2.4	9.8	2	80	B2
172	A B	0.073	17.3	13.1	10.5	8.375	2.8 2.8	2.8	2.1 2.0	9.8	2	30	B7
173	A B	0.078	17.3	12.0	10.5	8.375	3.0 3.0	3.0	3.5 2.8	9.3	2	30	B2
174	A B	0.078	18.8	12.0	10.5	8.375	3.8 3.9	3.8	3.0 2.3	9.1	2	30	B2
175	B A	0.078	17.3	17.9	10.5	8.375	2.8 3.0	2.9	1.9 1.6	9.5	2	80	B2
176	A B	0.078	17.0	13.9	10.5	8.375	2.5 2.5	2.5	2.0 2.0	10.0	2	80	B2
177	A B	0.078	17.1	11.5	10.5	8.375	2.8 2.9	2.8	2.0 2.0	9.5	2	80	B2
178	A B	0.084	17.1	12.3	10.5	8.375	2.6 2.6	2.6	1.8 2.0	9.9	2	80	B2
179	A B	0.084	17.0	12.5	10.5	8.375	2.5 2.6	2.6	2.0 2.0	9.9	2	80	B2
180	A B	0.084	17.0	12.5	10.5	8.375	2.6 2.5	2.6	1.3 2.0	9.9	2	80	B2
181	A B	0.078	16.8	10.0	10.5	8.375	2.8 2.8	2.8	1.8 1.3	9.3	2	30	B2
182	A B	0.078	18.5	10.0	10.5	8.375	3.5 3.5	3.5	2.3 2.0	9.5	2	30	B2
183	A B	0.078	20.4	10.0	10.5	8.375	3.9 4.5	4.2	1.5 2.0	10.0	2	30	B2
184	A B	0.084	17.3	12.3	10.5	8.375	2.8 2.6	2.7	2.0 1.8	9.9	2	80	B2
185	A B	0.084	17.0	12.5	10.5	8.375	2.5 2.5	2.5	2.0 2.0	10.0	2	80	B2
186	A B	0.078	17.1	17.2	10.5	8.375	2.8 2.5	2.6	1.9 1.4	9.9	2	30	B2

[o] Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
162	A B	50266 49289	50266 49289	99555	49777	63628 62391	63009	67912	0.15	FP/SS FP/SS
163	A B	64232 61892	58650 61819	120469	60235	81306 78345	76246	51193	0.26 0.087	SS/FP SS/FP
164	A B	87080 76851	75744 76814	152558	76279	110228 97279	96556	68539	0.774 0.199	FP FP/SS
165	A B	57472 58835	57188 58114	115302	57651	72749 74474	72976	53801	 0.288	FP FP
166	A B	63698 60130	63640 60130	123770	61885	80630 76114	78335	52489	 0.263	FB FB
167	A B	70102 59494	56934 59408	116343	58171	88737 75309	73635	69558	0.261 .25(.027)	FB/SS FP/SS
168	A B	73700 66200	63140 66170	129310	64655	93291 83797	81842	84150	- -	FP FB
169	A B	67136 87053	67136 64423	131559	65780	84983 110194	83265	85128	- 0.369	SS/FP FB/SB
170	A B	57158 54943	56965 54772	111737	55869	72352 69548	70720	48595	0.167 0.212	SS/FP SS/FP
171	A B	68293 90408	68293 58642	126934	63467	86446 114441	80338	67605	- -	FP/SS FP/SS
172	A B	79626 78291	79553 78291	157845	78922	100792 99103	99902	98813	- -	FB/SS FP
173	A B	61367 71322	61286 61434	122721	61360	77680 90281	77671	57719	0.171 .285(.129)	FP/SS FP/SS
174	A B	69451 69474	69451 69474	138925	69463	87913 87942	87927	60971	0.26 .181(.104)	SS/FP FP/SS
175	B A	91801 97200	91801 89056	180857	90429	116204 123038	114467	79881	- -	FP/SS FP/SS
176	A B	83079 68634	68532 68634	137165	68583	105164 86878	86814	59883	- -	FP FP
177	A B	63275 54846	55094 54733	109827	54914	80094 69425	69511	48649	- -	FP FP/SS
178	A B	55700 55774	53308 55206	108513	54257	70507 70601	68679	67247	- 0.213	SS SB
179	A B	66444 69470	61714 69470	131183	65592	84107 87936	83027	69147	0.203 0.235	FP/SB SB/FP
180	A B	80648 58800	80648 58340	138988	69494	102086 74430	87967	72985	- -	SS/FP SS/FP
181	A B	56092 66796	56092 59870	115962	57981	71002 84551	73394	70503	0.253 .237(.033)	FP/SS FB/SS
182	A B	53926 56134	53865 56048	109914	54957	68261 71055	69566	65996	- .251(.249)	FP FP/SS
183	A B	39553 41461	39553 38589	78142	39071	50067 52483	49457	68864	0.388 0.754	SS/FP FP
184	A B	78824 66728	75418 64012	139430	69715	99777 84466	88247	68323	0.129 -	FP/SS FP
185	A B	68947 69633	68071 69604	137674	68837	87275 88143	87136	70469	- -	FP/SS FP/SS
186	A B	77125 72603	74150 72603	146753	73377	97627 91903	92882	96574	0.196 -	FP/SS FP/SS

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
162	A B	60	0.38	0.11	2	8.00 (3.5)	0.88	8	4.0 (2.0)	0.50	4.00 (2.0)	0.375	2	3.16	60
163	A B	60	0.38	0.11	2	3.50 (1.7)	-	-	-	0.50	3.50 (1.75)	-	-	3.16	60
164	A B	60	0.38	0.11	2	3.50 (1.7)	-	-	-	0.50	3.50 (1.75)	-	-	3.16	60
165	A B	60	0.38	0.11	2	8.00 (3.0)	-	-	-	0.50	4.00 (1.5)	-	-	6.32	120
166	A B	60	0.38	0.11	2	8.00 (3.0)	-	-	-	0.50	4.00 (1.5)	-	-	6.32	120
167	A B	60	0.38	0.11	2	3.00 (2.0)	-	-	-	0.50	3.00 (1.5)	-	-	3.16	60
168	A B	60	0.38	0.11	2	8.00 (1.7)	-	-	-	0.50	2.00 (1.0)	-	-	3.16	60
169	A B	60	0.38	0.11	2	2.67	-	-	-	0.50	2.00 (1.0)	-	-	3.16	60
170	A B	60	0.38	0.11	2	3.50 (1.7)	-	-	-	0.50	3.50 (1.75)	-	-	3.16	60
171	A B	60	0.38	0.11	2	3.50 (1.7)	-	-	-	0.50	3.50 (1.75)	-	-	3.16	60
172	A B	60	0.38	0.11	2	5.00 (5.0)	-	-	-	0.50	4.00 (2.0)	-	-	4.74	60
173	A B	60	0.5	0.20	2	7.13 (2.0)	1.20	6	4.0 (4.0)	0.50	2.00 (1.2)	-	-	3.16	60
174	A B	60	0.5	0.20	2	7.13 (2.0)	1.20	6	4.0 (4.0)	0.50	2.00 (1.2)	-	-	3.16	60
175	B A	60	0.38	0.11	4	3.00 (1.5)	2.00	10	3.0 (1.5)	0.50	3.00 (1.5)	-	-	3.16	60
176	A B	60	0.38	0.11	4	3.00 (1.5)	2.00	10	3.0 (1.5)	0.50	3.00 (1.5)	-	-	3.16	60
177	A B	60	0.38	0.11	4	3.00 (1.5)	2.00	10	3.0 (1.5)	0.50	3.00 (1.5)	-	-	3.16	60
178	A B	60	0.38	0.11	5	3.00 (1.5)	1.10	10	3.0 (1.5)	0.63	3.50 (1.75)	-	-	3.16	60
179	A B	60	0.38	0.11	5	3.00 (1.5)	1.10	10	3.0 (1.5)	0.63	3.50 (1.75)	-	-	3.16	60
180	A B	60	0.38	0.11	5	3.00 (1.5)	1.10	10	3.0 (1.5)	0.63	3.50 (1.75)	-	-	3.16	60
181	A B	60	0.38	0.11	5	3.00 (0.9)	2.00	10	3.0 (2.3)	0.50	1.75 (0.9)	-	-	3.16	60
182	A B	60	0.38	0.11	5	3.00 (0.9)	2.00	10	3.0 (2.3)	0.50	1.75 (0.9)	-	-	3.16	60
183	A B	60	0.38	0.11	5	3.00 (0.9)	2.00	10	3.0 (2.3)	0.50	1.75 (0.9)	-	-	3.16	60
184	A B	60	0.38	0.11	5	3.00 (1.5)	1.10	10	3.0 (1.5)	0.63	3.50 (1.75)	-	-	3.16	60
185	A B	60	0.38	0.11	5	3.00 (1.5)	1.10	10	3.0	0.63	3.50 (1.75)	-	-	3.16	60
186	A B	60	0.38	0.11	5	3.00 (1.5)	0.55	5	3.0 (1.5)	0.38	3.50 (1.75)	0.375	2	3.16	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
187	8-5-90-5#3-i-2.5-2-13	A B	90°	Para	A1035[b]	13.8 13.5	13.6	5560	11	1
188	8-5-90-5#3-i-2.5-2-12(1)	A B	90°	Para	A1035[c]	11.5 11.1	11.3	5090	7	1
189	8-5-90-5#3-i-2.5-2-12	A B	90°	Para	A1035[c]	11.3 12.3	11.8	5960	7	1
190	8-5-90-5#3-i-2.5-2-12(2)	A B	90°	Para	A1035[c]	12.4 12.0	12.2	5240	6	1
191	8-5-90-5#3-i-2.5-2-8	A B	90°	Para	A1035[c]	7.8 7.4	7.6	5240	6	1
192	8-5-90-5#3-i-2.5-2-10a	B	90°	Para	A1035[a]	10.5	10.5	5270	7	1
193	8-5-90-5#3-i-2.5-2-10	A B	90°	Para	A1035[c]	10.0 9.3	9.6	5920	13	1
194	(2d) 8-5-90-5#3-i-2.5-2-10	A B	90°	Para	A615	9.9 10.0	9.9	5920	14	1
195	(2d) 8-5-90-9#3-i-2.5-2-10	A B	90°	Para	A1035	10.3 10.0	10.1	5920	17	1
196	(2@3) 8-5-90-5#3-i-2.5-2-10	A B	90°	Para	A615	10.0 10.5	10.3	4810	12	1
197	(2@5) 8-5-90-5#3-i-2.5-2-10	A B	90°	Para	A615	9.9 9.5	9.7	4810	12	1
198	8-8-90-5#3-i-2.5-2-8	A B	90°	Para	A1035[b]	7.3 7.3	7.3	8290	16	1
199	8-8-90-5#3-i-2.5-2-9	A B	90°	Para	A615	8.6 9.0	8.8	7710	25	1
200	8-8-90-5#3-i-2.5-9-9	A B	90°	Para	A615	9.0 9.3	9.1	7710	25	1
201	(2@3) 8-8-90-5#3-i-2.5-9-9	A B	90°	Para	A615	9.3 9.5	9.4	7440	22	1
202	(2@4) 8-8-90-5#3-i-2.5-9-9	A B	90°	Para	A615	8.9 9.1	9.0	7440	22	1
203	8-12-90-5#3-i-2.5-2-9	A B	90°	Para	A1035[b]	9.0 9.0	9.0	11160	77	1
204	8-12-90-5#3-i-2.5-2-10	A B	90°	Para	A1035[c]	9.0 9.9	9.4	11800	38	1
205	8-12-90-5#3-i-2.5-2-12	A B	90°	Para	A1035[c]	12.2 12.3	12.2	11760	34	1
206	8-12-90-5#3vr-i-2.5-2-10	A B	90°	Perp	A1035[c]	10.3 10.2	10.2	11800	38	1
207	8-12-90-4#3vr-i-2.5-2-10	A B	90°	Perp	A1035[c]	10.6 10.3	10.4	11850	39	1
208	8-15-90-5#3-i-2.5-2-6	A B	90°	Para	A1035[c]	6.5 6.1	6.3	15800	60	1
209	8-15-90-5#3-i-2.5-2-10	A B	90°	Para	A1035[c]	10.6 9.7	10.1	15800	60	1
210	8-5-90-5#3-i-3.5-2-15	A B	90°	Para	A1035[b]	15.8 15.8	15.8	4850	7	1
211	8-5-90-5#3-i-3.5-2-13	A B	90°	Para	A1035[b]	13.3 13.0	13.1	5570	12	1

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

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout[o]
187	A B	0.078	17.1	15.3	10.5	8.375	2.5 2.4	2.4	1.5 1.8	10.3	2	30	B2
188	A B	0.073	16.8	14.1	10.5	8.375	2.5 2.5	2.5	2.6 3.0	9.8	2	30	B2
189	A B	0.073	16.6	14.3	10.5	8.375	2.5 2.4	2.4	3.0 2.0	9.8	2	30	B2
190	A B	0.073	16.1	14.1	10.5	8.375	2.5 2.6	2.6	1.8 2.1	9.0	2	30	B2
191	A B	0.073	16.6	10.3	10.5	8.375	2.8 2.9	2.8	2.6 2.9	9.0	2	30	B2
192	B	0.08	17	12.3	10.5	8.375	2.5	2.5	1.8	9.8	2	80	B2
193	A B	0.073	17.5	12.2	19.5	8.375	2.5 2.8	2.6	2.2 2.9	10.3	2	57	B17
194	A B	0.073	18.0	12.1	19.5	8.375	2.8 3.0	2.9	2.1 2.3	10.3	2	57	B17
195	A B	0.073	17.5	12.4	19.5	8.375	2.5 2.8	2.6	2.3 2.3	10.3	2	57	B17
196	A B	0.073	9.2	12.0	10.5	8.375	2.4 2.8	2.6	2.0 1.5	2.0	2	30	B2
197	A B	0.073	10.9	12.0	10.5	8.375	2.3 2.4	2.3	2.1 2.5	4.3	2	30	B2
198	A B	0.078	16.1	10.0	10.5	8.375	2.9 2.8	2.8	2.8 2.8	8.5	2	30	B2
199	A B	0.073	17.8	11.0	10.5	8.375	2.8 3.3	3.0	2.4 2.0	9.8	2	30	B2
200	A B	0.073	17.3	18.0	10.5	8.375	2.5 2.8	2.6	9.0 8.8	10.0	2	30	B7
201	A B	0.073	9.0	18.0	10.5	8.375	2.5 2.5	2.5	8.8 8.5	2.0	2	30	B7
202	A B	0.073	10.3	18.0	10.5	8.375	2.5 2.5	2.5	9.1 8.9	3.3	2	30	B7
203	A B	0.078	16.6	11.5	10.5	8.375	2.5 2.6	2.6	2.5 2.5	9.5	2	30	B2
204	A B	0.073	16.8	12.2	10.5	8.375	2.6 2.3	2.4	3.2 2.3	9.9	2	30	B2
205	A B	0.073	16.9	14.2	10.5	8.375	2.4 2.5	2.4	2.0 1.9	10.0	2	30	B2
206	A B	0.073	16.6	11.9	10.5	8.375	2.5 2.4	2.4	1.7 1.7	9.8	2	30	B2
207	A B	0.073	16.0	12.4	10.5	8.375	2.5 2.5	2.5	1.8 2.1	9.0	2	30	B2
208	A B	0.073	17.0	8.3	10.5	8.375	2.6 2.6	2.6	1.8 2.2	9.8	2	30	B11
209	A B	0.073	16.7	12.1	10.5	8.375	2.4 2.4	2.4	1.6 2.4	9.9	2	30	B11
210	A B	0.078	19.3	17.0	10.5	8.375	3.6 3.5	3.5	1.3 1.3	10.3	2	30	B2
211	A B	0.078	19.3	15.4	10.5	8.375	3.4 3.5	3.4	2.1 2.4	10.4	2	30	B2

[o] Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
187	A B	93116 81340	83412 81340	164752	82376	117868 102962	104273	90710	- -	SS/FP FP/SS
188	A B	66726 75878	66726 66001	132727	66363	84463 96048	84004	72061	- -	SS/FP SS/FP
189	A B	84900 72000	* 72000	72000	72000	107468 91139	91139	80992		SS SS
190	A B	72359 77425	72321 70619	142939	71470	91593 98006	90468	78770		FP/SS FP/SS
191	A B	48024 47008	47948 47008	94956	47478	60790 59503	60099	48878	 0.321	FP FP
192	B	82800	82800	82800	82800	104800	104800	68100	0.164	FP/SS
193	A B	70403 70390	70322 70390	140712	70356	89118 89102	89058	66122		FP/SS FP/SS
194	A B	54654 54816	54654 54816	109469	54735	69182 69387	69284	68286		FB/SS FB/SS
195	A B	54261 55261	54261 55261	109522	54761	68685 69951	69318	55645		FB/SS FB/SS
196	A B	61451 58224	57620 58224	115845	57922	77787 73702	73319	63438	0.05 0.37	FB/SS FB/SS
197	A B	59715 52232	59715 52205	111921	55960	75589 66116	70836	59957	0.12 0.29	FB FB
198	A B	56006 51206	49326 51206	100532	50266	70893 64818	63628	58938	0.3 .375 (.092)	FP FP
199	A B	64834 64027	64834 63961	128795	64397	82068 81047	81516	69089	 0	FB FB
200	A B	61960 65209	61894 64703	126597	63298	78431 82543	80125	71539	0.05 0	FB FB
201	A B	56456 61169	56420 61165	117585	58792	71463 77430	74421	72200	0.082 -	FP FP
202	A B	55664 59345	55603 59307	114911	57455	70461 75120	72728	69312	0.117 0	FB FB
203	A B	66512 63119	66512 62994	129507	64753	84193 79897	81966	84890	0.224 0.252	FP/SS FP/SS
204	A B	66000 64599	64479 64582	129061	64530	83544 81771	81684	91533	0.44 0.547	FB/SS SS/FP
205	A B	90544 86469	88954 86469	175422	87711	114613 109454	111027	118308	- -	FB/SS SS/FP
206	A B	59428 64145	59428 61011	120439	60219	75225 81196	76227	99111	0.236 0.246	FP FP
207	A B	80288 59267	59214 59267	118481	59241	101630 75021	74988	81157	0.123 0.101	FP/SS FP
208	A B	48315 48683	48315 48683	96998	48499	61158 61624	61391	70845	- -	FP FP
209	A B	111610 90223	89783 90223	180007	90003	141278 114207	113928	113633	- 0.407	FB/SS FB/SS
210	A B	81187 87144	81187 79494	160681	80341	102768 110309	101697	97934	.214(.026) -	SS/FP SS/FP
211	A B	89620 75971	78290 75847	154137	77069	113443 96166	97555	87460	- -	SS SS/FP

*Data not available

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
187	A B	60	0.38	0.11	5	3.00 (1.5)	1.00	5	3.0 (1.5)	0.50	3.00 (1.5)	0.375	1	3.16	60
188	A B	60	0.38	0.11	5	3.00 (1.5)	0.55	5	3.0 (1.5)	0.38	3.50 (1.750	0.5	2	3.16	60
189	A B	60	0.38	0.11	5	3.00 (1.5)	0.55	5	3.0 (1.5)	0.38	3.50 (1.75)	0.5	2	3.16	60
190	A B	60	0.38	0.11	5	3.00 (1.5)	0.55	5	3.0 (1.5)	0.38	3.50 (1.75)	0.375	1	3.16	60
191	A B	60	0.38	0.11	5	3.00 (1.5)	1.55	5	3.0 (1.5)	0.50	3.00 (1.5)	0.5	1	3.16	60
192	B	60	0.375	0.11	5	3.0 (1.5)	1.10	10	3.0 (1.5)	0.63	3.50 (1.75)	-	-	3.16	60
193	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.50	4.00 (2.0)	-	-	4.34	120
194	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.50	4.00 (2.0)	-	-	4.34	120
195	A B	60	0.38	0.11	9	3.00 (1.5)	-	-	-	0.50	4.00 (2.0)	-	-	4.34	120
196	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.38	4.00 (1.5)	-	-	3.16	120
197	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.38	4.00 (1.5)	-	-	3.16	120
198	A B	60	0.38	0.11	5	3.00 (0.9)	1.20	6	4.0 (3.5)	0.50	1.50 (0.9)	-	-	3.16	60
199	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.38	4.00 (2.5)	-	-	3.16	120
200	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.38	4.00 (2.5)	-	-	4.74	120
201	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.38	4.00 (2.5)	-	-	4.74	60
202	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.38	4.00 (2.5)	-	-	4.74	60
203	A B	60	0.38	0.11	5	3.00 (1.5)	0.88	8	4.0 (2.0)	0.50	4.00 (2.0)	0.375	2	3.16	60
204	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.50	1.75 (1.0)	-	-	3.16	60
205	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.38	4.00 (2.0)	-	-	3.16	120
206	A B	60	0.38	0.11	5	1.75	-	-	-	0.50	1.75 (1.0)	-	-	3.16	60
207	A B	60	0.38	0.11	4	2.25	-	-	-	0.50	1.75 (1.0)	-	-	3.16	60
208	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.38	2.75 (1.4)	-	-	6.32	60
209	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.38	3.00 (1.5)	-	-	6.32	60
210	A B	60	0.38	0.11	5	3.00 (1.5)	0.55	5	3.0 (1.5)	0.38	3.50 (1.75)	0.375	2	3.16	60
211	A B	60	0.38	0.11	5	3.00 (1.5)	1.00	5	3.0 (1.5)	0.50	3.00 (1.5)	0.375	1	3.16	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
212	8-5-90-5#3-i-3.5-2-12(1)	A B	90°	Para	A1035[c]	12.8 12.3	12.5	5090	7	1
213	8-5-90-5#3-i-3.5-2-12	A B	90°	Para	A1035[c]	12.5 11.8	12.1	6440	9	1
214	8-8-90-5#3-i-3.5-2-8	A B	90°	Para	A1035[b]	8.0 8.0	8.0	7910	15	1
215	8-12-90-5#3-i-3.5-2-9*	A B	90°	Para	A1035[b]	9.0 9.0	9.0	11160	77	1
216	(2@5) 8-5-180-5#3-i-2.5-2-10	A B	180°	Para	A615	10.0 10.3	10.1	5540	17	1
217	8-12-180-5#3-i-2.5-2-10	A B	180°	Para	A1035[c]	9.9 9.6	9.8	11800	38	1
218	8-12-180-5#3vr-i-2.5-2-10	A B	180°	Perp	A1035[c]	11.1 10.5	10.8	11800	38	1
219	8-12-180-4#3vr-i-2.5-2-10	A B	180°	Perp	A1035[c]	10.5 10.0	10.3	11850	39	1
220	8-15-180-5#3-i-2.5-2-9.5	A B	180°	Para	A1035[c]	9.6 9.8	9.7	15550	87	1
221	8-5-90-4#4s-i-2.5-2-15	A B	90°	Para	A1035[b]	15.6 15.6	15.6	4810	6	1
222	8-5-90-4#4s-i-2.5-2-12(1)	A B	90°	Para	A1035[c]	12.3 12.5	12.4	5180	8	1
223	8-5-90-4#4s-i-2.5-2-12	A B	90°	Para	A1035[c]	12.0 12.6	12.3	6210	8	1
224	8-5-90-4#4s-i-3.5-2-15	A B	90°	Para	A1035[b]	15.5 15.1	15.3	4810	6	1
225	8-5-90-4#4s-i-3.5-2-12(1)	A B	90°	Para	A1035[c]	12.0 11.9	11.9	5910	14	1
226	8-5-90-4#4s-i-3.5-2-12	A B	90°	Para	A1035[c]	12.0 12.5	12.3	5960	7	1

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

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout[o]
212	A B	0.073	18.7	14.3	10.5	8.375	3.5 3.4	3.5	1.6 2.1	9.8	2	30	B2
213	A B	0.073	18.6	14.2	10.5	8.375	3.4 3.5	3.4	1.7 2.4	9.8	2	30	B2
214	A B	0.078	18.0	10.0	10.5	8.375	3.5 3.6	3.6	2.0 2.0	8.9	2	30	B2
215	A B	0.078	18.1	11.5	10.5	8.375	3.3 3.4	3.3	2.5 2.5	9.5	2	30	B2
216	A B	0.073	11.0	12.0	10.5	8.375	2.5 2.5	2.5	2.0 1.8	4.0	2	30	B10
217	A B	0.073	16.9	12.2	10.5	8.375	2.3 2.8	2.5	2.3 2.6	9.9	2	30	B2
218	A B	0.073	16.8	12.4	10.5	8.375	2.5 2.5	2.5	1.3 1.9	9.8	2	30	B2
219	A B	0.073	17.0	12.3	10.5	8.375	2.8 2.5	2.6	1.8 2.3	9.8	2	30	B2
220	A B	0.073	17.3	11.7	10.5	8.375	2.5 2.8	2.6	2.1 1.9	10.0	2	30	B10
221	A B	0.078	17.0	17.3	10.5	8.375	3.0 2.9	2.9	1.6 1.6	9.1	2	30	B2
222	A B	0.073	17.1	14.4	10.5	8.375	2.5 2.6	2.6	2.1 1.9	10.0	2	30	B2
223	A B	0.073	16.6	14.3	10.5	8.375	2.6 2.5	2.6	2.3 1.6	9.5	2	30	B2
224	A B	0.078	19.6	17.3	10.5	8.375	4.1 4.0	4.1	1.8 2.1	9.5	2	30	B2
225	A B	0.073	19.0	14.3	10.5	8.375	3.8 3.5	3.6	2.3 2.4	9.8	2	30	B2
226	A B	0.073	18.3	14.4	10.5	8.375	3.8 3.5	3.6	2.4 1.9	9.0	2	30	B2

[o] Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
212	A B	78862 75869	78813 74050	152863	76431	99825 96037	96749	79625	- -	SS/FP SS
213	A B	79156 79258	79156 79145	158301	79150	100198 100327	100190	86877	 0.162	FP FP/SS
214	A B	55391 56240	55391 56228	111619	55810	70116 71190	70645	63527	- -	FP FP
215	A B	68822 82227	68822 66841	135663	67831	87116 104084	85863	84890	 0.415	FP/SS FP/SS
216	A B	58132 75155	58132 75155	133288	66644	73585 95134	84359	67287	 0.111	FB FB
217	A B	63041 81419	63041 65173	128214	64107	79798 103062	81148	94564	- 0.339	FP/SS FP
218	A B	67538 68023	67538 68023	135560	67780	85491 86105	85798	104869	- 0.321	FP FB
219	A B	69654 68753	69654 68723	138377	69188	88170 87030	87580	79699	- -	FP FP
220	A B	85951 85951	85951 85951	171901	85951	108798 108798	108798	107512	- -	SS FP/SS
221	A B	93337 107709	93337 93969	187306	93653	118148 136340	118548	77404	0.21 -	SS/FP FP/SS
222	A B	100177 90092	91540 90092	181632	90816	126806 114041	114957	63618	- -	FP/SS FP/SS
223	A B	116352 99672	99838 99672	199509	99755	147281 126167	126272	69305		FP/SS SS/FP
224	A B	105974 90156	91613 90118	181730	90865	134144 114121	115019	75856	- -	FP/SS SS/FP
225	A B	115165 92876	113609 77301	190910	95455	145779 117565	120829	65551	- -	SS FP/SS
226	A B	103861 96919	99392 96919	196312	98156	131470 122683	124248	67551		SS/FP FP/SS

Table B.2 Cont. Comprehensive test results and data for specimens containing two No. 8 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
212	A B	60	0.38	0.11	5	3.00 (1.5)	0.55	5	3.0 (1.5)	0.38	3.50 (1.75)	0.5	2	3.16	60
213	A B	60	0.38	0.11	5	3.00 (1.50	0.55	5	3.0 (1.5)	0.38	3.50 (1.75)	0.5	2	3.16	60
214	A B	60	0.38	0.11	5	3.00 (0.9)	1.20	6	4.0 (3.5)	0.50	1.50 (0.9)	-	-	3.16	60
215	A B	60	0.38	0.11	5	3.00 (1.5)	0.88	8	4.0 (2.0)	0.50	4.00 (2.0)	0.375	2	3.16	60
216	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.50	4.00 (1.5)	-	-	6.32	120
217	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.50	1.75 (1.0)	-	-	3.16	60
218	A B	60	0.38	0.11	5	1.75 (1.5)	-	-	-	0.50	1.75 (1.0)	-	-	3.16	60
219	A B	60	0.38	0.11	4	2.25 (2.3)	-	-	-	0.50	1.75 (1.0)	-	-	3.16	60
220	A B	60	0.38	0.11	5	3.00 (1.5)	-	-	-	0.50	4.00 (2.0)	-	-	6.32	60
221	A B	60	0.5	0.20	4	4.00 (2.0)	0.88	8	4.0 (4.0)	0.38	3.50 (1.75)	0.375	2	3.16	60
222	A B	60	0.5	0.20	4	4.00 (4.0)	1.60	8	4.0 (4.0)	0.50	3.50 (1.75)	0.5	1	3.16	60
223	A B	60	0.5	0.20	4	4.00 (4.0)	1.60	8	4.0 (4.0)	0.50	3.50 (1.75)	0.5	1	3.16	60
224	A B	60	0.5	0.20	4	4.00 (2.0)	0.88	8	4.0 (4.0)	0.38	3.50 (1.75)	0.375	2	3.16	60
225	A B	60	0.5	0.20	4	4.00 (4.0)	1.60	8	4.0 (4.0)	0.50	3.50 (1.75)	0.5	1	3.16	60
226	A B	60	0.5	0.20	4	4.00 (4.0)	1.60	8	4.0 (4.0)	0.50	3.50 (1.75)	0.5	1	3.16	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.3 Comprehensive test results and data for specimens containing two No. 11 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
227	11-8-90-0-o-2.5-2-25	A B	90°	-	A1035	25.3 25.1	25.2	9460	9	1.41
228	11-8-90-0-o-2.5-2-17	A B	90°	-	A1035	16.8 16.4	16.6	9460	9	1.41
229	11-12-90-0-o-2.5-2-17	A B	90°	-	A1035	17.1 16.6	16.9	11800	36	1.41
230	11-12-180-0-o-2.5-2-17	A B	180°	-	A1035	16.9 17.3	17.1	11800	36	1.41
231	11-5-90-0-i-2.5-2-14	A B	90°	-	A615	13.5 15.3	14.4	4910	13	1.41
232	11-5-90-0-i-2.5-2-26	A B	90°	-	A1035	26.0 26.0	26.0	5360	6	1.41
233	11-5-90-0-i-2.5-2-16	A B	90°	-	A1035	16.3 15.8	16.0	4890	8	1.41
234	(2@5.35) 11-5-90-0-i-2.5-13-13	A B	90°	-	A615	14.0 13.9	13.9	5330	11	1.41
235	(2@7.5) 11-8-90-0-i-2.5-2-15	A B	90°	-	A1035	14.8 14.8	14.8	7070	30	1.41
236	(2@7.5) 11-8-90-0-i-2.5-2-18	A B	90°	-	A1035	17.3 17.0	17.1	7070	30	1.41
237	11-8-90-0-i-2.5-2-17	A B	90°	-	A1035	17.3 18.0	17.6	9460	9	1.41
238	11-8-90-0-i-2.5-2-21	A B	90°	-	A1035	20.0 21.1	20.6	7870	6	1.41
239	11-8-90-0-i-2.5-2-17	A B	90°	-	A1035	16.3 18.1	17.2	8520	7	1.41
240	(2@7.5) 11-12-90-0-i-2.5-2-17	A B	90°	-	A615	17.3 17.5	17.4	11476	50	1.41
241	11-12-90-0-i-2.5-2-17	A B	90°	-	A1035	16.1 16.9	16.5	11880	35	1.41
242	11-12-90-0-i-2.5-2-17.5	A B	90°	-	A1035	17.6 17.8	17.7	13330	31	1.41
243	11-12-90-0-i-2.5-2-25	A B	90°	-	A1035	24.9 24.4	24.6	13330	34	1.41
244	11-15-90-0-i-2.5-2-24	A B	90°	-	A1035	24.0 24.8	24.4	16180	62	1.41
245	11-15-90-0-i-2.5-2-11	A B	90°	-	A1035	12.1 11.5	11.8	16180	63	1.41
246	(2d) 11-15-90-0-i-2.5-2-10	A B	90°	-	A615	9.5 9.5	9.5	14050	76	1.41
247	11-15-90-0-i-2.5-2-15	A B	90°	-	A1035	14.0 14.0	14.0	14050	77	1.41
248	11-5-90-0-i-3.5-2-17	A B	90°	-	A1035	18.1 17.6	17.9	5600	24	1.41
249	11-5-90-0-i-3.5-2-14	A B	90°	-	A615	14.8 15.3	15.0	4910	13	1.41
250	11-5-90-0-i-3.5-2-26	A B	90°	-	A1035	26.3 25.8	26.0	5960	8	1.41
251	11-8-180-0-i-2.5-2-21	A B	180°	-	A1035	21.3 20.9	21.1	7870	6	1.41

Table B.3 Cont. Comprehensive test results and data for specimens containing two No. 11 hooked bars

	Hook	R_r	b **in.**	h **in.**	h_{cl} **in.**	h_c **in.**	c_{so} **in.**	$c_{so,avg}$ **in.**	c_{th} **in.**	c_h **in.**	N_h	**Axial Load** **kips**	**Long. Reinf. Layout**[o]
227	A B	0.085	21.9	27.4	19.5	8.375	2.6 2.9	2.8	2.2 2.3	13.6	2	169	B16
228	A B	0.085	21.4	19.3	19.5	8.375	2.5 2.4	2.4	2.6 2.9	13.8	2	116	B16
229	A B	0.085	21.6	19.3	19.5	8.375	2.5 2.5	2.5	2.2 2.7	13.8	2	117	B7
230	A B	0.085	21.3	19.2	19.5	8.375	2.5 2.6	2.5	2.3 1.9	13.4	2	114	B7
231	A B	0.069	21.6	16.0	19.5	8.375	2.8 2.8	2.8	2.5 0.8	13.3	2	97	B7
232	A B	0.085	21.5	28.1	19.5	8.375	2.5 2.9	2.7	2.1 2.1	13.3	2	169	B12
233	A B	0.085	22.1	18.7	19.5	8.375	2.7 2.8	2.7	2.8 2.6	13.8	2	116	B18
234	A B	0.085	14.1	26.0	19.5	8.375	2.6 2.6	2.6	12.0 12.1	6.2	2	103	B14
235	A B	0.085	17.2	17.4	19.5	8.375	2.5 2.5	2.5	2.8 2.6	9.3	2	84	B14
236	A B	0.085	17.6	20.1	19.5	8.375	2.8 2.7	2.7	2.8 3.1	9.3	2	99	B14
237	A B	0.085	21.2	19.3	19.5	8.375	2.5 2.5	2.5	2.0 1.3	13.4	2	114	B16
238	A B	0.085	21.1	23.4	19.5	8.375	2.5 2.8	2.6	3.4 2.3	13.0	2	138	B13
239	A B	0.085	21.3	19.3	19.5	8.375	2.5 2.5	2.5	3.0 1.1	13.5	2	115	B8
240	A B	0.085	17.8	19.4	19.5	8.375	2.6 2.8	2.7	2.0 2.0	9.6	2	96	B14
241	A B	0.085	21.2	19.3	19.5	8.375	2.5 2.6	2.6	3.1 2.4	13.3	2	114	B13
242	A B	0.085	22.8	19.8	19.5	8.375	3.8 2.5	3.1	2.1 2.0	13.8	2	126	B7
243	A B	0.085	20.9	27.3	19.5	8.375	2.5 2.5	2.5	2.4 2.9	13.1	2	160	B12
244	A B	0.085	21.3	26.0	19.5	8.375	2.5 2.5	2.5	2.0 1.3	13.5	2	155	B11
245	A B	0.085	20.9	13.1	19.5	8.375	2.4 2.8	2.6	1.0 1.6	13.0	2	77	B2
246	A B	0.085	21.9	12.0	19.5	8.375	2.8 2.7	2.7	2.5 2.5	13.6	2	74	B15
247	A B	0.085	21.4	17.0	19.5	8.375	2.8 2.8	2.8	3.0 3.0	13.0	2	102	B15
248	A B	0.085	23.8	20.0	19.5	8.375	4.0 3.9	3.9	1.8 2.5	13.1	2	133	B7
249	A B	0.069	23.7	16.3	19.5	8.375	3.8 3.9	3.8	1.5 1.0	13.3	2	108	B7
250	A B	0.085	23.8	28.4	19.5	8.375	3.8 3.8	3.8	2.1 2.6	13.5	2	189	B12
251	A B	0.085	21.1	23.1	19.5	8.375	2.9 2.4	2.7	1.8 2.2	13.0	2	137	B13

[o] Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.3 Cont. Comprehensive test results and data for specimens containing two No. 11 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
227	A	194500	178670	349530	174765	124679	112029	124103	-	SB
	B	170700	170860			109423			-	SB
228	A	121403	108779	214417	107209	77822	68723	81606	-	SB/FB
	B	105721	105638			67770			-	SB/TK
229	A	123725	105010	210804	105402	79311	67565	92862	0.143	FB/TK
	B	105794	105794			67817			-	FP/TK
230	A	83343	83343	166986	83493	53425	53521	93894	-	SS/FP
	B	90122	83644			57770			-	SB
231	A	67249	67249	133180	66590	43108	42686	51027	0.139	FP/SS
	B	81430	65931			52199			-	SS
232	A	165682	150653	297454	148727	106206	95338	96429	-	FB/SS
	B	146801	146801			94103			-	FB/SS/TK
233	A	85060	80730	178792	89396	54526	57305	56680		SS
	B	98253	98062			62983			-	SS
234	A	58206	58206	121186	60593	37311	38842	51547		FP
	B	63035	62981			40407			-	FP
235	A	76673	76635	150627	75313	49150	48278	62828		FP/SS
	B	74284	73991			47618			-	FP/SS
236	A	99745	99278	194757	97379	63939	62422	72945		FP/SS
	B	95484	95479			61208			-	FP/SS
237	A	131998	131969	264111	132055	84614	84651	86842	-	FP/TK
	B	141233	132141			90534			-	FB/TK
238	A	127061	127061	250252	125126	81449	80209	92409	-	FP/TK
	B	147904	123191			94810			-	FB
239	A	105626	105537	209557	104779	67709	67166	80368	-	SS
	B	115172	104020			73828			-	FP
240	A	105142	105142	213436	106718	67398	68409	94292		SS
	B	109014	108295			69881			-	SS
241	A	148361	148361	268741	134371	95103	86135	91106	-	SB
	B	120380	120380			77167			-	SB/FP
242	A	125648	125648	249245	124622	80544	79886	103451	-	SS/TK
	B	123622	123597			79245			0.25	SS
243	A	205050	201395	399486	199743	131443	128040	144027	-	SB
	B	198110	198091			126994			-	SB
244	A	212601	212601	426530	213265	136283	136708	157068	-	SB/TK
	B	231323	213928			148284			-	SB/TK
245	A	48563	48563	96252	48126	31130	30850	76117	-	FL
	B	47717	47689			30588			0.252	FL
246	A	52097	52097	102962	51481	33395	33001	57045	-	FP
	B	50882	50866			32617			-	FP
247	A	93327	93327	184335	92168	59825	59082	84066	-	SB
	B	91008	91008			58339			-	SB
248	A	105772	105772	216244	108122	67803	69309	67763	0.187	SS/TK
	B	117570	110472			75366			-	SS
249	A	82601	70046	139027	69514	52949	44560	53246	-	FP/SS
	B	68982	68982			44219			-	FP/SS/TK
250	A	198346	183026	364508	182254	127145	116829	101683	-	SB/FB
	B	181661	181481			116449			-	FB/SB
251	A	137773	129406	256246	128123	88316	82130	94656	-	FB
	B	126839	126839			81307			-	FB/SB

Table B.3 Cont. Comprehensive test results and data for specimens containing two No. 11 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
227	A B	60	-	-	-	-	-	-	-	0.50	6.0 (3.0)	-	-	9.48	60
228	A B	60	-	-	-	-	-	-	-	0.50	6.0 (3.0)	-	-	9.48	60
229	A B	60	-	-	-	-	-	-	-	0.50	3.5 (1.75)	-	-	4.74	60
230	A B	60	-	-	-	-	-	-	-	0.50	3.5 (1.75)	-	-	4.74	60
231	A B	60	-	-	-	-	2.4	12	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
232	A B	60	-	-	-	-	1.86	6	4.0 (2.0)	0.50	4.0 (2.0)	0.375	1	6.32	60
233	A B	60	-	-	-	-	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
234	A B	60	-	-	-	-	-	-	-	0.50	7.0 (3.5)	-	-	7.90	60
235	A B	60	-	-	-	-	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
236	A B	60	-	-	-	-	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
237	A B	60	-	-	-	-	-	-	-	0.50	6.0 (3.0)	-	-	9.48	60
238	A B	60	-	-	-	-	-	-	-	0.50	6.0 (3.0)	-	-	9.40	60
239	A B	60	-	-	-	-	-	-	-	0.50	8.0 (4.0)	-	-	6.28	60
240	A B	60	-	-	-	-	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
241	A B	60	-	-	-	-	-	-	-	0.50	6.0 (3.0)	-	-	9.40	60
242	A B	60	-	-	-	-	2.4	12	4.0 (2.0)	0.50	4.0 (2.0)	-	-	4.74	60
243	A B	60	-	-	-	-	3.6	18	4.0 (2.0)	0.50	4.0 (2.0)	0.5	1	6.32	60
244	A B	60	-	-	-	-	-	-	-	0.50	3.5 (1.75)	-	-	6.32	60
245	A B	60	-	-	-	-	-	-	-	0.50	3.0 (1.5)	-	-	3.16	60
246	A B	60	-	-	-	-	-	-	-	0.50	4.5 (2.3)	-	-	6.94	120
247	A B	60	-	-	-	-	-	-	-	0.50	4.5 (2.3)	-	-	6.94	120
248	A B	60	-	-	-	-	2.4	12	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
249	A B	60	-	-	-	-	2.4	12	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
250	A B	60	-	-	-	-	1.86	6	4.0 (2.0)	0.50	4.0 (2.0)	0.375	1	6.32	60
251	A B	60	-	-	-	-	-	-	-	0.50	6.0 (3.0)	-	-	9.40	60

[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.3 Cont. Comprehensive test results and data for specimens containing two No. 11 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
252	11-8-180-0-i-2.5-2-17	A B	180°	-	A1035	17.8 18.0	17.9	8520	7	1.41
253	11-12-180-0-i-2.5-2-17	A B	180°	-	A1035	16.6 16.6	16.6	11880	35	1.41
254	11-5-90-1#4-i-2.5-2-17	A B	90°	Para	A1035	17.8 17.6	17.7	5790	25	1.41
255	11-5-90-1#4-i-3.5-2-17	A B	90°	Para	A1035	17.8 17.8	17.8	5790	25	1.41
256	11-5-90-2#3-i-2.5-2-17	A B	90°	Para	A1035	17.4 17.8	17.6	5600	24	1.41
257	11-5-90-2#3-i-2.5-2-14	A B	90°	Para	A615	13.5 13.8	13.6	4910	13	1.41
258	(2@5.35) 11-5-90-2#3-i-2.5-13-13	A B	90°	Para	A615	13.9 13.8	13.8	5330	11	1.41
259	(2@7.5) 11-8-90-2#3-i-2.5-2-17	A B	90°	Para	A1035	16.3 16.5	16.4	7070	31	1.41
260	(2@7.5) 11-12-90-2#3-i-2.5-2-16	A B	90°	Para	A615	15.4 15.3	15.3	11850	51	1.41
261	11-12-90-2#3-i-2.5-2-17.5	A B	90°	Para	A1035	18.0 17.5	17.8	13710	30	1.41
262	11-12-90-2#3-i-2.5-2-25	A B	90°	Para	A1035	25.0 24.5	24.8	13710	30	1.41
263	11-15-90-2#3-i-2.5-2-23	A B	90°	Para	A1035	23.5 23.5	23.5	16180	62	1.41
264	11-15-90-2#3-i-2.5-2-10.5	A B	90°	Para	A1035	11.8 10.5	11.1	16180	63	1.41
265	(2d) 11-15-90-2#3-i-2.5-2-10	A B	90°	Para	A615	10.0 10.0	10.0	14050	76	1.41
266	11-15-90-2#3-i-2.5-2-15	A B	90°	Para	A1035	14.0 14.3	14.1	14050	80	1.41
267	11-5-90-2#3-i-3.5-2-17	A B	90°	Para	A1035	17.5 17.8	17.6	7070	28	1.41
268	11-5-90-2#3-i-3.5-2-14	A B	90°	Para	A615	14.5 13.4	13.9	4910	12	1.41
269	11-5-90-5#3-i-2.5-2-14	A B	90°	Para	A615	14.3 13.5	13.9	4910	12	1.41
270	11-5-90-5#3-i-3.5-2-14	A B	90°	Para	A615	14.6 14.5	14.6	4910	14	1.41
271	11-8-90-6#3-o-2.5-2-16	A B	90°	Para	A1035	15.9 16.5	16.2	9420	8	1.41
272	11-8-90-6#3-o-2.5-2-22	A B	90°	Para	A1035	21.5 22.3	21.9	9120	7	1.41
273	11-12-90-6#3-o-2.5-2-17	A B	90°	Para	A1035	15.6 17.3	16.4	11800	36	1.41
274	11-12-180-6#3-o-2.5-2-17	A B	180°	Para	A1035	16.6 16.4	16.5	11800	36	1.41
275	11-5-90-6#3-i-2.5-2-20	A B	90°	Para	A1035	19.5 19.0	19.3	5420	7	1.41
276	11-5-90-6#3-i-2.5-2-16	A B	90°	Para	A1035	15.5 15.3	15.4	5030	9	1.41

Table B.3 Cont. Comprehensive test results and data for specimens containing two No. 11 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°
252	A B	0.085	21.4	19.1	19.5	8.375	2.4 2.5	2.4	1.4 1.1	13.8	2	115	B8
253	A B	0.085	21.6	19.2	19.5	8.375	3.0 2.5	2.8	2.5 2.5	13.3	2	116	B13
254	A B	0.085	21.4	19.6	19.5	8.375	2.8 2.8	2.8	1.8 2.0	13.1	2	117	B7
255	A B	0.085	23.6	19.5	19.5	8.375	3.8 3.9	3.8	1.8 1.8	13.1	2	129	B7
256	A B	0.085	21.3	19.6	19.5	8.375	2.5 2.6	2.6	2.3 1.8	13.4	2	117	B7
257	A B	0.069	21.7	16.0	19.5	8.375	2.8 2.9	2.8	2.5 2.3	13.3	2	97	B7
258	A B	0.085	14.3	26.0	19.5	8.375	2.7 2.6	2.6	12.1 12.3	6.2	2	104	B14
259	A B	0.085	17.5	19.1	19.5	8.375	2.5 2.8	2.7	3.0 2.5	9.3	2	94	B14
260	A B	0.085	17.9	18.1	19.5	8.375	2.9 3.0	3.0	2.6 2.9	9.1	2	90	B14
261	A B	0.085	21.1	19.5	19.5	8.375	2.5 2.5	2.5	1.5 2.0	13.3	2	115	B7
262	A B	0.085	21.4	27.3	19.5	8.375	2.6 3.0	2.8	2.3 2.8	13.0	2	164	B12
263	A B	0.085	21.3	25.0	19.5	8.375	2.8 2.8	2.8	1.5 1.5	13.0	2	149	B11
264	A B	0.085	21.8	12.8	19.5	8.375	2.5 2.8	2.6	1.0 2.3	13.8	2	78	B2
265	A B	0.085	22.0	12.0	19.5	8.375	2.8 3.0	2.9	2.0 2.0	13.4	2	74	B15
266	A B	0.085	21.5	17.0	19.5	8.375	2.6 2.6	2.6	3.0 2.8	13.6	2	102	B15
267	A B	0.085	23.4	19.7	19.5	8.375	3.6 3.6	3.6	2.1 2.0	13.4	2	129	B7
268	A B	0.069	23.7	16.1	19.5	8.375	3.8 3.9	3.8	1.6 2.8	13.3	2	107	B7
269	A B	0.069	21.8	16.0	19.5	8.375	2.8 2.9	2.8	1.8 2.5	13.4	2	98	B7
270	A B	0.069	23.7	16.0	19.5	8.375	3.9 3.9	3.9	1.4 1.5	13.1	2	106	B7
271	A B	0.085	21.6	18.1	19.5	8.375	2.5 2.6	2.6	2.3 1.6	13.6	2	109	B16
272	A B	0.085	21.4	24.4	19.5	8.375	2.5 2.6	2.6	2.9 2.1	13.5	2	146	B16
273	A B	0.085	21.4	19.3	19.5	8.375	2.5 2.4	2.4	3.6 2.0	13.8	2	116	B7
274	A B	0.085	21.6	19.5	19.5	8.375	2.5 2.8	2.6	2.9 3.1	13.5	2	118	B7
275	A B	0.085	20.9	22.3	19.5	8.375	2.6 2.6	2.6	2.8 3.3	12.9	2	130	B7
276	A B	0.085	21.9	18.4	19.5	8.375	2.7 2.8	2.7	3.0 3.0	13.6	2	113	B18

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.3 Cont. Comprehensive test results and data for specimens containing two No. 11 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
252	A	101710	101710	200907	100453	65199	64393	83583	-	FP
	B	121269	99197			77737			-	FB
253	A	106726	106726	214921	107461	68414	68885	91796	0.156	SB/FP
	B	108195	108195			69356			-	SS
254	A	99443	99403	202995	101498	63746	65063	68180	-	SS/FP
	B	119681	103592			76718			-	FP/SS
255	A	105692	103693	212540	106270	67751	68122	68421	-	SS
	B	108846	108846			69773			-	SS/FP/TK
256	A	108406	98172	201390	100695	69491	64548	66578	-	SS/FP
	B	103234	103218			66176			-	SS/FP
257	A	77718	77718	154845	77422	49819	49630	48365	0.206	FP/SS
	B	77214	77127			49496			-	SS
258	A	68288	68250	138247	69123	43774	44310	51084	-	FP
	B	70143	69997			44963				FP
259	A	105741	104665	212061	106031	67783	67968	69750	-	FP/SS
	B	107791	107397			69097			-	FP/SS
260	A	107954	107954	217436	108718	69201	69691	84456	-	SS/FP
	B	109513	109482			70201			-	SS/FP
261	A	133178	132555	260779	130389	85371	83583	105286	-	SS
	B	129868	128223			83249			-	SS
262	A	210112	210112	416108	208054	134687	133368	146807	-	BY
	B	205996	205996			132049			-	BY
263	A	232100	212550	419150	209575	148782	134343	151429	-	SB
	B	206900	206600			132628			-	SB/FB
264	A	50558	50558	100105	50053	32409	32085	71687	0.249	FL
	B	49575	49547			31779			-	FL
265	A	64250	64250	127881	63940	41186	40987	60036	-	FP
	B	63631	63631			40789				FP
266	A	115577	115577	230377	115189	74088	73839	84801	-	FP/SB
	B	114801	114801			73590			-	FP/SB
267	A	107807	107807	219287	109644	69107	70284	75074	-	SS/FP/TK
	B	111480	111480			71462			-	SS
268	A	92719	82732	164549	82275	59435	52740	49474	-	FP/SS
	B	81848	81817			52467			-	SS/FP/TK
269	A	105597	96267	190339	95170	67690	61006	49252	0.397	SS/FP
	B	94115	94072			60330			0.375	SS/FP
270	A	101315	101315	195979	97989	64946	62814	51693	-	FP/SS
	B	94663	94663			60682			-	SS/FP
271	A	138900	138793	273507	136753	89038	87662	99487	-	SB/FB
	B	134714	134714			86355			-	SB/FB
272	A	186100	170000	340498	170249	119295	109134	132284	-	SB
	B	170498	170498			109294			-	SB/FB
273	A	116430	116390	231757	115878	74635	74281	113068	-	FB/SS
	B	147268	115367			94403			-	SB/FB
274	A	130005	112424	226243	113121	83337	72514	113498	-	SB
	B	113819	113819			72961			0.112	FB/SS
275	A	153119	137617	272543	136272	98153	87354	89741	0.274	FP/SS
	B	134977	134927			86524			-	FP/SS
276	A	120540	120540	231247	115623	77269	74118	69050	-	SS
	B	110898	110707			71089			-	SS

Table B.3 Cont. Comprehensive test results and data for specimens containing two No. 11 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
252	A B	60	-	-	-	-	-	-	-	0.50	8.0 (4.0)	-	-	6.28	60
253	A B	60	-	-	-	-	-	-	-	0.50	6.0 (3.0)	-	-	9.40	60
254	A B	60	0.5	0.20	1	8.75	2.2	11	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
255	A B	60	0.5	0.20	1	8.75	2.2	11	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
256	A B	60	0.38	0.11	2	8.00 (6.2)	2	10	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
257	A B	60	0.38	0.11	2	8.00 (6.2)	2.4	12	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
258	A B	60	0.38	0.11	2	8.00 (8.0)	-	-	-	0.50	7.0 (3.5)	-	-	7.90	60
259	A B	60	0.38	0.11	2	8.00 (8.0)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
260	A B	60	0.38	0.11	2	8.00 (8.0)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
261	A B	60	0.38	0.11	2	12.00 (6.0)	2.4	12	4.0 (2.0)	0.50	4.0 (2.0)	-	-	4.74	60
262	A B	60	0.38	0.11	2	12.00 (6.0)	3.2	16	4.0 (2.0)	0.50	4.0 (2.0)	0.5	1	6.32	60
263	A B	60	0.38	0.11	2	8.00 (8.0)	-	-	-	0.50	3.0 (1.5)	-	-	6.32	60
264	A B	60	0.38	0.11	2	8.00 (8.0)	-	-	-	0.50	2.8 (1.4)	-	-	3.16	60
265	A B	60	0.38	0.11	2	8.00 (8.0)	-	-	-	0.50	4.5 (2.3)	-	-	6.94	120
266	A B	60	0.38	0.11	2	8.00 (8.0)	-	-	-	0.50	4.5 (2.3)	-	-	6.94	120
267	A B	60	0.38	0.11	2	8.00 (6.2)	2	10	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
268	A B	60	0.38	0.11	2	8.00 (6.2)	2.4	12	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
269	A B	60	0.38	0.11	5	4.00 (2.0)	2.4	12	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
270	A B	60	0.38	0.11	5	4.00 (2.0)	2.4	12	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
271	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	6.0 (3.0)	-	-	9.48	60
272	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	6.0 (3.0)	-	-	9.48	60
273	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	3.5 (1.75)	-	-	4.74	60
274	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	3.5 (1.75)	-	-	4.74	60
275	A B	60	0.38	0.11	6	4.00 (2.0)	1.2	6	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
276	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.3 Cont. Comprehensive test results and data for specimens containing two No. 11 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
277	(2@5.35) 11-5-90-6#3-i-2.5-13-13	A B	90°	Para	A615	14.0 13.8	13.9	5280	12	1.41
278	(2@5.35) 11-5-90-6#3-i-2.5-18-18	A B	90°	Para	A1035	19.3 19.5	19.4	5280	12	1.41
279	(2@7.5) 11-8-90-6#3-i-2.5-2-15	A B	90°	Para	A1035	13.8 14.3	14.0	7070	31	1.41
280	11-8-90-6#3-i-2.5-2-16	A B	90°	Para	A1035	15.5 16.4	15.9	9120	7	1.41
281	11-8-90-6#3-i-2.5-2-22	A B	90°	Para	A1035	21.3 21.5	21.4	9420	8	1.41
282	11-8-90-6#3-i-2.5-2-22	A B	90°	Para	A1035	21.9 22.0	21.9	9420	8	1.41
283	11-8-90-6#3-i-2.5-2-15	A B	90°	Para	A1035	15.8 15.3	15.5	7500	5	1.41
284	11-8-90-6#3-i-2.5-2-19	A B	90°	Para	A1035	19.1 19.4	19.2	7500	5	1.41
285	(2@7.5) 11-12-90-6#3-i-2.5-2-14	A B	90°	Para	A1035	13.5 13.6	13.6	11960	52	1.41
286	11-12-90-6#3-i-2.5-2-17	A B	90°	Para	A1035	17.1 16.5	16.8	12370	37	1.41
287	11-12-90-6#3-i-2.5-2-16	A B	90°	Para	A1035	14.8 16.0	15.4	13710	31	1.41
288	11-12-90-6#3-i-2.5-2-22	A B	90°	Para	A1035	21.9 21.5	21.7	13710	31	1.41
289	11-15-90-6#3-i-2.5-2-22	A B	90°	Para	A1035	22.3 22.4	22.3	16180	62	1.41
290	11-15-90-6#3-i-2.5-2-9.5	A B	90°	Para	A1035	9.0 10.3	9.6	16180	63	1.41
291	(2d) 11-15-90-6#3-i-2.5-2-10a	A B	90°	Para	A615	9.5 10.0	9.8	14050	76	1.41
292	(2d) 11-15-90-6#3-i-2.5-2-10b	A B	90°	Para	A615	9.5 9.8	9.6	14050	77	1.41
293	11-15-90-6#3-i-2.5-2-15	A B	90°	Para	A1035	14.5 15.0	14.8	14050	80	1.41
294	11-5-90-6#3-i-3.5-2-20	A B	90°	Para	A1035	20.5 20.3	20.4	5420	7	1.41
295	11-8-180-6#3-i-2.5-2-15	A B	180°	Para	A1035	15.1 15.5	15.3	7500	5	1.41
296	11-8-180-6#3-i-2.5-2-19	A B	180°	Para	A1035	19.6 19.9	19.8	7870	6	1.41
297	(2@7.5) 11-12-180-6#3-i-2.5-2-14	A B	180°	Para	A1035	14.4 14.4	14.4	12190	56	1.41
298	11-12-180-6#3-i-2.5-2-17	A B	180°	Para	A1035	16.9 16.5	16.7	12370	37	1.41
299	11-12-180-6#3-i-2.5-2-17	A B	180°	Para	A1035	16.8 16.8	16.8	12370	37	1.41
300	11-5-90-5#4s-i-2.5-2-20	A B	90°	Para	A1035	20.0 20.3	20.1	5420	7	1.41
301	11-5-90-5#4s-i-3.5-2-20	A B	90°	Para	A1035	19.8 19.3	19.5	5960	8	1.41

Table B.3 Cont. Comprehensive test results and data for specimens containing two No. 11 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°
277	A B	0.085	14.2	26.0	19.5	8.375	2.4 2.8	2.6	12.0 12.3	6.2	2	103	B14
278	A B	0.085	14.3	36.0	19.5	8.375	2.7 2.6	2.6	16.8 16.5	6.2	2	144	B14
279	A B	0.085	18.3	17.5	19.5	8.375	3.2 3.0	3.1	3.8 3.3	9.3	2	90	B14
280	A B	0.085	21.2	18.3	19.5	8.375	2.5 2.5	2.5	2.8 1.9	13.4	2	108	B16
281	A B	0.085	21.4	24.1	19.5	8.375	2.5 2.6	2.6	2.8 2.6	13.5	2	145	B11
282	A B	0.085	21.7	24.2	19.5	8.375	2.6 2.9	2.8	2.3 2.2	13.4	2	147	B16
283	A B	0.085	21.6	17.3	19.5	8.375	2.8 2.5	2.6	1.5 2.0	13.5	2	104	B13
284	A B	0.085	21.4	21.0	19.5	8.375	2.5 2.6	2.6	2.0 1.7	13.5	2	126	B13
285	A B	0.085	17.4	16.4	19.5	8.375	2.7 2.8	2.7	2.6 3.0	9.1	2	80	B14
286	A B	0.085	21.4	19.1	19.5	8.375	2.6 3.0	2.8	1.9 2.6	13.0	2	114	B13
287	A B	0.085	20.8	18.0	19.5	8.375	2.5 2.5	2.5	3.3 2.0	13.0	2	105	B7
288	A B	0.085	22.1	24.3	19.5	8.375	2.9 3.1	3.0	2.4 2.8	13.3	2	150	B12
289	A B	0.085	21.8	24.0	19.5	8.375	3.0 2.5	2.8	1.8 1.6	13.5	2	147	B10
290	A B	0.085	21.6	11.5	19.5	8.375	2.5 3.0	2.8	2.5 1.3	13.3	2	69	B2
291	A B	0.085	21.5	12.0	19.5	8.375	2.6 2.8	2.7	2.5 2.0	13.4	2	72	B15
292	A B	0.085	21.4	12.0	19.5	8.375	2.8 2.8	2.8	2.5 2.3	13.0	2	72	B10
293	A B	0.085	21.5	17.0	19.5	8.375	2.6 2.6	2.6	2.5 2.0	13.6	2	102	B15
294	A B	0.085	23.6	22.3	19.5	8.375	3.8 3.9	3.8	1.8 2.0	13.1	2	147	B7
295	A B	0.085	21.8	17.1	19.5	8.375	2.9 3.1	3.0	2.0 1.6	13.0	2	104	B13
296	A B	0.085	21.8	21.2	19.5	8.375	2.9 2.9	2.9	1.5 1.3	13.3	2	129	B13
297	A B	0.085	17.6	16.6	19.5	8.375	2.5 3.2	2.9	2.0 2.4	9.1	2	82	B14
298	A B	0.085	21.7	19.8	19.5	8.375	2.6 2.8	2.7	2.9 3.3	13.5	2	120	B7
299	A B	0.085	21.4	19.4	19.5	8.375	2.5 2.8	2.6	2.7 2.6	13.4	2	117	B13
300	A B	0.085	21.4	22.3	19.5	8.375	2.5 2.8	2.6	2.3 2.0	13.4	2	134	B7
301	A B	0.085	23.4	22.0	19.5	8.375	3.8 3.8	3.8	2.3 2.8	13.1	2	144	B7

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.3 Cont. Comprehensive test results and data for specimens containing two No. 11 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
277	A	83757	83556	179496	89748	53691	57531	63843	-	FP
	B	95951	95940			61507			-	FP
278	A	118507	116107	243210	121605	75966	77952	89150		FP
	B	128624	127103			82451			-	FP
279	A	107629	107442	212380	106190	68993	68070	74542	-	FP/SS
	B	104987	104938			67300			-	FP/SS
280	A	147508	136385	265971	132986	94556	85247	96379	-	FP/SS
	B	129692	129586			83136			-	FP/SS
281	A	204260	186246	369138	184569	130936	118314	131369	-	*
	B	183175	182892			117420			-	SS
282	A	197739	190740	382084	191042	126756	122463	134827	-	*
	B	191344	191344			122656			-	SB/FB
283	A	142278	108602	216623	108312	91204	69431	85001	-	SS
	B	108021	108021			69245			-	SS/FP
284	A	182735	144766	290860	145430	117138	93224	105395	-	FB/SS
	B	146093	146093			93650			-	FB/SS
285	A	100805	100724	204076	102038	64618	65409	93940	-	SS/FP
	B	103464	103353			66323			-	SS/FP
286	A	179693	161019	323295	161648	115188	103620	118408	0.334	FB/SB
	B	162285	162277			104029			-	SP/SS
287	A	115139	115089	230394	115197	73807	73844	113998	-	SS/FP
	B	127542	115306			81758			0.952	SB/FB
288	A	206283	203983	402379	201189	132233	128967	160802	-	SS/FB
	B	199234	198395			127714			-	FB
289	A	204557	200084	395618	197809	131126	126801	179722	-	FB/SS
	B	195710	195534			125455			-	SB/FB
290	A	58154	58154	114765	57383	37278	36784	77527	0.358	FL
	B	56612	56612			36290			-	FL
291	A	83558	83558	165362	82681	53563	53001	73169	-	FP
	B	81804	81804			52438			-	FP
292	A	76605	76605	151158	75579	49106	48448	72244		FP
	B	74596	74553			47818			-	FP
293	A	145670	145664	290534	145267	93378	93120	110692	-	FP
	B	144870	144870			92866			-	FP
294	A	150216	136607	271643	135821	96293	87065	94986	-	SS/FP
	B	135259	135036			86704			-	SS
295	A	112423	112423	223356	111678	72066	71588	83973	-	SS
	B	110981	110933			71142			-	SS
296	A	170000	149000	298000	149000	108974	95513	110947	-	FB/SS
	B	149000	149000			95513			-	FB/SS
297	A	90862	90862	187911	93955	58245	60228	100536	-	SS/FP
	B	97049	97049			62211			-	SS/FP
298	A	123150	115105	232743	116371	78942	74597	117527	-	FP
	B	117638	117638			75409			0.379	FP/SB
299	A	148872	148872	297356	148678	95431	95306	118188	-	FP/SS
	B	173034	148484			110919			-	SB/FB
300	A	141399	141399	282090	141045	90640	90414	75057	-	FP/SS
	B	161640	140691			103615			-	FP/SS
301	A	186703	152402	305934	152967	119681	98056	76262	-	SS/FP
	B	153546	153532			98427			-	FP/SS

*Test terminated prior to failure of second hooked bar

Table B.3 Cont. Comprehensive test results and data for specimens containing two No. 11 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.[2]	N_{tr}	s_{tr}[a] in.	A_{cti} in.[2]	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.[2]	f_{ys} ksi
277	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	7.0 (3.5)	-	-	7.90	60
278	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	7.0 (3.5)	-	-	7.90	60
279	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
280	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	6.0 (3.0)	-	-	9.48	60
281	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	2.5 (1.3)	-	-	6.32	60
282	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	6.0 (3.0)	-	-	9.48	60
283	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	6.0 (3.0)	-	-	9.40	60
284	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	6.0 (3.0)	-	-	9.40	60
285	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
286	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	6.0 (3.0)	-	-	9.40	60
287	A B	60	0.38	0.11	6	4.00 (2.0)	2.4	12	4.0 (2.0)	0.50	4.0 (2.0)	0.375	1	4.74	60
288	A B	60	0.38	0.11	6	4.00 (2.0)	3.06	12	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	6.32	60
289	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	3.0 (1.5)	-	-	6.32	60
290	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	2.3 (1.1)	-	-	3.16	60
291	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	4.5 (2.3)	-	-	6.94	120
292	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	4.5 (2.3)	-	-	6.32	120
293	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	4.5 (2.3)	-	-	6.94	120
294	A B	60	0.38	0.11	6	4.00 (2.0)	1.2	6	4.0 (2.0)	0.50	4.0 (2.0)	0.375	2	4.74	60
295	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	6.0 (3.0)	-	-	9.40	60
296	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	6.0 (3.0)	-	-	9.40	60
297	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
298	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	3.0 (1.5)	-	-	4.74	60
299	A B	60	0.38	0.11	6	4.00 (2.0)	-	-	-	0.50	6.0 (3.0)	-	-	9.40	60
300	A B	60	0.5	0.20	5	5.00 (2.5)	4	10	5.0 (2.5)	0.50	5.0 (2.5)	0.375	2	4.74	60
301	A B	60	0.5	0.20	5	5.00 (2.5)	4	10	5.0 (2.5)	0.50	5.0 (2.5)	0.375	2	4.74	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.4 Comprehensive test results and data for specimens containing multiple No. 5 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
302	(3@10) 5-5-90-0-i-2.5-2-7	A B C	90°	-	A1035	6.3 6.8 7.0	6.7	5880	11	0.625
303	(3) 5-5-90-0-i-2.5-2-8	A B C	90°	-	A1035	8.0 8.0 7.8	7.9	4830	9	0.625
304	(3@4.5) 5-5-90-0-i-2.5-7-7	A B C	90°	-	A1035	7.1 7.0 7.0	7.0	5880	11	0.625
305	(4@3) 5-5-90-0-i-2.5-7-7	A B C D	90°	-	A1035	7.0 7.3 7.0 7.0	7.1	5880	11	0.625
306	(4@4) 5-5-90-0-i-2.5-2-6	A B C D	90°	-	A1035	5.4 5.3 4.8 5.3	5.2	6430	11	0.625
307	(4@4) 5-5-90-0-i-2.5-2-10	A B C D	90°	-	A1035	9.0 8.0 9.3 9.9	9.0	6470	12	0.625
308	(4@4) 5-8-90-0-i-2.5-2-6	A B C D	90°	-	A1035	6.3 5.8 5.8 6.0	5.9	6950	18	0.625
309	(4@6) 5-8-90-0-i-2.5-2-6	A B C D	90°	-	A1035	6.0 6.0 5.8 6.0	5.9	6693	21	0.625
310	(4@6) 5-8-90-0-i-2.5-6-6	A B C D	90°	-	A1035	6.3 6.3 6.3 6.3	6.3	6693	21	0.625
311	(3@4) 5-8-90-0-i-2.5-2-6	A B C	90°	-	A1035	6.0 5.6 6.0	5.9	6950	18	0.625
312	(3@6) 5-8-90-0-i-2.5-2-6	A B C	90°	-	A1035	6.4 5.9 5.8	6.0	6950	18	0.625
313	(3@10) 5-5-90-2#3-i-2.5-2-7	A B C	90°	Para	A1035	6.9 7.0 7.0	7.0	5950	12	0.625
314	(3@4.5) 5-5-90-2#3-i-2.5-7-7	A B C	90°	Para	A1035	6.4 6.6 6.5	6.5	5880	11	0.625
315	(4@3) 5-5-90-2#3-i-2.5-7-7	A B C D	90°	Para	A1035	7.0 7.0 7.0 7.0	7.0	5950	12	0.625

Table B.4 Cont. Comprehensive test results and data for specimens containing multiple No. 5 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°
302	A B C	0.073	18.28	9.0	5.3	8.375	2.5 8.7 2.7	2.6	2.8 2.3 2.0	5.6 5.6 -	3	30	B2
303	A B C	0.073	13.07	10.1	5.3	8.375	2.5 6.3 2.6	2.5	2.1 2.1 2.4	3.1 3.0 -	3	30	B2
304	A B C	0.073	11.63	14.0	5.3	8.375	2.6 5.3 2.6	2.6	6.9 7.0 7.0	2.1 2.5 -	3	30	B2
305	A B C D	0.073	11.5	14.1	5.3	8.375	2.1 4.1 4.5 2.5	2.3	7.0 6.8 7.1 7.1	1.4 1.6 1.4 -	4	30	B2
306	A B C D	0.073	13.2	8.2	5.3	8.375	2.4 4.9 5.1 2.8	2.6	2.8 2.9 3.4 2.9	1.9 1.9 1.8	4	30	B1
307	A B C D	0.073	13.2	12.3	5.3	8.375	2.6 5.0 5.0 2.8	2.7	3.3 4.3 3.0 2.4	1.8 1.9 1.6 -	4	30	B1
308	A B C D	0.073	12.9	8.0	5.3	8.375	2.5 5.0 5.0 2.5	2.5	1.8 2.3 2.3 2.0	1.9 1.6 1.9 -	4	30	B2
309	A B C D	0.073	17.3	8.0	5.3	8.375	2.7 6.5 6.5 2.7	2.7	2.0 2.0 2.3 2.0	3.1 3.1 3.1 -	4	30	B2
310	A B C D	0.073	17.1	12.0	5.3	8.375	2.5 6.3 6.5 2.7	2.6	5.8 5.8 5.8 5.8	3.1 3.1 3.1 -	4	30	B7
311	A B C	0.073	10.75	8.0	5.3	8.375	2.6 5.6 2.7	2.6	2.0 2.4 2.0	1.8 1.9 -	3	30	B2
312	A B C	0.073	13.25	8.0	5.3	8.375	2.6 6.2 2.7	2.6	1.6 2.1 2.3	3.0 3.1 -	3	30	B2
313	A B C	0.073	18.52	9.1	5.3	8.375	2.5 8.8 2.7	2.6	2.3 2.1 2.1	5.8 5.8 -	3	30	B2
314	A B C	0.073	11.28	14.2	5.3	8.375	2.3 5.3 2.5	2.4	7.9 7.6 7.6	2.4 2.3 -	3	30	B2
315	A B C D	0.073	11.8	14.0	5.3	8.375	2.5 4.7 4.5 2.5	2.5	7.0 7.0 7.0 7.0	1.6 1.4 1.4 -	4	30	B2

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.4 Cont. Comprehensive test results and data for specimens containing multiple No. 5 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
302	A	21501	20743	63103	21034	69358	67852	58424	-	FP
	B	27199	21207			87738			-	FP
	C	22321	21152			72005			-	FP
303	A	24392	23610	83608	27869	78685	89901	62879	-	FP
	B	33639	32864			108513			-	FP
	C	28681	27134			92521			-	FP
304	A	24271	24271	67088	22363	78294	72138	61725	-	FP
	B	22471	22471			72486			-	FP
	C	20347	20347			65634			-	FP
305	A	13033	13009	60191	15048	42043	48541	61893	-	FP
	B	16815	16790			54242			-	FP
	C	14879	14874			47996			-	FP
	D	15518	15518			50059			-	FP
306	A	12150	12150	58167	14542	39194	46909	47396	-	FP
	B	16822	16822			54265			-	FP
	C	15517	15510			50055			-	FP
	D	13684	13684			44142			-	FP
307	A	27937	27938	113608	28402	90119	91619	83022	-	FP
	B	28572	28455			92168			0.358	FP
	C	44806	31762			144535			-	FP
	D	27649	25453			89190			-	FP
308	A	17307	17307	61916	15479	55829	49932	56570	-	FP/SS
	B	17615	17430			56823			-	FP/SS
	C	14066	13684			45374			-	FP/SS
	D	14082	13495			45426			-	FP/SS
309	A	20647	17356	77211	19303	66603	62267	55514	-	FP
	B	22459	22123			72448			-	FP
	C	22914	22649			73916			-	FP
	D	15140	15082			48839			-	FP
310	A	16185	16185	64205	16051	52210	51778	58436	-	FP/SS
	B	14727	14728			47506			-	FP/SS
	C	16472	16472			53135			-	FP/SS
	D	16819	16819			54255			-	FP/SS
311	A	18497	18326	50416	16805	59668	54211	55975	-	FP
	B	17550	17370			56613			-	FP
	C	14720	14720			47484			-	FP
312	A	25526	25526	74657	24886	82342	80277	57166	-	FP
	B	34858	25964			112445			-	FP
	C	23167	23167			74732			-	FP
313	A	29818	29751	93888	31296	96185	100954	61356	-	FP/SS
	B	46276	34654			149278			-	FP/SS
	C	30092	29482			97070			-	FP/SS
314	A	23897	23612	69916	23305	77088	75179	56992	-	FP
	B	24090	23163			77710			-	FP
	C	23142	23142			74651			-	FP/SB
315	A	16337	16337	78307	19577	52699	63151	61709	-	FP
	B	21347	21322			68862			-	FP
	C	20389	20389			65771			-	FP
	D	20259	20259			65352			-	FP

Table B.4 Cont. Comprehensive test results and data for specimens containing multiple No. 5 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
302	A B C	60	-	-	-	-	-	-	-	0.375	3.0 (1.5)	-	-	3.16	60
303	A B C	60	-	-	-	-	-	-	-	0.500	3.0 (1.5)	-	-	3.16	60
304	A B C	60	-	-	-	-	-	-	-	0.375	4.0 (2.0)	-	-	3.16	60
305	A B C D	60	-	-	-	-	-	-	-	0.375	4.0 (2.0)	-	-	3.16	60
306	A B C D	60	-	-	-	-	1.10	10	2.0 (1.0)	0.375	2.5 (1.3)	0.375	1	1.27	60
307	A B C D	60	-	-	-	-	1.10	10	2.0 (1.00	0.375	3.0 (1.5)	0.500	1	1.27	60
308	A B C D	60	-	-	-	-	-	-	-	0.375	3.0 (1.5)	-	-	3.16	60
309	A B C D	60	-	-	-	-	-	-	-	0.375	3.0 (1.5)	-	-	3.16	60
310	A B C D	60	-	-	-	-	-	-	-	0.375	3.0 (1.5)	-	-	4.74	60
311	A B C	60	-	-	-	-	-	-	-	0.375	3.0 (1.5)	-	-	3.16	60
312	A B C	60	-	-	-	-	-	-	-	0.375	3.0 (1.5)	-	-	3.16	60
313	A B C	60	0.38	0.11	2	3 (3.0)	-	-	-	0.375	3.0 (1.5)	-	-	3.16	60
314	A B C	60	0.38	0.11	2	3 (3.0)	-	-	-	0.375	4.0 (2.0)	-	-	3.16	60
315	A B C D	60	0.38	0.11	2	3.0 (3.0)	-	-	-	0.375	4.0 (2.0)	-	-	3.16	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.4 Cont. Comprehensive test results and data for specimens containing multiple No. 5 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
316	(4@4) 5-5-90-2#3-i-2.5-2-6	A B C D	90°	Para	A1035	6.3 6.1 6.3 6.4	6.3	6430	11	0.625
317	(4@4) 5-5-90-2#3-i-2.5-2-8	A B C D	90°	Para	A1035	8.4 7.8 8.0 7.8	8.0	6430	11	0.625
318	(3@6) 5-8-90-5#3-i-2.5-2-6.25	A B C	90°	Para	A1035	5.0 6.3 5.3	5.5	10110	196	0.625
319	(3@4) 5-8-90-5#3-i-2.5-2-6	A B C	90°	Para	A1035	6.0 6.3 6.0	6.1	6700	22	0.625
320	(3@6) 5-8-90-5#3-i-2.5-2-6	A B C	90°	Para	A1035	6.0 6.0 6.0	6.0	6700	22	0.625
321	(3@10) 5-5-90-5#3-i-2.5-2-7	A B C	90°	Para	A1035	6.9 7.0 6.8	6.9	5950	12	0.625
322	(3) 5-5-90-5#3-i-2.5-2-8	A B C	90°	Para	A1035	7.8 7.8 7.8	7.8	4660	7	0.625
323	(3@4.5) 5-5-90-5#3-i-2.5-7-7	A B C	90°	Para	A1035	6.8 6.8 7.0	6.8	5950	12	0.625
324	(4@3) 5-5-90-5#3-i-2.5-7-7	A B C D	90°	Para	A1035	7.3 7.0 6.9 7.0	7.0	5950	12	0.625
325	(4@4) 5-5-90-5#3-i-2.5-2-7	A B C D	90°	Para	A1035	6.6 7.9 7.5 6.5	7.1	6430	11	0.625
326	(4@4) 5-5-90-5#3-i-2.5-2-6	A B C D	90°	Para	A1035	6.0 6.5 6.6 6.3	6.3	6430	11	0.625
327	(4@6) 5-8-90-5#3-i-2.5-2-6	A B C D	90°	Para	A1035	6.0 6.0 6.0 6.0	6.0	6690	21	0.625
328	(4@6) 5-8-90-5#3-i-2.5-6-6	A B C D	90°	Para	A1035	6.8 6.0 6.5 6.3	6.4	6690	21	0.625

Table B.4 Cont. Comprehensive test results and data for specimens containing multiple No. 5 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°
316	A B C D	0.073	12.9	8.1	5.3	8.375	2.5 5.0 4.8 2.5	2.5	1.9 2.0 1.9 1.8	1.9 1.9 1.6 -	4	30	B1
317	A B C D	0.073	13.0	10.1	5.3	8.375	2.5 5.0 4.9 2.5	2.5	1.8 2.4 2.1 2.4	1.9 1.9 1.8 -	4	30	B1
318	A B C	0.073	12.75	8.8	5.3	8.375	2.5 5.4 2.5	2.5	3.8 2.6 3.6	2.9 3.0 -	3	30	B1
319	A B C	0.073	10.85	8.0	5.3	8.375	2.5 5.0 2.5	2.5	2.0 1.8 2.0	2.1 1.9 -	3	30	B2
320	A B C	0.073	13.38	8.0	5.3	8.375	2.5 5.0 2.5	2.5	2.0 2.0 2.0	3.4 3.1 -	3	30	B2
321	A B C	0.073	18.5	10.7	5.3	8.375	2.6 8.7 2.7	2.6	2.3 7.0 2.3	5.5 5.9 -	3	30	B2
322	A B C	0.073	12.82	10.2	5.3	8.375	2.5 6.0 2.6	2.5	2.5 2.5 2.3	2.9 3.0 -	3	30	B2
323	A B C	0.073	11.27	14.0	5.3	8.375	2.5 5.1 2.6	2.5	7.3 7.3 7.0	2.0 2.4 -	3	30	B2
324	A B C D	0.073	11.9	14.3	5.3	8.375	2.3 4.4 4.7 2.7	2.5	7.0 7.3 7.4 7.3	1.5 1.5 1.4 -	4	30	B2
325	A B C D	0.073	12.5	9.1	5.3	8.375	2.5 4.6 4.6 2.4	2.4	2.5 1.3 1.6 2.6	1.5 2.0 1.6 -	4	30	B1
326	A B C D	0.073	13.1	8.5	5.3	8.375	2.5 5.1 5.0 2.6	2.6	2.5 2.0 1.9 2.3	2.0 1.8 1.8 -	4	30	B1
327	A B C D	0.073	17.8	8.0	5.3	8.375	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	30	B2
328	A B C D	0.073	16.8	8.0	5.3	8.375	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	30	B7

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.4 Cont. Comprehensive test results and data for specimens containing multiple No. 5 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
316	A	22446	21831	85621	21405	72406	69049	57277	-	FP
	B	22211	18818			71648			0.23	FP
	C	24049	23273			77577			-	FP
	D	21725	21699			70081			0.484	FP
317	A	23977	23111	104069	26017	77345	83926	73028	-	FP
	B	31206	28774			100665			0.365	FP
	C	35987	28714			116087			-	FP
	D	23712	23469			76490			0.398	FP
318	A	27125	27035	77489	25830	87498	83321	79002	-	FP
	B	32375	24934			104436			-	FP
	C	27035	25519			87210			-	FP
319	A	35751	35751	104667	34889	115326	112545	71151	-	FP
	B	34693	34518			111913			-	FP
	C	34397	34397			110958			-	FP
320	A	37827	37754	109345	36448	122023	117576	70176	-	FP
	B	34172	34152			110232			-	FP
	C	37469	37439			120868			-	FP
321	A	29485	27458	95052	31684	95112	102207	75777	-	FP/SB
	B	36685	34719			118338			-	FP/SB
	C	33007	32875			106475			-	FP/SB
322	A	34695	34636	99781	33260	111918	107291	75578	-	FP/SB
	B	34774	34483			112174			-	FP
	C	39269	30662			126675			-	FP
323	A	34328	34328	105337	35112	110736	113266	75300	-	FP/SB
	B	36923	34633			119105			-	FP/SB
	C	36432	36376			117522			-	FP/SB
324	A	29016	29016	117482	29370	93599	94744	61996	-	FP/SB
	B	29660	29505			95678			-	FP/SB
	C	29333	29298			94621			-	FP/SB
	D	29740	29664			95936			-	FP/SB
325	A	27259	26864	108458	27114	87932	87466	65295	-	FP
	B	37030	32039			119452			-	FP
	C	29522	29523			95232			-	FP
	D	22950	20032			74032			-	FP
326	A	24862	24863	103591	25898	80200	83541	58136	-	FP
	B	27208	27018			87768			-	FP
	C	26773	26774			86365			0.333	FP
	D	26616	24937			85858			-	FP
327	A	30306	30282	113284	28321	97761	91358	56099	-	FP
	B	30095	30085			97081			-	FP
	C	27572	27573			88942			-	FP
	D	25343	25344			81752			-	FP
328	A	3210	32083	124607	31152	10354	100489	59605	-	FP
	B	29935	29930			96565			-	FP
	C	30839	30839			99481			-	FP
	D	31800	31755			102581			-	FP

Table B.4 Cont. Comprehensive test results and data for specimens containing multiple No. 5 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
316	A B C D	60	0.38	0.11	2	4.0 (3.0)	0.66	6	4.0 (1.0)	0.375	3.0 (1.5)	0.375	2	1.27	60
317	A B C D	60	0.38	0.11	2	5.0 (3.0)	1.20	6	2.5 (1.0)	0.375	3.0 (1.5)	0.500	2	1.27	60
318	A B C	60	0.38	0.11	5	1.7 (1.3)	-	-	-	0.50	3.0 (1.8)	0.375	1	1.27	60
319	A B C	60	0.38	0.11	5	1.7 (0.9)	-	-	-	0.38	3.0 (1.5)	-	-	3.16	120
320	A B C	60	0.38	0.11	5	1.7 (0.9)	-	-	-	0.38	3.0 (1.5)	-	-	3.16	120
321	A B C	60	0.38	0.11	5	1.7 (0.9)	-	-	-	0.38	3.0 (1.5)	-	-	3.16	60
322	A B C	60	0.38	0.11	5	1.9 (0.75)	-	-	-	0.50	3.0 (1.5)	-	-	3.16	60
323	A B C	60	0.38	0.11	5	1.8 (0.9)	-	-	-	0.375	4.0 (2.0)	-	-	3.16	60
324	A B C D	60	0.38	0.11	5	1.8 (0.9)	-	-	-	0.375	4.0 (2.0)	-	-	3.16	60
325	A B C D	60	0.38	0.11	5	1.8 (0.75)	0.55	5	1.8 (0.75)	0.375	2.8 (1.5)	0.500	2	1.27	60
326	A B C D	60	0.38	0.11	5	2.0 (0.75)	0.55	5	2.0 (1.0)	0.375	3.0 (1.5)	0.375	2	1.27	60
327	A B C D	60	0.38	0.11	5	1.7 (0.9)	-	-	-	0.375	3.0 (1.5)	-	-	3.16	120
328	A B C D	60	0.38	0.11	5	1.7 (0.9)	-	-	-	0.375	3.0 (1.5)	-	-	4.74	120

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.4 Cont. Comprehensive test results and data for specimens containing multiple No. 5 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
329	(4@4) 5-8-90-5#3-i-2.5-2-6	A B C D	90°	Para	A1035	5.8 5.5 6.3 6.5	6.0	6700	22	0.625
330	(3@6) 5-8-90-5#3-i-3.5-2-6.25	A B C	90°	Para	A1035	6.3 6.3 6.3	6.3	10110	196	0.625
331	(2s) 5-5-90-0-i-2.5-2-8	A B C D	90°	-	A1035	8.0 8.0 6.5 6.4	7.2	4660	7	0.625
332	(3s) 5-5-90-0-i-2.5-2-8	A B C D E F	90°	-	A1035	8.0 7.8 8.0 6.6 6.5 6.8	7.3	4830	9	0.625
333	(2s) 5-5-90-2#3-i-2.5-2-8	A B C D	90°	Para	A1035	7.5 7.3 5.8 5.8	6.6	4860	8	0.625
334	(3s) 5-5-90-2#3-i-2.5-2-8	A B C D E F	90°	Para	A1035	7.6 7.9 7.8 6.0 5.9 6.3	6.9	4830	8	0.625
335	(2s) 5-5-90-5#3-i-2.5-2-8	A B C D	90°	Para	A1035	7.8 7.5 6.3 6.0	6.9	4660	7	0.625
336	(3s) 5-5-90-5#3-i-2.5-2-8	A B C D E F	90°	Para	A1035	7.3 7.3 7.3 5.6 5.6 5.6	6.4	4860	8	0.625
337	(2s) 5-5-90-6#3-i-2.5-2-8	A B C D	90°	Para	A1035	8.0 8.0 6.3 6.1	7.1	4660	7	0.625
338	(3s) 5-5-90-6#3-i-2.5-2-8	A B C D E F	90°	Para	A1035	7.5 7.6 7.6 6.0 6.0 6.0	6.8	4860	8	0.625

Table B.4 Cont. Comprehensive test results and data for specimens containing multiple No. 5 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°
329	A B C D	0.073	13.1	8.0	5.3	8.375	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	30	B2
330	A B C	0.073	15	8.3	5.3	8.375	3.5 6.6 3.8	3.6	2.1 2.1 2.1	2.6 3.3 -	3	30	B1
331	A B C D	0.073	13.0	10.5	5.3	8.375	2.4 2.6 2.4 2.6	2.5	2.4 2.5 3.9 4.1	6.8 6.8 6.8 6.8	4	30	B2
332	A B C D E F	0.073	13.1	10.2	5.3	8.375	2.6 6.2 2.9 2.7 6.1 2.9	2.8	2.3 2.5 2.2 3.6 3.8 3.4	2.9 2.9 2.9 2.9 2.9 2.9	6	30	B2
333	A B C D	0.073	13.0	9.9	5.3	8.375	2.5 2.7 2.5 2.7	2.6	2.5 2.6 4.3 4.1	6.5 6.5 6.5 6.5	4	30	B2
334	A B C D E F	0.073	13.4	10.4	5.3	8.375	2.5 6.4 2.5 2.5 6.4 2.5	2.5	2.8 2.5 2.6 4.4 4.5 4.1	3.3 3.3 2.9 3.3 3.3 2.9	6	30	B2
335	A B C D	0.073	13.1	10.1	5.3	8.375	2.5 2.6 2.5 2.6	2.5	2.4 2.6 3.9 4.1	6.8 6.8 6.8 6.8	4	30	B2
336	A B C D E F	0.073	13.4	10.2	5.3	8.375	2.5 6.4 2.5 2.5 6.4 2.5	2.5	2.9 2.9 3.0 4.5 4.5 4.6	3.3 3.3 3.1 3.3 3.3 3.1	6	30	B2
337	A B C D	0.073	12.9	10.2	5.3	8.375	2.3 2.6 2.3 2.6	2.4	2.3 2.1 4.0 4.0	6.8 6.8 6.8 6.8	4	30	B2
338	A B C D E F	0.073	13.3	10.1	5.3	8.375	2.5 6.3 2.7 2.5 6.3 2.7	2.6	2.6 2.5 2.5 4.1 4.1 4.1	3.1 3.1 3.0 3.1 3.1 3.0	6	30	B2

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.4 Cont. Comprehensive test results and data for specimens containing multiple No. 5 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
329	A	27967	27968	109970	27493	90216	88686	56141	-	FP
	B	27348	27348			88219			-	FP
	C	28550	28551			92097			-	FP
	D	26208	26103			84542			-	FP
330	A	36112	36112	105803	35268	116491	113766	89775	-	FP
	B	33789	33344			108996			-	FP
	C	40826	36347			131696			0.454	FP
331	A	16451	16402	66910	16727	53068	53959	56328	-	FP
	B	17860	17626			57614			-	FP
	C	16108	15896			51962			-	FP
	D	17180	16986			55418			-	FP
332	A	19256	18970	100822	16804	62115	54205	57756	-	FP/SB
	B	17777	17190			57344			-	FP/SB
	C	16665	16415			53759			-	FP/SB
	D	17653	17256			56945			-	FP/SB
	E	16840	16221			54324			-	FP/SB
	F	16076	14769			51859			-	FP/SB
333	A	24315	24192	98921	24730	78436	79775	52285	-	FP
	B	26070	25851			84097			-	FP
	C	24318	24318			78445			-	FP
	D	24942	24560			80457			-	FP
334	A	17748	17684	121700	20283	57252	65430	54791	-	FP/SB
	B	18646	18646			60149			-	FP/SB
	C	20129	19132			64933			-	FP/SB
	D	20126	20090			64921			-	FP/SB
	E	22971	19481			74100			-	FP/SB
	F	26728	26667			86220			-	FP/SB
335	A	26624	26565	104722	26180	85883	84453	67045	-	FP/SB
	B	25700	24572			82902			-	FP/SB
	C	35101	26610			113230			-	FP/SB
	D	30396	26975			98052			-	FP/SB
336	A	19579	19569	135587	22598	63157	72896	64137	-	FP/SB
	B	19723	19702			63621			-	FP/SB
	C	21562	21518			69555			-	FP/SB
	D	26618	26016			85866			-	FP/SB
	E	25828	25085			83316			-	FP/SB
	F	23711	23697			76488			-	FP/SB
337	A	30896	30675	118113	29528	99666	95253	69191	-	FP/SB
	B	28622	28481			92329			-	FP/SB
	C	33425	30220			107822			-	FP/SB
	D	34127	28737			110087			-	FP/SB
338	A	22860	21119	132487	22081	73743	71230	67655	-	FP/SB
	B	17958	17707			57928			-	FP/SB
	C	22305	19794			71950			-	FP/SB
	D	27432	25862			88492			-	FP/SB
	E	27393	25053			88365			-	FP/SB
	F	23024	22953			74270			-	FP/SB

Table B.4 Cont. Comprehensive test results and data for specimens containing multiple No. 5 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
329	A B C D	60	0.38	0.11	5	1.7 (0.9)	-	-	-	0.375	3.0 (1.5)	-	-	3.16	120
330	A B C	60	0.38	0.11	5	1.7 (1.3)	-	-	-	0.50	3.0 (1.8)	0.375	1	1.27	60
331	A B C D	60	-	-	-	-	-	-	-	0.500	3.0 (1.5)	-	-	3.16	60
332	A B C D E F	60	-	-	-	-	-	-	-	0.500	3.0 (1.5)	-	-	3.16	60
333	A B C D	60	0.38	0.11	2	3.0 (3.0)	-	-	-	0.500	3.0 (1.5)	-	-	3.16	60
334	A B C D E F	60	0.38	0.11	2	3.0 (3.0)	-	-	-	0.500	3.0 (1.5)	-	-	3.16	60
335	A B C D	60	0.38	0.11	5	1.9 (2.4)	-	-	-	0.500	3.0 (1.5)	-	-	3.16	60
336	A B C D E F	60	0.38	0.11	5	1.9 (2.4)	-	-	-	0.500	3.0 (1.5)	-	-	3.16	60
337	A B C D	60	0.38	0.11	6	1.9 (0.6)	-	-	-	0.500	3.0 (1.5)	-	-	3.16	60
338	A B C D E F	60	0.38	0.11	6	1.9 (0.6)	-	-	-	0.500	3.0 (1.5)	-	-	3.16	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.5 Comprehensive test results and data for specimens containing multiple No. 8 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
339	(3@5.5) 8-5-90-0-i-2.5-2-16	A B C	90°	-	A1035[b]	16.5 15.8 16.0	16.1	6255	13	1
340	(3@5.5) 8-5-90-0-i-2.5-2-10	A B C	90°	-	A1035[b]	9.0 9.4 9.8	9.4	6461	14	1
341	(3@5.5) 8-5-90-0-i-2.5-2-8	A B C	90°	-	A615	7.5 8.0 8.0	7.8	5730	18	1
342	(3@3) 8-5-90-0-i-2.5-2-10	A B C	90°	-	A615	10.0 10.3 10.0	10.1	4490	10	1
343	(3@5) 8-5-90-0-i-2.5-2-10	A B C	90°	-	A615	10.3 10.1 10.0	10.1	4490	10	1
344	(3@5.5) 8-8-90-0-i-2.5-2-8	A B C	90°	-	A1035[b]	7.8 8.8 7.3	7.9	8700	24	1
345	(3@3) 8-8-90-0-i-2.5-9-9	A B C	90°	-	A615	9.5 9.5 9.3	9.4	7510	21	1
346	(3@4) 8-8-90-0-i-2.5-9-9	A B C	90°	-	A615	9.3 9.3 9.3	9.3	7510	21	1
347	(3@3) 8-12-90-0-i-2.5-2-12	A B C	90°	-	A1035[c]	12.1 12.1 12.2	12.1	11040	31	1
348	(3@4) 8-12-90-0-i-2.5-2-12	A B C	90°	-	A1035[c]	12.9 12.5 12.5	12.6	11440	32	1
349	(3@5) 8-12-90-0-i-2.5-2-12	A B C	90°	-	A1035[c]	12.3 12.0 12.3	12.2	11460	33	1
350	(4@3) 8-8-90-0-i-2.5-9-9	A B C D	90°	-	A615	9.4 9.3 9.3 9.6	9.4	7510	21	1
351	(4@4) 8-8-90-0-i-2.5-9-9	A B C D	90°	-	A615	9.4 9.1 9.0 9.1	9.2	7510	21	1
352	(3@3) 8-5-180-0-i-2.5-2-10	A B C	180°	-	A615	9.8 10.0 9.8	9.8	5260	15	1
353	(3@5) 8-5-180-0-i-2.5-2-10	A B C	180°	-	A615	10.0 10.0 10.0	10.0	5260	15	1
354	(3@5.5) 8-5-90-2#3-i-2.5-2-14	A B C	90°	Para	A1035[b]	14.6 13.9 14.8	14.4	6460	14	1

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

Table B.5 Cont. Comprehensive test results and data for specimens containing multiple No. 8 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout[o]
339	A B C	0.078	17.3	18.1	10.5	8.375	2.6 8.0 2.8	2.7	1.6 2.4 2.1	4.4 4.5 -	3	30	B2
340	A B C	0.078	16.9	12.2	10.5	8.375	2.6 7.9 2.5	2.6	3.2 2.8 2.4	4.4 4.4 -	3	30	B2
341	A B C	0.073	17	10.0	10.5	8.375	2.5 8.0 2.5	2.5	2.5 2.0 2.0	4.5 4.5 -	3	30	B10
342	A B C	0.073	12.8	12.0	10.5	8.375	2.6 5.5 2.5	2.6	2.0 1.8 2.0	2.4 2.3 -	3	30	B2
343	A B C	0.073	16	12.0	10.5	8.375	2.3 7.3 2.5	2.4	1.8 1.9 2.0	4.0 4.3 -	3	30	B2
344	A B C	0.078	16.4	10.1	10.5	8.375	3.0 8.2 2.8	2.9	2.4 1.4 2.9	4.3 3.4 -	3	30	B2
345	A B C	0.073	12.3	18.0	10.5	8.375	2.5 5.6 2.5	2.5	8.5 8.5 8.8	2.1 2.1 -	3	30	B7
346	A B C	0.073	14.1	18.0	10.5	8.375	2.5 6.5 2.5	2.5	8.8 8.8 8.8	3.0 3.1 -	3	30	B7
347	A B C	0.073	12.1	14.0	10.5	8.375	2.5 5.4 2.4	2.5	1.8 1.9 1.8	2.1 2.0 -	3	30	B2
348	A B C	0.073	13.9	14.1	10.5	8.375	2.5 6.4 2.5	2.5	1.3 1.6 1.6	2.9 3.0 -	3	30	B2
349	A B C	0.073	15.9	14.0	10.5	8.375	2.4 7.4 2.5	2.4	1.8 2.0 1.8	4.0 4.0 -	3	30	B2
350	A B C D	0.073	15.0	18.0	10.5	8.375	2.5 5.5 5.5 2.5	2.5	8.6 8.8 8.8 8.4	2.0 2.0 2.0 -	4	30	B12
351	A B C D	0.073	18.3	18.0	10.5	8.375	2.5 6.6 6.5 2.5	2.5	8.6 8.9 9.0 8.9	3.1 3.1 3.0 -	4	30	B12
352	A B C	0.073	11.6	12.0	10.5	8.375	2.4 5.4 2.3	2.3	2.3 2.0 2.3	2.0 2.0 -	3	30	B10
353	A B C	0.073	16.5	12.0	10.5	8.375	2.5 7.8 2.5	2.5	2.0 2.0 2.0	4.3 4.3 -	3	30	B10
354	A B C	0.078	17.1	16.1	10.5	8.375	2.8 8.0 2.5	2.6	1.5 2.2 1.3	4.4 4.5 -	3	30	B2

[o] Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.5 Cont. Comprehensive test results and data for specimens containing multiple No. 8 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
	A	65266	65265			82615			-	FP
339	B	103741	76608	188393	62798	131318	79491	90858	0.191	FP
	C	46521	46520			58887			-	FP
	A	26783	26683			33903			-	FP
340	B	57434	55164	108161	36054	72701	45637	53826	-	FP
	C	26314	26314			33309			-	FP
	A	30459	30459			38556				FP
341	B	23292	23292	73234	24411	29484	30900	42354		FP
	C	19482	19482			24661			0.15	FP
	A	30671	30671			38824			0.09	FP
342	B	43708	33363	85439	28480	55327	36050	48261	0.12	FP
	C	21404	21405			27094			-	FP
	A	30145	30145			38158			0.015	FP
343	B	38965	34709	96899	32300	49323	40886	48357	-	FP
	C	3259	32045			4126			-	FP
	A	41000	37670			51899			-	FP
344	B	41000	37670	113010	37670	51899	47684	52744	-	FP
	C	41000	37670			51899			-	FP
	A	24580	24580			31114				FP
345	B	25019	25019	64314	21438	31670	27137	58289		FP
	C	14714	14714			18625				FP
	A	29402	29403			37218			0.026	FP
346	B	27244	27226	79058	26353	34486	33358	57258		FP
	C	22429	22429			28391				FP
	A	56490	56461			71506			0.194	SB
347	B	46273	38034	144116	48039	58573	60808	90999	-	FP
	C	55048	49621			69681			-	FP
	A	56769	56681			71859			0.255	FP/SS
348	B	76126	57568	167466	55822	96362	70661	96453	-	FP
	C	57723	53216			73067			-	FP/SS
	A	53307	53307			67477			-	FP
349	B	66123	42900	157056	52352	83700	66268	93033	-	FP
	C	60849	60849			77024			-	FP
	A	22186	22181			28083				FP
350	B	21191	21153	74637	18659	26824	23619	58031		FP
	C	18263	18251			23117				FP
	D	13052	13052			16521				FP
	A	20362	20362			25775				FP
351	B	19012	19012	72146	18036	24066	22831	56677		FP
	C	18477	18449			23389				FP
	D	14323	14323			18130				FP
	A	37063	37064			46915				FP
352	B	59803	59799	141746	47249	75700	59809	50941		FP
	C	44883	44884			56814				FP
	A	41465	40204			52487				FP
353	B	60400	59739	137789	45930	76456	58139	51804		FP
	C	37920	37846			48000			0.123	FP
	A	66835	66811			84601			-	FP
354	B	65764	42778	171782	57261	83246	72482	82766	-	FP
	C	62311	62193			78875			-	FP

Table B.5 Cont. Comprehensive test results and data for specimens containing multiple No. 8 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.²	N_{tr}	s_{tr}[a] in.	A_{cti} in.²	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.²	f_{ys} ksi
339	A B C	60	-	-	-	-	2.0	10	3 (1.5)	0.50	3.0 (1.5)	0.375	1	3.16	60
340	A B C	60	-	-	-	-	2.0	10	3 (1.5)	0.50	3.0 (1.5)	0.500	1	3.16	60
341	A B C	60	-	-	-	-	-	-	-	0.50	4.0 (1.5)	-	-	6.32	120
342	A B C	60	-	-	-	-	-	-	-	0.38	3.0 (1.5)	-	-	3.16	120
343	A B C	60	-	-	-	-	-	-	-	0.38	4.0 (1.5)	-	-	3.16	120
344	A B C	60	-	-	-	-	2.2	20	3 (2.1)	0.50	1.8 (0.9)	-	-	3.16	60
345	A B C	60	-	-	-	-	-	-	-	0.38	4.0 (2.5)	-	-	4.74	60
346	A B C	60	-	-	-	-	-	-	-	0.38	4.0 (2.5)	-	-	4.74	60
347	A B C	60	0.38	0.11	-	-	-	-	-	0.38	3.0 (1.5)	-	-	3.16	120
348	A B C	60	0.38	0.11	-	-	-	-	-	0.38	3.0 (1.5)	-	-	3.16	120
349	A B C	60	0.38	0.11	-	-	-	-	-	0.38	3.0 (1.5)	-	-	3.16	120
350	A B C D	60	-	-	-	-	-	-	-	0.375	4.0 (2.5)	-	-	6.32	60
351	A B C D	60	-	-	-	-	-	-	-	0.375	4.0 (2.5)	-	-	6.32	60
352	A B C	60	-	0.11	-	-	-	-	-	0.50	4.0 (1.5)	-	-	6.32	120
353	A B C	60	-	0.11	-	-	-	-	-	0.50	3.0 (1.5)	-	-	6.32	120
354	A B C	60	0.38	0.11	2	8 (3.5)	2.0	10	2.5 (1.3)	0.38	3.0 (1.5)	0.500	2	3.16	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.5 Cont. Comprehensive test results and data for specimens containing multiple No. 8 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
355	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5	A B C	90°	Para	A1035[b]	9.8 8.8 8.9	9.1	6460	14	1
356	(3@5.5) 8-5-90-2#3-i-2.5-2-14(1)	A B C	90°	Para	A1035[c]	14.7 15.2 14.8	14.9	5450	7	1
357	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5(1)	A B C	90°	Para	A1035[c]	7.3 8.9 8.4	8.2	5450	7	1
358	(3@3) 8-5-90-2#3-i-2.5-2-10	A B C	90°	Para	A615	9.9 10.1 10.0	10.0	4760	11	1
359	(3@5) 8-5-90-2#3-i-2.5-2-10	A B C	90°	Para	A615	10.5 10.6 10.4	10.5	4760	11	1
360	(3@3) 8-5-180-2#3-i-2.5-2-10	A B C	180°	Para	A615	10.5 10.3 10.0	10.3	5400	16	1
361	(3@5) 8-5-180-2#3-i-2.5-2-10	A B C	180°	Para	A615	9.6 9.8 9.8	9.7	5400	16	1
362	(3@5.5) 8-5-90-5#3-i-2.5-2-8	A B C	90°	Para	A1035[b]	8.0 8.1 7.8	8.0	6620	15	1
363	(3@5.5) 8-5-90-5#3-i-2.5-2-12	A B C	90°	Para	A1035[b]	12.4 12.1 12.1	12.2	6620	15	1
364	(3@5.5) 8-5-90-5#3-i-2.5-2-8(1)	A B C	90°	Para	A1035[c]	7.3 8.4 7.3	7.6	5660	8	1
365	(3@5.5) 8-5-90-5#3-i-2.5-2-12(1)	A B C	90°	Para	A1035[c]	11.4 12.5 12.0	12.0	5660	8	1
366	(3@5.5) 8-5-90-5#3-i-2.5-2-8(2)	A B C	90°	Para	A615	8.0 8.0 8.5	8.2	5730	18	1
367	(3@3) 8-5-90-5#3-i-2.5-2-10	A B C	90°	Para	A615	10.0 9.8 9.9	9.9	4810	12	1
368	(3@5) 8-5-90-5#3-i-2.5-2-10	A B C	90°	Para	A615	10.0 10.0 9.8	9.9	4850	13	1
369	(3@3) 8-8-90-5#3-i-2.5-9-9	A B C	90°	Para	A615	9.5 9.0 9.5	9.3	7440	22	1
370	(3@4) 8-8-90-5#3-i-2.5-9-9	A B C	90°	Para	A615	8.9 9.1 9.3	9.1	7440	22	1

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

Table B.5 Cont. Comprehensive test results and data for specimens containing multiple No. 8 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°
355	A B C	0.078	16.5	10.7	10.5	8.375	2.5 7.8 2.5	2.5	0.9 1.9 1.8	4.3 4.3 -	3	30	B4
356	A B C	0.073	16.8	16.4	10.5	8.375	2.8 7.9 2.6	2.7	1.7 1.2 1.6	4.2 4.3 -	3	30	B2
357	A B C	0.073	16.8	10.8	10.5	8.375	2.3 7.9 2.6	2.5	3.5 1.8 2.3	4.5 4.3 -	3	30	B2
358	A B C	0.073	12.1	12.0	10.5	8.375	2.6 5.6 2.5	2.6	2.1 1.9 2.0	2.0 2.0 -	3	30	B7
359	A B C	0.073	16.6	12.0	10.5	8.375	2.5 8.0 2.8	2.6	1.5 1.4 1.6	4.5 3.9 -	3	30	B2
360	A B C	0.073	12.3	12.0	10.5	8.375	2.5 5.5 2.8	2.6	1.5 1.8 2.0	2.0 2.0 -	3	30	B10
361	A B C	0.073	16.1	12.0	10.5	8.375	2.5 7.8 2.3	2.4	2.4 2.3 2.3	4.2 4.2 -	3	30	B10
362	A B C	0.078	16.6	10.2	10.5	8.375	2.5 7.6 2.5	2.5	2.2 2.1 2.4	4.1 4.5 -	3	30	B10
363	A B C	0.078	16.8	14.2	10.5	8.375	2.5 7.8 2.5	2.5	1.8 2.1 2.1	4.3 4.5 -	3	30	B1
364	A B C	0.073	16.6	10.1	10.5	8.375	2.9 7.6 2.9	2.9	2.9 1.8 2.9	3.8 4.1 -	3	30	B2
365	A B C	0.073	16.9	14.2	10.5	8.375	2.5 7.8 2.6	2.6	2.8 1.7 2.2	4.3 4.5 -	3	30	B2
366	A B C	0.073	17	10.0	10.5	8.375	2.8 8.0 2.3	2.5	2.0 2.0 1.5	4.5 4.5 -	3	30	B10
367	A B C	0.073	12.3	12.0	10.5	8.375	2.8 5.9 2.3	2.5	2.0 2.3 2.1	2.1 2.1 -	3	30	B7
368	A B C	0.073	16.3	12.0	10.5	8.375	2.5 7.5 2.8	2.6	2.0 2.0 2.3	4.0 4.0 -	3	30	B3
369	A B C	0.073	12	18.0	10.5	8.375	2.5 5.5 2.5	2.5	8.5 9.0 8.5	2.0 2.0 -	3	30	B7
370	A B C	0.073	14	18.0	10.5	8.375	2.5 6.5 2.5	2.5	9.1 8.9 8.8	3.0 3.0 -	3	30	B7

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.5 Cont. Comprehensive test results and data for specimens containing multiple No. 8 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
	A	25157	24718			31844			0.215	FP
355	B	68732	58920	122656	40885	87003	51754	52387	0.285	FP
	C	39164	39019			49575			-	FP
	A	58682	58531			74281			-	FP/TK
356	B	97141	67310	196009	65336	122963	82704	78438	-	FP/TK
	C	70217	70168			88882			-	FP/TK
	A	36593	35595			46320			-	FP
357	B	43607	30047	97104	32368	55199	40972	43284	-	FP
	C	35210	31462			44570			-	FP
	A	42191	42191			53406			0.26	FP
358	B	4159	41586	122162	40721	5264	51545	49174	0.18	FP
	C	38385	38385			48589			-	FP
	A	43315	43030			54829			0.26	FP
359	B	54636	48236	134004	44668	69159	56542	51745	0.26	FP
	C	42769	42739			54138			-	FP
	A	59807	59807			75705				FP
360	B	56145	56145	163728	54576	71070	69083	53801		FP
	C	47776	47776			60476			0.32	FP
	A	59312	59313			75078				FP
361	B	4934	49344	154502	51501	6246	65191	50958		FP
	C	45845	45845			58032			0.14	FP
	A	30586	30530			38716			0.388	FP
362	B	46989	46919	111379	37126	59480	46995	57814	0.477	FP
	C	34069	33930			43125			-	FP
	A	60325	60281			76361			0.198	FP
363	B	110823	80058	198283	66094	140282	83664	88689	-	FP
	C	59279	57944			75037			-	FP
	A	29839	29789			37771			-	FP
364	B	30241	29643	94108	31369	38280	39708	51219	0.297	FP
	C	34714	34676			43942			0.381	FP
	A	55543	44226			70308			-	FP
365	B	74581	74581	143554	47851	94406	60571	80327	0.435	FP
	C	44410	24747			56215			0.927	FP
	A	57652	57652			72977				FP
366	B	43308	43309	143982	47994	54820	60752	55196		FP
	C	43030	43021			54468			0.54	FP
	A	48766	48766			61729			-	FP
367	B	44849	44503	141829	47276	56771	59843	61149	0.13	FP
	C	48560	48560			61468			0	FP
	A	58896	58896			74552			-	FP
368	B	63376	55612	183916	61305	80223	77602	61662	-	FP
	C	69408	69408			87858			-	FP
	A	43346	43346			54868				FP
369	B	49666	38730	119286	39762	62868	50332	71880		FP
	C	37210	37211			47101				FP
	A	48534	48534			61435			0.1	FP
370	B	38602	30171	109678	36559	48863	46278	70115		FP
	C	31956	30973			40451				FP

Table B.5 Cont. Comprehensive test results and data for specimens containing multiple No. 8 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti}[b] in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
355	A B C	60	0.38	0.11	2	8 (3.5)	2.0	10	2.5 (1.3)	0.38	2.5 (1.3)	0.500	2	1.89	60
356	A B C	60	0.38	0.11	2	6 (3.5)	1.6	8	3 (1.3)	0.38	2.5 (1.5)	0.375	2	3.16	60
357	A B C	60	0.38	0.11	2	6 (3.5)	2.0	10	3 (1.3)	0.50	2.5 (1.3)	0.375	1	3.16	60
358	A B C	60	0.38	0.11	2	8.0 (3.0)	-	-	-	0.50	5.0 (1.5)	-	-	4.74	120
359	A B C	60	0.38	0.11	2	8.0 (3.0)	-	-	-	0.38	3.0 (1.5)	-	-	3.16	120
360	A B C	60	0.38	0.11	2	8.0 (3.0)	-	-	-	0.50	4.0 (1.5)	-	-	6.32	120
361	A B C	60	0.38	0.11	2	8.0 (3.0)	-	-	-	0.50	3.0 (1.5)	-	-	6.32	120
362	A B C	60	0.38	0.11	5	3 (1.5)	2.0	10	3.3 (1.5)	0.38	2.5 (1.3)	0.500	2	1.89	60
363	A B C	60	0.38	0.11	5	3 (1.5)	2.0	10	3.2 (1.5)	0.38	2.5 (1.3)	0.500	2	1.27	60
364	A B C	60	0.38	0.11	5	3 (1.5)	2.0	10	3 (1.5)	0.50	2.5 (1.3)	0.375	1	3.16	60
365	A B C	60	0.38	0.11	5	3 (1.5)	1.0	5	2.8 (1.5)	0.50	3.5 (1.3)	0.500	1	3.16	60
366	A B C	60	0.38	0.11	5	3 (1.5)	-	-	-	0.50	4.0 (1.5)	-	-	6.32	120
367	A B C	60	0.38	0.11	5	3 (1.5)	-	-	-	0.50	4.0 (1.5)	-	-	4.74	120
368	A B C	60	0.38	0.11	5	3 (1.5)	-	-	-	0.38	3.0 (1.5)	-	-	3.95	120
369	A B C	60	0.38	0.11	5	3 (1.5)	-	-	-	0.38	4.0 (2.5)	-	-	4.74	60
370	A B C	60	0.38	0.11	5	3 (1.5)	-	-	-	0.38	4.0 (2.5)	-	-	4.74	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[b] Value in parenthesis is the c-to-c spacing of the first cross-tie within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.5 Cont. Comprehensive test results and data for specimens containing multiple No. 8 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
371	(3@3) 8-12-90-5#3-i-2.5-2-12	A B C	90°	Para	A1035[c]	11.9 11.9 11.6	11.8	11040	31	1
372	(3@4) 8-12-90-5#3-i-2.5-2-12	A B C	90°	Para	A1035[c]	12.5 12.0 12.5	12.3	11440	32	1
373	(3@5) 8-12-90-5#3-i-2.5-2-12	A B C	90°	Para	A1035[c]	11.9 12.4 12.3	12.2	11460	33	1
374	(4@3) 8-8-90-5#3-i-2.5-9-9	A B C D	90°	Para	A615	9.3 9.3 9.3 9.3	9.3	7440	22	1
375	(4@4) 8-8-90-5#3-i-2.5-9-9	A B C D	90°	Para	A615	9.5 9.5 9.3 9.6	9.5	7440	22	1
376	(3@3) 8-5-180-5#3-i-2.5-2-10	A B C	180°	Para	A615	10.1 9.9 9.8	9.9	5540	17	1
377	(3@5) 8-5-180-5#3-i-2.5-2-10	A B C	180°	Para	A615	9.9 9.8 9.5	9.7	5540	17	1

Table B.5 Cont. Comprehensive test results and data for specimens containing multiple No. 8 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°
371	A B C	0.073	12	14.1	10.5	8.375	2.5 5.5 2.5	2.5	2.3 2.3 2.5	2.0 2.0 -	3	30	B2
372	A B C	0.073	13.8	14.3	10.5	8.375	2.5 6.3 2.5	2.5	1.8 2.3 1.8	2.8 3.0 -	3	30	B2
373	A B C	0.073	16	14.1	10.5	8.375	2.5 7.5 2.5	2.5	2.2 1.7 1.8	4.0 4.0 -	3	30	B2
374	A B C D	0.073	15.3	18.0	10.5	8.375	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	30	B7
375	A B C D	0.073	18.0	18.0	10.5	8.375	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	30	B7
376	A B C	0.073	12.5	12.0	10.5	8.375	2.8 5.8 2.8	2.8	1.9 2.1 2.3	2.0 2.0 -	3	30	B10
377	A B C	0.073	15.8	12.0	10.5	8.375	2.3 7.0 2.8	2.5	2.1 2.3 2.5	3.8 4.0 -	3	30	B10

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.5 Cont. Comprehensive test results and data for specimens containing multiple No. 8 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
371	A	70368	68183	186619	62206	89073	78742	110622	0.302	FP
	B	84954	56310			107537			0.256	FP
	C	62126	62127			78641			0.251	FP
372	A	70706	69965	194819	64940	89501	82202	117781	0.262	FP
	B	100028	68745			126618			-	FP
	C	63666	56110			80590			0.205	FP
373	A	59447	59447	194282	64761	75249	81976	116689	-	FP
	B	85455	65587			108171			-	FP
	C	69248	69248			87656			0.18	FP
374	A	32930	32930	125763	31441	41683	39798	71238		FP
	B	38749	38749			49049				FP
	C	27318	27290			34580				FP
	D	26809	26794			33936				FP
375	A	33657	33657	117937	29484	42604	37322	72922		FP
	B	30733	30723			38902				FP
	C	27886	27886			35299				FP
	D	25671	25671			32495				FP
376	A	50346	46175	176632	58877	63729	74528	65903		FP
	B	67397	65274			85313				FP
	C	66969	65183			84771			0.269	FP
377	A	55363	55236	176006	58669	70080	74264	64518		FP
	B	60892	60892			77078				FP
	C	59877	59877			75794			0.382	FP

Table B.5 Cont. Comprehensive test results and data for specimens containing multiple No. 8 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
371	A B C	60	0.38	0.11	5	3 (1.5)	-	-	-	0.38	3.0 (1.5)	-	-	3.16	120
372	A B C	60	0.38	0.11	5	3 (1.50	-	-	-	0.38	3.0 (1.5)	-	-	3.16	120
373	A B C	60	0.38	0.11	5	3 (1.5)	-	-	-	0.38	3.0 (1.5)	-	-	3.16	120
374	A B C D	60	0.38	0.11	5	3.0 (1.5)	-	-	-	0.375	4.0 (2.5)	-	-	4.74	60
375	A B C D	60	0.38	0.11	5	3.0 (1.5)	-	-	-	0.375	4.0 (2.5)	-	-	4.74	60
376	A B C	60	0.38	0.11	5	3 (1.5)	-	-	-	0.50	4.0 (1.5)	-	-	6.32	120
377	A B C	60	0.38		5	3 (1.5)	-	-	-	0.50	3.0 (1.5)	-	-	6.32	120

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.6 Comprehensive test results and data for specimens containing multiple No. 11 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
378	(3@5.35) 11-5-90-0-i-2.5-13-13	A B C	90°	-	A615	13.8 14.3 13.5	13.8	5330	11	1.41
379	(3@3.75) 11-8-90-0-i-2.5-2-20	A B C	90°	-	A1035	19.6 20.0 20.0	19.9	7070	30	1.41
380	(3@3.75) 11-8-90-0-i-2.5-2-24	A B C	90°	-	A1035	23.5 23.5 23.5	23.5	7070	30	1.41
381	(3@3.75) 11-12-90-0-i-2.5-2-22	A B C	90°	-	A615	21.9 21.3 21.9	21.7	11460	50	1.41
382	(3@5.35) 11-5-90-2#3-i-2.5-13-13	A B C	90°	Para	A615	14.0 14.0 13.8	13.9	5330	11	1.41
383	(3@3.75) 11-8-90-2#3-i-2.5-2-23	A B C	90°	Para	A1035	22.0 22.0 21.9	22.0	7070	31	1.41
384	(3@3.75) 11-12-90-2#3-i-2.5-2-21	A B C	90°	Para	A615	21.0 21.0 20.9	21.0	11850	51	1.41
385	(3@5.35) 11-5-90-6#3-i-2.5-13-13	A B C	90°	Para	A615	13.5 13.5 13.8	13.6	5280	12	1.41
386	(3@5.35) 11-5-90-6#3-i-2.5-18-18	A B C	90°	Para	A1035	18.6 18.6 18.6	18.6	5280	12	1.41
387	(3@3.75) 11-8-90-6#3-i-2.5-2-21	A B C	90°	Para	A1035	19.9 20.1 20.2	20.0	7070	51	1.41
388	(3@3.75) 11-12-90-6#3-i-2.5-2-19	A B C	90°	Para	A1035	18.4 18.1 18.4	18.3	11960	52	1.41
389	(3@3.75) 11-12-180-6#3-i-2.5-2-19	A B C	180°	Para	A1035	18.9 18.8 18.9	18.8	12190	56	1.41
390	(2s) 11-5-90-0-i-2.5-2-16	A B C D	90°	-	A1035	16.0 16.3 13.3 13.5	14.8	5030	9	1.41
391	(2s) 11-5-90-2#3-i-2.5-2-16	A B C D	90°	Para	A1035	15.9 16.0 13.3 13.3	14.6	5140	10	1.41
392	(2s) 11-5-90-6#3-i-2.5-2-16	A B C D	90°	Para	A1035	15.5 15.5 12.3 12.8	14.0	5030	9	1.41

Table B.6 Cont. Comprehensive test results and data for specimens containing multiple No. 11 hooked bars

	Hook	R_r	b **in.**	h **in.**	h_{cl} **in.**	h_c **in.**	c_{so} **in.**	$c_{so,avg}$ **in.**	c_{th} **in.**	c_h **in.**	N_h	**Axial Load** **kips**	**Long. Reinf. Layout**[o]
378	A B C	0.085	22.3	26.0	19.5	8.375	2.6 10.0 2.6	2.6	12.3 11.8 12.5	6.6 6.3 -	3	162	B14
379	A B C	0.085	17.5	22.1	19.5	8.375	2.7 7.9 2.7	2.7	2.4 2.0 2.3	3.8 4.1 -	3	108	B14
380	A B C	0.085	17.9	26.3	19.5	8.375	2.7 8.1 2.9	2.8	2.8 2.8 2.9	4.0 4.1 -	3	132	B14
381	A B C	0.085	18.1	24.1	19.5	8.375	2.8 8.3 2.9	2.9	2.1 2.8 2.4	4.1 4.1 -	3	122	B14
382	A B C	0.085	21.5	26.0	19.5	8.375	2.6 10.0 2.6	2.6	12.0 12.0 12.3	6.1 6.1 -	3	157	B14
383	A B C	0.085	17.5	25.4	19.5	8.375	2.5 7.8 2.8	2.7	3.3 3.3 3.8	3.8 4.1 -	3	124	B14
384	A B C	0.085	17.9	23.0	19.5	8.375	2.7 8.2 2.8	2.7	1.8 2.1 2.3	4.1 4.1 -	3	115	B14
385	A B C	0.085	21.3	26.0	19.5	8.375	2.6 10.0 2.7	2.6	12.5 12.5 12.3	6.0 5.8 -	3	155	B14
386	A B C	0.085	21.2	36.0	19.5	8.375	2.5 10.0 2.8	2.7	17.4 17.4 17.4	6.1 5.6 -	3	214	B14
387	A B C	0.085	18.1	23.3	19.5	8.375	2.8 8.4 2.7	2.7	3.4 3.2 3.2	4.2 4.2 -	3	118	B14
388	A B C	0.085	17.9	21.1	19.5	8.375	2.8 8.2 2.8	2.8	2.8 3.0 2.6	4.0 4.1 -	3	106	B14
389	A B C	0.085	17.5	21.1	19.5	8.375	2.9 8.2 2.5	2.7	2.1 2.3 2.5	3.8 4.0 -	3	104	B14
390	A B C D	0.085	21.7	18.1	19.5	8.375	2.5 2.8 2.5 2.8	2.7	2.0 2.0 4.8 4.8	13.6 13.6 13.6 13.6	4	110	B18
391	A B C D	0.085	21.7	18.4	19.5	8.375	2.5 2.5 2.5 2.5	2.5	2.6 2.3 5.5 5.0	13.8 13.8 13.8 13.8	4	112	B18
392	A B C D	0.085	22	18.4	19.5	8.375	2.8 2.8 2.8 2.8	2.8	2.9 2.9 6.1 5.6	13.6 13.6 13.6 13.6	4	113	B18

[o] Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.6 Cont. Comprehensive test results and data for specimens containing multiple No. 11 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
	A	45416	45405			29113			0.113	FP
378	B	49897	49897	154517	51506	31985	33016	51162	-	FP
	C	59323	59215			38028			-	FP
	A	99788	99284			63967			-	FP/SS
379	B	112356	91009	295464	98488	72023	63133	84665	-	FP/SS
	C	107432	105171			68867			-	FP/SS
	A	118707	118707			76094			-	FP/SS
380	B	140381	132010	380928	126976	89988	81395	100099	-	FP/SS
	C	130244	130212			83490			-	FP/SS
	A	127199	126150			81538			-	SS/FP
381	B	131246	125954	369539	123180	84132	78961	117518	-	SS/FP
	C	118472	117434			75944			-	SS/FP
	A	50926	50926			32645			-	FP
382	B	58487	58487	173762	57921	37492	37129	51470	-	FP
	C	64473	64349			41329			-	FP
	A	119045	117909			76311			-	FP/SS
383	B	139657	120432	349768	116589	89524	74737	93539	-	FP/SS
	C	111428	111428			71428			-	FP/SS
	A	129640	129578			83103			-	SS
384	B	131158	127727	383435	127812	84076	81930	115585	-	SS
	C	126160	126130			80872			-	SS
	A	59664	59647			38246			-	FP
385	B	66536	66536	198533	66178	42651	42422	62501	-	FP
	C	72350	72350			46378			-	FP
	A	103312	100804			66226			-	FP
386	B	147805	121063	335601	111867	94747	71710	85699	-	FP
	C	113923	113733			73027			-	FP
	A	118266	118209			75811			-	FP/SS
387	B	174241	112198	333863	111288	111693	71338	106701	-	FP/SS
	C	104398	103456			66922			-	FP/SS
	A	115766	115766			74209			-	FP/SS
388	B	120830	120824	354900	118300	77455	75833	126707	-	FP/SS
	C	118310	118310			75840			-	FP/SS
	A	119106	119075			76350			-	FP/SS
389	B	173226	120760	357136	119045	111042	76311	131695	-	FP/SS
	C	123231	117301			78994			-	FP/SS
	A	55287	55287			35440			-	SS
390	B	59579	59571	191800	47950	38192	30737	52994		SS
	C	37935	37353			24317			-	SS
	D	39589	39589			25377			-	SS
	A	57407	57407			36800			-	SS
391	B	62971	62971	231994	57998	40366	37178	53008		SS
	C	53264	53239			34143			-	SS
	D	58430	58377			37455			-	SS
	A	61785	61701			39606			-	SS
392	B	67354	67354	248710	62177	43176	39857	62875		SS
	C	61978	61978			39730			-	SS
	D	57746	57676			37017			-	SS

Table B.6 Cont. Comprehensive test results and data for specimens containing multiple No. 11 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
378	A B C	60	-	-	-	-	-	-	-	0.50	7.0 (3.5)	-	-	7.90	60
379	A B C	60	-	-	-	-	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
380	A B C	60	-	-	-	-	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
381	A B C	60	-	-	-	-	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
382	A B C	60	0.38	0.11	2	8 (8.0)	-	-	-	0.50	7.0 (3.5)	-	-	7.90	60
383	A B C	60	0.38	0.11	2	8 (8.0)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
384	A B C	60	0.38	0.11	2	8 (8.0)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
385	A B C	60	0.38	0.11	6	4 (2.0)	-	-	-	0.50	7.0 (3.5)	-	-	7.90	60
386	A B C	60	0.38	0.11	6	4 (2.0)	-	-	-	0.50	7.0 (3.5)	-	-	7.90	60
387	A B C	60	0.38	0.11	6	4 (2.0)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
388	A B C	60	0.38	0.11	6	4 (2.0)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
389	A B C	60	0.38	0.11	6	4 (2.0)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
390	A B C D	60	-	-	-	-	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
391	A B C D	60	0.38	0.11	2	8 (8.0)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
392	A B C D	60	0.38	0.11	6	4 (4.8)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.6 Cont. Comprehensive test results and data for specimens containing multiple No. 11 hooked bars

	Specimen	Hook	Bend Angle	Trans. Reinf. Orient.	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Age days	d_b in.
393	(2s) 11-5-90-7#3-i-2.5-2-16	A	90°	Para	A1035	15.5	14.3	5140	10	1.41
		B				15.5				
		C				13.0				
		D				13.0				
394	(2s) 11-5-90-8#3-i-2.5-2-16	A	90°	Para	A1035	15.9	14.6	5140	10	1.41
		B				15.9				
		C				13.3				
		D				13.3				

Table B.6 Cont. Comprehensive test results and data for specimens containing multiple No. 11 hooked bars

	Hook	R_r	b in.	h in.	h_{cl} in.	h_c in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	Axial Load kips	Long. Reinf. Layout°
393	A	0.085	21.8	18.4	19.5	8.375	2.8	2.7	2.9	13.5	4	112	B18
	B						2.7		2.9	13.5			
	C						2.8		5.4	13.5			
	D						2.7		5.4	13.5			
394	A	0.085	21.7	18.6	19.5	8.375	2.5	2.5	2.3	13.8	4	113	B18
	B						2.5		3.1	13.8			
	C						2.5		4.9	13.8			
	D						2.5		5.8	13.8			

° Longitudinal column configurations shown in Appendix B, Layouts B1 – B19

Table B.6 Cont. Comprehensive test results and data for specimens containing multiple No. 11 hooked bars

	Hook	T_{max} lb	T_{ind} lb	T_{total} lb	T lb	$f_{su,max}$ psi	f_{su} psi	$f_{s,ACI}$ psi	Slip at Failure in.	Failure Type
393	A	73174	73124	269727	67432	46906	43225	64693	-	SS
	B	77729	77621			49826				SS
	C	60463	60239			38759			-	SS
	D	58805	58743			37695			-	SS
394	A	81845	77857	282018	70505	52464	45195	66123	-	SS
	B	74134	74134			47522				SS
	C	67907	65363			43530			-	SS
	D	64726	64664			41491			-	SS

Table B.6 Cont. Comprehensive test results and data for specimens containing multiple No. 11 hooked bars

	Hook	f_{yt} ksi	d_{tr} in.	$A_{tr,l}$ in.^{2}	N_{tr}	s_{tr}[a] in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s[c] in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
393	A B C D	60	0.38	0.11	7	4 (1.5)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60
394	A B C D	60	0.38	0.11	8	3.3 (1.5)	-	-	-	0.50	2.5 (1.5)	-	-	7.90	60

[a] Value in parenthesis is the c-to-c spacing of the first hoop within the joint to the straight portion of the hooked bars
[c] Value in parenthesis is the c-to-c spacing of the first hoop above the joint to the straight portion of the hooked bars

Table B.7 Test results for other researches referenced in this study

		Specimen	Bend Angle	ℓ_{eh} in.	f_{cm} psi	f_y psi	d_b in.	b in.	h_{cl} in.
Marques and Jirsa (1975)	395	J7-180-12-1H	180°	10	4350	64000	0.88	12	11.5
	396	J7-180-15-1 H	180°	13	4000	64000	0.88	12	11.5
	397	J7-90-12-1H	90°	10	4150	64000	0.88	12	11.5
	398	J7-90-15-1-H	90°	13	4600	64000	0.88	12	11.5
	399	J7-90-15-1- L	90°	13	4800	64000	0.88	12	11.5
	400	J7-90-15-1M	90°	13	5050	64000	0.88	12	11.5
	401	J11-180-15-1H	180°	13.1	4400	68000	1.41	12	11.3
	402	J11-90-12-1H	90°	10.1	4600	68000	1.41	12	11.3
	403	J11-90-15-1H	90°	13.1	4900	68000	1.41	12	11.3
	404	J11-90-15-1L	90°	13.1	4750	68000	1.41	12	11.3
	405	J 7- 90 -15 -3a - H	90°	13	3750	64000	0.88	12	11.5
	406	J 7- 90 -15 -3 - H	90°	13	4650	64000	0.88	12	11.5
	407	J 11- 90 -15 -3a - L	90°	13.1	5000	68000	1.41	12	11.3
	408	J 11- 90 -15 -3 - L	90°	13.1	4850	68000	1.41	12	11.3
Pinc et al. (1977)	409	9-12	90°	10	4700	65000	1.13	12	*
	410	11-15	90°	13.1	5400	60000	1.41	12	*
	411	11-18	90°	16.1	4700	60000	1.41	12	*
Hamad et al. (1993)	412	7-90-U	90°	10	2570	60000[a]	0.88	12	11
	413	7-90-U'	90°	10	5400	60000[a]	0.88	12	11
	414	11-90-U	90°	13	2570	60000[a]	1.41	12	11
	415	11-90-U'	90°	13	5400	60000[a]	1.41	12	11
	416	11-180-U-HS	180°	13	7200	60000[a]	1.41	12	11
	417	11-90-U-HS	90°	13	7200	60000[a]	1.41	12	11
	418	11-90-U-T6	90°	13	3700	60000[a]	1.41	12	11
	419	7-180-U-T4	180°	10	3900	60000[a]	0.88	12	11
	420	11-90-U-T4	90°	13	4230	60000[a]	1.41	12	11
Ramirez & Russel (2008)	421	I-1	90°	6.5	8910	81900	0.75	15	12
	422	I-3	90°	6.5	12460	81900	0.75	15	12
	423	I-5	90°	6.5	12850	81900	0.75	15	12
	424	I-2	90°	12.5	8910	63100	1.41	15	12
	425	I-2'	90°	15.5	9540	63100	1.41	15	12
	426	I-4	90°	12.5	12460	63100	1.41	15	12
	427	I-6	90°	12.5	12850	63100	1.41	15	12
	428	III-13	90°	6.5	13980	81900	0.75	15	12
	429	III-15	90°	6.5	16350	81900	0.75	15	12
	430	III-14	90°	12.5	13980	63100	1.41	15	12
	431	III-16	90°	12.5	16500	63100	1.41	15	12
Lee & Park (2010)	432	H1	90°	18.7	4450	87000	0.88	14.6	*
	433	H2	90°	11.9	8270	87000	0.88	14.6	*
	434	H3	90°	15	4450	87000	0.88	14.6	*

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

Table B.7 Cont. Test results for other researches referenced in this study

		h_c	c_{so}	c_{th}	c_h	N_h	A_h	d_{tr}	$A_{tr,l}$†	N_{tr}	s_{tr}	T
		in.	in.	in.	in.		in.^{2}	in.	in.^{2}		in.	lb
Marques and Jirsa (1975)	395	6	2.88	2	4.5	2	0.6	-	-	-	-	36600
	396	6	2.88	2	4.5	2	0.6	-	-	-	-	52200
	397	6	2.88	2	4.5	2	0.6	-	-	-	-	37200
	398	6	2.88	2	4.5	2	0.6	-	-	-	-	54600
	399	6	2.88	2	4.5	2	0.6	-	-	-	-	58200
	400	6	2.88	2	4.5	2	0.6	-	-	-	-	60000
	401	6	2.88	1.5	3.4	2	1.56	-	-	-	-	70200
	402	6	2.88	1.5	3.4	2	1.56	-	-	-	-	65520
	403	6	2.88	1.5	3.4	2	1.56	-	-	-	-	74880
	404	6	2.88	1.5	3.4	2	1.56	-	-	-	-	81120
	405	6	2.88	2	4.5	2	0.6	0.375	0.11	8	2.5	58800
	406	6	2.88	2	4.5	2	0.6	0.375	0.11	4	5	62400
	407	6	2.88	1.5	3.4	2	1.56	0.375	0.11	8	2.5	107640
	408	6	2.88	1.5	3.4	2	1.56	0.375	0.11	4	5	96720
Pinc et al. (1977)	409	*	2.88	2	4	2	1	-	-	-		47000
	410	*	2.88	2	3.4	2	1.56	-	-	-		78000
	411	*	2.88	2	3.4	2	1.56	-	-	-		90480
Hamad et al. (1993)	412	6	3	2	4.25	2	0.6	-	-	-	-	25998
	413	6	3	2	4.25	2	0.6	-	-	-	-	36732
	414	6	3	2	3.18	2	1.56	-	-	-	-	48048
	415	6	3	2	3.18	2	1.56	-	-	-	-	75005
	416	6	3	2	3.18	2	1.56	-	-	-	-	58843
	417	6	3	2	3.18	2	1.56	-	-	-	-	73788
	418	6	3	2	3.18	2	1.56	0.375	0.11	4	6	71807
	419	6	3	2	4.25	2	0.6	0.375	0.11	2	4	34620
	420	6	3	2	3.18	2	1.56	0.375	0.11	6	4	83190
Ramirez & Russel (2008)	421	6	2.5	2.5	8.5	2	0.44	-	-	-	-	30000
	422	6	2.5	2.5	8.5	2	0.44	-	-	-	-	30000
	423	6	2.5	2.5	8.5	2	0.44	-	-	-	-	30500
	424	6	2.5	2.5	7.18	2	1.56	-	-	-	-	88000
	425	6	2.5	2.5	7.18	2	1.56	-	-	-	-	105000
	426	6	2.5	2.5	7.18	2	1.56	-	-	-	-	99100
	427	6	2.5	2.5	7.18	2	1.56	-	-	-	-	114000
	428	6	2.5	2.5	8.5	2	0.44	0.375	0.11	4	7.5	41300
	429	6	2.5	2.5	8.5	2	0.44	0.375	0.11	4	7.5	38500
	430	6	2.5	2.5	7.18	2	1.56	0.375	0.11	6	7.5	105000
	431	6	2.5	2.5	7.18	2	1.56	0.375	0.11	6	7.5	120000
Lee & Park (2010)	432	*	3	2	7	2	0.6	-	-	-	-	59208
	433	*	3	2	7	2	0.6	-	-	-	-	52797
	434	*	3	2	7	2	0.6	0.375	0.11	4	2.63	53761

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

Table B.7 Cont. Test results for other researches referenced in this study

		Specimen	Bend Angle	ℓ_{eh}	f_{cm}	f_y	d_b	b	h_{cl}
				in.	psi	psi	in.	in.	in.
Joh et al. (1995)	435	LA 1-1	90°	7.9	4480	95440	0.75	11.8	12.9
	436	LA 1-3	90°	12.6	5433	95440	0.75	11.8	12.9
	437	LA 3-2	90°	7.9	5192	95440	0.75	11.8	12.9
	438	LA 4-1	90°	7.9	5049	95440	0.75	10.7	12.9
	439	LA 4-2	90°	7.9	5049	95440	0.75	12.9	12.9
	440	LA 5-1	90°	7.9	5049	95440	0.75	13.8	12.9
	441	LA 5-2	90°	7.9	5049	95440	0.75	15.7	12.9
	442	LA 7-1	90°	7.9	4651	95440	0.75	11.8	12.9
	443	LA 7-2	90°	7.9	4495	95440	0.75	11.8	12.9
	444	LA 8-1	90°	7.9	5405	95440	0.75	11.8	12.9
	445	LA 8-2	90°	7.9	5661	95440	0.75	11.8	12.9
	446	LA 10-1	90°	7.9	6927	95440	0.75	11.8	12.9
	447	LA 10-2	90°	7.9	10724	95440	0.75	11.8	12.9
Joh and Shibata (1996)	448	LA 8-1	90°	7.9	5405	96980	0.75	11.8	12.9
	449	LA 8-2	90°	7.9	5661	96980	0.75	11.8	12.9
	450	LA 8-3	90°	7.9	4338	96980	0.75	11.8	12.9
	451	LA 8-4	90°	7.9	4153	96980	0.75	11.8	12.9
	452	LA 8-5	90°	7.9	3698	96980	0.75	11.8	12.9
	453	LA 8-6	90°	7.9	3968	96980	0.75	11.8	12.9
	454	LA 8-7	90°	7.9	7737	96980	0.75	11.8	12.9
	455	LA 8-8	90°	7.9	8065	96980	0.75	11.8	12.9
	456	LA 5-1	90°	7.9	4473	96980	0.75	13.8	12.9
	457	LA 5-2	90°	7.9	4757	96980	0.75	15.7	12.9
	458	LA 5-3	90°	7.9	5041	96980	0.75	17.2	12.9
	459	LA 5-4	90°	7.9	4544	96980	0.75	22.5	12.9
	460	LA 5-5	90°	7.9	3564	96980	0.75	27.6	12.9
Johnson & Jirsa (1981)	461	4-3.5-8-M	90°	2	4500	67500	0.5	24	6
	462	4-5-11-M	90°	3.5	4500	67500	0.5	24	9
	463	4-5-14-M	90°	3.5	4500	67500	0.5	24	12
	464	7-5-8-L	90°	3.5	2500	67500	0.88	24	6
	465	7-5-8-M	90°	3.5	4600	67500	0.88	24	6
	466	7-5-8-H	90°	3.5	5450	67500	0.88	24	6
	467	7-5-14-L	90°	3.5	2500	67500	0.88	24	12
	468	7-5-14-M	90°	3.5	4100	67500	0.88	24	12
	469	7-5-14-H	90°	3.5	5450	67500	0.88	24	12
	470	7-7-8-M	90°	5.5	4480	67500	0.88	24	6
	471	7-7-11-M	90°	5.5	4480	67500	0.88	24	9
	472	7-7-14-M	90°	5.5	5450	67500	0.88	24	12
	473	9-7-11-M	90°	5.5	4500	67500	1.13	24	9
	474	9-7-14-M	90°	5.5	5450	67500	1.13	24	12

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

Table B.7 Cont. Test results for other researches referenced in this study

		h_c	c_{so}	c_{th}	c_h	N_h	A_h	d_{tr}	$A_{tr,l}$[†]	N_{tr}	s_{tr}	T
		in.	in.	in.	in.		in.^{2}	in.	in.^{2}		in.	lb
Joh et al. (1995)	435	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	13120
	436	*	2.2	3.1	1.5	4	0.44	0.24	0.045	8	3.54	34343
	437	*	2.2	11.8	1.5	4	0.44	0.24	0.045	8	3.54	20231
	438	*	2.2	7.9	1.1	4	0.44	0.24	0.045	8	3.54	13230
	439	*	2.2	7.9	1.9	4	0.44	0.24	0.045	8	3.54	17640
	440	*	3.1	7.9	1.5	4	0.44	0.24	0.045	8	3.54	16593
	441	*	4.1	7.9	1.5	4	0.44	0.24	0.045	8	3.54	14939
	442	*	2.2	7.9	1.5	4	0.44	0.24	0.045	16	3.54	15159
	443	*	2.2	7.9	1.5	4	0.44	0.24	0.045	32	1.77	22822
	444	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	25247
	445	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	25027
	446	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	19294
	447	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	26956
Joh and Shibata (1996)	448	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	25468
	449	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	26019
	450	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	21113
	451	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	21058
	452	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	17089
	453	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	20286
	454	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	34178
	455	*	2.2	7.9	1.5	4	0.44	0.24	0.045	8	3.54	28941
	456	*	3.1	7.9	1.5	4	0.44	0.24	0.045	8	3.54	17695
	457	*	4.1	7.9	1.5	4	0.44	0.24	0.045	8	3.54	15380
	458	*	4.9	7.9	1.5	4	0.44	0.24	0.045	8	3.54	19349
	459	*	7.5	7.9	1.5	4	0.44	0.24	0.045	8	3.54	17420
	460	*	10.0	7.9	1.5	4	0.44	0.24	0.045	8	3.54	14608
Johnson & Jirsa (1981)	461	4	11.75	1.5	-	1	0.2	-	-	-	-	4400
	462	4	11.75	1.5	-	1	0.2	-	-	-	-	12000
	463	4	11.75	1.5	-	1	0.2	-	-	-	-	9800
	464	4	11.56	1.5	-	1	0.6	-	-	-	-	13000
	465	4	11.56	1.5	-	1	0.6	-	-	-	-	16500
	466	4	11.56	1.5	-	1	0.6	-	-	-	-	19500
	467	4	11.56	1.5	-	1	0.6	-	-	-	-	8500
	468	4	11.56	1.5	-	1	0.6	-	-	-	-	11200
	469	4	11.56	1.5	-	1	0.6	-	-	-	-	11900
	470	4	11.56	1.5	-	1	0.6	-	-	-	-	32000
	471	4	11.56	1.5	-	1	0.6	-	-	-	-	27000
	472	4	11.56	1.5	-	1	0.6	-	-	-	-	22000
	473	4	11.44	1.5	-	1	1	-	-	-	-	30800
	474	4	11.44	1.5	-	1	1	-	-	-	-	24800

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

Table B.7 Cont. Test results for other researches referenced in this study

		Specimen	Bend Angle	ℓ_{eh}	f_{cm}	f_y	d_b	b	h_{cl}
				in.	psi	psi	in.	in.	in.
Johnson & Jirsa (1981)	475	9-7-18-M	90°	5.5	4570	67500	1.13	24	16
	476	7-8-11-M	90°	6.5	5400	67500	0.88	24	9
	477	7-8-14-M	90°	6.5	4100	67500	0.88	24	12
	478	9-8-14-M	90°	6.5	5400	67500	1.13	24	12
	479	11-8.5-11-L	90°	7	2400	67500	1.41	24	9
	480	11-8.5-11-M	90°	7	4800	67500	1.41	24	9
	481	11-8.5-11-H	90°	7	5450	67500	1.41	24	9
	482	11-8.5-14-L	90°	7	2400	67500	1.41	24	12
	483	11-8.5-14-M	90°	7	4750	67500	1.41	24	12
	484	11-8.5-14-H	90°	7	5450	67500	1.41	24	12
	485	7-7-11-M	90°	5.5	3800	67500	0.875	72	9
	486	7-7-11-L	90°	5.5	3000	67500	0.875	72	9
	487	11-8.5-11-M	90°	7	3800	67500	1.41	72	9
	488	11-8.5-11-L	90°	7	3000	67500	1.41	72	9
	489	7-5-8-M	90°	5.5	3640	67500	0.88	24	6
	490	7-5-14-M	90°	5.5	3640	67500	0.88	24	12

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

Table B.7 Cont. Test results for other researches referenced in this study

		h_c	c_{so}	c_{th}	c_h	N_h	A_h	d_{tr}	$A_{tr,l}$[†]	N_{tr}	s_{tr}	T
		in.	in.	in.	in.		in.^{2}	in.	in.^{2}		in.	lb
Johnson & Jirsa (1981)	475	4	11.44	1.5	-	1	1	-	-	-	-	22300
	476	4	11.56	1.5	-	1	1	-	-	-	-	34800
	477	4	11.56	1.5	-	1	1	-	-	-	-	26500
	478	4	11.44	1.5	-	1	1	-	-	-	-	30700
	479	4	11.3	1.5	-	1	1.56	-	-	-	-	37000
	480	4	11.3	1.5	-	1	1.56	-	-	-	-	51500
	481	4	11.3	1.5	-	1	1.56	-	-	-	-	54800
	482	4	11.3	1.5	-	1	1.56	-	-	-	-	31000
	483	4	11.3	1.5	-	1	1.56	-	-	-	-	39000
	484	4	11.3	1.5	-	1	1.56	-	-	-	-	45500
	485	4	24.56	1.5	11	3	0.6	-	-	-	-	24000
	486	4	14.06	1.5	22	3	0.6	-	-	-	-	22700
	487	4	24.3	1.5	11	3	1.56	-	-	-	-	38000
	488	4	13.8	1.5	22	3	1.56	-	-	-	-	40000
	489	4	11.56	1.5	-	1	0.6	-	-	-	-	14700
	490	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

APPENDIX C: TEST-TO-CALCULATED

Table C.1 Test-to-calculated ratios for specimens containing two No. 5 hooked bars

	Specimen	*T*	Descriptive Equation		Design Equation	
		lb	T_h **(lb)**	T/T_h	T_h **(lb)**	T/T_h
1	5-5-90-0-o-1.5-2-5	14069	16590	0.85	11683	1.20
2	5-5-90-0-o-1.5-2-6.5	17813	21808	0.82	14989	1.19
3	5-5-90-0-o-1.5-2-8	23455	28265	0.83	19038	1.23
4	5-5-90-0-o-2.5-2-5	19283	15692	1.23	11099	1.74
5	5-5-90-0-o-2.5-2-8	30340	32889	0.92	21882	1.39
6	5-5-180-0-o-1.5-2-9.5	29486	31992	0.92	21457	1.37
7	5-5-180-0-o-1.5-2-11.25	32374	38963	0.83	25721	1.26
8	5-5-180-0-o-2.5-2-9.5	30128	32435	0.93	21720	1.39
9	5-5-90-0-i-2.5-2-8	32448	27694	1.17	23435	1.38
10	(2@9) 5-5-90-0-i-2.5-7-7	28980	24683	1.17	20984	1.38
11	5-5-90-0-i-2.5-2-10	33583	33379	1.01	27789	1.21
12	5-5-90-0-i-2.5-2-7	26265	24025	1.09	20524	1.28
13	5-8-90-0-i-2.5-2-6	29570	26929	1.10	22557	1.31
14	5-8-90-0-i-2.5-2-6(1)	22425	25578	0.88	21478	1.04
15	5-8-90-0-i-2.5-2-8	31673	31422	1.01	25998	1.22
16	(2@4) 5-8-90-0-i-2.5-2-6	22353	21867	1.02	14023	1.59
17	(2@6) 5-8-90-0-i-2.5-2-6	23951	22372	1.07	19095	1.25
18	5-12-90-0-i-2.5-2-10	41657	46084	0.90	36861	1.13
19	5-12-90-0-i-2.5-2-5	19220	21064	0.91	17860	1.08
20	5-15-90-0-i-2.5-2-5.5	32511	28183	1.15	23203	1.40
21	5-15-90-0-i-2.5-2-7.5	42221	34999	1.21	28332	1.49
22	5-5-90-0-i-3.5-2-10	41927	37416	1.12	30879	1.36
23	5-5-90-0-i-3.5-2-7	26516	26381	1.01	22373	1.19
24	5-8-90-0-i-3.5-2-6	25475	25154	1.01	21176	1.20
25	5-8-90-0-i-3.5-2-6(1)	24541	26867	0.91	22463	1.09
26	5-8-90-0-i-3.5-2-8	32745	34767	0.94	28555	1.15
27	5-12-90-0-i-3.5-2-5	22121	22652	0.98	19144	1.16
28	5-12-90-0-i-3.5-2-10	45432	45589	1.00	36399	1.25
29	5-8-180-0-i-2.5-2-7	27108	29722	0.91	24668	1.10
30	5-8-180-0-i-3.5-2-7	30754	30000	1.03	24880	1.24
31	5-5-90-1#3-i-2.5-2-8	33136	31647	1.05	25872	1.28
32	5-5-90-1#3-i-2.5-2-6	19915	22011	0.90	18576	1.07
33	5-8-90-1#3-i-2.5-2-6	26573	28369	0.94	23553	1.13
34	5-8-90-1#3-i-2.5-2-6(1)	27379	27963	0.98	23044	1.19
35	5-8-90-1#3-i-3.5-2-6	30084	28046	1.07	22834	1.32
36	5-8-90-1#3-i-3.5-2-6(1)	25905	29527	0.88	24628	1.05
37	5-5-180-1#3-i-2.5-2-8	36448	32428	1.12	26080	1.40
38	5-5-180-1#3-i-2.5-2-6	23916	25343	0.94	21292	1.12
39	5-8-180-1#3-i-2.5-2-7	32909	33787	0.97	27413	1.20
40	5-8-180-1#3-i-3.5-2-7	30500	32570	0.94	26702	1.14
41	5-5-90-1#4-i-2.5-2-8	27537	34155	0.81	25764	1.07
42	5-5-90-1#4-i-2.5-2-6	21457	26954	0.80	19823	1.08
43	5-8-90-1#4-i-2.5-2-6	24292	31837	0.76	23788	1.02
44	5-8-90-1#4-i-3.5-2-6	25241	34092	0.74	25701	0.98
45	5-5-180-1#4-i-2.5-2-8	38421	35826	1.07	25813	1.49
46	5-5-180-1#4-i-2.5-2-6	22977	29617	0.78	22163	1.04
47	5-5-180-2#3-o-1.5-2-11.25	43051	44008	0.98	34851	1.24
48	5-5-180-2#3-o-1.5-2-9.5	20282	33802	0.60	23792	0.85
49	5-5-180-2#3-o-2.5-2-9.5	39698	35208	1.13	22513	1.76
50	5-5-180-2#3-o-2.5-2-11.25	42324	43097	0.98	27374	1.55

Table C.1 Cont. Test-to-calculated ratios for specimens containing two No. 5 hooked bars

	Specimen	*T*	Descriptive Equation		Design Equation	
		lb	T_h (lb)	T/T_h	T_h (lb)	T/T_h
51	(2@9) 5-5-90-2#3-i-2.5-7-7	34232	29304	1.17	23651	1.45
52	5-5-90-2#3-i-2.5-2-8	37154	32213	1.15	25789	1.44
53	5-5-90-2#3-i-2.5-2-6	29444	24865	1.18	20263	1.45
54	5-8-90-2#3-i-2.5-2-6	30638	27940	1.10	22685	1.35
55	5-8-90-2#3-i-2.5-2-8	40168	38077	1.05	30033	1.34
56	5-12-90-2#3-i-2.5-2-5	24348	28654	0.85	23941	1.02
57	5-15-90-2#3-i-2.5-2-6	42638	34576	1.23	26473	1.61
58	5-15-90-2#3-i-2.5-2-4	18667	21256	0.88	17579	1.06
59	5-5-90-2#3-i-3.5-2-6	21093	24241	0.87	20621	1.02
60	5-5-90-2#3-i-3.5-2-8	44665	31107	1.44	24034	1.86
61	5-8-90-2#3-i-3.5-2-6	30035	29018	1.04	23702	1.27
62	5-8-90-2#3-i-3.5-2-8	28656	32671	0.88	27074	1.06
63	5-12-90-2#3-i-3.5-2-5	28364	26786	1.06	21827	1.30
64	5-12-90-2#3-i-3.5-2-10	45245	52161	0.87	40125	1.13
65	5-5-180-2#3-i-2.5-2-8	34078	32916	1.04	26805	1.27
66	5-5-180-2#3-i-2.5-2-6	26728	23970	1.12	19723	1.36
67	5-8-180-2#3-i-2.5-2-7	29230	33301	0.88	27518	1.06
68	5-8-180-2#3-i-3.5-2-7	30931	31916	0.97	26086	1.19
69	5-8-90-4#3-i-2.5-2-8	26411	39300	0.67	29524	0.89
70	5-8-90-4#3-i-3.5-2-8	38480	42586	0.90	30505	1.26
71	5-5-90-5#3-o-1.5-2-5	22060	29500	0.75	13955	1.58
72	5-5-90-5#3-o-1.5-2-8	25110	40908	0.61	22073	1.14
73	5-5-90-5#3-o-1.5-2-6.5	21711	35752	0.61	18652	1.16
74	5-5-90-5#3-o-2.5-2-5	22529	29767	0.76	14139	1.59
75	5-5-90-5#3-o-2.5-2-8	28429	39451	0.72	20666	1.38
76	5-5-90-5#3-i-2.5-2-8	43030	38887	1.11	23673	1.82
77	(2@9) 5-5-90-5#3-i-2.5-7-7	40954	37412	1.09	22546	1.82
78	5-5-90-5#3-i-2.5-2-7	31696	34379	0.92	20976	1.51
79	(2@4) 5-8-90-5#3-i-2.5-2-6	41100	34774	1.18	19290	2.13
80	(2@6) 5-8-90-5#3-i-2.5-2-6	39800	34774	1.14	20382	1.95
81	5-12-90-5#3-i-2.5-2-5	34420	35294	0.98	21172	1.63
82	5-15-90-5#3-i-2.5-2-4	31318	30850	1.02	17420	1.80
83	5-15-90-5#3-i-2.5-2-5	39156	36351	1.08	21377	1.83
84	5-5-90-5#3-i-3.5-2-7	36025	37373	0.96	23128	1.56
85	5-12-90-5#3-i-3.5-2-5	30441	33714	0.90	20177	1.51
86	5-12-90-5#3-i-3.5-2-10	46051	62805	0.73	41610	1.11

Table C.2 Test-to-calculated ratios for specimens containing two No. 8 hooked bars

	Specimen	*T*	Descriptive Equation		Design Equation	
		lb	T_h (lb)	T/T_h	T_h (lb)	T/T_h
87	8-5-90-0-o-2.5-2-10a	42314	46572	0.91	31037	1.36
88	8-5-90-0-o-2.5-2-10b	33651	43947	0.77	29400	1.14
89	8-5-90-0-o-2.5-2-10c	55975	48782	1.15	32343	1.73
90	8-8-90-0-o-2.5-2-8	33015	43209	0.76	28644	1.15
91	8-8-90-0-o-3.5-2-8	35872	39842	0.90	26575	1.35
92	8-8-90-0-o-4-2-8	37511	41666	0.90	27708	1.35
93	8-5-90-0-i-2.5-2-16	83239	75129	1.11	60373	1.38
94	8-5-90-0-i-2.5-2-9.5	44485	42617	1.04	35768	1.24
95	8-5-90-0-i-2.5-2-12.5	65819	60617	1.09	49477	1.33
96	8-5-90-0-i-2.5-2-18	80881	88700	0.91	70243	1.15
97	8-5-90-0-i-2.5-2-13	65539	62317	1.05	50689	1.29
98	8-5-90-0-i-2.5-2-15(1)	63767	71202	0.90	57241	1.11
99	8-5-90-0-i-2.5-2-15	75478	71921	1.05	57711	1.31
100	8-5-90-0-i-2.5-2-10	47681	46311	1.03	38498	1.24
101	(2d) 8-5-90-0-i-2.5-2-10	32373	46939	0.69	38979	0.83
102	(2@3) 8-5-90-0-i-2.5-2-10	40313	45003	0.90	25149	1.60
103	(2@5) 8-5-90-0-i-2.5-2-10	40052	42961	0.93	31542	1.27
104	8-8-90-0-i-2.5-2-8	45243	41955	1.08	34923	1.30
105	8-8-90-0-i-2.5-2-10	51455	48013	1.07	39571	1.30
106	8-8-90-0-i-2.5-2-8(1)	36821	40839	0.90	33987	1.08
107	8-8-90-0-i-2.5-2-9	35100	47355	0.74	39070	0.90
108	8-8-90-0-i-2.5-9-9	37679	45332	0.83	37528	1.00
109	(2@3) 8-8-90-0-i-2.5-9-9	30672	44981	0.68	24855	1.23
110	(2@4) 8-8-90-0-i-2.5-9-9	34195	49341	0.69	30934	1.11
111	8-12-90-0-i-2.5-2-9	49923	49806	1.00	40599	1.23
112	8-12-90-0-i-2.5-2-12.5	66937	74357	0.90	58670	1.14
113	8-12-90-0-i-2.5-2-12	65879	69883	0.94	55416	1.19
114	8-15-90-0-i-2.5-2-8.5	43575	53940	0.81	43363	1.00
115	8-15-90-0-i-2.5-2-13	78120	80729	0.97	62892	1.24
116	8-5-90-0-i-3.5-2-18	95372	87736	1.09	69538	1.37
117	8-5-90-0-i-3.5-2-13	68099	62317	1.09	50689	1.34
118	8-5-90-0-i-3.5-2-15(2)	87709	70361	1.25	56782	1.54
119	8-5-90-0-i-3.5-2-15(1)	70651	75028	0.94	59958	1.18
120	8-8-90-0-i-3.5-2-8(1)	43845	38261	1.15	32077	1.37
121	8-8-90-0-i-3.5-2-10	55567	48690	1.14	40085	1.39
122	8-8-90-0-i-3.5-2-8(2)	42034	42225	1.00	35050	1.20
123	8-12-90-0-i-3.5-2-9	60238	49806	1.21	40599	1.48
124	8-8-90-0-i-4-2-8	37431	39749	0.94	33153	1.13
125	8-5-180-0-i-2.5-2-11	46143	47517	0.97	39651	1.16
126	8-5-180-0-i-2.5-2-14	49152	62857	0.78	51250	0.96
127	(2@3) 8-5-180-0-i-2.5-2-10	51825	45482	1.14	25307	2.05
128	(2@5) 8-5-180-0-i-2.5-2-10	53165	44724	1.19	32620	1.63
129	8-8-180-0-i-2.5-2-11.5	71484	47561	1.50	39129	1.83
130	8-12-180-0-i-2.5-2-12.5	75208	73178	1.03	57812	1.30
131	8-5-180-0-i-3.5-2-11	59292	50452	1.18	41904	1.41
132	8-5-180-0-i-3.5-2-14	63504	63466	1.00	51708	1.23
133	8-15-180-0-i-2.5-2-13.5	89916	87654	1.03	67784	1.33
134	8-5-90-1#3-i-2.5-2-16	74809	76528	0.98	62264	1.20
135	8-5-90-1#3-i-2.5-2-12.5	64837	62408	1.04	51311	1.26
136	8-5-90-1#3-i-2.5-2-9.5	62233	45676	1.36	37253	1.67

Table C.2 Cont. Test-to-calculated ratios for specimens containing two No. 8 hooked bars

	Specimen	T	Descriptive Equation		Design Equation	
		lb	T_h (lb)	T/T_h	T_h (lb)	T/T_h
137	8-5-180-1#3-i-2.5-2-11	49732	54866	0.91	46088	1.08
138	8-5-180-1#3-i-2.5-2-14	69021	73077	0.94	59903	1.15
139	8-5-180-1#3-i-3.5-2-11	55390	53929	1.03	44869	1.23
140	8-5-180-1#3-i-3.5-2-14	75994	73873	1.03	60002	1.27
141	8-8-180-1#4-i-2.5-2-11.5	72231	74729	0.97	58671	1.23
142	8-5-90-2#3-i-2.5-2-16	79629	75277	1.06	60857	1.31
143	8-5-90-2#3-i-2.5-2-9.5	53621	46047	1.16	38034	1.41
144	8-5-90-2#3-i-2.5-2-12.5	72067	60267	1.20	49017	1.47
145	8-5-90-2#3-i-2.5-2-8.5	50561	46878	1.08	38904	1.30
146	8-5-90-2#3-i-2.5-2-14	76964	69663	1.10	56350	1.37
147	8-5-90-2#3-i-2.5-2-10	56203	52765	1.07	43565	1.29
148	(2d) 8-5-90-2#3-i-2.5-2-10	45580	52765	0.86	44207	1.03
149	(2@3) 8-5-90-2#3-i-2.5-2-10	46810	50430	0.93	33903	1.38
150	(2@5) 8-5-90-2#3-i-2.5-2-10	48515	48369	1.00	36877	1.32
151	8-8-90-2#3-i-2.5-2-8	47876	46448	1.03	38345	1.25
152	8-8-90-2#3-i-2.5-2-10	61024	56438	1.08	45968	1.33
153	8-12-90-2#3-i-2.5-2-9	61013	55632	1.10	45078	1.35
154	8-12-90-2#3-i-2.5-2-11	68683	68317	1.01	54906	1.25
155	8-12-90-2#3vr-i-2.5-2-11	52673	66832	0.79	54822	0.96
156	8-15-90-2#3-i-2.5-2-6	37569	41980	0.89	34389	1.09
157	8-15-90-2#3-i-2.5-2-11	83320	74429	1.12	58330	1.43
158	8-5-90-2#3-i-3.5-2-17	89914	87988	1.02	69876	1.29
159	8-5-90-2#3-i-3.5-2-13	80360	69408	1.16	55865	1.44
160	8-8-90-2#3-i-3.5-2-8	48773	46320	1.05	38124	1.28
161	8-8-90-2#3-i-3.5-2-10	53885	51149	1.05	41926	1.29
162	8-12-90-2#3-i-3.5-2-9	49777	55632	0.89	45777	1.09
163	8-5-180-2#3-i-2.5-2-11	60235	51589	1.17	42570	1.41
164	8-5-180-2#3-i-2.5-2-14	76279	67579	1.13	54837	1.39
165	(2@3) 8-5-180-2#3-i-2.5-2-10	57651	52121	1.11	33907	1.70
166	(2@5) 8-5-180-2#3-i-2.5-2-10	61885	50898	1.22	38304	1.62
167	8-8-180-2#3-i-2.5-2-11.5	58171	60020	0.97	49172	1.18
168	8-12-180-2#3-i-2.5-2-11	64655	67539	0.96	54571	1.18
169	8-12-180-2#3vr-i-2.5-2-11	65780	68388	0.96	55120	1.19
170	8-5-180-2#3-i-3.5-2-11	55869	49685	1.12	41230	1.36
171	8-5-180-2#3-i-3.5-2-14	63467	66666	0.95	55028	1.15
172	8-15-180-2#3-i-2.5-2-11	78922	74738	1.06	58935	1.34
173	8-8-90-2#4-i-2.5-2-10	61360	55642	1.10	43325	1.42
174	8-8-90-2#4-i-3.5-2-10	69463	58394	1.19	45018	1.54
175	8-5-90-4#3-i-2.5-2-16	90429	84927	1.06	64839	1.39
176	8-5-90-4#3-i-2.5-2-12.5	68583	64842	1.06	50312	1.36
177	8-5-90-4#3-i-2.5-2-9.5	54914	53811	1.02	41703	1.32
178	8-5-90-5#3-o-2.5-2-10a	54257	64389	0.84	36714	1.48
179	8-5-90-5#3-o-2.5-2-10b	65592	65442	1.00	36590	1.79
180	8-5-90-5#3-o-2.5-2-10c	69494	67845	1.02	37956	1.83
181	8-8-90-5#3-o-2.5-2-8	57981	61211	0.95	33764	1.72
182	8-8-90-5#3-o-3.5-2-8	54957	58006	0.95	31641	1.74
183	8-8-90-5#3-o-4-2-8	39071	59986	0.65	34210	1.14
184	8-5-90-5#3-i-2.5-2-10b	69715	64827	1.08	44817	1.56
185	8-5-90-5#3-i-2.5-2-10c	68837	65977	1.04	45870	1.50
186	8-5-90-5#3-i-2.5-2-15	73377	88206	0.83	64715	1.13

Table C.2 Cont. Test-to-calculated ratios for specimens containing two No. 8 hooked bars

	Specimen	*T*	Descriptive Equation		Design Equation	
		lb	T_h (lb)	T/T_h	T_h (lb)	T/T_h
187	8-5-90-5#3-i-2.5-2-13	82376	81399	1.01	57706	1.43
188	8-5-90-5#3-i-2.5-2-12(1)	66363	68448	0.97	48388	1.37
189	8-5-90-5#3-i-2.5-2-12	72000	73089	0.99	51691	1.39
190	8-5-90-5#3-i-2.5-2-12(2)	71470	73181	0.98	51972	1.38
191	8-5-90-5#3-i-2.5-2-8	47478	50814	0.93	33881	1.40
192	8-5-90-5#3-i-2.5-2-10a	82800	64998	1.27	43843	1.89
193	8-5-90-5#3-i-2.5-2-10	70356	62248	1.13	42411	1.66
194	(2d) 8-5-90-5#3-i-2.5-2-10	54735	63827	0.86	45220	1.21
195	(2d) 8-5-90-9#3-i-2.5-2-10	54761	64756	0.85	46059	1.19
196	(2@3) 8-5-90-5#3-i-2.5-2-10	57922	62545	0.93	38234	1.51
197	(2@5) 8-5-90-5#3-i-2.5-2-10	55960	59889	0.93	40217	1.39
198	8-8-90-5#3-i-2.5-2-8	50266	53905	0.93	36216	1.39
199	8-8-90-5#3-i-2.5-2-9	64397	61468	1.05	41985	1.53
200	8-8-90-5#3-i-2.5-9-9	63298	63149	1.00	43572	1.45
201	(2@3) 8-8-90-5#3-i-2.5-9-9	58792	64009	0.92	38939	1.51
202	(2@4) 8-8-90-5#3-i-2.5-9-9	57455	62009	0.93	39639	1.45
203	8-12-90-5#3-i-2.5-2-9	64753	67624	0.96	46998	1.38
204	8-12-90-5#3-i-2.5-2-10	64530	71125	0.91	49997	1.29
205	8-12-90-5#3-i-2.5-2-12	87711	88286	0.99	61761	1.42
206	8-12-90-5#3vr-i-2.5-2-10	60219	73090	0.82	54617	1.10
207	8-12-90-4#3vr-i-2.5-2-10	59241	71471	0.83	55960	1.06
208	8-15-90-5#3-i-2.5-2-6	48499	55381	0.88	37187	1.30
209	8-15-90-5#3-i-2.5-2-10	90003	80522	1.12	54855	1.64
210	8-5-90-5#3-i-3.5-2-15	80341	89282	0.90	64725	1.24
211	8-5-90-5#3-i-3.5-2-13	77069	78905	0.98	56199	1.37
212	8-5-90-5#3-i-3.5-2-12(1)	76431	74237	1.03	52397	1.46
213	8-5-90-5#3-i-3.5-2-12	79150	76326	1.04	53614	1.48
214	8-8-90-5#3-i-3.5-2-8	55810	57419	0.97	39042	1.43
215	8-12-90-5#3-i-3.5-2-9	67831	67624	1.00	46705	1.45
216	(2@5) 8-5-180-5#3-i-2.5-2-10	66644	63847	1.04	42105	1.58
217	8-12-180-5#3-i-2.5-2-10	64107	73041	0.87	51697	1.24
218	8-12-180-5#3vr-i-2.5-2-10	67780	76760	0.88	56902	1.19
219	8-12-180-4#3vr-i-2.5-2-10	69188	70313	0.98	53847	1.28
220	8-15-180-5#3-i-2.5-2-9.5	85951	77101	1.11	52519	1.64
221	8-5-90-4#4s-i-2.5-2-15	93653	92347	1.01	62439	1.50
222	8-5-90-4#4s-i-2.5-2-12(1)	90816	77767	1.17	50653	1.79
223	8-5-90-4#4s-i-2.5-2-12	99755	80526	1.24	51839	1.92
224	8-5-90-4#4s-i-3.5-2-15	90865	90815	1.00	61520	1.48
225	8-5-90-4#4s-i-3.5-2-12(1)	95455	77759	1.23	50050	1.91
226	8-5-90-4#4s-i-3.5-2-12	98156	79496	1.23	51204	1.92

Table C.3 Test-to-calculated ratios for specimens containing two No. 11 hooked bars

	Specimen	*T*	Descriptive Equation		Design Equation	
		lb	T_h (lb)	T/T_h	T_h (lb)	T/T_h
227	11-8-90-0-o-2.5-2-25	174765	170198	1.03	102866	1.70
228	11-8-90-0-o-2.5-2-17	107209	108022	0.99	67641	1.58
229	11-12-90-0-o-2.5-2-17	105402	117661	0.90	72833	1.45
230	11-12-180-0-o-2.5-2-17	83493	119079	0.70	73642	1.13
231	11-5-90-0-i-2.5-2-14	66590	76344	0.87	62288	1.07
232	11-5-90-0-i-2.5-2-26	148727	148978	1.00	115156	1.29
233	11-5-90-0-i-2.5-2-16	89396	85644	1.04	69258	1.29
234	(2@5.35) 11-5-90-0-i-2.5-13-13	60593	75637	0.80	56106	1.08
235	(2@7.5) 11-8-90-0-i-2.5-2-15	75313	87421	0.86	70012	1.08
236	(2@7.5) 11-8-90-0-i-2.5-2-18	97379	102785	0.95	81285	1.20
237	11-8-90-0-i-2.5-2-17	132055	115557	1.14	89976	1.47
238	11-8-90-0-i-2.5-2-21	125126	129367	0.97	100252	1.25
239	11-8-90-0-i-2.5-2-17	104779	109031	0.96	85476	1.23
240	(2@7.5) 11-12-90-0-i-2.5-2-17	106718	120453	0.89	93088	1.15
241	11-12-90-0-i-2.5-2-17	134371	115057	1.17	89169	1.51
242	11-12-90-0-i-2.5-2-17.5	124622	128351	0.97	98378	1.27
243	11-12-90-0-i-2.5-2-25	199743	183761	1.09	136964	1.46
244	11-15-90-0-i-2.5-2-24	213265	192429	1.11	142303	1.50
245	11-15-90-0-i-2.5-2-11	48126	87717	0.55	68962	0.70
246	11-15-90-0-i-2.5-2-10	51481	66433	0.77	53538	0.96
247	11-15-90-0-i-2.5-2-15	92168	101163	0.91	78899	1.17
248	11-5-90-0-i-3.5-2-17	108122	100521	1.08	80042	1.35
249	11-5-90-0-i-3.5-2-14	69514	79950	0.87	64996	1.07
250	11-5-90-0-i-3.5-2-26	182254	153715	1.19	118252	1.54
251	11-8-180-0-i-2.5-2-21	128123	132782	0.96	102690	1.25
252	11-8-180-0-i-2.5-2-17	100453	113768	0.88	88895	1.13
253	11-12-180-0-i-2.5-2-17	107461	116002	0.93	89844	1.20
254	11-5-90-1#4-i-2.5-2-17	101498	114117	0.89	88970	1.14
255	11-5-90-1#4-i-3.5-2-17	106270	114501	0.93	89014	1.19
256	11-5-90-2#3-i-2.5-2-17	100695	106103	0.95	83355	1.21
257	11-5-90-2#3-i-2.5-2-14	77422	79521	0.97	63064	1.23
258	(2@5.35) 11-5-90-2#3-i-2.5-13-13	69123	82388	0.84	60731	1.14
259	(2@7.5) 11-8-90-2#3-i-2.5-2-17	106031	105400	1.01	82236	1.29
260	(2@7.5) 11-12-90-2#3-i-2.5-2-16	108718	113531	0.96	87435	1.24
261	11-12-90-2#3-i-2.5-2-17.5	130389	137403	0.95	104348	1.25
262	11-12-90-2#3-i-2.5-2-25	208054	193798	1.07	141870	1.47
263	11-15-90-2#3-i-2.5-2-23	209575	192436	1.09	140332	1.49
264	11-15-90-2#3-i-2.5-2-10.5	50053	89681	0.56	70020	0.71
265	11-15-90-2#3-i-2.5-2-10	63940	77713	0.82	60467	1.06
266	11-15-90-2#3-i-2.5-2-15	115189	109619	1.05	83961	1.37
267	11-5-90-2#3-i-3.5-2-17	109644	113531	0.97	88408	1.24
268	11-5-90-2#3-i-3.5-2-14	82275	81314	1.01	64405	1.28
269	11-5-90-5#3-i-2.5-2-14	95170	96365	0.99	72025	1.32
270	11-5-90-5#3-i-3.5-2-14	97989	100321	0.98	75367	1.30
271	11-8-90-6#3-o-2.5-2-16	136753	128137	1.07	75755	1.81
272	11-8-90-6#3-o-2.5-2-22	170249	167392	1.02	98188	1.73
273	11-12-90-6#3-o-2.5-2-17	115878	137253	0.84	83154	1.39
274	11-12-180-6#3-o-2.5-2-17	113121	137725	0.82	83711	1.35
275	11-5-90-6#3-i-2.5-2-20	136272	130785	1.04	98124	1.39
276	11-5-90-6#3-i-2.5-2-16	115623	105604	1.09	78580	1.47

Table C.3 Cont. Test-to-calculated ratios for specimens containing two No. 11 hooked bars

	Specimen	*T*	Descriptive Equation		Design Equation	
		lb	T_h (lb)	T/T_h	T_h (lb)	T/T_h
277	(2@5.35) 11-5-90-6#3-i-2.5-13-13	89748	97957	0.92	71650	1.25
278	(2@5.35) 11-5-90-6#3-i-2.5-18-18	121605	130710	0.93	96745	1.26
279	(2@7.5) 11-8-90-6#3-i-2.5-2-15	106190	105507	1.01	78684	1.35
280	11-8-90-6#3-i-2.5-2-16	132986	125392	1.06	92837	1.43
281	11-8-90-6#3-i-2.5-2-22	184569	165165	1.12	119218	1.55
282	11-8-90-6#3-i-2.5-2-22	191042	169230	1.13	121589	1.57
283	11-8-90-6#3-i-2.5-2-15	108312	116769	0.93	88212	1.23
284	11-8-90-6#3-i-2.5-2-19	145430	141425	1.03	105266	1.38
285	(2@7.5) 11-12-90-6#3-i-2.5-2-14	102038	116119	0.88	87329	1.17
286	11-12-90-6#3-i-2.5-2-17	161648	141727	1.14	102672	1.57
287	11-12-90-6#3-i-2.5-2-16	115197	134072	0.86	101012	1.14
288	11-12-90-6#3-i-2.5-2-22	201189	184342	1.09	130743	1.54
289	11-15-90-6#3-i-2.5-2-22	197809	197732	1.00	140654	1.41
290	11-15-90-6#3-i-2.5-2-9.5	57383	93144	0.62	70144	0.82
291	11-15-90-6#3-i-2.5-2-10a	82681	91221	0.91	66709	1.24
292	11-15-90-6#3-i-2.5-2-10b	75579	90279	0.84	66369	1.14
293	11-15-90-6#3-i-2.5-2-15	145267	129939	1.12	94524	1.54
294	11-5-90-6#3-i-3.5-2-20	135821	137640	0.99	103906	1.31
295	11-8-180-6#3-i-2.5-2-15	111678	115538	0.97	86838	1.29
296	11-8-180-6#3-i-2.5-2-19	149000	146730	1.02	109092	1.37
297	(2@7.5) 11-12-180-6#3-i-2.5-2-14	93955	122768	0.77	93821	1.00
298	11-12-180-6#3-i-2.5-2-17	116371	140769	0.83	106721	1.09
299	11-12-180-6#3-i-2.5-2-17	148678	141488	1.05	103822	1.43
300	11-5-90-5#4s-i-2.5-2-20	141045	155285	0.91	102086	1.38
301	11-5-90-5#4s-i-3.5-2-20	152967	154586	0.99	100079	1.53

Table C.4 Test-to-calculated ratios for specimens containing multiple No. 5 hooked bars

	Specimen	***T***	**Descriptive Equation**		**Design Equation**	
		lb	**T_h (lb)**	**T/T_h**	**T_h (lb)**	**T/T_h**
302	(3@10) 5-5-90-0-i-2.5-2-7	21034	23873	0.88	20348	1.03
303	(3) 5-5-90-0-i-2.5-2-8	27869	27142	1.03	22641	1.23
304	(3@4.5) 5-5-90-0-i-2.5-7-7	22363	25339	0.88	17679	1.26
305	(4@3) 5-5-90-0-i-2.5-7-7	15048	25414	0.59	14937	1.01
306	(4@4) 5-5-90-0-i-2.5-2-6	14542	18612	0.78	12057	1.21
307	(4@4) 5-5-90-0-i-2.5-2-10	28402	34130	0.83	20742	1.37
308	(4@4) 5-8-90-0-i-2.5-2-6	15479	22119	0.70	13995	1.11
309	(4@6) 5-8-90-0-i-2.5-2-6	19303	21875	0.88	18719	1.03
310	(4@6) 5-8-90-0-i-2.5-6-6	16051	23126	0.69	19704	0.81
311	(3@4) 5-8-90-0-i-2.5-2-6	16805	21867	0.77	13850	1.21
312	(3@6) 5-8-90-0-i-2.5-2-6	24886	22372	1.11	18782	1.32
313	(3@10) 5-5-90-2#3-i-2.5-2-7	31296	27838	1.12	23934	1.31
314	(3@4.5) 5-5-90-2#3-i-2.5-7-7	23305	25976	0.90	21818	1.07
315	(4@3) 5-5-90-2#3-i-2.5-7-7	19577	27300	0.72	21405	0.91
316	(4@4) 5-5-90-2#3-i-2.5-2-6	21405	24896	0.86	19835	1.08
317	(4@4) 5-5-90-2#3-i-2.5-2-8	26017	31785	0.82	24873	1.05
318	(3@6) 5-8-90-5#3-i-2.5-2-6.25	25830	31106	0.83	21876	1.18
319	(3@4) 5-8-90-5#3-i-2.5-2-6‡	34889	30837	1.13	19403	1.80
320	(3@6) 5-8-90-5#3-i-2.5-2-6‡	36448	30503	1.19	20719	1.76
321	(3@10) 5-5-90-5#3-i-2.5-2-7	31684	33145	0.96	23601	1.34
322	(3) 5-5-90-5#3-i-2.5-2-8	33260	34613	0.96	24464	1.36
323	(3@4.5) 5-5-90-5#3-i-2.5-7-7	35112	32975	1.06	21451	1.64
324	(4@3) 5-5-90-5#3-i-2.5-7-7	29370	31631	0.93	21549	1.36
325	(4@4) 5-5-90-5#3-i-2.5-2-7	27114	32589	0.83	22920	1.18
326	(4@4) 5-5-90-5#3-i-2.5-2-6	25898	29471	0.88	20722	1.25
327	(4@6) 5-8-90-5#3-i-2.5-2-6‡	28321	28370	1.00	21572	1.31
328	(4@6) 5-8-90-5#3-i-2.5-6-6‡	31152	29873	1.04	22443	1.39
329	(4@4) 5-8-90-5#3-i-2.5-2-6‡	27493	28379	0.97	19701	1.40
330	(3@6) 5-8-90-5#3-i-3.5-2-6.25	35268	34487	1.02	23702	1.49
331	(2s) 5-5-90-0-i-2.5-2-8	16727	24303	0.69	13272	1.26
332	(3s) 5-5-90-0-i-2.5-2-8	16804	24752	0.68	13487	1.25
333	(2s) 5-5-90-2#3-i-2.5-2-8	24730	24228	1.02	17844	1.39
334	(3s) 5-5-90-2#3-i-2.5-2-8	20283	24729	0.82	16404	1.24
335	(2s) 5-5-90-5#3-i-2.5-2-8	26180	29292	0.89	19511	1.34
336	(3s) 5-5-90-5#3-i-2.5-2-8	22598	25871	0.87	18818	1.20
337	(2s) 5-5-90-6#3-i-2.5-2-8	29528	30093	0.98	19793	1.49
338	(3s) 5-5-90-6#3-i-2.5-2-8	22081	27168	0.81	19905	1.11

Table C.5 Test-to-calculated ratios for specimens containing multiple No. 8 hooked bars

	Specimen	*T*	Descriptive Equation		Design Equation	
		lb	T_h (lb)	T/T_h	T_h (lb)	T/T_h
339	(3@5.5) 8-5-90-0-i-2.5-2-16	62798	78804	0.80	57394	1.09
340	(3@5.5) 8-5-90-0-i-2.5-2-10	36054	44309	0.81	33409	1.08
341	(3@5.5) 8-5-90-0-i-2.5-2-8	24411	35196	0.69	27611	0.88
342	(3@3) 8-5-90-0-i-2.5-2-10	28480	43069	0.66	25019	1.14
343	(3@5) 8-5-90-0-i-2.5-2-10	32300	43162	0.75	31678	1.02
344	(3@5.5) 8-8-90-0-i-2.5-2-8	37670	40269	0.94	28012	1.34
345	(3@3) 8-8-90-0-i-2.5-9-9	21438	46543	0.46	26010	0.82
346	(3@4) 8-8-90-0-i-2.5-9-9	26353	45650	0.58	28568	0.92
347	(3@3) 8-12-90-0-i-2.5-2-12	48039	68592	0.70	36620	1.31
348	(3@4) 8-12-90-0-i-2.5-2-12	55822	72422	0.77	42646	1.31
349	(3@5) 8-12-90-0-i-2.5-2-12	52352	69611	0.75	47356	1.11
350	(4@3) 8-8-90-0-i-2.5-9-9	18659	46320	0.40	25536	0.73
351	(4@4) 8-8-90-0-i-2.5-9-9	18036	45149	0.40	28352	0.64
352	(3@3) 8-5-180-0-i-2.5-2-10	47249	43916	1.08	24503	1.93
353	(3@5) 8-5-180-0-i-2.5-2-10	45930	44724	1.03	33224	1.38
354	(3@5.5) 8-5-90-2#3-i-2.5-2-14	57261	74514	0.77	57181	1.00
355	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5	40885	46883	0.87	35954	1.14
356	(3@5.5) 8-5-90-2#3-i-2.5-2-14(1)	65336	73377	0.89	54846	1.19
357	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5(1)	32368	40340	0.80	31763	1.02
358	(3@3) 8-5-90-2#3-i-2.5-2-10	40721	47180	0.86	29281	1.39
359	(3@5) 8-5-90-2#3-i-2.5-2-10	44668	49641	0.90	37951	1.18
360	(3@3) 8-5-180-2#3-i-2.5-2-10	54576	50152	1.09	30720	1.78
361	(3@5) 8-5-180-2#3-i-2.5-2-10	51501	47504	1.08	35863	1.44
362	(3@5.5) 8-5-90-5#3-i-2.5-2-8	37126	49157	0.76	37360	0.99
363	(3@5.5) 8-5-90-5#3-i-2.5-2-12	66094	71221	0.93	54106	1.22
364	(3@5.5) 8-5-90-5#3-i-2.5-2-8(1)	31369	45852	0.68	34233	0.92
365	(3@5.5) 8-5-90-5#3-i-2.5-2-12(1)	47851	67278	0.71	52922	0.90
366	(3@5.5) 8-5-90-5#3-i-2.5-2-8(2)	47994	48617	0.99	36463	1.32
367	(3@3) 8-5-90-5#3-i-2.5-2-10	47276	54763	0.86	37878	1.25
368	(3@5) 8-5-90-5#3-i-2.5-2-10	61305	55066	1.11	40326	1.52
369	(3@3) 8-8-90-5#3-i-2.5-9-9	39762	57763	0.69	40348	0.99
370	(3@4) 8-8-90-5#3-i-2.5-9-9	36559	56541	0.65	41431	0.88
371	(3@3) 8-12-90-5#3-i-2.5-2-12	62206	78344	0.79	53678	1.16
372	(3@4) 8-12-90-5#3-i-2.5-2-12	64940	82403	0.79	58558	1.11
373	(3@5) 8-12-90-5#3-i-2.5-2-12	64761	81663	0.79	61119	1.06
374	(4@3) 8-8-90-5#3-i-2.5-9-9	31441	57318	0.55	40862	0.77
375	(4@4) 8-8-90-5#3-i-2.5-9-9	29484	58487	0.50	43758	0.67
376	(3@3) 8-5-180-5#3-i-2.5-2-10	58877	56797	1.04	38255	1.54
377	(3@5) 8-5-180-5#3-i-2.5-2-10	58669	55773	1.05	40793	1.44

Table C.6 Test-to-calculated ratios for specimens containing multiple No. 11 hooked bars

	Specimen	*T*	Descriptive Equation		Design Equation	
		lb	T_h (lb)	T/T_h	T_h (lb)	T/T_h
378	(3@5.35) 11-5-90-0-i-2.5-13-13	51506	75024	0.69	57226	0.90
379	(3@3.75) 11-8-90-0-i-2.5-2-20	98488	120813	0.82	69135	1.42
380	(3@3.75) 11-8-90-0-i-2.5-2-24	126976	144871	0.88	82201	1.54
381	(3@3.75) 11-12-90-0-i-2.5-2-22	123180	152996	0.81	85977	1.43
382	(3@5.35) 11-5-90-2#3-i-2.5-13-13	57921	80470	0.72	58812	0.98
383	(3@3.75) 11-8-90-2#3-i-2.5-2-23	116589	139560	0.84	82299	1.42
384	(3@3.75) 11-12-90-2#3-i-2.5-2-21	127812	153987	0.83	90059	1.42
385	(3@5.35) 11-5-90-6#3-i-2.5-13-13	66178	88507	0.75	64554	1.03
386	(3@5.35) 11-5-90-6#3-i-2.5-18-18	111867	118451	0.94	85444	1.31
387	(3@3.75) 11-8-90-6#3-i-2.5-2-21	111288	137046	0.81	90225	1.23
388	(3@3.75) 11-12-90-6#3-i-2.5-2-19	118300	144116	0.82	92752	1.28
389	(3@3.75) 11-12-180-6#3-i-2.5-2-19	119045	148999	0.80	95272	1.25
390	(2s) 11-5-90-0-i-2.5-2-16	47950	79067	0.61	38813	1.24
391	(2s) 11-5-90-2#3-i-2.5-2-16	57998	82366	0.70	41707	1.39
392	(2s) 11-5-90-6#3-i-2.5-2-16	62177	86027	0.72	47297	1.31
393	(2s) 11-5-90-7#3-i-2.5-2-16	67432	87963	0.77	48292	1.40
394	(2s) 11-5-90-8#3-i-2.5-2-16	70505	93648	0.75	54352	1.30

Table C.7 Test-to-calculated ratios for specimens referenced in this study

		Specimen	*T*	Descriptive Equation		Design Equation	
			lb	T_h (lb)	T/T_h	T_h (lb)	T/T_h
Marques and Jirsa (1975)	395	J7-180-12-1H	36600	39778	0.92	33026	1.11
	396	J7-180-15-1 H	52200	51573	1.01	42042	1.24
	397	J7-90-12-1H	37200	39229	0.95	32639	1.14
	398	J7-90-15-1-H	54600	53744	1.02	43537	1.25
	399	J7-90-15-1- L	58200	54423	1.07	44003	1.32
	400	J7-90-15-1M	60000	55244	1.09	44565	1.35
	401	J11-180-15-1H	70200	66598	1.05	38546	1.82
	402	J11-90-12-1H	65520	50830	1.29	30017	2.18
	403	J11-90-15-1H	74880	68746	1.09	39598	1.89
	404	J11-90-15-1L	81120	68119	1.19	39291	2.06
	405	J 7- 90 -15 -3a - H	58800	72216	0.81	46775	1.26
	406	J 7- 90 -15 -3 - H	62400	64568	0.97	48899	1.28
	407	J 11- 90 -15 -3a - L	107640	99840	1.08	59542	1.81
	408	J 11- 90 -15 -3 - L	96720	83695	1.16	51916	1.86
Pinc et al. (1977)	409	9-12	47000	45887	1.02	30929	1.52
	410	11-15	78000	70745	1.10	40571	1.92
	411	11-18	90480	84990	1.06	48196	1.88
Hamad et al. (1993)	412	7-90-U	25998	34058	0.76	28281	0.92
	413	7-90-U'	36732	42398	0.87	34049	1.08
	414	11-90-U	48048	56593	0.85	32888	1.46
	415	11-90-U'	75005	70451	1.06	39596	1.89
	416	11-180-U-HS	58843	76691	0.77	42549	1.38
	417	11-90-U-HS	73788	76691	0.96	42549	1.73
	418	11-90-U-T6	71807	78173	0.92	48506	1.48
	419	7-180-U-T4	34620	49179	0.70	38510	0.90
	420	11-90-U-T4	83190	88451	0.94	57932	1.44
Ramirez & Russel (2008)	421	I-1	30000	28654	1.05	23729	1.26
	422	I-3	30000	31635	0.95	25805	1.16
	423	I-5	30500	31924	0.96	26005	1.17
	424	I-2	88000	78316	1.12	62763	1.40
	425	I-2'	105000	100904	1.04	79168	1.33
	426	I-4	99100	86464	1.15	68255	1.45
	427	I-6	114000	86632	1.32	67573	1.69
	428	III-13	41300	47134	0.88	30227	1.37
	429	III-15	38500	48680	0.79	31753	1.21
	430	III-14	105000	112286	0.94	83448	1.26
	431	III-16	120000	116765	1.03	85623	1.40
Lee & Park (2010)	432	H1	59208.122	79135	0.75	62252	0.95
	433	H2	52796.624	57788	0.91	45951	1.15
	434	H3	53761	78275	0.69	57090	0.94

Table C.7 Cont. Test-to-calculated ratios for specimens referenced in this study

		Specimen	*T*	Descriptive Equation		Design Equation	
			lb	T_h (lb)	T/T_h	T_h (lb)	T/T_h
Joh et al. (1995)	435	LA 1-1	13120	30584	0.43	20180	0.65
	436	LA 1-3	34343	52489	0.65	32839	1.05
	437	LA 3-2	20231	31861	0.63	20717	0.98
	438	LA 4-1	13230	31616	0.42	19935	0.66
	439	LA 4-2	17640	31616	0.56	21574	0.82
	440	LA 5-1	16593	31616	0.52	20685	0.80
	441	LA 5-2	14939	31616	0.47	20736	0.72
	442	LA 7-1	15159	32796	0.46	26712	0.57
	443	LA 7-2	22822	36336	0.63	25770	0.89
	444	LA 8-1	25247	32219	0.78	20772	1.22
	445	LA 8-2	25027	32637	0.77	21020	1.19
	446	LA 10-1	19294	34526	0.56	22296	0.87
	447	LA 10-2	26956	39023	0.69	24591	1.10
Joh and Shibata (1996)	448	LA 8-1	25468	32219	0.79	20765	1.23
	449	LA 8-2	26019	32637	0.80	20990	1.24
	450	LA 8-3	21113	30312	0.70	19781	1.07
	451	LA 8-4	21058	29949	0.70	19569	1.08
	452	LA 8-5	17089	29003	0.59	19121	0.89
	453	LA 8-6	20286	29574	0.69	19369	1.05
	454	LA 8-7	34178	35610	0.96	22426	1.52
	455	LA 8-8	28941	36025	0.80	22833	1.27
	456	LA 5-1	17695	30570	0.58	20035	0.88
	457	LA 5-2	15380	31097	0.49	20416	0.75
	458	LA 5-3	19349	31601	0.61	20592	0.94
	459	LA 5-4	17420	30704	0.57	20122	0.87
	460	LA 5-5	14608	28709	0.51	19016	0.77
Johnson & Jirsa (1981)	461	4-3.5-8-M	4400	5383	0.82	5148	0.85
	462	4-5-11-M	12000	9876	1.22	9010	1.33
	463	4-5-14-M	9800	9876	0.99	9010	1.09
	464	7-5-8-L	13000	10803	1.20	10080	1.29
	465	7-5-8-M	16500	12931	1.28	11740	1.41
	466	7-5-8-H	19500	13595	1.43	12248	1.59
	467	7-5-14-L	8500	10803	0.79	10080	0.84
	468	7-5-14-M	11200	12500	0.90	11407	0.98
	469	7-5-14-H	11900	13595	0.88	12248	0.97
	470	7-7-8-M	32000	20948	1.53	18327	1.75
	471	7-7-11-M	27000	20948	1.29	18327	1.47
	472	7-7-14-M	22000	22195	0.99	19247	1.14
	473	9-7-11-M	30800	23635	1.30	20891	1.47
	474	9-7-14-M	24800	25009	0.99	21916	1.13

Table C.7 Cont. Test-to-calculated ratios for specimens referenced in this study

		Specimen	*T*	Descriptive Equation		Design Equation	
			lb	**T_h (lb)**	**T/T_h**	**T_h (lb)**	**T/T_h**
Johnson & Jirsa (1981)	475	9-7-18-M	22300	23743	0.94	20972	1.06
	476	7-8-11-M	34800	26531	1.31	22694	1.53
	477	7-8-14-M	26500	24461	1.08	21184	1.25
	478	9-8-14-M	30700	29895	1.03	25841	1.19
	479	11-8.5-11-L	37000	28324	1.31	25363	1.46
	480	11-8.5-11-M	51500	34750	1.48	30162	1.71
	481	11-8.5-11-H	54800	36077	1.52	31135	1.76
	482	11-8.5-14-L	31000	28324	1.09	25363	1.22
	483	11-8.5-14-M	39000	34643	1.13	30084	1.30
	484	11-8.5-14-H	45500	36077	1.26	31135	1.46
	485	7-7-11-M	24000	19955	1.20	17588	1.36
	486	7-7-11-L	22700	18611	1.22	16578	1.37
	487	11-8.5-11-M	38000	32436	1.17	28451	1.34
	488	11-8.5-11-L	40000	30251	1.32	26819	1.49
	489	7-5-8-M	14700	12069	1.22	11072	1.33
	490	7-5-14-M	11300	12069	0.94	11072	1.02

APPENDIX D: MONTE CARLO ANALYSIS

Table D.1 Hypothetical beams used in Monte Carlo analysis

Beam No.	N_h	f_s	d_b	b	c_{ch}	c_{so}	c_{ch}/d_b	$A_{tr,l}$	f'_c
1	2	60000	0.75	8	2.25	2.50	3.00	0.11	4000
2	3	60000	0.75	12	2.75	2.50	3.67	0.11	4000
3	3	60000	1	12	2.50	2.50	2.50	0.11	4000
4	3	60000	1.128	12	2.37	2.50	2.10	0.11	4000
5	3	60000	0.75	24	8.75	2.50	11.67	0.11	4000
6	4	60000	0.75	24	5.58	2.50	7.44	0.11	4000
7	6	60000	0.75	24	3.05	2.50	4.07	0.11	4000
8	8	60000	0.75	24	1.96	2.50	2.62	0.11	4000
9	3	60000	1	24	8.50	2.50	8.50	0.11	4000
10	4	60000	1	24	5.33	2.50	5.33	0.11	4000
11	6	60000	1	24	2.80	2.50	2.80	0.11	4000
12	3	60000	1.41	24	8.09	2.50	5.74	0.11	4000
13	4	60000	1.41	24	4.92	2.50	3.49	0.11	4000
14	3	60000	1	18	5.50	2.50	5.50	0.11	4000
15	4	60000	1	18	3.33	2.50	3.33	0.11	4000
16	3	60000	1.128	18	5.37	2.50	4.76	0.11	4000
17	4	60000	1.128	18	3.21	2.50	2.84	0.11	4000
18	3	60000	1.41	18	5.09	2.50	3.61	0.11	4000
19	2	60000	0.75	8	2.25	2.50	3.00	0.11	6000
20	3	60000	0.75	12	2.75	2.50	3.67	0.11	6000
21	3	60000	1	12	2.50	2.50	2.50	0.11	6000
22	3	60000	1.128	12	2.37	2.50	2.10	0.11	6000
23	3	60000	0.75	24	8.75	2.50	11.67	0.11	6000
24	4	60000	0.75	24	5.58	2.50	7.44	0.11	6000
25	6	60000	0.75	24	3.05	2.50	4.07	0.11	6000
26	8	60000	0.75	24	1.96	2.50	2.62	0.11	6000
27	3	60000	1	24	8.50	2.50	8.50	0.11	6000
28	4	60000	1	24	5.33	2.50	5.33	0.11	6000
29	6	60000	1	24	2.80	2.50	2.80	0.11	6000
30	3	60000	1.41	24	8.09	2.50	5.74	0.11	6000
31	4	60000	1.41	24	4.92	2.50	3.49	0.11	6000
32	3	60000	1	18	5.50	2.50	5.50	0.11	6000
33	4	60000	1	18	3.33	2.50	3.33	0.11	6000
34	3	60000	1.128	18	5.37	2.50	4.76	0.11	6000
35	4	60000	1.128	18	3.21	2.50	2.84	0.11	6000
36	3	60000	1.41	18	5.09	2.50	3.61	0.11	6000
37	2	60000	0.75	8	2.25	2.50	3.00	0.11	8000
38	3	60000	0.75	12	2.75	2.50	3.67	0.11	8000
39	3	60000	1	12	2.50	2.50	2.50	0.11	8000
40	3	60000	1.128	12	2.37	2.50	2.10	0.11	8000
41	3	60000	0.75	24	8.75	2.50	11.67	0.11	8000
42	4	60000	0.75	24	5.58	2.50	7.44	0.11	8000
43	6	60000	0.75	24	3.05	2.50	4.07	0.11	8000
44	8	60000	0.75	24	1.96	2.50	2.62	0.11	8000
45	3	60000	1	24	8.50	2.50	8.50	0.11	8000
46	4	60000	1	24	5.33	2.50	5.33	0.11	8000
47	6	60000	1	24	2.80	2.50	2.80	0.11	8000
48	3	60000	1.41	24	8.09	2.50	5.74	0.11	8000
49	4	60000	1.41	24	4.92	2.50	3.49	0.11	8000
50	3	60000	1	18	5.50	2.50	5.50	0.11	8000

Table D.1 Cont. Hypothetical beams used in Monte Carlo analysis*

Beam No.	No Confinement		1 No.3 parallel		2 No.3 parallel		No. 3 spaced at $3d_b$ parallel		No. 3 spaced at $3d_b$ perpendicular	
	N	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}
1	-	10.7	2	6.8	4	6.8	6	6.8	6	7.8
2	-	9.9	2	7.2	4	6.6	6	6.6	6	8.3
3	-	17.3	2	14.3	4	11.2	6	10.7	10	14.3
4	-	21.6	2	18.5	4	15.4	6	13.1	10	18.5
5	-	7.1	2	6.1	4	5.9	6	5.9	6	6.5
6	-	7.1	2	6.4	4	5.9	6	5.9	6	6.7
7	-	9.4	2	8.2	4	7.0	6	6.5	6	8.7
8	-	11.1	2	9.8	4	8.5	6	7.2	8	10.1
9	-	11.0	2	10.1	4	9.3	6	9.1	6	10.4
10	-	12.2	2	11.2	4	10.3	6	9.4	8	11.4
11	-	16.8	2	15.4	4	13.9	6	12.5	10	15.4
12	-	19.1	2	18.3	4	17.4	6	16.6	8	18.5
13	-	26.0	2	24.5	4	22.9	6	21.4	12	24.1
14	-	11.9	2	10.7	4	9.5	6	9.4	8	10.9
15	-	15.8	2	13.9	4	12.0	6	10.3	10	13.9
16	-	15.8	2	14.3	4	12.7	6	11.6	8	14.6
17	-	20.0	2	18.0	4	16.0	6	14.0	10	18.0
18	-	25.6	2	23.6	4	21.6	6	19.6	12	23.2
19	-	9.6	2	6.2	4	6.2	6	6.2	6	7.0
20	-	8.9	2	6.5	4	6.0	6	6.0	6	7.5
21	-	15.7	2	12.9	4	10.1	6	9.7	8	13.5
22	-	19.6	2	16.7	4	13.9	6	11.8	10	16.7
23	-	6.4	2	5.5	4	5.4	6	5.4	4	6.1
24	-	6.4	2	5.8	4	5.4	6	5.4	4	6.2
25	-	8.5	2	7.4	4	6.3	6	5.9	6	7.8
26	-	10.1	2	8.9	4	7.7	6	6.5	8	9.1
27	-	9.9	2	9.1	4	8.4	6	8.2	6	9.4
28	-	11.0	2	10.1	4	9.3	6	8.5	6	10.5
29	-	15.2	2	13.9	4	12.6	6	11.3	10	13.9
30	-	17.3	2	16.5	4	15.7	6	15.0	8	16.7
31	-	23.5	2	22.1	4	20.7	6	19.3	10	22.1
32	-	10.7	2	9.7	4	8.6	6	8.5	6	10.1
33	-	14.3	2	12.6	4	10.9	6	9.3	8	12.9
34	-	14.3	2	12.9	4	11.5	6	10.5	8	13.2
35	-	18.1	2	16.3	4	14.4	6	12.6	10	16.3
36	-	23.2	2	21.4	4	19.5	6	17.7	10	21.4
37	-	9.0	2	5.7	4	5.7	6	5.7	6	6.5
38	-	8.3	2	6.0	4	5.6	6	5.6	6	6.9
39	-	14.6	2	12.0	4	9.4	6	9.0	8	12.5
40	-	18.2	2	15.6	4	12.9	6	11.0	10	15.6
41	-	6.0	2	5.2	4	5.0	6	5.0	4	5.7
42	-	6.0	2	5.4	4	5.0	6	5.0	4	5.7
43	-	7.9	2	6.9	4	5.9	6	5.5	6	7.3
44	-	9.4	2	8.3	4	7.2	6	6.0	6	8.7
45	-	9.2	2	8.5	4	7.8	6	7.7	6	8.8
46	-	10.2	2	9.4	4	8.6	6	7.9	6	9.8
47	-	14.1	2	12.9	4	11.7	6	10.5	8	13.2
48	-	16.1	2	15.4	4	14.7	6	13.9	8	15.5
49	-	21.9	2	20.6	4	19.3	6	18.0	10	20.6
50	-	10.0	2	9.0	4	8.0	6	7.9	6	9.4

*Values of development length ℓ_{dh} are based on Eq. (5.22)

Table D.1 Cont. Hypothetical beams used in Monte Carlo analysis

Beam No.	N_h	f_s	d_b	b	c_{ch}	c_{so}	c_{ch}/d_b	$A_{tr,l}$	f'_c
51	4	60000	1	18	3.33	2.50	3.33	0.11	8000
52	3	60000	1.128	18	5.37	2.50	4.76	0.11	8000
53	4	60000	1.128	18	3.21	2.50	2.84	0.11	8000
54	3	60000	1.41	18	5.09	2.50	3.61	0.11	8000
55	2	60000	0.75	8	2.25	2.50	3.00	0.11	10000
56	3	60000	0.75	12	2.75	2.50	3.67	0.11	10000
57	3	60000	1	12	2.50	2.50	2.50	0.11	10000
58	3	60000	1.128	12	2.37	2.50	2.10	0.11	10000
59	3	60000	0.75	24	8.75	2.50	11.67	0.11	10000
60	4	60000	0.75	24	5.58	2.50	7.44	0.11	10000
61	6	60000	0.75	24	3.05	2.50	4.07	0.11	10000
62	8	60000	0.75	24	1.96	2.50	2.62	0.11	10000
63	3	60000	1	24	8.50	2.50	8.50	0.11	10000
64	4	60000	1	24	5.33	2.50	5.33	0.11	10000
65	6	60000	1	24	2.80	2.50	2.80	0.11	10000
66	3	60000	1.41	24	8.09	2.50	5.74	0.11	10000
67	4	60000	1.41	24	4.92	2.50	3.49	0.11	10000
68	3	60000	1	18	5.50	2.50	5.50	0.11	10000
69	4	60000	1	18	3.33	2.50	3.33	0.11	10000
70	3	60000	1.128	18	5.37	2.50	4.76	0.11	10000
71	4	60000	1.128	18	3.21	2.50	2.84	0.11	10000
72	3	60000	1.41	18	5.09	2.50	3.61	0.11	10000
73	2	60000	0.75	8	2.25	2.50	3.00	0.11	12000
74	3	60000	0.75	12	2.75	2.50	3.67	0.11	12000
75	3	60000	1	12	2.50	2.50	2.50	0.11	12000
76	3	60000	1.128	12	2.37	2.50	2.10	0.11	12000
77	3	60000	0.75	24	8.75	2.50	11.67	0.11	12000
78	4	60000	0.75	24	5.58	2.50	7.44	0.11	12000
79	6	60000	0.75	24	3.05	2.50	4.07	0.11	12000
80	8	60000	0.75	24	1.96	2.50	2.62	0.11	12000
81	3	60000	1	24	8.50	2.50	8.50	0.11	12000
82	4	60000	1	24	5.33	2.50	5.33	0.11	12000
83	6	60000	1	24	2.80	2.50	2.80	0.11	12000
84	3	60000	1.41	24	8.09	2.50	5.74	0.11	12000
85	4	60000	1.41	24	4.92	2.50	3.49	0.11	12000
86	3	60000	1	18	5.50	2.50	5.50	0.11	12000
87	4	60000	1	18	3.33	2.50	3.33	0.11	12000
88	3	60000	1.128	18	5.37	2.50	4.76	0.11	12000
89	4	60000	1.128	18	3.21	2.50	2.84	0.11	12000
90	3	60000	1.41	18	5.09	2.50	3.61	0.11	12000
91	2	60000	0.75	8	2.25	2.50	3.00	0.11	15000
92	3	60000	0.75	12	2.75	2.50	3.67	0.11	15000
93	3	60000	1	12	2.50	2.50	2.50	0.11	15000
94	3	60000	1.128	12	2.37	2.50	2.10	0.11	15000
95	3	60000	0.75	24	8.75	2.50	11.67	0.11	15000
96	4	60000	0.75	24	5.58	2.50	7.44	0.11	15000
97	6	60000	0.75	24	3.05	2.50	4.07	0.11	15000
98	8	60000	0.75	24	1.96	2.50	2.62	0.11	15000
99	3	60000	1	24	8.50	2.50	8.50	0.11	15000
100	4	60000	1	24	5.33	2.50	5.33	0.11	15000

Table D.1 Cont. Hypothetical beams used in Monte Carlo analysis*

Beam No.	No Confinement		1 No.3 parallel		2 No.3 parallel		No. 3 spaced at $3d_b$ parallel		No. 3 spaced at $3d_b$ perpendicular	
	N	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}
51	-	13.3	2	11.7	4	10.1	6	8.7	8	12.0
52	-	13.3	2	12.0	4	10.7	6	9.8	8	12.3
53	-	16.8	2	15.1	4	13.4	6	11.7	8	15.5
54	-	21.6	2	19.9	4	18.2	6	16.5	10	19.9
55	-	8.5	2	5.4	4	5.4	6	5.4	6	6.2
56	-	7.9	2	5.7	4	5.3	6	5.3	6	6.6
57	-	13.8	2	11.4	4	8.9	6	8.5	8	11.8
58	-	17.2	2	14.7	4	12.2	6	10.4	8	15.2
59	-	5.7	2	4.9	4	4.7	6	4.7	4	5.3
60	-	5.7	2	5.1	4	4.7	6	4.7	4	5.4
61	-	7.5	2	6.5	4	5.6	6	5.2	6	6.9
62	-	8.8	2	7.8	4	6.8	6	5.7	6	8.2
63	-	8.7	2	8.0	4	7.4	6	7.3	6	8.3
64	-	9.7	2	8.9	4	8.2	6	7.5	6	9.2
65	-	13.4	2	12.2	4	11.1	6	9.9	8	12.4
66	-	15.2	2	14.5	4	13.9	6	13.2	6	14.8
67	-	20.7	2	19.4	4	18.2	6	17.0	10	19.4
68	-	9.4	2	8.5	4	7.6	6	7.4	6	8.9
69	-	12.6	2	11.1	4	9.6	6	8.2	8	11.4
70	-	12.6	2	11.4	4	10.1	6	9.2	6	11.9
71	-	15.9	2	14.3	4	12.7	6	11.1	8	14.6
72	-	20.4	2	18.8	4	17.2	6	15.6	8	19.1
73	-	8.1	2	5.2	4	5.2	6	5.2	6	5.9
74	-	7.5	2	5.4	4	5.0	6	5.0	6	6.3
75	-	13.2	2	10.8	4	8.5	6	8.2	8	11.3
76	-	16.4	2	14.1	4	11.7	6	9.9	8	14.5
77	-	5.4	2	4.7	4	4.5	6	4.5	4	5.1
78	-	5.4	2	4.8	4	4.5	6	4.5	4	5.2
79	-	7.1	2	6.2	4	5.3	6	4.9	6	6.6
80	-	8.5	2	7.5	4	6.5	6	5.5	6	7.9
81	-	8.3	2	7.7	4	7.0	6	6.9	6	7.9
82	-	9.2	2	8.5	4	7.8	6	7.2	6	8.8
83	-	12.8	2	11.7	4	10.6	6	9.5	8	11.9
84	-	14.5	2	13.9	4	13.2	6	12.6	6	14.2
85	-	19.8	2	18.6	4	17.4	6	16.2	8	18.8
86	-	9.0	2	8.1	4	7.2	6	7.1	6	8.5
87	-	12.0	2	10.6	4	9.1	6	7.9	8	10.9
88	-	12.0	2	10.9	4	9.7	6	8.8	6	11.3
89	-	15.2	2	13.7	4	12.1	6	10.6	8	14.0
90	-	19.5	2	18.0	4	16.4	6	14.9	8	18.3
91	-	7.7	2	4.9	4	4.9	6	4.9	4	6.3
92	-	7.1	2	5.1	4	4.8	6	4.8	4	6.3
93	-	12.5	2	10.3	4	8.0	6	7.7	8	10.7
94	-	15.6	2	13.3	4	11.0	6	9.4	8	13.7
95	-	5.1	2	4.4	4	4.3	6	4.3	4	4.8
96	-	5.1	2	4.6	4	4.3	6	4.3	4	4.9
97	-	6.8	2	5.9	4	5.0	6	4.7	4	6.4
98	-	8.0	2	7.1	4	6.1	6	5.2	6	7.4
99	-	7.9	2	7.3	4	6.7	6	6.6	4	7.6
100	-	8.7	2	8.1	4	7.4	6	6.8	6	8.3

*Values of development length ℓ_{dh} are based on Eq. (5.22)

Table D.1 Cont. Hypothetical beams used in Monte Carlo analysis

Beam No.	N_h	f_s	d_b	b	c_{ch}	c_{so}	c_{ch}/d_b	$A_{tr,l}$	f'_c
101	6	60000	1	24	2.80	2.50	2.80	0.11	15000
102	3	60000	1.41	24	8.09	2.50	5.74	0.11	15000
103	4	60000	1.41	24	4.92	2.50	3.49	0.11	15000
104	3	60000	1	18	5.50	2.50	5.50	0.11	15000
105	4	60000	1	18	3.33	2.50	3.33	0.11	15000
106	3	60000	1.128	18	5.37	2.50	4.76	0.11	15000
107	4	60000	1.128	18	3.21	2.50	2.84	0.11	15000
108	3	60000	1.41	18	5.09	2.50	3.61	0.11	15000
109	2	80000	0.75	8	2.25	2.50	3.00	0.11	4000
110	3	80000	0.75	12	2.75	2.50	3.67	0.11	4000
111	3	80000	1	12	2.50	2.50	2.50	0.11	4000
112	3	80000	1.128	12	2.37	2.50	2.10	0.11	4000
113	3	80000	0.75	24	8.75	2.50	11.67	0.11	4000
114	4	80000	0.75	24	5.58	2.50	7.44	0.11	4000
115	6	80000	0.75	24	3.05	2.50	4.07	0.11	4000
116	8	80000	0.75	24	1.96	2.50	2.62	0.11	4000
117	3	80000	1	24	8.50	2.50	8.50	0.11	4000
118	4	80000	1	24	5.33	2.50	5.33	0.11	4000
119	6	80000	1	24	2.80	2.50	2.80	0.11	4000
120	3	80000	1.41	24	8.09	2.50	5.74	0.11	4000
121	4	80000	1.41	24	4.92	2.50	3.49	0.11	4000
122	3	80000	1	18	5.50	2.50	5.50	0.11	4000
123	4	80000	1	18	3.33	2.50	3.33	0.11	4000
124	3	80000	1.128	18	5.37	2.50	4.76	0.11	4000
125	4	80000	1.128	18	3.21	2.50	2.84	0.11	4000
126	3	80000	1.41	18	5.09	2.50	3.61	0.11	4000
127	2	80000	0.75	8	2.25	2.50	3.00	0.11	6000
128	3	80000	0.75	12	2.75	2.50	3.67	0.11	6000
129	3	80000	1	12	2.50	2.50	2.50	0.11	6000
130	3	80000	1.128	12	2.37	2.50	2.10	0.11	6000
131	3	80000	0.75	24	8.75	2.50	11.67	0.11	6000
132	4	80000	0.75	24	5.58	2.50	7.44	0.11	6000
133	6	80000	0.75	24	3.05	2.50	4.07	0.11	6000
134	8	80000	0.75	24	1.96	2.50	2.62	0.11	6000
135	3	80000	1	24	8.50	2.50	8.50	0.11	6000
136	4	80000	1	24	5.33	2.50	5.33	0.11	6000
137	6	80000	1	24	2.80	2.50	2.80	0.11	6000
138	3	80000	1.41	24	8.09	2.50	5.74	0.11	6000
139	4	80000	1.41	24	4.92	2.50	3.49	0.11	6000
140	3	80000	1	18	5.50	2.50	5.50	0.11	6000
141	4	80000	1	18	3.33	2.50	3.33	0.11	6000
142	3	80000	1.128	18	5.37	2.50	4.76	0.11	6000
143	4	80000	1.128	18	3.21	2.50	2.84	0.11	6000
144	3	80000	1.41	18	5.09	2.50	3.61	0.11	6000
145	2	80000	0.75	8	2.25	2.50	3.00	0.11	8000
146	3	80000	0.75	12	2.75	2.50	3.67	0.11	8000
147	3	80000	1	12	2.50	2.50	2.50	0.11	8000
148	3	80000	1.128	12	2.37	2.50	2.10	0.11	8000
149	3	80000	0.75	24	8.75	2.50	11.67	0.11	8000
150	4	80000	0.75	24	5.58	2.50	7.44	0.11	8000

Table D.1 Cont. Hypothetical beams used in Monte Carlo analysis*

Beam No.	No Confinement		1 No.3 parallel		2 No.3 parallel		No. 3 spaced at $3d_b$ parallel		No. 3 spaced at $3d_b$ perpendicular	
	N	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}
101	-	12.1	2	11.0	4	10.0	6	9.0	8	11.2
102	-	13.8	2	13.1	4	12.5	6	11.9	6	13.4
103	-	18.7	2	17.6	4	16.5	6	15.3	8	17.8
104	-	8.5	2	7.7	4	6.9	6	6.7	6	8.0
105	-	11.4	2	10.0	4	8.6	6	7.4	6	10.5
106	-	11.4	2	10.3	4	9.2	6	8.3	6	10.7
107	-	14.4	2	12.9	4	11.5	6	10.0	8	13.2
108	-	18.4	2	17.0	4	15.5	6	14.1	8	17.3
109	-	14.2	2	9.4	4	9.4	6	9.4	8	9.4
110	-	13.2	2	9.8	4	9.1	6	9.1	8	10.5
111	-	23.1	2	19.3	4	15.4	6	14.8	12	18.5
112	-	28.9	2	24.9	4	20.9	6	18.0	14	23.3
113	-	9.5	2	8.4	4	8.2	6	8.2	6	8.8
114	-	9.5	2	8.7	4	8.2	6	8.2	8	8.8
115	-	12.5	2	11.1	4	9.6	6	9.0	10	11.1
116	-	14.8	2	13.2	4	11.5	6	9.9	10	13.2
117	-	14.6	2	13.7	4	12.7	6	12.6	8	13.9
118	-	16.2	2	15.1	4	14.0	6	13.0	10	15.1
119	-	22.4	2	20.6	4	18.8	6	17.0	12	20.2
120	-	25.5	2	24.5	4	23.6	6	22.6	12	24.3
121	-	34.7	2	32.7	4	30.8	6	28.9	14	32.0
122	-	15.8	2	14.5	4	13.1	6	12.9	10	14.5
123	-	21.1	2	18.7	4	16.3	6	14.3	12	18.2
124	-	21.1	2	19.2	4	17.4	6	16.0	10	19.2
125	-	26.7	2	24.2	4	21.6	6	19.1	14	23.1
126	-	34.2	2	31.7	4	29.2	6	26.7	14	30.7
127	-	12.9	2	8.5	4	8.5	6	8.5	8	8.5
128	-	11.9	2	8.9	4	8.2	6	8.2	8	9.5
129	-	20.9	2	17.4	4	13.9	6	13.4	10	17.4
130	-	26.1	2	22.5	4	18.9	6	16.3	12	21.8
131	-	8.6	2	7.6	4	7.4	6	7.4	6	8.0
132	-	8.6	2	7.8	4	7.4	6	7.4	6	8.1
133	-	11.3	2	10.0	4	8.6	6	8.1	8	10.3
134	-	13.4	2	11.9	4	10.4	6	8.9	10	11.9
135	-	13.2	2	12.3	4	11.5	6	11.4	8	12.5
136	-	14.7	2	13.6	4	12.6	6	11.7	8	13.9
137	-	20.2	2	18.6	4	17.0	6	15.3	12	18.3
138	-	23.1	2	22.2	4	21.3	6	20.4	10	22.2
139	-	31.3	2	29.6	4	27.8	6	26.1	14	28.9
140	-	14.3	2	13.1	4	11.8	6	11.7	8	13.3
141	-	19.1	2	16.9	4	14.8	6	12.9	10	16.9
142	-	19.1	2	17.4	4	15.7	6	14.5	10	17.4
143	-	24.1	2	21.8	4	19.5	6	17.2	12	21.4
144	-	30.9	2	28.6	4	26.4	6	24.1	14	27.7
145	-	12.0	2	7.9	4	7.9	6	7.9	6	8.9
146	-	11.1	2	8.2	4	7.7	6	7.7	8	8.8
147	-	19.4	2	16.2	4	12.9	6	12.4	10	16.2
148	-	24.3	2	20.9	4	17.6	6	15.1	12	20.3
149	-	8.0	2	7.1	4	6.9	6	6.9	6	7.4
150	-	8.0	2	7.3	4	6.9	6	6.9	6	7.6

*Values of development length ℓ_{dh} are based on Eq. (5.22)

Table D.1 Cont. Hypothetical beams used in Monte Carlo analysis

Beam No.	N_h	f_s	d_b	b	c_{ch}	c_{so}	c_{ch}/d_b	$A_{tr,l}$	f'_c
151	6	80000	0.75	24	3.05	2.50	4.07	0.11	8000
152	8	80000	0.75	24	1.96	2.50	2.62	0.11	8000
153	3	80000	1	24	8.50	2.50	8.50	0.11	8000
154	4	80000	1	24	5.33	2.50	5.33	0.11	8000
155	6	80000	1	24	2.80	2.50	2.80	0.11	8000
156	3	80000	1.41	24	8.09	2.50	5.74	0.11	8000
157	4	80000	1.41	24	4.92	2.50	3.49	0.11	8000
158	3	80000	1	18	5.50	2.50	5.50	0.11	8000
159	4	80000	1	18	3.33	2.50	3.33	0.11	8000
160	3	80000	1.128	18	5.37	2.50	4.76	0.11	8000
161	4	80000	1.128	18	3.21	2.50	2.84	0.11	8000
162	3	80000	1.41	18	5.09	2.50	3.61	0.11	8000
163	2	80000	0.75	8	2.25	2.50	3.00	0.11	10000
164	3	80000	0.75	12	2.75	2.50	3.67	0.11	10000
165	3	80000	1	12	2.50	2.50	2.50	0.11	10000
166	3	80000	1.128	12	2.37	2.50	2.10	0.11	10000
167	3	80000	0.75	24	8.75	2.50	11.67	0.11	10000
168	4	80000	0.75	24	5.58	2.50	7.44	0.11	10000
169	6	80000	0.75	24	3.05	2.50	4.07	0.11	10000
170	8	80000	0.75	24	1.96	2.50	2.62	0.11	10000
171	3	80000	1	24	8.50	2.50	8.50	0.11	10000
172	4	80000	1	24	5.33	2.50	5.33	0.11	10000
173	6	80000	1	24	2.80	2.50	2.80	0.11	10000
174	3	80000	1.41	24	8.09	2.50	5.74	0.11	10000
175	4	80000	1.41	24	4.92	2.50	3.49	0.11	10000
176	3	80000	1	18	5.50	2.50	5.50	0.11	10000
177	4	80000	1	18	3.33	2.50	3.33	0.11	10000
178	3	80000	1.128	18	5.37	2.50	4.76	0.11	10000
179	4	80000	1.128	18	3.21	2.50	2.84	0.11	10000
180	3	80000	1.41	18	5.09	2.50	3.61	0.11	10000
181	2	80000	0.75	8	2.25	2.50	3.00	0.11	12000
182	3	80000	0.75	12	2.75	2.50	3.67	0.11	12000
183	3	80000	1	12	2.50	2.50	2.50	0.11	12000
184	3	80000	1.128	12	2.37	2.50	2.10	0.11	12000
185	3	80000	0.75	24	8.75	2.50	11.67	0.11	12000
186	4	80000	0.75	24	5.58	2.50	7.44	0.11	12000
187	6	80000	0.75	24	3.05	2.50	4.07	0.11	12000
188	8	80000	0.75	24	1.96	2.50	2.62	0.11	12000
189	3	80000	1	24	8.50	2.50	8.50	0.11	12000
190	4	80000	1	24	5.33	2.50	5.33	0.11	12000
191	6	80000	1	24	2.80	2.50	2.80	0.11	12000
192	3	80000	1.41	24	8.09	2.50	5.74	0.11	12000
193	4	80000	1.41	24	4.92	2.50	3.49	0.11	12000
194	3	80000	1	18	5.50	2.50	5.50	0.11	12000
195	4	80000	1	18	3.33	2.50	3.33	0.11	12000
196	3	80000	1.128	18	5.37	2.50	4.76	0.11	12000
197	4	80000	1.128	18	3.21	2.50	2.84	0.11	12000
198	3	80000	1.41	18	5.09	2.50	3.61	0.11	12000
199	2	80000	0.75	8	2.25	2.50	3.00	0.11	15000
200	3	80000	0.75	12	2.75	2.50	3.67	0.11	15000

Table D.1 Cont. Hypothetical beams used in Monte Carlo analysis*

Beam No.	No Confinement		1 No.3 parallel		2 No.3 parallel		No. 3 spaced at $3d_b$ parallel		No. 3 spaced at $3d_b$ perpendicular	
	N	ℓ_{dh}	N	ℓ_{dh}	N	ℓ_{dh}	N	ℓ_{dh}	N	ℓ_{dh}
151	-	10.5	2	9.3	4	8.0	6	7.5	8	9.5
152	-	12.5	2	11.1	4	9.7	6	8.3	10	11.1
153	-	12.3	2	11.5	4	10.7	6	10.6	8	11.6
154	-	13.6	2	12.7	4	11.8	6	10.9	8	12.9
155	-	18.8	2	17.3	4	15.8	6	14.3	12	17.0
156	-	21.5	2	20.6	4	19.8	6	19.0	10	20.6
157	-	29.2	2	27.5	4	25.9	6	24.3	12	27.2
158	-	13.3	2	12.2	4	11.0	6	10.8	8	12.4
159	-	17.7	2	15.7	4	13.7	6	12.0	10	15.7
160	-	17.7	2	16.2	4	14.6	6	13.5	10	16.2
161	-	22.5	2	20.3	4	18.2	6	16.0	12	19.9
162	-	28.8	2	26.7	4	24.6	6	22.5	12	26.2
163	-	11.3	2	7.5	4	7.5	6	7.5	6	8.4
164	-	10.5	2	7.8	4	7.3	6	7.3	6	8.9
165	-	18.4	2	15.3	4	12.2	6	11.8	10	15.3
166	-	23.0	2	19.8	4	16.6	6	14.3	12	19.2
167	-	7.5	2	6.7	4	6.5	6	6.5	6	7.0
168	-	7.5	2	6.9	4	6.5	6	6.5	6	7.2
169	-	10.0	2	8.8	4	7.6	6	7.1	8	9.0
170	-	11.8	2	10.5	4	9.2	6	7.9	8	10.7
171	-	11.6	2	10.9	4	10.1	6	10.0	8	11.0
172	-	12.9	2	12.0	4	11.1	6	10.3	8	12.2
173	-	17.8	2	16.4	4	14.9	6	13.5	10	16.4
174	-	20.3	2	19.5	4	18.7	6	18.0	10	19.5
175	-	27.6	2	26.0	4	24.5	6	23.0	12	25.7
176	-	12.6	2	11.5	4	10.4	6	10.3	8	11.7
177	-	16.8	2	14.9	4	13.0	6	11.3	10	14.9
178	-	16.8	2	15.3	4	13.8	6	12.7	8	15.6
179	-	21.2	2	19.2	4	17.2	6	15.2	10	19.2
180	-	27.2	2	25.2	4	23.2	6	21.2	12	24.8
181	-	10.8	2	7.1	4	7.1	6	7.1	6	8.1
182	-	10.0	2	7.4	4	6.9	6	6.9	6	8.5
183	-	17.6	2	14.6	4	11.7	6	11.2	10	14.6
184	-	21.9	2	18.9	4	15.9	6	13.7	10	18.9
185	-	7.2	2	6.4	4	6.2	6	6.2	6	6.7
186	-	7.2	2	6.6	4	6.2	6	6.2	6	6.8
187	-	9.5	2	8.4	4	7.3	6	6.8	6	8.9
188	-	11.3	2	10.0	4	8.8	6	7.5	8	10.3
189	-	11.1	2	10.4	4	9.7	6	9.6	6	10.7
190	-	12.3	2	11.5	4	10.6	6	9.9	8	11.6
191	-	17.0	2	15.6	4	14.3	6	12.9	10	15.6
192	-	19.4	2	18.6	4	17.9	6	17.2	8	18.8
193	-	26.3	2	24.9	4	23.4	6	21.9	12	24.6
194	-	12.0	2	11.0	4	10.0	6	9.8	8	11.2
195	-	16.0	2	14.2	4	12.4	6	10.8	10	14.2
196	-	16.0	2	14.6	4	13.2	6	12.2	8	14.9
197	-	20.3	2	18.4	4	16.4	6	14.5	10	18.4
198	-	26.0	2	24.1	4	22.2	6	20.3	12	23.7
199	-	10.2	2	6.8	4	6.8	6	6.8	6	7.6
200	-	9.5	2	7.0	4	6.6	6	6.6	6	8.0

*Values of development length ℓ_{dh} are based on Eq. (5.22)

Table E.1 Cont. Hypothetical beams used in Monte Carlo analysis

Beam No.	N_h	f_s	d_b	b	c_{ch}	c_{so}	c_{ch}/d_b	$A_{tr,l}$	f'_c
201	3	80000	1	12	2.50	2.50	2.50	0.11	15000
202	3	80000	1.128	12	2.37	2.50	2.10	0.11	15000
203	3	80000	0.75	24	8.75	2.50	11.67	0.11	15000
204	4	80000	0.75	24	5.58	2.50	7.44	0.11	15000
205	6	80000	0.75	24	3.05	2.50	4.07	0.11	15000
206	8	80000	0.75	24	1.96	2.50	2.62	0.11	15000
207	3	80000	1	24	8.50	2.50	8.50	0.11	15000
208	4	80000	1	24	5.33	2.50	5.33	0.11	15000
209	6	80000	1	24	2.80	2.50	2.80	0.11	15000
210	3	80000	1.41	24	8.09	2.50	5.74	0.11	15000
211	4	80000	1.41	24	4.92	2.50	3.49	0.11	15000
212	3	80000	1	18	5.50	2.50	5.50	0.11	15000
213	4	80000	1	18	3.33	2.50	3.33	0.11	15000
214	3	80000	1.128	18	5.37	2.50	4.76	0.11	15000
215	4	80000	1.128	18	3.21	2.50	2.84	0.11	15000
216	3	80000	1.41	18	5.09	2.50	3.61	0.11	15000
217	2	100000	0.75	8	2.25	2.50	3.00	0.11	4000
218	3	100000	0.75	12	2.75	2.50	3.67	0.11	4000
219	3	100000	1	12	2.50	2.50	2.50	0.11	4000
220	3	100000	1.128	12	2.37	2.50	2.10	0.11	4000
221	3	100000	0.75	24	8.75	2.50	11.67	0.11	4000
222	4	100000	0.75	24	5.58	2.50	7.44	0.11	4000
223	6	100000	0.75	24	3.05	2.50	4.07	0.11	4000
224	8	100000	0.75	24	1.96	2.50	2.62	0.11	4000
225	3	100000	1	24	8.50	2.50	8.50	0.11	4000
226	4	100000	1	24	5.33	2.50	5.33	0.11	4000
227	6	100000	1	24	2.80	2.50	2.80	0.11	4000
228	3	100000	1.41	24	8.09	2.50	5.74	0.11	4000
229	4	100000	1.41	24	4.92	2.50	3.49	0.11	4000
230	3	100000	1	18	5.50	2.50	5.50	0.11	4000
231	4	100000	1	18	3.33	2.50	3.33	0.11	4000
232	3	100000	1.128	18	5.37	2.50	4.76	0.11	4000
233	4	100000	1.128	18	3.21	2.50	2.84	0.11	4000
234	3	100000	1.41	18	5.09	2.50	3.61	0.11	4000
235	2	100000	0.75	8	2.25	2.50	3.00	0.11	6000
236	3	100000	0.75	12	2.75	2.50	3.67	0.11	6000
237	3	100000	1	12	2.50	2.50	2.50	0.11	6000
238	3	100000	1.128	12	2.37	2.50	2.10	0.11	6000
239	3	100000	0.75	24	8.75	2.50	11.67	0.11	6000
240	4	100000	0.75	24	5.58	2.50	7.44	0.11	6000
241	6	100000	0.75	24	3.05	2.50	4.07	0.11	6000
242	8	100000	0.75	24	1.96	2.50	2.62	0.11	6000
243	3	100000	1	24	8.50	2.50	8.50	0.11	6000
244	4	100000	1	24	5.33	2.50	5.33	0.11	6000
245	6	100000	1	24	2.80	2.50	2.80	0.11	6000
246	3	100000	1.41	24	8.09	2.50	5.74	0.11	6000
247	4	100000	1.41	24	4.92	2.50	3.49	0.11	6000
248	3	100000	1	18	5.50	2.50	5.50	0.11	6000
249	4	100000	1	18	3.33	2.50	3.33	0.11	6000
250	3	100000	1.128	18	5.37	2.50	4.76	0.11	6000

Table E.1 Cont. Hypothetical beams used in Monte Carlo analysis*

Beam No.	No Confinement		1 No.3 parallel		2 No.3 parallel		No. 3 spaced at $3d_b$ parallel		No. 3 spaced at $3d_b$ perpendicular	
	N	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}
201	-	16.6	2	13.8	4	11.1	6	10.6	8	14.4
202	-	20.7	2	17.9	4	15.0	6	12.9	10	17.9
203	-	6.8	2	6.0	4	5.9	6	5.9	4	6.5
204	-	6.8	2	6.2	4	5.9	6	5.9	4	6.6
205	-	9.0	2	7.9	4	6.9	6	6.4	6	8.4
206	-	10.7	2	9.5	4	8.3	6	7.1	8	9.7
207	-	10.5	2	9.8	4	9.1	6	9.0	6	10.1
208	-	11.7	2	10.9	4	10.0	6	9.3	8	11.0
209	-	16.1	2	14.8	4	13.5	6	12.2	10	14.8
210	-	18.3	2	17.6	4	16.9	6	16.2	8	17.8
211	-	24.9	2	23.5	4	22.1	6	20.8	12	23.3
212	-	11.4	2	10.4	4	9.4	6	9.3	6	10.8
213	-	15.2	2	13.5	4	11.7	6	10.2	8	13.8
214	-	15.2	2	13.8	4	12.5	6	11.5	8	14.1
215	-	19.2	2	17.4	4	15.5	6	13.7	10	17.4
216	-	24.6	2	22.8	4	21.0	6	19.2	10	22.8
217	-	17.8	2	12.1	4	12.1	6	12.1	10	12.1
218	-	16.5	2	12.6	4	11.8	6	11.8	10	12.6
219	-	28.9	2	24.3	4	19.8	6	19.1	14	22.5
220	-	36.1	2	31.4	4	26.7	6	23.2	16	28.5
221	-	11.9	2	10.8	4	10.5	6	10.5	8	11.0
222	-	11.9	2	11.0	4	10.5	6	10.5	10	11.0
223	-	15.7	2	14.0	4	12.2	6	11.6	12	13.6
224	-	18.5	2	16.6	4	14.7	6	12.7	14	15.8
225	-	18.3	2	17.3	4	16.4	6	16.2	12	17.1
226	-	20.3	2	19.1	4	17.8	6	16.8	12	18.8
227	-	28.0	2	25.9	4	23.7	6	21.6	16	24.6
228	-	31.9	2	30.9	4	29.8	6	28.8	14	30.5
229	-	43.3	2	41.1	4	38.8	6	36.6	18	39.3
230	-	19.8	2	18.3	4	16.9	6	16.6	12	18.0
231	-	26.4	2	23.6	4	20.8	6	18.4	14	22.5
232	-	26.4	2	24.3	4	22.2	6	20.6	14	23.4
233	-	33.4	2	30.4	4	27.4	6	24.4	16	28.6
234	-	42.7	2	39.8	4	36.9	6	34.0	18	37.5
235	-	16.1	2	11.0	4	11.0	6	11.0	8	11.0
236	-	14.9	2	11.3	4	10.6	6	10.6	10	11.3
237	-	26.1	2	22.0	4	17.9	6	17.2	14	20.3
238	-	32.6	2	28.3	4	24.1	6	21.0	16	25.8
239	-	10.7	2	9.7	4	9.5	6	9.5	8	9.9
240	-	10.7	2	10.0	4	9.5	6	9.5	8	10.1
241	-	14.2	2	12.6	4	11.1	6	10.4	10	12.6
242	-	16.8	2	15.0	4	13.2	6	11.5	12	14.6
243	-	16.5	2	15.6	4	14.8	6	14.7	10	15.6
244	-	18.3	2	17.2	4	16.1	6	15.1	12	17.0
245	-	25.3	2	23.4	4	21.4	6	19.5	14	22.6
246	-	28.8	2	27.9	4	27.0	6	26.0	14	27.5
247	-	39.2	2	37.1	4	35.1	6	33.1	16	35.9
248	-	17.9	2	16.6	4	15.2	6	15.0	10	16.6
249	-	23.8	2	21.3	4	18.8	6	16.6	14	20.3
250	-	23.8	2	21.9	4	20.0	6	18.6	12	21.6

*Values of development length ℓ_{dh} are based on Eq. (5.22)

Table E.1 Cont. Hypothetical beams used in Monte Carlo analysis

Beam No.	N_h	f_s	d_b	b	c_{ch}	c_{so}	c_{ch}/d_b	$A_{tr,l}$	f'_c
251	4	100000	1.128	18	3.21	2.50	2.84	0.11	6000
252	3	100000	1.41	18	5.09	2.50	3.61	0.11	6000
253	2	100000	0.75	8	2.25	2.50	3.00	0.11	8000
254	3	100000	0.75	12	2.75	2.50	3.67	0.11	8000
255	3	100000	1	12	2.50	2.50	2.50	0.11	8000
256	3	100000	1.128	12	2.37	2.50	2.10	0.11	8000
257	3	100000	0.75	24	8.75	2.50	11.67	0.11	8000
258	4	100000	0.75	24	5.58	2.50	7.44	0.11	8000
259	6	100000	0.75	24	3.05	2.50	4.07	0.11	8000
260	8	100000	0.75	24	1.96	2.50	2.62	0.11	8000
261	3	100000	1	24	8.50	2.50	8.50	0.11	8000
262	4	100000	1	24	5.33	2.50	5.33	0.11	8000
263	6	100000	1	24	2.80	2.50	2.80	0.11	8000
264	3	100000	1.41	24	8.09	2.50	5.74	0.11	8000
265	4	100000	1.41	24	4.92	2.50	3.49	0.11	8000
266	3	100000	1	18	5.50	2.50	5.50	0.11	8000
267	4	100000	1	18	3.33	2.50	3.33	0.11	8000
268	3	100000	1.128	18	5.37	2.50	4.76	0.11	8000
269	4	100000	1.128	18	3.21	2.50	2.84	0.11	8000
270	3	100000	1.41	18	5.09	2.50	3.61	0.11	8000
271	2	100000	0.75	8	2.25	2.50	3.00	0.11	10000
272	3	100000	0.75	12	2.75	2.50	3.67	0.11	10000
273	3	100000	1	12	2.50	2.50	2.50	0.11	10000
274	3	100000	1.128	12	2.37	2.50	2.10	0.11	10000
275	3	100000	0.75	24	8.75	2.50	11.67	0.11	10000
276	4	100000	0.75	24	5.58	2.50	7.44	0.11	10000
277	6	100000	0.75	24	3.05	2.50	4.07	0.11	10000
278	8	100000	0.75	24	1.96	2.50	2.62	0.11	10000
279	3	100000	1	24	8.50	2.50	8.50	0.11	10000
280	4	100000	1	24	5.33	2.50	5.33	0.11	10000
281	6	100000	1	24	2.80	2.50	2.80	0.11	10000
282	3	100000	1.41	24	8.09	2.50	5.74	0.11	10000
283	4	100000	1.41	24	4.92	2.50	3.49	0.11	10000
284	3	100000	1	18	5.50	2.50	5.50	0.11	10000
285	4	100000	1	18	3.33	2.50	3.33	0.11	10000
286	3	100000	1.128	18	5.37	2.50	4.76	0.11	10000
287	4	100000	1.128	18	3.21	2.50	2.84	0.11	10000
288	3	100000	1.41	18	5.09	2.50	3.61	0.11	10000
289	2	100000	0.75	8	2.25	2.50	3.00	0.11	12000
290	3	100000	0.75	12	2.75	2.50	3.67	0.11	12000
291	3	100000	1	12	2.50	2.50	2.50	0.11	12000
292	3	100000	1.128	12	2.37	2.50	2.10	0.11	12000
293	3	100000	0.75	24	8.75	2.50	11.67	0.11	12000
294	4	100000	0.75	24	5.58	2.50	7.44	0.11	12000
295	6	100000	0.75	24	3.05	2.50	4.07	0.11	12000
296	8	100000	0.75	24	1.96	2.50	2.62	0.11	12000
297	3	100000	1	24	8.50	2.50	8.50	0.11	12000
298	4	100000	1	24	5.33	2.50	5.33	0.11	12000
299	6	100000	1	24	2.80	2.50	2.80	0.11	12000
300	3	100000	1.41	24	8.09	2.50	5.74	0.11	12000

Table E.1 Cont. Hypothetical beams used in Monte Carlo analysis*

Beam No.	No Confinement		1 No.3 parallel		2 No.3 parallel		No. 3 spaced at $3d_b$ parallel		No. 3 spaced at $3d_b$ perpendicular	
	N	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}
251	-	30.2	2	27.5	4	24.8	6	22.1	16	25.8
252	-	38.6	2	36.0	4	33.4	6	30.8	16	34.4
253	-	15.0	2	10.2	4	10.2	6	10.2	8	10.2
254	-	13.9	2	10.6	4	9.9	6	9.9	8	11.2
255	-	24.3	2	20.5	4	16.6	6	16.0	12	19.7
256	-	30.3	2	26.4	4	22.4	6	19.5	14	24.8
257	-	10.0	2	9.0	4	8.9	6	8.9	8	9.2
258	-	10.0	2	9.3	4	8.9	6	8.9	8	9.4
259	-	13.2	2	11.7	4	10.3	6	9.7	10	11.7
260	-	15.6	2	14.0	4	12.3	6	10.7	12	13.6
261	-	15.4	2	14.6	4	13.8	6	13.6	10	14.6
262	-	17.1	2	16.0	4	15.0	6	14.1	10	16.0
263	-	23.5	2	21.8	4	20.0	6	18.2	14	21.0
264	-	26.8	2	26.0	4	25.1	6	24.2	12	25.8
265	-	36.5	2	34.6	4	32.7	6	30.8	16	33.4
266	-	16.6	2	15.4	4	14.2	6	14.0	10	15.4
267	-	22.2	2	19.8	4	17.5	6	15.5	12	19.4
268	-	22.2	2	20.4	4	18.6	6	17.4	12	20.1
269	-	28.1	2	25.6	4	23.0	6	20.5	14	24.6
270	-	35.9	2	33.5	4	31.1	6	28.6	16	32.0
271	-	14.1	2	9.6	4	9.6	6	9.6	8	9.6
272	-	13.1	2	10.0	4	9.4	6	9.4	8	10.6
273	-	23.0	2	19.4	4	15.7	6	15.2	12	18.6
274	-	28.7	2	24.9	4	21.2	6	18.5	14	23.4
275	-	9.4	2	8.6	4	8.4	6	8.4	8	8.7
276	-	9.4	2	8.8	4	8.4	6	8.4	8	8.9
277	-	12.5	2	11.1	4	9.7	6	9.2	10	11.1
278	-	14.7	2	13.2	4	11.7	6	10.1	10	13.2
279	-	14.5	2	13.8	4	13.0	6	12.9	8	13.9
280	-	16.1	2	15.2	4	14.2	6	13.3	10	15.2
281	-	22.3	2	20.6	4	18.9	6	17.2	12	20.2
282	-	25.4	2	24.6	4	23.7	6	22.9	12	24.4
283	-	34.5	2	32.7	4	30.9	6	29.1	14	32.0
284	-	15.7	2	14.6	4	13.4	6	13.2	10	14.6
285	-	21.0	2	18.8	4	16.6	6	14.6	12	18.3
286	-	21.0	2	19.3	4	17.6	6	16.4	12	19.0
287	-	26.6	2	24.2	4	21.8	6	19.4	14	23.2
288	-	34.0	2	31.7	4	29.4	6	27.1	14	30.8
289	-	13.5	2	9.2	4	9.2	6	9.2	8	9.2
290	-	12.5	2	9.5	4	8.9	6	8.9	8	10.1
291	-	22.0	2	18.5	4	15.0	6	14.5	12	17.8
292	-	27.4	2	23.8	4	20.3	6	17.6	14	22.4
293	-	9.0	2	8.2	4	8.0	6	8.0	6	8.5
294	-	9.0	2	8.4	4	8.0	6	8.0	6	8.6
295	-	11.9	2	10.6	4	9.3	6	8.8	8	10.9
296	-	14.1	2	12.6	4	11.1	6	9.7	10	12.6
297	-	13.9	2	13.2	4	12.4	6	12.3	8	13.3
298	-	15.4	2	14.5	4	13.6	6	12.7	10	14.5
299	-	21.3	2	19.7	4	18.0	6	16.4	12	19.3
300	-	24.2	2	23.5	4	22.7	6	21.9	12	23.3

*Values of development length ℓ_{dh} are based on Eq. (5.22)

Table E.1 Cont. Hypothetical beams used in Monte Carlo analysis

Beam No.	N_h	f_s	d_b	b	c_{ch}	c_{so}	c_{ch}/d_b	$A_{tr,l}$	f'_c
301	4	100000	1.41	24	4.92	2.50	3.49	0.11	12000
302	3	100000	1	18	5.50	2.50	5.50	0.11	12000
303	4	100000	1	18	3.33	2.50	3.33	0.11	12000
304	3	100000	1.128	18	5.37	2.50	4.76	0.11	12000
305	4	100000	1.128	18	3.21	2.50	2.84	0.11	12000
306	3	100000	1.41	18	5.09	2.50	3.61	0.11	12000
307	2	100000	0.75	8	2.25	2.50	3.00	0.11	15000
308	3	100000	0.75	12	2.75	2.50	3.67	0.11	15000
309	3	100000	1	12	2.50	2.50	2.50	0.11	15000
310	3	100000	1.128	12	2.37	2.50	2.10	0.11	15000
311	3	100000	0.75	24	8.75	2.50	11.67	0.11	15000
312	4	100000	0.75	24	5.58	2.50	7.44	0.11	15000
313	6	100000	0.75	24	3.05	2.50	4.07	0.11	15000
314	8	100000	0.75	24	1.96	2.50	2.62	0.11	15000
315	3	100000	1	24	8.50	2.50	8.50	0.11	15000
316	4	100000	1	24	5.33	2.50	5.33	0.11	15000
317	6	100000	1	24	2.80	2.50	2.80	0.11	15000
318	3	100000	1.41	24	8.09	2.50	5.74	0.11	15000
319	4	100000	1.41	24	4.92	2.50	3.49	0.11	15000
320	3	100000	1	18	5.50	2.50	5.50	0.11	15000
321	4	100000	1	18	3.33	2.50	3.33	0.11	15000
322	3	100000	1.128	18	5.37	2.50	4.76	0.11	15000
323	4	100000	1.128	18	3.21	2.50	2.84	0.11	15000
324	3	100000	1.41	18	5.09	2.50	3.61	0.11	15000
325	2	120000	0.75	8	2.25	2.50	3.00	0.11	4000
326	3	120000	0.75	12	2.75	2.50	3.67	0.11	4000
327	3	120000	1	12	2.50	2.50	2.50	0.11	4000
328	3	120000	1.128	12	2.37	2.50	2.10	0.11	4000
329	3	120000	0.75	24	8.75	2.50	11.67	0.11	4000
330	4	120000	0.75	24	5.58	2.50	7.44	0.11	4000
331	6	120000	0.75	24	3.05	2.50	4.07	0.11	4000
332	8	120000	0.75	24	1.96	2.50	2.62	0.11	4000
333	3	120000	1	24	8.50	2.50	8.50	0.11	4000
334	4	120000	1	24	5.33	2.50	5.33	0.11	4000
335	6	120000	1	24	2.80	2.50	2.80	0.11	4000
336	3	120000	1.41	24	8.09	2.50	5.74	0.11	4000
337	4	120000	1.41	24	4.92	2.50	3.49	0.11	4000
338	3	120000	1	18	5.50	2.50	5.50	0.11	4000
339	4	120000	1	18	3.33	2.50	3.33	0.11	4000
340	3	120000	1.128	18	5.37	2.50	4.76	0.11	4000
341	4	120000	1.128	18	3.21	2.50	2.84	0.11	4000
342	3	120000	1.41	18	5.09	2.50	3.61	0.11	4000
343	2	120000	0.75	8	2.25	2.50	3.00	0.11	6000
344	3	120000	0.75	12	2.75	2.50	3.67	0.11	6000
345	3	120000	1	12	2.50	2.50	2.50	0.11	6000
346	3	120000	1.128	12	2.37	2.50	2.10	0.11	6000
347	3	120000	0.75	24	8.75	2.50	11.67	0.11	6000
348	4	120000	0.75	24	5.58	2.50	7.44	0.11	6000
349	6	120000	0.75	24	3.05	2.50	4.07	0.11	6000
350	8	120000	0.75	24	1.96	2.50	2.62	0.11	6000

Table E.1 Cont. Hypothetical beams used in Monte Carlo analysis*

Beam No.	No Confinement		1 No.3 parallel		2 No.3 parallel		No. 3 spaced at $3d_b$ parallel		No. 3 spaced at $3d_b$ perpendicular	
	N	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}
301	-	32.9	2	31.2	4	29.5	6	27.8	14	30.5
302	-	15.0	2	13.9	4	12.8	6	12.6	8	14.1
303	-	20.0	2	17.9	4	15.8	6	14.0	12	17.5
304	-	20.0	2	18.4	4	16.8	6	15.7	10	18.4
305	-	25.4	2	23.1	4	20.8	6	18.5	12	22.6
306	-	32.5	2	30.3	4	28.1	6	25.9	14	29.4
307	-	12.8	2	8.7	4	8.7	6	8.7	8	8.7
308	-	11.8	2	9.0	4	8.5	6	8.5	8	9.6
309	-	20.8	2	17.5	4	14.2	6	13.7	10	17.5
310	-	25.9	2	22.5	4	19.2	6	16.7	12	21.9
311	-	8.5	2	7.7	4	7.6	6	7.6	6	8.0
312	-	8.5	2	7.9	4	7.6	6	7.6	6	8.2
313	-	11.3	2	10.0	4	8.8	6	8.3	8	10.3
314	-	13.3	2	11.9	4	10.5	6	9.1	10	11.9
315	-	13.1	2	12.4	4	11.8	6	11.7	8	12.6
316	-	14.6	2	13.7	4	12.8	6	12.0	8	13.9
317	-	20.1	2	18.6	4	17.1	6	15.5	12	18.3
318	-	22.9	2	22.2	4	21.4	6	20.7	10	22.2
319	-	31.2	2	29.5	4	27.9	6	26.3	14	28.9
320	-	14.2	2	13.2	4	12.1	6	11.9	8	13.4
321	-	19.0	2	17.0	4	15.0	6	13.2	10	17.0
322	-	19.0	2	17.4	4	15.9	6	14.8	10	17.4
323	-	24.0	2	21.8	4	19.7	6	17.5	12	21.4
324	-	30.7	2	28.6	4	26.6	6	24.5	14	27.8
325	-	21.3	2	15.0	4	15.0	6	15.0	12	15.0
326	-	19.8	2	15.4	4	14.6	6	14.6	12	14.6
327	-	34.7	2	29.5	4	24.4	6	23.6	16	26.5
328	-	43.3	2	38.0	4	32.6	6	28.7	20	32.6
329	-	14.2	2	13.2	4	13.0	6	13.0	10	13.2
330	-	14.2	2	13.5	4	13.0	6	13.0	12	13.3
331	-	18.8	2	16.9	4	15.1	6	14.3	14	16.2
332	-	22.2	2	20.1	4	17.9	6	15.7	16	18.7
333	-	21.9	2	21.1	4	20.2	6	20.1	14	20.7
334	-	24.3	2	23.1	4	21.8	6	20.8	14	22.6
335	-	33.6	2	31.2	4	28.8	6	26.4	18	29.3
336	-	38.3	2	37.3	4	36.3	6	35.3	18	36.5
337	-	52.0	2	49.5	4	47.0	6	44.5	22	46.5
338	-	23.7	2	22.3	4	20.8	6	20.6	14	21.7
339	-	31.6	2	28.6	4	25.5	6	22.8	18	26.1
340	-	31.7	2	29.4	4	27.2	6	25.5	16	28.1
341	-	40.1	2	36.7	4	33.4	6	30.0	20	33.4
342	-	51.3	2	48.1	4	44.9	6	41.7	20	44.9
343	-	19.3	2	13.6	4	13.6	6	13.6	12	13.6
344	-	17.9	2	13.9	4	13.2	6	13.2	12	13.2
345	-	31.3	2	26.7	4	22.0	6	21.3	16	23.9
346	-	39.1	2	34.3	4	29.5	6	26.0	18	30.4
347	-	12.9	2	12.0	4	11.8	6	11.8	10	12.0
348	-	12.9	2	12.2	4	11.8	6	11.8	10	12.2
349	-	17.0	2	15.3	4	13.6	6	12.9	12	15.0
350	-	20.1	2	18.1	4	16.2	6	14.2	14	17.3

*Values of development length ℓ_{dh} are based on Eq. (5.22)

Table E.1 Cont. Hypothetical beams used in Monte Carlo analysis

Beam No.	N_h	f_s	d_b	b	c_{ch}	c_{so}	c_{ch}/d_b	$A_{tr,l}$	f'_c
351	3	120000	1	24	8.50	2.50	8.50	0.11	6000
352	4	120000	1	24	5.33	2.50	5.33	0.11	6000
353	6	120000	1	24	2.80	2.50	2.80	0.11	6000
354	3	120000	1.41	24	8.09	2.50	5.74	0.11	6000
355	4	120000	1.41	24	4.92	2.50	3.49	0.11	6000
356	3	120000	1	18	5.50	2.50	5.50	0.11	6000
357	4	120000	1	18	3.33	2.50	3.33	0.11	6000
358	3	120000	1.128	18	5.37	2.50	4.76	0.11	6000
359	4	120000	1.128	18	3.21	2.50	2.84	0.11	6000
360	3	120000	1.41	18	5.09	2.50	3.61	0.11	6000
361	2	120000	0.75	8	2.25	2.50	3.00	0.11	8000
362	3	120000	0.75	12	2.75	2.50	3.67	0.11	8000
363	3	120000	1	12	2.50	2.50	2.50	0.11	8000
364	3	120000	1.128	12	2.37	2.50	2.10	0.11	8000
365	3	120000	0.75	24	8.75	2.50	11.67	0.11	8000
366	4	120000	0.75	24	5.58	2.50	7.44	0.11	8000
367	6	120000	0.75	24	3.05	2.50	4.07	0.11	8000
368	8	120000	0.75	24	1.96	2.50	2.62	0.11	8000
369	3	120000	1	24	8.50	2.50	8.50	0.11	8000
370	4	120000	1	24	5.33	2.50	5.33	0.11	8000
371	6	120000	1	24	2.80	2.50	2.80	0.11	8000
372	3	120000	1.41	24	8.09	2.50	5.74	0.11	8000
373	4	120000	1.41	24	4.92	2.50	3.49	0.11	8000
374	3	120000	1	18	5.50	2.50	5.50	0.11	8000
375	4	120000	1	18	3.33	2.50	3.33	0.11	8000
376	3	120000	1.128	18	5.37	2.50	4.76	0.11	8000
377	4	120000	1.128	18	3.21	2.50	2.84	0.11	8000
378	3	120000	1.41	18	5.09	2.50	3.61	0.11	8000
379	2	120000	0.75	8	2.25	2.50	3.00	0.11	10000
380	3	120000	0.75	12	2.75	2.50	3.67	0.11	10000
381	3	120000	1	12	2.50	2.50	2.50	0.11	10000
382	3	120000	1.128	12	2.37	2.50	2.10	0.11	10000
383	3	120000	0.75	24	8.75	2.50	11.67	0.11	10000
384	4	120000	0.75	24	5.58	2.50	7.44	0.11	10000
385	6	120000	0.75	24	3.05	2.50	4.07	0.11	10000
386	8	120000	0.75	24	1.96	2.50	2.62	0.11	10000
387	3	120000	1	24	8.50	2.50	8.50	0.11	10000
388	4	120000	1	24	5.33	2.50	5.33	0.11	10000
389	6	120000	1	24	2.80	2.50	2.80	0.11	10000
390	3	120000	1.41	24	8.09	2.50	5.74	0.11	10000
391	4	120000	1.41	24	4.92	2.50	3.49	0.11	10000
392	3	120000	1	18	5.50	2.50	5.50	0.11	10000
393	4	120000	1	18	3.33	2.50	3.33	0.11	10000
394	3	120000	1.128	18	5.37	2.50	4.76	0.11	10000
395	4	120000	1.128	18	3.21	2.50	2.84	0.11	10000
396	3	120000	1.41	18	5.09	2.50	3.61	0.11	10000
397	2	120000	0.75	8	2.25	2.50	3.00	0.11	12000
398	3	120000	0.75	12	2.75	2.50	3.67	0.11	12000
399	3	120000	1	12	2.50	2.50	2.50	0.11	12000
400	3	120000	1.128	12	2.37	2.50	2.10	0.11	12000

Table E.1 Cont. Hypothetical beams used in Monte Carlo analysis*

Beam No.	No Confinement		1 No.3 parallel		2 No.3 parallel		No. 3 spaced at $3d_b$ parallel		No. 3 spaced at $3d_b$ perpendicular	
	N	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}
351	-	19.8	2	19.0	4	18.3	6	18.1	12	18.9
352	-	22.0	2	20.9	4	19.7	6	18.8	14	20.4
353	-	30.4	2	28.2	4	26.0	6	23.9	18	26.5
354	-	34.6	2	33.7	4	32.8	6	31.9	16	33.2
355	-	47.0	2	44.7	4	42.5	6	40.2	20	42.5
356	-	21.4	2	20.1	4	18.8	6	18.6	12	19.9
357	-	28.6	2	25.8	4	23.0	6	20.6	16	24.1
358	-	28.6	2	26.6	4	24.6	6	23.1	14	25.8
359	-	36.2	2	33.2	4	30.1	6	27.1	18	30.7
360	-	46.4	2	43.5	4	40.6	6	37.7	20	40.6
361	-	17.9	2	12.6	4	12.6	6	12.6	10	12.6
362	-	16.6	2	13.0	4	12.2	6	12.2	10	13.0
363	-	29.2	2	24.8	4	20.5	6	19.8	14	23.1
364	-	36.4	2	31.9	4	27.4	6	24.2	16	29.2
365	-	12.0	2	11.1	4	11.0	6	11.0	10	11.1
366	-	12.0	2	11.3	4	11.0	6	11.0	10	11.3
367	-	15.8	2	14.2	4	12.7	6	12.0	12	13.9
368	-	18.7	2	16.9	4	15.0	6	13.2	14	16.1
369	-	18.4	2	17.7	4	17.0	6	16.9	12	17.6
370	-	20.5	2	19.4	4	18.4	6	17.5	12	19.2
371	-	28.2	2	26.2	4	24.2	6	22.2	16	25.0
372	-	32.2	2	31.4	4	30.5	6	29.7	14	31.0
373	-	43.7	2	41.6	4	39.5	6	37.4	18	40.0
374	-	20.0	2	18.7	4	17.5	6	17.3	12	18.5
375	-	26.6	2	24.0	4	21.4	6	19.1	14	23.0
376	-	26.6	2	24.7	4	22.9	6	21.5	14	24.0
377	-	33.7	2	30.9	4	28.0	6	25.2	16	29.2
378	-	43.1	2	40.4	4	37.7	6	35.0	18	38.3
379	-	17.0	2	11.9	4	11.9	6	11.9	10	11.9
380	-	15.7	2	12.3	4	11.6	6	11.6	10	12.3
381	-	27.6	2	23.5	4	19.4	6	18.8	14	21.9
382	-	34.4	2	30.2	4	25.9	6	22.9	16	27.6
383	-	11.3	2	10.5	4	10.4	6	10.4	8	10.7
384	-	11.3	2	10.7	4	10.4	6	10.4	8	10.8
385	-	15.0	2	13.5	4	12.0	6	11.4	10	13.5
386	-	17.7	2	16.0	4	14.2	6	12.5	12	15.6
387	-	17.4	2	16.8	4	16.1	6	16.0	10	16.8
388	-	19.4	2	18.4	4	17.4	6	16.5	12	18.2
389	-	26.7	2	24.8	4	22.9	6	21.0	16	23.7
390	-	30.4	2	29.7	4	28.9	6	28.1	14	29.3
391	-	41.4	2	39.4	4	37.4	6	35.4	18	37.8
392	-	18.9	2	17.7	4	16.6	6	16.4	12	17.5
393	-	25.2	2	22.7	4	20.2	6	18.1	14	21.7
394	-	25.2	2	23.4	4	21.6	6	20.3	14	22.7
395	-	31.9	2	29.2	4	26.5	6	23.9	16	27.6
396	-	40.8	2	38.2	4	35.7	6	33.1	18	36.2
397	-	16.2	2	11.4	4	11.4	6	11.4	10	11.4
398	-	15.0	2	11.7	4	11.1	6	11.1	10	11.7
399	-	26.4	2	22.4	4	18.5	6	17.9	14	20.9
400	-	32.9	2	28.8	4	24.8	6	21.8	16	26.4

*Values of development length ℓ_{dh} are based on Eq. (5.22)

Table E.1 Cont. Hypothetical beams used in Monte Carlo analysis

Beam No.	N_h	f_s	d_b	b	c_{ch}	c_{so}	c_{ch}/d_b	$A_{tr,l}$	f'_c
401	3	120000	0.75	24	8.75	2.50	11.67	0.11	12000
402	4	120000	0.75	24	5.58	2.50	7.44	0.11	12000
403	6	120000	0.75	24	3.05	2.50	4.07	0.11	12000
404	8	120000	0.75	24	1.96	2.50	2.62	0.11	12000
405	3	120000	1	24	8.50	2.50	8.50	0.11	12000
406	4	120000	1	24	5.33	2.50	5.33	0.11	12000
407	6	120000	1	24	2.80	2.50	2.80	0.11	12000
408	3	120000	1.41	24	8.09	2.50	5.74	0.11	12000
409	4	120000	1.41	24	4.92	2.50	3.49	0.11	12000
410	3	120000	1	18	5.50	2.50	5.50	0.11	12000
411	4	120000	1	18	3.33	2.50	3.33	0.11	12000
412	3	120000	1.128	18	5.37	2.50	4.76	0.11	12000
413	4	120000	1.128	18	3.21	2.50	2.84	0.11	12000
414	3	120000	1.41	18	5.09	2.50	3.61	0.11	12000
415	2	120000	0.75	8	2.25	2.50	3.00	0.11	15000
416	3	120000	0.75	12	2.75	2.50	3.67	0.11	15000
417	3	120000	1	12	2.50	2.50	2.50	0.11	15000
418	3	120000	1.128	12	2.37	2.50	2.10	0.11	15000
419	3	120000	0.75	24	8.75	2.50	11.67	0.11	15000
420	4	120000	0.75	24	5.58	2.50	7.44	0.11	15000
421	6	120000	0.75	24	3.05	2.50	4.07	0.11	15000
422	8	120000	0.75	24	1.96	2.50	2.62	0.11	15000
423	3	120000	1	24	8.50	2.50	8.50	0.11	15000
424	4	120000	1	24	5.33	2.50	5.33	0.11	15000
425	6	120000	1	24	2.80	2.50	2.80	0.11	15000
426	3	120000	1.41	24	8.09	2.50	5.74	0.11	15000
427	4	120000	1.41	24	4.92	2.50	3.49	0.11	15000
428	3	120000	1	18	5.50	2.50	5.50	0.11	15000
429	4	120000	1	18	3.33	2.50	3.33	0.11	15000
430	3	120000	1.128	18	5.37	2.50	4.76	0.11	15000
431	4	120000	1.128	18	3.21	2.50	2.84	0.11	15000
432	3	120000	1.41	18	5.09	2.50	3.61	0.11	15000

Table E.1 Cont. Hypothetical beams used in Monte Carlo analysis*

Beam No.	No Confinement		1 No.3 parallel		2 No.3 parallel		No. 3 spaced at $3d_b$ parallel		No. 3 spaced at $3d_b$ perpendicular	
	N	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}	***N***	ℓ_{dh}
401	-	10.8	2	10.1	4	9.9	6	9.9	8	10.2
402	-	10.8	2	10.2	4	9.9	6	9.9	8	10.4
403	-	14.3	2	12.9	4	11.4	6	10.9	10	12.9
404	-	16.9	2	15.2	4	13.6	6	11.9	12	14.9
405	-	16.6	2	16.0	4	15.4	6	15.3	10	16.0
406	-	18.5	2	17.5	4	16.6	6	15.8	12	17.4
407	-	25.5	2	23.7	4	21.9	6	20.1	14	23.0
408	-	29.1	2	28.3	4	27.6	6	26.8	14	28.0
409	-	39.5	2	37.6	4	35.7	6	33.8	18	36.1
410	-	18.0	2	16.9	4	15.8	6	15.6	10	16.9
411	-	24.0	2	21.7	4	19.3	6	17.3	14	20.8
412	-	24.1	2	22.4	4	20.7	6	19.4	12	22.0
413	-	30.4	2	27.9	4	25.3	6	22.8	16	26.4
414	-	39.0	2	36.5	4	34.1	6	31.7	16	35.1
415	-	15.3	2	10.8	4	10.8	6	10.8	8	10.8
416	-	14.2	2	11.1	4	10.5	6	10.5	10	11.1
417	-	24.9	2	21.2	4	17.5	6	17.0	12	20.5
418	-	31.1	2	27.3	4	23.4	6	20.7	14	25.7
419	-	10.2	2	9.5	4	9.4	6	9.4	8	9.7
420	-	10.2	2	9.7	4	9.4	6	9.4	8	9.8
421	-	13.5	2	12.2	4	10.8	6	10.3	10	12.2
422	-	16.0	2	14.4	4	12.8	6	11.3	12	14.1
423	-	15.7	2	15.1	4	14.5	6	14.4	10	15.1
424	-	17.5	2	16.6	4	15.7	6	14.9	10	16.6
425	-	24.1	2	22.4	4	20.7	6	19.0	14	21.7
426	-	27.5	2	26.8	4	26.1	6	25.4	12	26.7
427	-	37.4	2	35.6	4	33.8	6	32.0	16	34.5
428	-	17.1	2	16.0	4	15.0	6	14.8	10	16.0
429	-	22.7	2	20.5	4	18.3	6	16.4	12	20.1
430	-	22.8	2	21.1	4	19.5	6	18.4	12	20.8
431	-	28.8	2	26.4	4	24.0	6	21.6	14	25.4
432	-	36.9	2	34.6	4	32.2	6	29.9	16	33.2

*Values of development length ℓ_{dh} are based on Eq. (5.22)

APPENDIX E: SPECIMENS IDENTIFICATION FOR DATA POINTS PRESENTED IN FIGURES

Table E.1 Specimens Identification for Data Points Presented in Figures

Figures	Specimens
Figure 4.1	9,11-15, 18-27, 29,30,93-100, 102-107, 111-126, 129-133, 231-233, 235-244, 246-253, 395-404, 409-417, 421-427, 432,433
Figure 4.2	303, 306-309, 311-313, 339-344, 347-349, 353, 379-381
Figure 4.3	52-63, 65-68, 142-147, 149-154, 157-164, 167, 168, 170-172, 256, 257, 259-261, 263, 265-268
Figure 4.4	316, 317, 333, 334, 354-357, 359, 361, 383, 384, 391
Figure 4.5	76, 78, 81-85, 184-193, 196-199, 203-207, 209-213, 217-220, 275, 276, 279-289, 291-299, 405, 428, 429, 434
Figure 4.6	318-320, 322, 325-327, 329, 330, 335-338, 362-368, 371-373, 387-389, 392-394
Figures 4.7-4.12, 4.42, 5.1, 5.9	9,11-15, 18-27, 29,30,93-100, 104-107, 111-126, 129-133, 231-233, 235-244, 246-253, 395-400, 412, 413, 421-426, 432,433
Figures 4.13-4.16, 4.43, 4.44, 5.2, 5.7, 5.8, 5.10	31-46, 52-63, 65-70, 76, 78, 81-85, 134-147, 149-154, 157-164, 167, 168, 170-177, 184-193, 196-199, 203-205, 209-215, 217, 220-226, 254-257, 259-261, 263, 265-270, 275, 276, 279-289, 291-294, 295-301
Figures 4.20-421, 5.3, 5.5, 5.11	9,11-15, 18-27, 29,30,93-100, 104-107, 111-126, 129-133, 231-233, 235-244, 246-253, 303, 306-309, 311, 312, 339-344, 347-349, 353, 379-381, 395-400, 412, 413, 421-426, 432,433,
Figures 4.22-4.23, 5.4, 5.6, 5.12	76, 78, 81-85, 184-193, 198, 199, 203-205, 209-213, 217, 220, 275, 276, 279-289, 291-299, 318-320, 322, 325-327, 329, 330, 362-368, 371-373, 377, 387-389405, 428, 429, 434
Figure 4.29	9,11-15, 18-27, 29,30,93-100, 104-107, 111-126, 129-133, 231-233, 235-244, 246-253, 303, 306-309, 311, 312, 331, 332, 339-344, 347-349, 353, 379-381, 390, 395-400, 412, 413, 421-426, 432,433,
Figures 4.30	76, 78, 81-85, 184-193, 198, 199, 203-205, 209-213, 217, 220, 275, 276, 279-289, 291-299, 318-320, 322, 325-327, 329, 330, 335-338, 362-368, 371-373, 377, 387-389, 392-394, 405, 428, 429, 434
Figure 4.35	9,11-15, 18-27, 29,30,93-101, 104-107, 111-126, 129-133, 231-233, 235-244, 246-253, 395-400, 412, 413, 421-426, 432,433
Figure 4.36	31-46, 52-63, 65-70, 76, 78, 81-85, 134-154, 157-164, 167, 168, 170-177, 184-199, 203-205, 209-215, 217, 220-226, 254-257, 259-261, 263, 265-270, 275, 276, 279-289, 291-294, 295-301
Figure 4.37	9-15, 18-27, 29,30,93-101, 104-126, 129-133, 231-244, 246-253, 278, 304, 305, 310, 345, 346, 350, 351, 395-400, 412, 413, 421-426, 432,433
Figure 4.38	31-46, 51-63, 65-70, 76-78, 81-85, 134-154, 157-164, 167, 168, 170-177, 184-199, 200-205, 209-215, 217, 220-226, 254-261, 263, 265-270, 275-277, 279-289, 291-294, 295-301, 314, 315, 323, 324, 328, 369, 370, 374, 375, 382, 385, 435-460