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A Report on Research Sponsored by

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Structural Engineering and Engineering Materials
SM Report No. 111
June 2015

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2385 Irving Hill Road, Lawrence, Kansas 66045-7563

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ABSTRACT

Hooked bars are used to anchor reinforcing steel where member dimensions prevent straight bars from developing their full yield strength. Prior to the current study, the quantity of data has been limited with regards to the capacity of hooked bars–particularly when high-strength steel or concrete is used. As a result, current design provisions in ACI 318-14 limit yield strength and concrete compressive strength to 80,000 psi and 10,000 psi, respectively, for the purpose of determining the development length of hooked bars. The purpose of this study was to determine the critical factors that affect the anchorage strength of hooked bars in concrete and to develop new design guidelines for development length allowing for the use of high-strength reinforcing steel and concrete. In this study, a total of 337 beam-column joint specimens were tested. Parameters included number of hooks (2, 3, or 4), concrete compressive strength (4,300 to 16,510 psi), bar diameter (No. 5, No. 8, and No. 11), concrete side cover (1.5 to 4 in.), amount of transverse reinforcement in the joint region, hooked bar spacing ($3d_b$ to $11d_b$ center-to-center), hook bend angle (90° or 180°), placement of the hook (inside or outside the column core, and inside or outside of the column compressive region), and embedment length.

The results of this study show that current ACI 318-14 code provisions are unconservative for larger hooked bars and higher compressive strength concrete. The effect of concrete compressive strength on the anchorage capacity of hooked bars is less than represented by the 0.5 power currently used in ACI provisions; the 0.25 power provides a more realistic estimate of capacity. The addition of confining transverse reinforcement in the hook region increases the anchorage capacity of hooked bars–the value of the increase depends on the quantity of confining reinforcement per hooked bar. Hooked bars with 90° and 180° bend angles exhibit similar capacities, and no increase in capacity was observed when increasing side cover from 2.5 to 3.5 in. Anchoring a hooked bar outside the column core or outside the compressive region of a column provides less capacity than anchoring the hooks at the far side of a beam-column joint or in a wall with a high side cover. Hooked bars also exhibit a reduction in capacity if the center-to-center spacing is less than seven bar diameters. These observations are used to develop a new design equation that allows for the conservative design of hooked bars.

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

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CHAPTER 1: INTRODUCTION

In reinforced concrete members, reinforcement must be bonded or anchored to the concrete so that it can develop its yield strength at sections subjected to maximum stresses. This is often accomplished by embedding the reinforcement far enough on either side of the critical section so that it is anchored by a combination of mechanical interlock and friction with the surrounding concrete. In many cases, however, such as exterior beam-column joints, the concrete dimensions are not adequate to fully develop the yield strength of the bar. In these cases, anchorage is often obtained through the use of hooked bars. Hooked bars are commonly used in reinforced concrete construction, but the anchorage strength of hooked bars has not been studied as extensively as other aspects of reinforced concrete design. Furthermore, very little research has been performed to determine the capacity of hooked high-strength bars or hooked bars in high-strength concrete. The purpose of this report is to describe the findings of an investigation into the most important parameters affecting the anchorage strength of standard hooked bars as defined in Section 25.3 of ACI 318-14. The study included hooked bar configurations with average stress at failure ranging from 22,800 to 141,600 psi and concrete with compressive strengths ranging from 4,300 to 16,510 psi. In addition to concrete compressive strength and yield strength of the reinforcement, the other parameters evaluated in this study were embedment length, quantity of transverse reinforcement, location of the hooked bar (inside or outside the column core and within the depth of the member), hooked bar size, side cover, hook spacing, number of hooked bars, and hook bend angle.

1.1 PREVIOUS WORK

Current design provisions for reinforced concrete including the ACI 318 Building Code Requirements for Structural Concrete (2014), ACI 349 Code Requirements for Nuclear Safety-Related Concrete Structures (2006), and the AASHTO Bridge Specifications (2012) have requirements for the development of bars with standard hooks that are based on tests conducted by Minor and Jirsa (1975) and Marques and Jirsa (1975). These experimental studies included only a small number of specimens that contained standard hooks; in addition, the range of material properties used in the specimens was very limited and did not include high-strength steel bars or high-strength concrete. Although limited in scope, the results of these prior studies are highly instructive. In addition to the work performed by Minor and Jirsa (1975) and Marques and Jirsa (1975), work by Pinc, Watkins, and Jirsa (1977), Soroushian, Obaseki, Nagi, and Rojas (1988), Hamad, Jirsa, and D'Abreu de Paulo (1993), and Ramirez and Russell (2008) is summarized next.

Minor and Jirsa (1975)

Minor and Jirsa (1975) tested a total of 80 specimens with parameters that included bar size (No. 5, 7, and 9) and bend angle (0°, 45°, 90°, 135°, and 180°). All of the specimens contained single hooks in concrete blocks with no transverse reinforcement. Bond was interrupted along the straight portion of the bar by a loose-fitting plastic tube that was sealed at the ends to prevent cement paste from entering. Unbonded lengths were 6, 8, and 7.5 in. for the No. 5, 7, and 9 bars, respectively. The lengths of the No. 5 bars in contact with the concrete (bonded lengths measured from the start of the bend) ranged from 1.6 to 6 in., the No. 7 bars had bonded lengths ranging from 4.3 to 8.5 in., and the No. 9 bars had a bonded length of 8.3 in. in all cases. Concrete compressive strengths ranged from 2,700 to 6,600 psi.

Minor and Jirsa concluded that for equal bond-length-to-bar-diameter ratios, both larger bend angles and smaller bend radii resulted in greater bar slip for a given stress. They indicated that it is preferable to use 90° instead of 180° hooks to reduce slip of the hook and maintain stiffness of the anchorage comparable with that of a straight bar.

Marques and Jirsa (1975)

Marques and Jirsa (1975) tested 22 beam-column joint specimens containing No. 7 and No. 11 bars with 90° and 180° standard hooks. They investigated the effects of column axial load, column longitudinal reinforcement, side concrete cover, and transverse reinforcement (ties) through the joint on the anchorage capacity of standard hooked bars. All specimens were cast with two hooked bars. The applied axial load in the specimens induced axial stresses that varied from 750 to 3,000 psi. The concrete compressive strength of the specimens ranged from 3,600 to 5,100 psi. No. 3 ties were spaced at either 2½ or 5 in. throughout the joint in the specimens in which transverse reinforcement was provided. The hooks had side covers ranging from 1½ to $2^7/_8$ in. and center-to-center spacing between hooks ranging from 4.84 to 8.13 in. Both the axial compression on the column and the tensile loads on the hooks were applied using hydraulic jacks. Cracking first occurred on the front face of the column and spread radially from the bars. Vertical cracks on the sides of the columns appeared as loading was increased. Failure occurred suddenly by side splitting with the entire side cover spalling, exposing the anchored bars.

Marques and Jirsa concluded that variations in axial load had a negligible effect on the anchorage strength of hooked bars and that there were no significant differences in behavior between 90° and 180° hooks. Larger embedment and the presence of closely spaced ties within the joint increased the capacity of hooked bars. Based on their results, Marques and Jirsa proposed the following design equation:

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

where f_h is the tensile stress developed in a standard hooked bar in psi, f_c' is the concrete compressive strength in psi, and d_b is the diameter of the hooked bar in in. The value of ψ ranges from 1.0 to 1.8 depending on the amount of lateral reinforcement provided. When additional development length is needed to achieve f_y in the hooked bar, Marques and Jirsa proposed that the straight lead embedment ℓ_l between the bend in the hook and critical section be calculated using. Eq. (1.2), where ℓ' is the greater of $4d_b$ or 4 in.

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

The first term in Eq. (1.2) equals the length of straight bar needed to sustain a stress of $f_y - f_h$ in accordance with the provisions of ACI 318-71.

Pinc, Watkins, and Jirsa (1977)

Pinc et al. (1977) tested 16 beam-column joint specimens, eight of which were cast with lightweight concrete. The specimens contained two 90° hooked bars. The column cross section varied from 12×12 in. to 12×24 in. in increments of 3 in. The series of tests with normalweight concrete was conducted using No. 9 and No. 11 bars. Transverse reinforcement was not provided through the joint, and specimens were cast with two hooked bars in the concrete. The compressive strength of the normalweight concrete ranged from 3,600 to 5,400 psi. A side cover of $2^7/_8$ in. was used in all specimens. The center-to-center spacing between the hooked bars ranged from 4.84 to 5.13 in. All specimens were subjected to a nominal axial stress of 800 psi. Visual damage at specimen failure included severe cracking and spalling on the sides of the column. Based on their test results and those of earlier researchers, Pinc et al. (1977) concluded that failure of hooked bars was not governed by pullout, but rather by loss of side cover, and that the principal factor affecting anchorage capacity was the embedment length and the amount of transverse reinforcement through the joint.

Jirsa, Lutz, and Gergely (1979)

In their rationale for standard hook provisions, Jirsa, Lutz, and Gergely (1979) addressed the change from the standard hook development equations in ACI 318-77 to the proposed development equations. Jirsa et al. (1979) discussed the recommendations and compared them to the existing Code requirements. Data from Marques and Jirsa (1975) and Pinc et al. (1977) were used as the basis for the recommendations. The new recommendations were a major departure from ACI 318-77 in that they no longer required the calculation of the straight bar length between the critical section and the hook. Instead, a total development length is calculated. The results of the studies (Marques and Jirsa 1975, Pinc et al. 1977) indicated that splitting of the cover parallel to the plane of the hook was the primary cause of the failure of hooked bars and that the splitting originates within the concrete at the inside of the hook. This led to the embedment length being expressed as a function of the bar diameter to govern the magnitude of the compressive stresses inside the hook. In addition, Jirsa et al. (1979) recommended a ϕ-factor of 0.8 be directly introduced into the anchorage provisions.

Johnson and Jirsa (1981)

Johnson and Jirsa (1981) tested 36 beam-wall specimens with 90° standard hooks. The intent of this study was to determine the effect of short embedment lengths, such as would occur when a beam framed into a wall, on anchorage capacity. Johnson and Jirsa investigated specimens with either one or three No. 4, No. 7, No. 9, or No. 11 hooked bars. The single-hook specimens had walls ranging from 3.5 to 8.5 in. thick with wall dimensions of 24×52 in. The three-hook specimens also had walls ranging from 3.5 to 8.5 in. thick, with wall dimensions of 72×52 in. The spacing between hooks was 11 or 22 in. All specimens had 1.5 in. tail cover over the hook with nominal concrete compressive strengths of 2,500, 4,500, or 5,800 psi. The walls were reinforced to resist the flexural demand, but for 34 of the 36 specimens, no horizontal or vertical reinforcement was placed in the hook region. Grade 60 reinforcement was used for all specimens. The distance between the hooked bar and the compression reaction ranged from 8 to 18 in.

Johnson and Jirsa noted sudden failures for all specimens, with concrete spalling off the front of the wall in a “pullout cone,” similar to that observed with an anchor bolt or stud. The extent of spalled concrete was proportional to the distance to the compression reaction; smaller distances were also associated with greater hooked bar capacity. Test results showed that for a given embedment length, increasing the bar diameter slightly increased the force the hook could carry. For the multiple hook specimens, hooked bars with 22-in. spacing developed forces comparable to those of the single hook specimens. The hooked bars with 11-in. spacing exhibited a slight reduction in capacity relative to the single hook specimens; however, this comparison was based on a failure load normalized to $\sqrt{f_{cm}}$. Johnson and Jirsa concluded that the interaction of stresses between the hooks with the 11 in. spacing led to a reduced capacity, and recommended that either a spacing of at least 12 d_b be used or that the anchor bolt provisions of ACI 349 be applied.

Soroushian, Obaseki, Nagi, and Rojas (1988)

Soroushian et al. (1988) tested seven beam-column joint specimens with 90° standard hooks. The specimens were tested without axial load on the columns. One specimen had two No. 6 hooked bars, five specimens had two No. 8 hooked bars, and one specimen had two No. 10 hooked bars. In specimens with dimensions of 14×12 in., the hooked bars were placed inside the column core with side cover of 3½ in. and tail cover of 2 in. The center-to-center spacing between hooked bars ranged from 5.73 to 6.25 in. Concrete compressive strengths ranged from 3,700 to 6,100 psi, and plastic tubes were placed on the straight embedment lengths (before the bent portion of the hooks) to eliminate bond along the straight bar lengths. Transverse reinforcement in the joint region consisted of No. 3 or No. 4 hoops spaced at 3 or 4 in. in accordance with the requirements of ACI 318-83 for reinforced concrete frames in zones of high seismic risk.

Reactions were centered 5.5 in. above and below the hooked bar. During loading, cracks in the plane of the hooks were first observed when the applied load reached about half of the ultimate load. Cracks normal to the plane of the hooks were observed at higher load levels. An expansion of the specimen in the direction normal to the plane of the hook and spalling of the concrete cover were determined to be the causes of failure. Soroushian et al. (1988) concluded that for the same embedment length, the capacity of hooked bar anchorages increased with bar size and with confinement of the concrete surrounding the hooked bars. They also concluded that concrete compressive strength did not significantly influence the hook pullout behavior.

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

Hamad et al. (1993) conducted 24 beam-column joint tests to compare the anchorage capacity of uncoated and epoxy-coated hooked bars. The specimens were similar to those of Marques and Jirsa (1975), with two hooked bars embedded in a short column representing a beam-column joint. Hydraulic rams applied tension to the hooked bars while the column reacted against a steel compression block representing the compression region of the simulated beam. Half of the specimens contained uncoated hooked bars. No. 7 and No. 11 bars had 90° or 180° hooks with a side cover of 3 in., tail cover of 2 in., and center-to-center spacing between hooks ranging from 4.6 to 5.13 in. Concrete compressive strengths ranged from 2,500 to 7,200 psi. Three different configurations of transverse reinforcement through the joint were provided: no reinforcement, No. 3 bars at 6 in. on center, and No. 3 bars at 4 in. on center. Columns had a cross-section of 12×12 in. with four No. 8 longitudinal bars or 12×15 in. with six No. 8 longitudinal bars. No axial load was applied to the columns. The simulated beams had an assumed depth of 20 in. and the same width as the columns (12 in.). Hamad et al. (1993) observed that anchorage strength increased with the amount of transverse reinforcement. The study also concluded that uncoated hooked bars consistently developed higher anchorage capacities than the companion epoxy-coated hooked bars.

Joh and Shibata (1996)

In the study by Joh and Shibata (1996), six beam-column joints were tested to investigate the effect of large side covers on the anchorage capacity of a beam-column joint. The concrete compressive strength for these specimens ranged from 238 to 355 kgf/cm^2 (3,380 to 5040 psi). The spacing between the bars was 57 mm (2.24 in.), and the side cover varied from 64.5 to 264.5 mm (2.54 to 10.4 in.). No axial stress was applied to these specimens.

Cracking patterns included three main cracks forming a trapezoidal type failure surface (Figure 1.1). For specimens with large side covers, however, the trapezoidal failure surface was not large enough to intercept the sides of the column, as shown in Figure 1.1. The angle of the inclined cracks propagating from the hooked bars are approximately 40° measured from the axis of the bar. Joh and Shibata found that transverse reinforcement becomes less effective in increasing the anchorage capacity when the side cover is so large that these cracks do not intersect the side of the column but surface on the face of the column. In this configuration (Figure 1.1), the ties are so far away from the hooked bars that the cracks never intercepted them and, thus, did not activate to help resist the crack propagation.

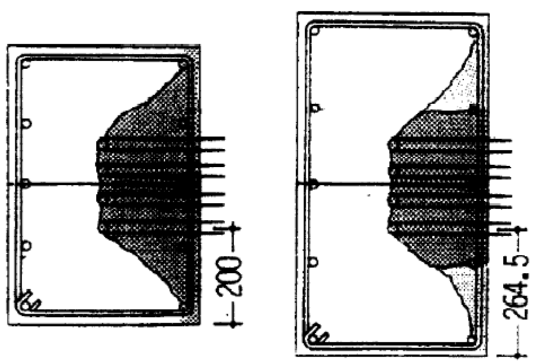


Figure 1.1 Failure surface for specimens with large side cover tested by Joh and Shibata (1996)

Ramirez and Russell (2008)

Ramirez and Russell (2008) tested 21 beam-column joint specimens containing 90° hooked No. 6 and No. 11 epoxy-coated and uncoated bars. Tension was applied to the hooked bars using hydraulic rams, and the compression region of the beam was simulated using a steel plate reacting against the column. The columns were tested without axial load. Concrete compressive strengths ranged from 8,900 to 16,500 psi. Some specimens had no transverse reinforcement while others had ties spaced at three bar diameters. Clear concrete tail cover to the back of the hook was either 2.5 in. or one bar diameter, and embedment lengths were either 6.5 or 12.5 in. All hooks had clear side covers of 3.5 in. and a center-to-center spacing between hooks of 6.6 in. for No. 11 bars and 7.25 in. for No. 6 bars.

Based on their tests, Ramirez and Russell (2008) recommended that the provisions for standard hooks in tension in ACI 318-05 be extended to include concrete with compressive strengths up to 15,000 psi as long as transverse reinforcement is provided at a spacing not exceeding three times the diameter of the hooked bar. They also stated that 2.5-in. concrete cover to the back of the hook was sufficient to prevent tail kickout – a value that could be reduced to one bar diameter for hooks confined by transverse reinforcement – but the factor applied to the required development length permitted by ACI 318-05 for hooked bars with 2.5-in. side cover to the bar should be increased to 0.8 from 0.7. They noted that the anchorage strength of epoxy-coated hooked bars was lower than of uncoated bars.

1.2 SCOPE OF WORK

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

This report is a greatly expanded version of a report by Searle et al. (2014), who presented work completed over the first two years of this project. Because the background information is the same, Chapters 1, 2, and 3 are very similar to those appearing in the earlier report. This report includes significantly more test results and both an analyses approach and design equations that differ from those presented by Searle et al.

CHAPTER 2: EXPERIMENTAL WORK

2.1 SPECIMEN DESIGN

Beam-column joint specimens were proportioned to investigate the effects of embedment length, side cover, amount and orientation (parallel to perpendicular to the hooked bar) of transverse reinforcement, location of the hooked bars (inside or outside the column core and within the depth of the member), concrete compressive strength, spacing between hooked bars, hooked bar size, and hook bend angle on the anchorage strength of hooked bars.

Table 2.1 shows the ranges of variables tested. A complete list of variables and their definitions can be found in Appendix A. No. 5, 8, and 11 hooks were tested in normalweight concrete with nominal compressive strengths ranging from 5,000 to 15,000 psi (actual strengths ranged from 4,300 to 16,510 psi). The standard specimen had two hooked bars placed either inside or outside the column core (the column core is defined as the region of concrete contained within the longitudinal reinforcement of the column). The majority of the two-hook specimens were constructed with a fixed out-to-out spacing between the hooked bars—8 in. for No. 5 hooks, 12 in. for No. 8 hooks, and 16.5 in. for No. 11 hooks. Later tests used variable distances between hooked bars. Most specimens had a nominal concrete cover to the tail of the hook of 2 in., with the hook anchored at the rear face of the column. For some specimens, however, the hook was anchored in the middle of the column, resulting in a tail cover as high as 18 in. Nominal side cover to the hooked bar varied from 1.5 to 4 in. In addition to the standard two-hooked bar specimens, specimens with three or four hooked bars were tested to investigate the effect of multiple and closely spaced hooked bars on anchorage strength. These specimens are referred to in this report as multiple hook specimens. Both the width and depth of these specimens were varied. The depth was determined by the desired embedment length, and the width was determined by the desired center-to-center spacing and side cover for the hooks. For example, a specimen with three No. 8 hooked bars with $3d_b$ center-to-center spacing and a 2.5-in. side cover had a width of 12 in.

Each of the variables described above is denoted in the specimen designation. For example, in the designation 11-12-90-2#3vr-i-2.5-2-17b(1), the first number (11) represents the bar size of the hooked bars, the second number (12) is the nominal concrete compressive strength in ksi, the third number (90) is the bend angle of the hooked bar in degrees, the fourth and fifth numbers along with the text (2#3vr) indicate the number, bar size, and orientation of the transverse reinforcement confining the hook (0 denotes no transverse reinforcement, vr denotes

Table 2.1 Range of variables tested

Parameters	**Range**
Bar Size of Hooks	5, 8, 11
Hook Bend Angle	90°, 180°
Nominal Concrete Compressive Strength, f_c' (psi)	5000, 8000, 12000, 15000
Placement of Hooks: Inside or Outside Column Core	i/o
Amount of Confining Transverse Reinforcement (Number and Bar Size)[a]	0, 1 No. 3, 2 No. 3, 4 No. 3, 5 No. 3, 6 No. 3, 1 No. 4, 2 No. 4, 4 No. 4 and 5 No. 4
Nominal Side Cover, c_{so} (in.)	1.5, 2.5, 3, 3.5, 4
Nominal Tail Cover, c_{th} (in.)[b]	2 to 18
Nominal Embedment Length, ℓ_{eh} (in.)	4 to 26
Number of Hooked Bars	2 to 4
Center-to-Center Spacing Between Hooks	$3d_b$ to $11d_b$

[a] Transverse reinforcement consisted of closed ties evenly spaced along the tail of a 90° hook, see Figure 2.6.
[b] Specimens with a nominal tail cover greater than 2 in. had the hook anchored in the middle of the column as opposed to at the back face of the column.

vertical ties, and no text denotes horizontal ties), the sixth symbol (i) indicates the location of the hooked bars (i for inside and o for outside the column core as defined by the longitudinal reinforcement), the seventh number (2.5) is the side cover in in., the eighth number (2) is the tail cover in in., the ninth number (17) indicates the embedment length of the hook to the nearest 0.25 in. The last letter (b) indicates that the specimen was part of a series, which occurred when multiple specimens of the same dimensions and amount of reinforcement were cast at the same time with the same concrete batch (the absence of a letter indicates the specimen is not part of a series). The last number in parentheses (1) indicates that the specimen or series was a replication (the first replication in this case) of an earlier specimen or series (the absence of a number indicates the specimen or series did not replicate an earlier specimen or series). Designations for specimens with closely spaced hooks are similar to the standard two-hook specimens, with the addition of a pair of numbers in parenthesis at the beginning of the specimen name indicating the number of hooks and the center-to-center spacing between hooks in terms of bar diameter. For example, the first two numbers in the name (3@5) 8-12-90-0-i-2.5-2-12 indicate that there were 3 hooked bars spaced at $5d_b$; the remainder of the designation uses the same nomenclature as the two-hook specimens.

Specimens were designed to represent exterior beam-column joints and were cast without the beam. The width of the column was determined by adding the side cover to the out-to-out spacing of the hooks. For the standard two-hook specimens, the out-to-out spacing of the hooks was fixed for a given bar diameter; for the multiple hook specimens and the two-hook specimens with closely spaced hooks, the out-to-out spacing of the two exterior hooked bars was dependent on the size, number, and center-to-center spacing of the hooked bars using an even space distribution between the number of hooked bars. For a series of specimens where side cover was the only variable being investigated, identical column reinforcement was used; only the side cover and width of the specimen changed. The depth equaled the sum of the tail cover and the embedment length. For this report, embedment length ℓ_{eh} refers to the distance measured from the front of the column face to the back of the tail of the hook, whereas the development length ℓ_{dh} refers to the minimum length of anchorage required in Section 25.4.3 of ACI 318-14 to ensure a bar can develop its yield strength. During specimen design, embedment lengths ℓ_{eh} were chosen to ensure anchorage failure prior to bar failure. Early on in the testing program this objective was accomplished by using an embedment length equal to 80% of the development length defined in ACI 318-14, and later on by extrapolating trends from test results.

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

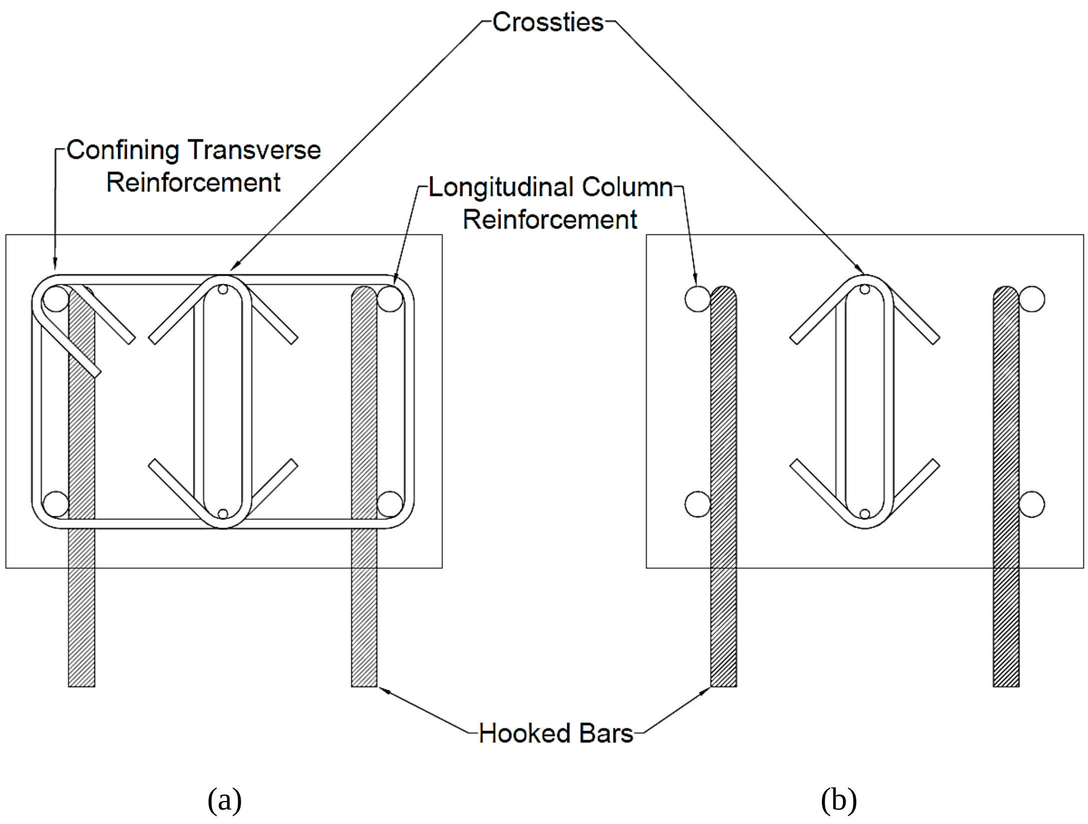


Figure 2.1a Cross section detail of specimens containing crossties (a) transverse reinforcement and (b) without transverse reinforcement. Shown with No. 3 longitudinal bars supporting the crossties

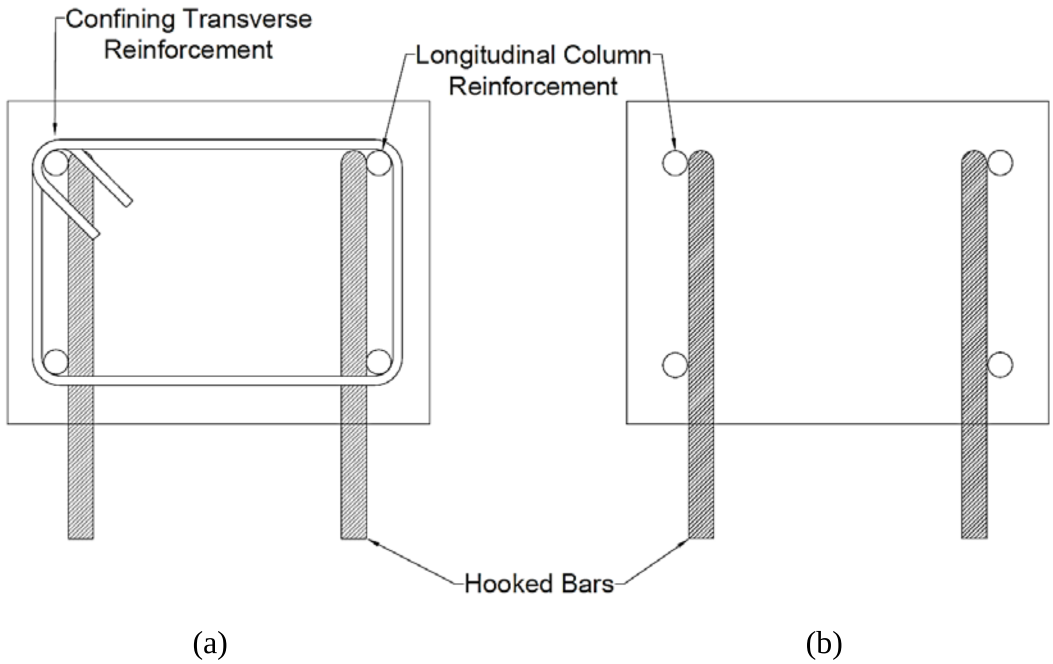
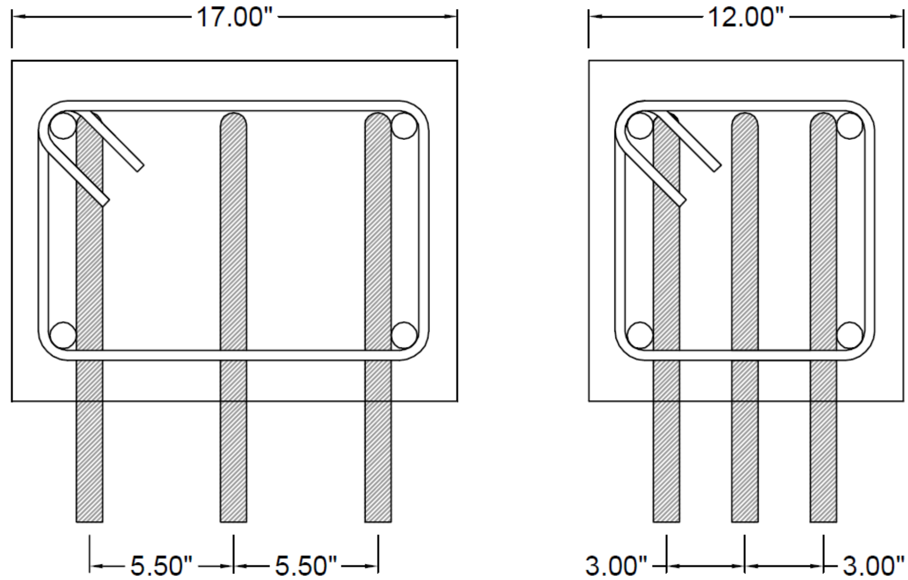


Figure 2.1b Cross section detail of specimens without crossties (a) with transverse reinforcement and (b) without transverse reinforcement.

Figure 2.2 shows the typical configuration for the multiple hook specimens. Figure 2.2a shows a specimen with 5.5d_b center-to-center spacing between No. 8 hooked bars. This specimen has the same width (17 in.) as a typical two-hook specimen with 2.5-in. side cover. Figure 2.2b shows a specimen with 3d_b center-to-center spacing between No. 8 hooked bars. This specimen has a width of 12 in.



(a) (b)

Figure 2.2 Typical configuration of multiple hook specimens with (a) 5.5d_b and (b) 3d_b center-to-center spacing between No. 8 bar hooks

The majority of the specimens contained one of three quantities of transverse reinforcement: (1) no transverse reinforcement, (2) two No. 3 ties spaced at 8d_b for No. 5 and No. 8 hooked bars and 8.5d_b for No. 11 hooked bars, or (3) No. 3 ties spaced at 3d_b along the tail and the bend of the hook, where d_b is the diameter of the hooked bar. No. 3 ties spaced at 3d_b equals the amount of transverse reinforcement required to allow the use of the 0.8 reduction factor in development length of hooks in accordance with Section 25.4.3 of ACI 318-14, shown in Figure 2.3. For No. 5 and No. 8 standard hooks, this is equal to five No. 3 ties spaced along the length of the tail and bend, while for a No. 11 standard hook, this is equal to six No. 3 ties. For cases (2) and (3), the first tie was placed 2d_b from the top of the hooked bar (1.5d_b from the center of the hooked bar), as shown in Figure 2.3. Additional specimens were fabricated with other transverse reinforcement configurations including: one No. 3 tie, four No. 3 ties, one No. 4 tie, two No. 4 ties, four No. 4 ties, and five No. 4 ties. Four No. 4 ties and five No. 4 ties with No. 4 crossties in both directions were used to provide confinement in accordance with ACI 318-14 Section 18.8.3 for joints in special moment frames. In addition, five specimens were tested with vertical ties as shown in Figure 2.4. Of the five, one contained 2 No. 3 ties, two contained 4

No. 3 ties, and two contained 5 No. 3 ties. The latter two cases both qualify for the 0.8 reduction factor in Section 25.4.3 of ACI 318-14.

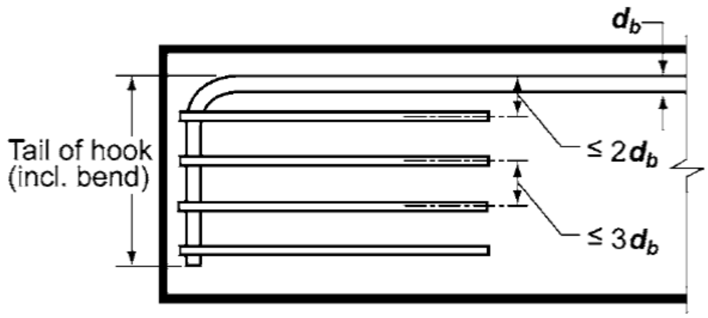
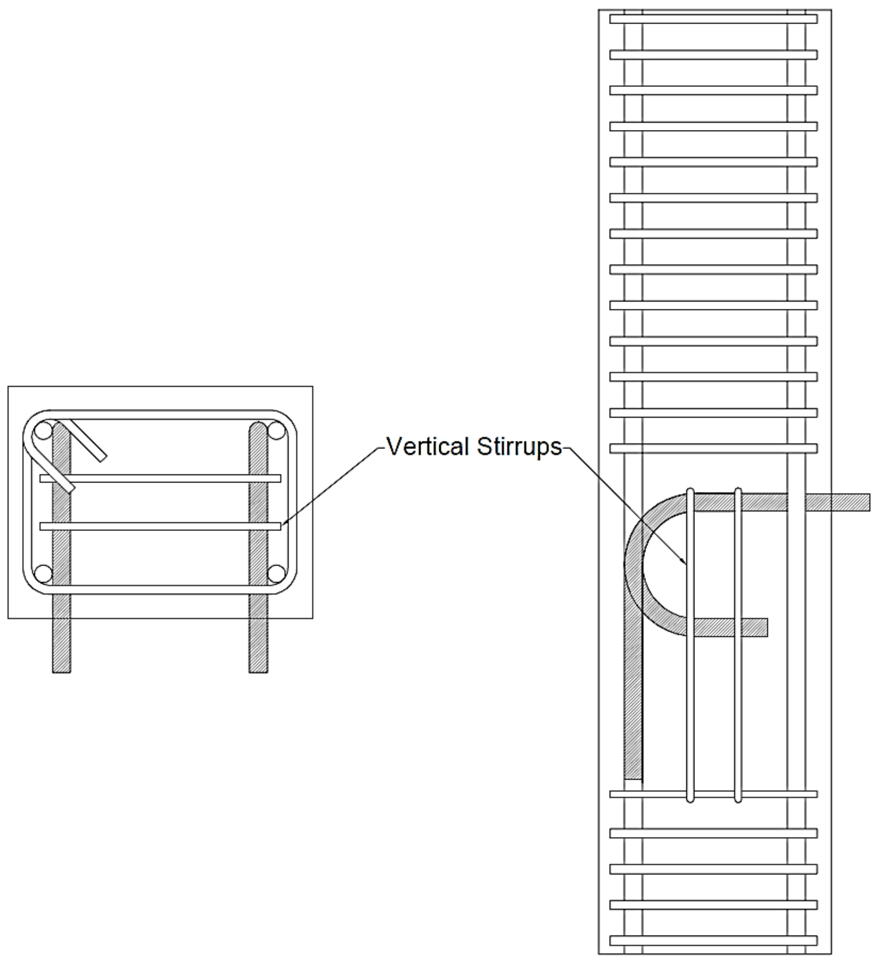


Figure 2.3 Ties placed along tail of hook in accordance with Section 25.4.3 shown in Figure R25.4.3.2b of ACI 318-14



(a) (b)

Figure 2.4 Details of specimen with vertical stirrups (a) cross-section and (b) side view

For the majority of the specimens tested, hooks were placed inside the column longitudinal reinforcement (that is, within the column core). Figure 2.5 shows the differences between the two cases. The width of the specimen, side cover, and hook spacing were kept the same; only the location of the column longitudinal reinforcement changed between the specimens.

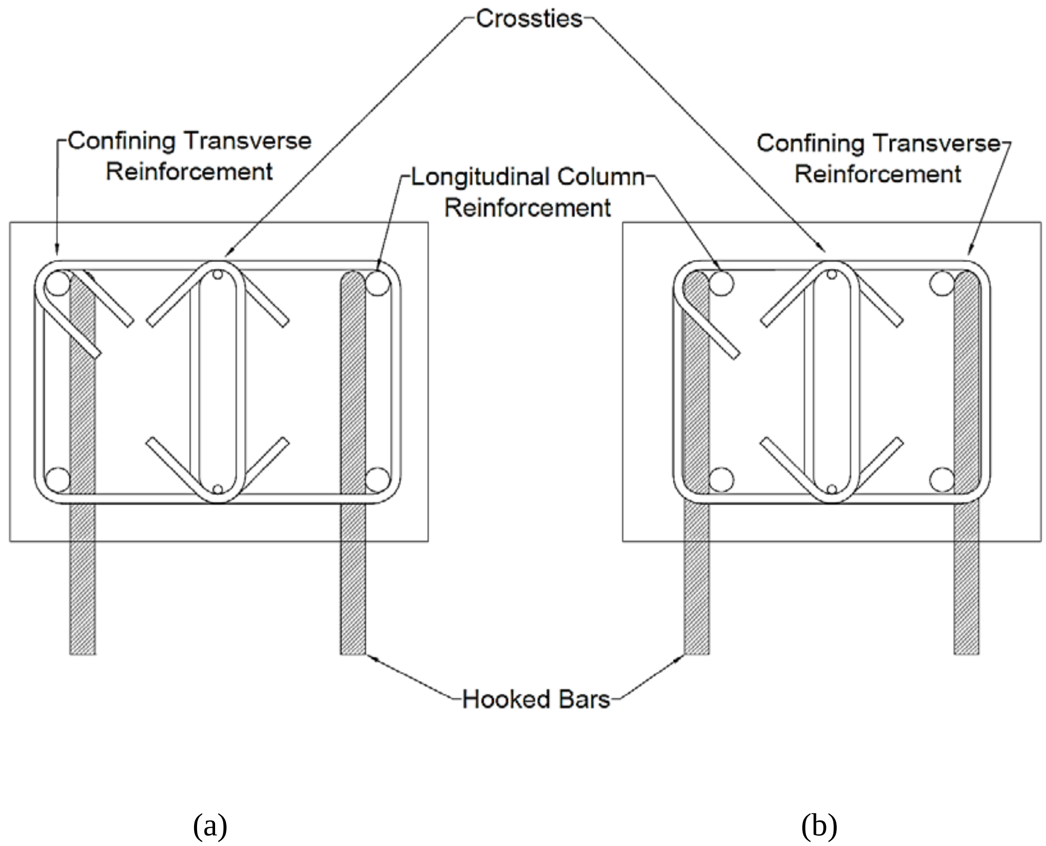
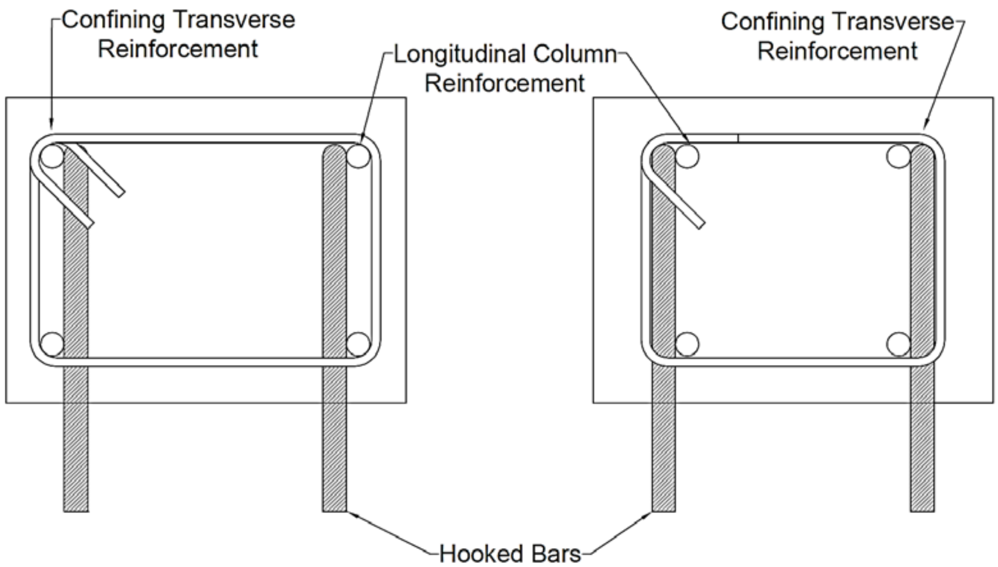


Figure 2.5a Cross section detail of specimens containing crossties with hooks placed (a) inside the column core, (b) outside the column core.

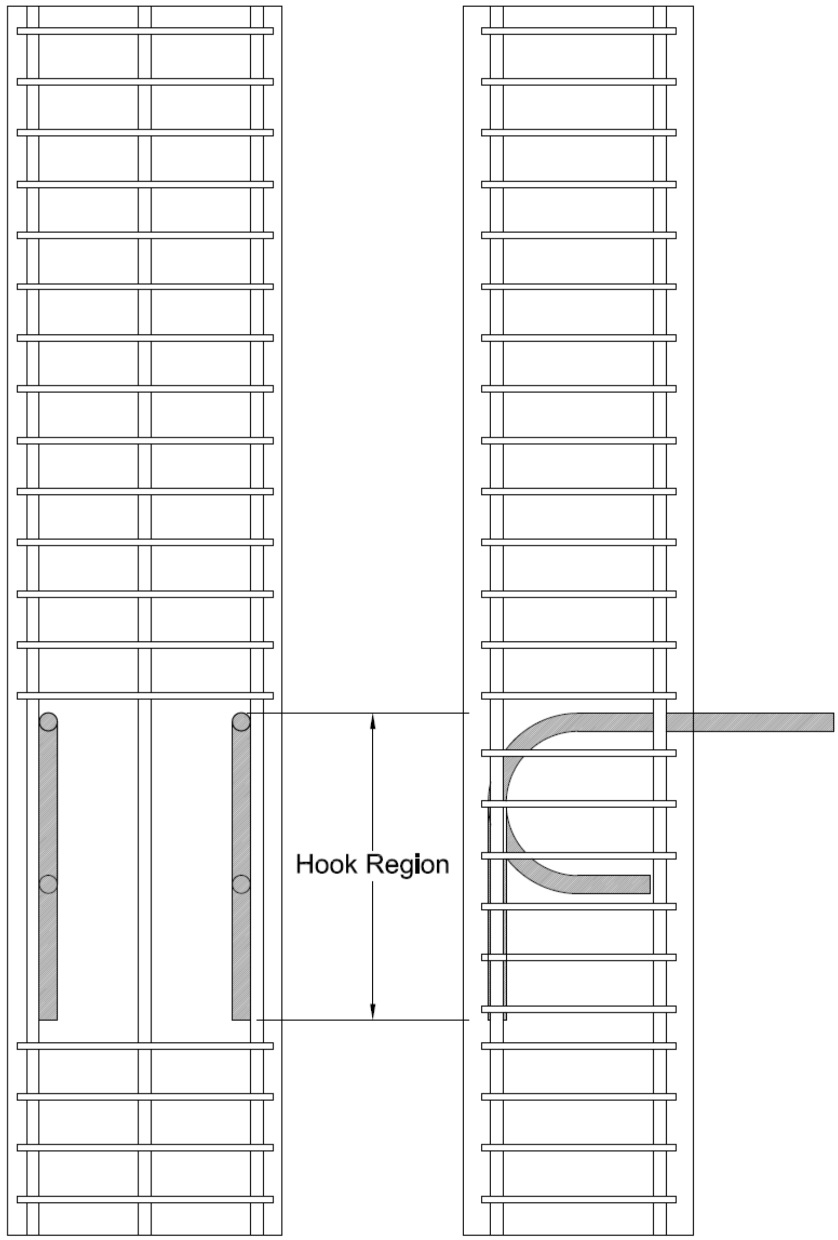


(a) (b)

Figure 2.5b Cross section detail of specimens without crossties with hooks placed (a) inside the column core, (b) outside the column core.

Typical two-hook specimen configurations are shown in Figure 2.6. Figure 2.6a shows the front view of a specimen with hooks inside the core and without transverse reinforcement; Figure 2.6b shows the side view of a specimen with hooks inside the core and No. 3 ties spaced at $3d_b$. The heights of specimens were chosen so that the support reactions from the test frame did not interfere with the hook region during testing, as shown in Figure 2.7. The column height was 52¾ in. for the specimens with No. 5 or No. 8 hooked bars and 96 in. for the specimens with No. 11 hooked bars.

Most specimens had a column steel reinforcement ratio between 0.008 and 0.025; however, a few specimens were cast with higher reinforcement ratios (up to 0.058). Specimens with reinforcement ratios greater than 0.04 were not be included in the development of the characteristic or design specimens, but are addressed separately in this report.



(a) (b)

Figure 2.6 Schematic of specimens (a) front view of specimen with hooks inside column core and no confining transverse reinforcement (b) side view of specimen with hooks inside column core and No. 3 ties spaced at $3d_b$ as confining transverse reinforcement

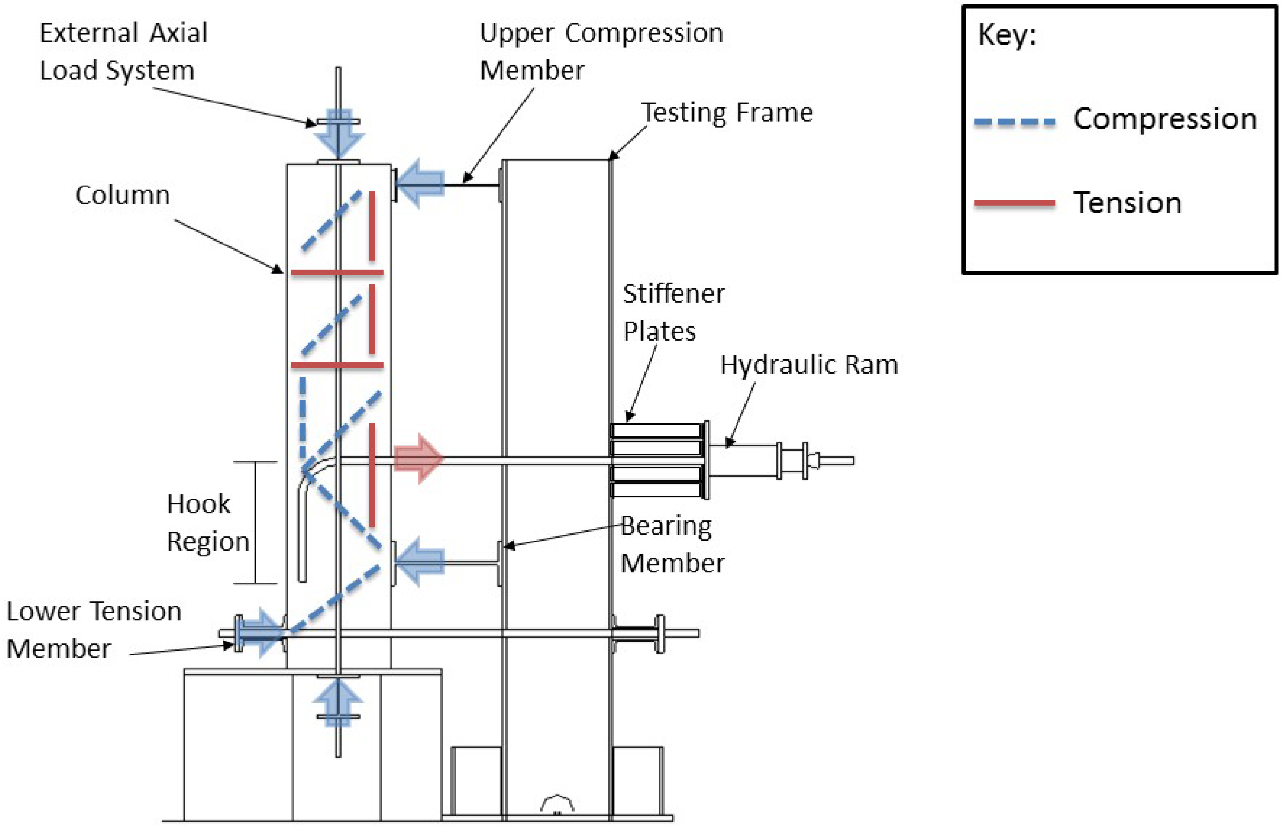


Figure 2.7 Strut-and-tie model of the test configuration

2.2 MATERIAL PROPERTIES

Specimens were cast using non-air-entrained ready-mix concrete with nominal compressive strengths of 5,000, 8,000, 12,000, and 15,000 psi. Actual strengths ranged from 4,300 to 16,510 psi. The concrete contained Type I/II portland cement, crushed limestone or granite with a maximum size of 0.75 in., Kansas River sand, and a high-range water-reducing admixture. Pea gravel was incorporated in the 12,000 psi concrete to improve the workability of the mix. ADVA 140 was used in the 5,000- and 8,000-psi concrete and ADVA 575 was used in the 12,000- and 15,000-psi concrete; both products are produced by W.R. Grace. Mixture proportions are listed in Table 2.2.

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

Table 2.3.

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

[1] ADVA 140. [2] ADVA 575

Table 2.3 Hooked bar properties

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

[1] From mill test report [2] Per ASTM A615, A706. [3] Per ACI 408R-3
[a] Heat 1, [b] Heat 2, [c] Heat 3

2.3 TEST PROCEDURE

Specimens were tested using a self-reacting system configured to simulate the axial, tensile, and compressive forces in a beam-column joint (Figure 2.8). The test frame is a modified version of the apparatus used by Marques and Jirsa (1975). The locations of reactions on the testing apparatus can be altered to accommodate different-sized specimens as shown in Table 2.4. The flange width of the upper compression member and the bearing member were $6^5/_8$-in. and $8^3/_8$-in., respectively.

A constant axial stress of 280 psi was applied to most of the specimens (for early tests, a constant force of 80,000 lb was used corresponding to a range in axial stress of 505 to 1,930 psi). The axial load was kept constant based on findings by Marques and Jirsa (1975) that changes in axial load resulted in negligible changes in the anchorage strength of the hooked bars.

Tensile forces were applied monotonically to the hooked bars using hydraulic jacks to simulate tensile forces in the beam reinforcement at the face of a beam-column joint. The bearing member located below the hooked bars simulated the compression zone of the beam and the horizontal reactions at the top and bottom of the specimen were used to prevent overturning. A detailed description of the test frame and testing procedure is provided by Peckover and Darwin (2013).

For the multiple-hook and closely spaced two-hook specimens, the test procedure was the same as for the standard two-hooked bar specimens. To accommodate the additional and closely spaced hooked bars, steel channel sections were used as a spreader beam to engage all bars. This beam was placed between the hydraulic jacks and the load cells, as shown in Figure 2.9.

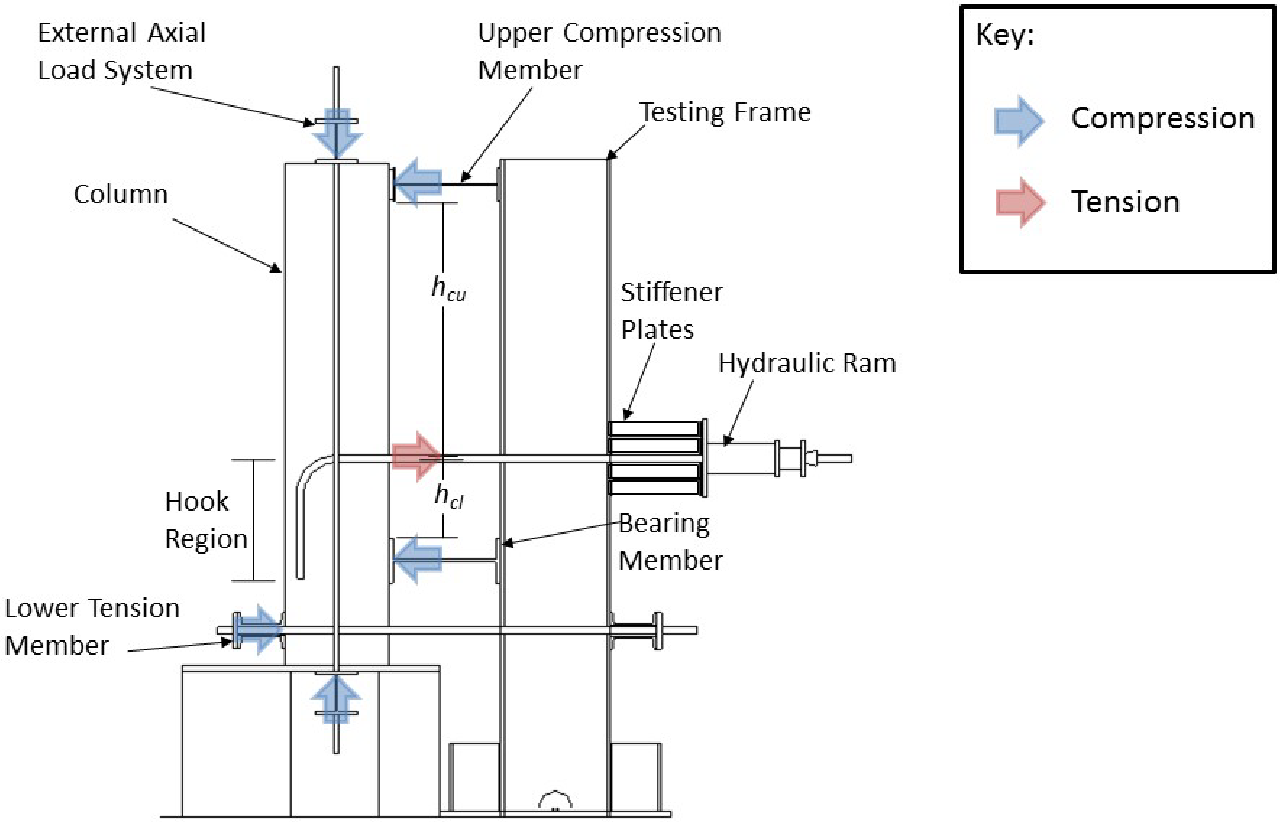


Figure 2.8 Forces applied to specimen during testing

Table 2.4 Location of reaction forces

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

[1]See Figure 2.8

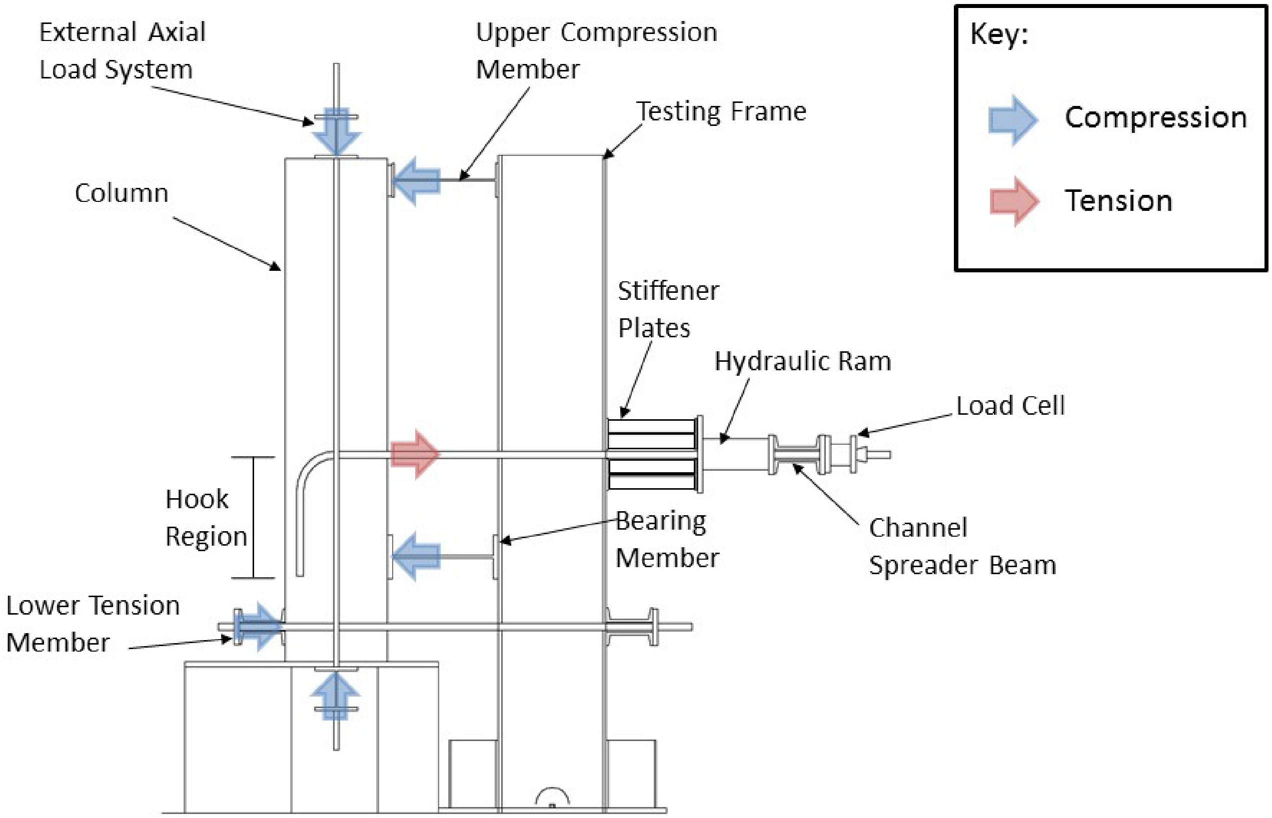


Figure 2.9 Test frame modification for multiple hook specimens

2.4 TEST PROGRAM

Tables 2.5 and 2.6, respectively, summarize the test parameters for the 219 beam-column joint specimens with two 90° hooked bars and the 57 specimens with two 180° hooked bars. The tables include bar size, side cover, and amount of transverse reinforcement. Of the 219 specimens with 90° hooks, 77 had no transverse reinforcement, 9 had one No. 3 tie, 6 had one No. 4 tie, 43 had two No. 3 ties, 2 had two No. 4 ties, 5 had four No. 3 ties, 8 had confinement in accordance with ACI 318-14 Section 18.8.3 for joints in special moment frames (designated as seismic), 67 had No. 3 ties spaced at $3d_b$, and 2 had No. 11 hooked bars confined by five No. 3 ties (and thus did not qualify for the 0.8 reduction factor in ACI 318-14 Section 25.4.3.2 because six ties would be needed to meet the requirement). Of the 57 specimens with 180° hooked bars, 18 had no transverse reinforcement, 8 had one No. 3 tie, 3 had one No. 4 tie, 18 had two No. 3 ties, and 10 had No. 3 ties spaced at $3d_b$. The ties confining the 180° hooks were horizontal (that is, parallel to the straight portion of the hook) for all but 3 specimens in which the ties were placed vertically. This is in contrast to the requirements of ACI 318-14, which limit the use of the 0.8 reduction factor for hooks with 180° bends to those bars that are enclosed with ties that are perpendicular to the development length of the bars (that is, ties placed vertically in the specimens used in this study).

The use of horizontal ties in conjunction with 180° hooked bars was based on observations of the failure modes of 90° hooked bars (Chapter 3), which indicated that ties parallel to the straight portion would provide increased anchorage capacity, independent of hook bend angle.

Table 2.5 Test program: Specimens containing 90° hooked bars

90° Hooks			**Amount of Confining Transverse Reinforcement (Number and Bar Size)**								
No. 5 Hooks	Inside Core		0	1 No. 3	1 No. 4	2 No. 3	2 No. 4	4 No. 3	Seismic	No. 3 Ties at $3d_b$	5 No. 3
	Side Cover (in.)	2.5	11	4	3	7	-	1	-	4	-
		3.5	7	2	1	6	-	1	-	3	-
	Outside Core										
	Side Cover (in.)	1.5	3	-	-	-	-	-	-	3	-
		2.5	1	-	-	-	-	-	-	2	-
No. 8 Hooks	Inside Core										
	Side Cover (in.)	2.5	21	3	-	14	1	3	3	23	-
		3.5	8	-	-	5	1	-	3	6	-
		4	1	-	-	-	-	-	-	-	-
	Outside Core										
	Side Cover (in.)	2.5	4	-	-	-	-	-	-	4	-
		3.5	1	-	-	-	-	-	-	1	-
		4	1	-	-	-	-	-	-	1	-
No. 11 Hooks	Inside Core										
	Side Cover (in.)	2.5	13	-	1	9	-	-	1	16	1
		3.5	3	-	1	2	-	-	1	1	1
	Outside Core										
	Side Cover (in.)	2.5	3	-	-	-	-	-	-	3	-

Table 2.6 Test program: Specimens containing 180° hooked bars

180° Hooks			Amount of Confining Transverse Reinforcement (Number and Bar Size)								
			0	1 No. 3	1 No. 4	2 No. 3	2 No. 4	4 No. 3	Seismic	No. 3 Ties at $3d_b$	5 No. 3
No. 5 Hooks	Inside Core	Side Cover (in.) 2.5	1	3	2	3	-	-	-	-	-
No. 5 Hooks	Inside Core	Side Cover (in.) 3.5	1	1	-	1	-	-	-	-	-
No. 5 Hooks	Outside Core	Side Cover (in.) 1.5	2	-	-	2	-	-	-	-	-
No. 5 Hooks	Outside Core	Side Cover (in.) 2.5	1	-	-	2	-	-	-	-	-
No. 8 Hooks	Inside Core	Side Cover (in.) 2.5	7	2	1	8	-	-	-	5	-
No. 8 Hooks	Inside Core	Side Cover (in.) 3.5	2	2	-	2	-	-	-	-	-
No. 11 Hooks	Inside Core	Side Cover (in.) 2.5	3	-	-	-	-	-	-	4	-
No. 11 Hooks	Outside Core	Side Cover (in.) 2.5	1	-	-	-	-	-	-	1	-

Tables 2.7 and 2.8 summarize the 61 beam-column joint specimens with multiple hooked bars, describing bar size, side cover, confining transverse reinforcement, and number of hooks. Of the 61 specimens, 55 had 90° hooked bars (Table 2.7) and 6 had 180° hooked bars (Table 2.8). Of the 90° hooked bars, 21 had no confining transverse reinforcement, 9 had two No. 3 ties as confining reinforcement, and 25 had No. 3 ties spaced at $3d_b$. Of the 180° hooked bar specimens, 2 had no confining transverse reinforcement, 2 had two No. 3 ties, and 2 had No. 3 ties spaced at $3d_b$. All hooks were placed inside the column core.

Table 2.7 Test program: Specimens with multiple 90° hooked bars

<table>
<tr><th colspan="3">90° Hooks</th><th colspan="3">Amount of Confining Transverse Reinforcement (Number and Bar Size)</th></tr>
<tr><td rowspan="7">No. 5 Hooks</td><td colspan="2"></td><td>0</td><td>2 No. 3</td><td>No. 3 Ties at $3d_b$</td></tr>
<tr><td colspan="5">Specimens with three hooks</td></tr>
<tr><td rowspan="2">Side Cover (in.)</td><td>2.5</td><td>2</td><td>-</td><td>3</td></tr>
<tr><td>3.5</td><td>-</td><td>-</td><td>1</td></tr>
<tr><td colspan="5">Specimens with four hooks</td></tr>
<tr><td>Side Cover (in.)</td><td>2.5</td><td>5</td><td>2</td><td>5</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td rowspan="4">No. 8 Hooks</td><td colspan="5">Specimens with three hooks</td></tr>
<tr><td>Side Cover (in.)</td><td>2.5</td><td>11</td><td>6</td><td>12</td></tr>
<tr><td colspan="5">Specimens with four hooks</td></tr>
<tr><td>Side Cover (in.)</td><td>2.5</td><td>2</td><td>-</td><td>2</td></tr>
<tr><td rowspan="2">No. 11 Hooks</td><td colspan="5">Specimens with three hooks</td></tr>
<tr><td>Side Cover (in.)</td><td>2.5</td><td>1</td><td>1</td><td>2</td></tr>
</table>

Table 2.8 Test program: Specimens with multiple 180° hooked bars

<table>
<tr><th colspan="3">180° Hooks</th><th colspan="3">Amount of Confining Transverse Reinforcement (Number and Bar Size)</th></tr>
<tr><td rowspan="3">No. 8 Hooks</td><td colspan="2"></td><td>0</td><td>2 No. 3</td><td>No. 3 Ties at $3d_b$</td></tr>
<tr><td colspan="5">Specimens with three hooks</td></tr>
<tr><td>Side Cover (in.)</td><td>2.5</td><td>2</td><td>2</td><td>2</td></tr>
</table>

CHAPTER 3: EXPERIMENTAL RESULTS

This chapter describes the general cracking patterns observed during the experimental program and summarizes the test results for 337 beam-column joint specimens containing standard hooked bars. Failure modes were classified into seven categories—front pullout, front blowout, side splitting, side blowout, tail kickout, bar yielding, and column yielding. The test specimens included hooked bars without transverse reinforcement and hooked bars with various amounts of transverse reinforcement. Low quantities of transverse reinforcement were provided by one No. 3 tie, one No. 4 tie, two No. 3 ties, two No. 4 ties, and four No. 3 ties. Higher quantities of transverse reinforcement were provided as required by ACI 318-14 Section 18.8.3 for joints in special moment frames, by ties spaced at $3d_b$ (which qualify for a 0.8 reduction in development length in accordance with ACI 318-14), and for some No. 11 hooked bars, by five No. 3 ties spaced at distances greater than $3d_b$, which do not qualify for the 0.8 reduction factor. Comprehensive tables describing the test specimens can be found in Appendix B.

3.1 CRACKING PATTERNS

Figure 3.1 shows the typical crack progression observed in the specimens. Cracking almost always began with a horizontal crack on the front face of the column at the level of the hooked bars, slightly extending around the side of the column (Figure 3.1a). This cracking pattern is similar to cracking observed with bond failures for straight bar reinforcement in reinforced concrete beams. As the load increased, the horizontal crack continued to grow along the side face of the column until it reached a depth approximately equal to the location of the bend of the hooked bar (Figure 3.1b), at which point radial cracks formed on the front of the column starting from the hooked reinforcement. Vertical and diagonal cracks also formed along the length of the horizontal crack on the side of the column. These cracks continued to grow towards the front of the column (Figure 3.1c). Cracks below the level of the hooked bar reinforcement extended towards the compression reactions (Figure 3.1d), where the bottom reaction represented the compression zone of the beam in a beam-column joint. Cracks above the level of the hooked bar reinforcement extended to a location just below the top reaction of the column. Near failure (Figure 3.1e), the inclined cracks on the side of the column extended across the front of the column and widened as concrete pulled out of the front of the column. The amount of cracking and spalling varied depending on the failure type, as described next.

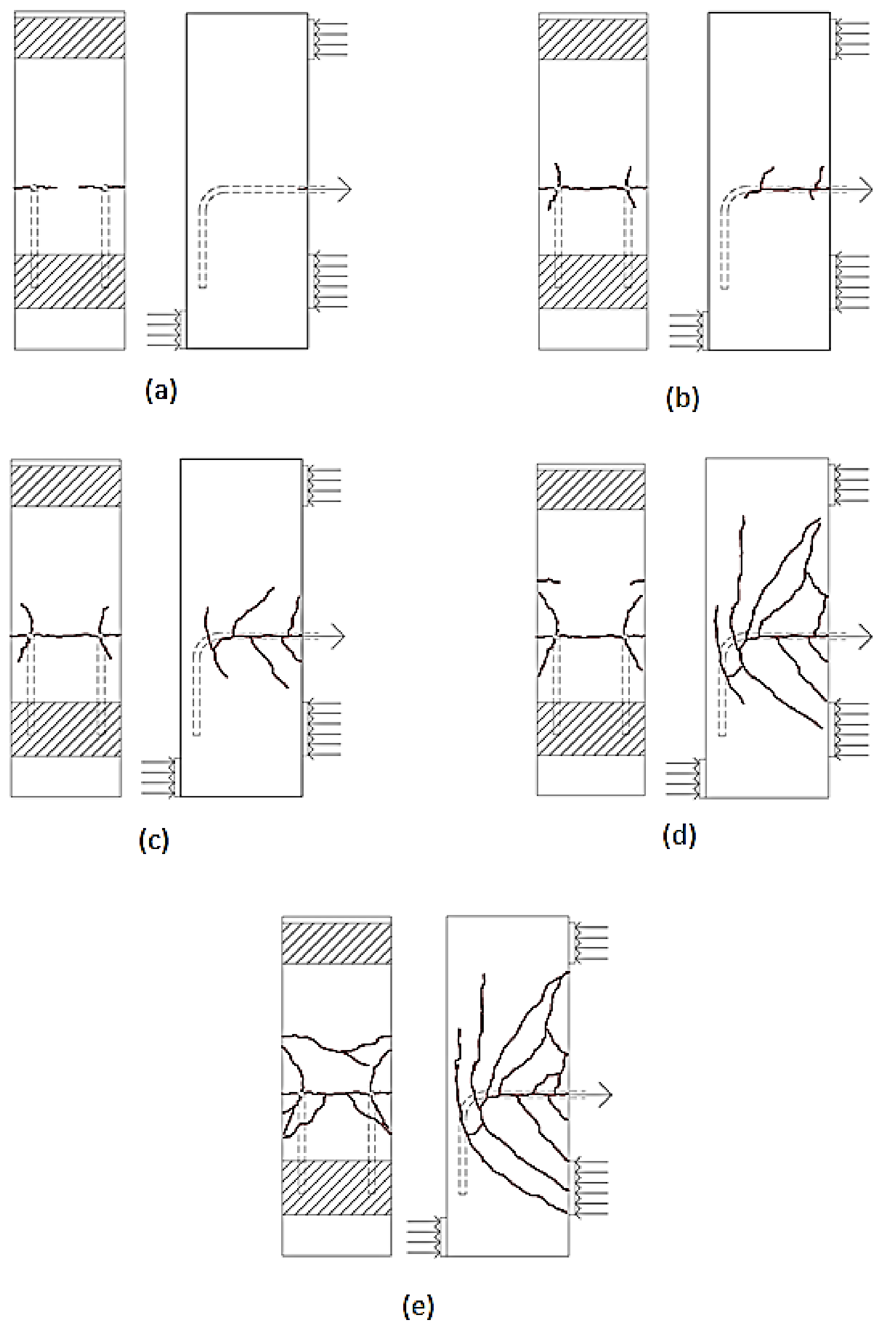


Figure 3.1 Front and side views of specimens indicating typical crack progression

3.2 FAILURE TYPES

3.2.1 Front Pullout

A front pullout (FP) failure (Figure 3.2) was characterized by a mass of concrete being pulled forward with the hook from the front face of the column. This failure mode was often coupled with side splitting or side blowout.

3.2.2 Front Blowout

A front blowout (FB) failure (Figure 3.3) was similar to a front pullout failure; however, front blowout failures were more sudden in nature, with a larger release of energy and bar slip than in front pullout failures. Likewise, front blowout failures were associated with spalling of the concrete on the front face of the column at failure. This failure mode was often coupled with side blowout or side splitting.

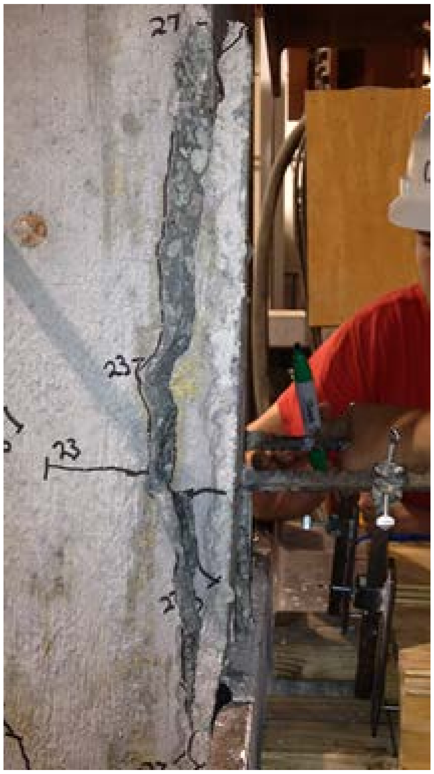


Figure 3.2 Front pullout (FP) failure

Figure 3.3 Front blowout (FB) failure

3.2.2 Side Splitting

A side splitting (SS) failure (Figure 3.4) occurred when the concrete cover on the side of the hooked bar cracked and separated from the column as the hooked anchorage lost strength. The splitting plane for this failure mode was in line with the vertical plane passing through the hooked bar. Often a long vertical crack on the back face of the column was observed at failure due to side splitting, as shown in Figure 3.4. This failure type was often coupled with front pullout or front blowout.

3.2.3 Side Blowout

Side blowout (SB) (Figure 3.5) was associated with side splitting in the same way that front blowout was associated with front pullout. A side blowout failure was more sudden in nature with a higher amount of energy released at failure than a side splitting failure. Also, during a side blowout failure, there was often a loss of concrete side cover to the outside reinforcement on the column (that is, if transverse reinforcement was present, the ties were exposed after failure; otherwise, the hooked bar was exposed after failure). This failure type was often coupled with front blowout or front pullout.

Figure 3.4 Side splitting (SS) failure

Figure 3.5 Side blowout (SB) failure

3.2.4 Tail Kickout

Tail kickout (TK) (Figure 3.6) was observed in a few specimens. This failure occurred when the tail extension of No. 8 or No. 11 90° hooked bars pushed the concrete cover off of the back of the column, often exposing the tail of the hooked bar. It commonly occurred for hooked bars without transverse reinforcement. Tail kickout was often sudden in nature. Tail kickout was observed in conjunction with other failure types and did not appear to be the main cause of failure.

Figure 3.6 Tail kickout (TK) failure

3.2.5 Bar Yielding

Bar yield (BY) occurred when the load on the hook exceeded the bar yield. Tests were stopped due to safety precautions to ensure that the bars did not fracture. This failure mode was not considered to be a hook anchorage failure, and any specimens exhibiting bar yielding were not included in the analyses of Chapters 4 and 5.

3.2.6 Flexural Yielding of Column

When longitudinal reinforcement on the tensile face of the column yielded prior to an anchorage failure, the result was not considered a hook anchorage failure and was, therefore, not included in the analyses presented in Chapters 4 and 5. This failure mode is represented by an FL in the tables.

3.3 TEST RESULTS

The results of all specimens with hook anchorage failures conducted to date are presented in this section. The data includes tests on concrete beam-column joints containing two No. 5, No. 8, and No. 11 hooked bars with 90° and 180° bends placed both inside and outside the longitudinal column reinforcement. The data also includes test results for multiple hooked bar specimens. Configurations with different amounts of transverse reinforcement were typically provided by single ties (hoops) evenly spaced within the tail of the hooks. The following nine conditions were investigated: (1) Hooked bars without confining reinforcement, representing a beam-column joint where column ties are not placed in the joint region. This is considered the reference case for hooked anchorage strength. (2) Hooked bars confined by one No. 3 tie. (3) Hooked bars confined by one No. 4 tie. (4) Hooked bars confined by two No. 3 ties. (5) Hooked bars confined by two No. 4 ties. (6) Hooked bars confined by four No. 3 ties. (7) Hooked bars confined by five No. 3 ties not spaced at $3d_b$. (8) The quantity of reinforcement required by ACI 318-14 Section 18.8.3 for reinforcement in joints of special moment frames. (9) The quantity of reinforcement required to allow the use the 0.8 reduction factor to calculate development length in accordance with ACI 318-14 Section 25.4.3.2. For No. 5 and No. 8 standard hooked bars, this was provided by five No. 3 ties confining the hooked bar. For No. 11 standard hooked bars, this was provided by six No. 3 ties confining the hooked bar.

For the multiple hooked bar specimens, the tests include reinforced concrete beam-column joints containing three or four No. 5 hooked bars or three No. 8 or No. 11 hooked bars with 90° bends placed inside the longitudinal column reinforcement. Three different amounts of transverse reinforcement were investigated for each bar size: (1) Hooked bars without transverse reinforcement; (2) hooked bars confined by two No. 3 ties; and (3) hooked bars confined by No.

3 ties spaced at $3d_b$, which is sufficient to allow the use of the 0.8 reduction factor to calculate development length in accordance with ACI 318-14 Section 25.4.3.2.

As mentioned in Chapter 2, some specimens had high column reinforcement ratios. Test results for specimens with column reinforcement ratios greater than 0.04 were not included in the data set used to develop of the basic equations for the anchorage capacity of hooked bars in Chapters 4 and 5, because these levels of column reinforcement are not commonly used in design and tended to result in anchorage capacities noticeably above those observed for specimens with more realistic column reinforcement ratios. These specimens are identified in the tables.

As also mentioned in Chapter 2, some specimens were cast with the hooks anchored in the middle of the column, as opposed to at the back face of the column. This was done on some specimens with a high anticipated flexural demand on the column to allow for increased flexural capacity without resorting to an excessively high column reinforcement ratio. This anchor location had the effect of increasing tail cover on the hook, but also removed the hooks from the compression region of the column. Because this had a detrimental effect on the anchorage capacity of the hooked bars, these specimens were not used to develop of the basic equations for the anchorage capacity of hooked bars, but were used to modify those equations to account for the location of the hook within the depth of the member. These specimens are identified in the tables.

In the following sections, two loads are presented for each hook; T_{ind} represents the maximum load an individual hook carried; T represents the peak total load for the specimen divided by the number of hooks in the specimen. In addition, two embedment lengths and side covers are reported for each hook; ℓ_{eh} and c_{so} are the actual embedment length and side cover measured for the individual hook, and $\ell_{eh,avg}$ and $c_{so,avg}$ are the average embedment length and side cover for the specimen.

3.3.1 No. 5 Hooked Bars

No. 5 Hooked Bars Without Transverse Reinforcement

Table 3.1 shows the results for 28 specimens with No. 5 hooked bars without transverse reinforcement. The specimens include 90° and 180° hooks placed inside and outside the longitudinal column reinforcement. Concrete compressive strengths ranged from 4,420 psi to

15,800 psi, and average embedment lengths ranged from 4.75 to 11.25 in. Nominal side covers were 1.5, 2.5, and 3.5 in. Excluding bars that yielded, the average ultimate bar forces at failure ranged from 14,100 to 42,200 lb, corresponding to bar stresses at failure of 45,400 and 136,100 psi, respectively. Only hook B of specimen 5-12-90-0-i-2.5-2-10 exhibited a tail kickout at failure.

Table 3.1 No. 5 hooked bars without confining reinforcement

Specimen[a]	**Hook**	**Bend Angle**	ℓ_{eh} **in.**	$\ell_{eh,avg}$ **in.**	f_{cm} **psi**	**Hook Bar Type**	b^b **in.**	c_{so} **in.**	$c_{so,avg}$ **in.**	c_{th} **in.**	c_h **in.**	T_{ind} **lb**	T **lb**	**Failure Type**[c]
5-5-90-0-o-1.5-2-5†	A B	90°	5.0 5.0	5.0	4930	A615	11	1.5 1.8	1.6	2.0 2.0	6.8	14100 19600	14070	FP/SB FP/SB
5-5-90-0-o-1.5-2-6.5†	A B	90°	6.5 5.9	6.2	5650	A1035	11	1.5 1.6	1.6	2.0 2.8	6.6	20800 18200	17815	FP FP/SB
5-5-90-0-o-1.5-2-8†	B	90°	7.9	7.9	5650	A1035	11	1.5	1.5	2.1	6.6	23500	23500	SB
5-5-90-0-o-2.5-2-5†	A B	90°	4.8 4.8	4.8	4930	A615	13	2.5 2.5	2.5	2.1 2.1	6.4	19500 24000	19285	FP/SB FP/SB
5-5-90-0-o-2.5-2-8†	A	90°	9.0	9.0	5780	A1035	13	2.6	2.6	1.5	6.6	30300	30300	SB
5-5-180-0-o-1.5-2-9.5†	A B	180°	9.6 9.3	9.4	4420	A1035	11	1.6 1.6	1.6	2.1 2.1	6.4	35200 30400	29485	FP FP/SB
5-5-180-0-o-1.5-2-11.25†	A	180°	11.3	11.3	4520	A1035	11	1.8	1.8	2.3	6.6	32400	32400	FP/SB
5-5-180-0-o-2.5-2-9.5†	A B	180°	9.5 9.5	9.5	4520	A1035	13	2.5 2.5	2.5	1.9 1.8	6.6	40400 24660	30130	FP FP
5-5-90-0-i-2.5-2-10	A B	90°	9.4 9.4	9.4	5230	A1035	13	2.8 2.6	2.7	2.9 2.9	6.4	37400 32900	33585	FP/SS FP/SS
5-5-90-0-i-2.5-2-7	A B	90°	6.9 7.0	6.9	5190	A1035	13	2.5 2.5	2.5	2.8 2.6	6.8	26600 26100	26265	FP/SS FP/SS
5-8-90-0-i-2.5-2-6†	A B	90°	6.8 6.8	6.8	8450	A615	13	2.8 2.6	2.7	1.3 1.3	6.4	27600 32100	29570	FB/SB SB/FB
5-8-90-0-i-2.5-2-6(1)	A B	90°	6.1 6.5	6.3	9080	A1035	13	2.5 2.5	2.5	2.6 2.3	7.0	21700 25000	22425	FP FP
5-8-90-0-i-2.5-2-8†	A B	90°	8.0 7.5	7.8	8580	A1035	13	2.5 2.8	2.6	2.0 2.5	6.6	31900 35900	31675	SS/FP SS/FP
(2@4) 5-8-90-0-i-2.5-2-6[d]	A B	90°	5.8 6.0	5.9	6950	A1035	8.13	2.7 3.7	3.2	2.3 2.0	1.9	23200 21700	22400	FP FP
(2@6) 5-8-90-0-i-2.5-2-6[d]	A B	90°	6.0 6.0	6.0	6950	A1035	9.38	2.6 2.7	2.6	2.0 2.0	3.1	25500 24000	24000	FP/SS FP/SS
5-12-90-0-i-2.5-2-10	A B	90°	10.0 11.0	10.5	10290	A1035	13	2.4 2.5	2.4	2.5 1.5	6.6	40800 42500	41655	SB FB/SB/TK
5-12-90-0-i-2.5-2-5	A B	90°	5.1 4.8	4.9	11600	A1035	13	2.6 2.6	2.6	2.1 2.5	6.5	19400 23170	19220	FP/SS FP
5-15-90-0-i-2.5-2-5.5	A B	90°	6.1 5.8	5.9	15800	A1035	13	2.4 2.4	2.4	1.6 1.9	6.6	36200 32400	32500	FP FB
5-15-90-0-i-2.5-2-7.5	A B	90°	7.3 7.3	7.3	15800	A1035	13	2.5 2.5	2.5	2.6 2.6	6.6	42000 42500	42200	FB *

[a]Notation described in Section 2.1 and Appendix A
*No failure of hook; equipment malfunction
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
[d]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio
[e]Not included in analysis in Chapters 4 and 5 due to yielding of hooked bars before anchorage failure

Table 3.1 Cont. No. 5 hooked bars without confining reinforcement

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]
5-5-90-0-i-3.5-2-10	A B	90°	10.5 10.4	10.4	5190	A1035	15	3.5 3.5	3.5	1.8 1.9	6.5	43200 41100	41925	SB/FP SB/FP
5-5-90-0-i-3.5-2-7	A B	90°	7.5 7.6	7.6	5190	A1035	15	3.4 3.5	3.4	1.3 1.1	7.0	27200 25900	26515	SS FP/SS
5-8-90-0-i-3.5-2-6†	A B	90°	6.3 6.4	6.3	8580	A615	15	3.6 3.5	3.6	1.8 1.6	6.6	25100 29100	25475	FP/SS FP/SS
5-8-90-0-i-3.5-2-6(1)	A B	90°	6.5 6.6	6.6	9300	A1035	15	3.8 3.8	3.8	2.1 1.9	6.9	24400 27500	24540	FP/SS FP/SS
5-8-90-0-i-3.5-2-8†	A B	90°	8.6 8.5	8.6	8380	A1035	15	3.6 3.5	3.6	1.4 1.5	7.1	39100 34300	32745	FB/SS SS
5-12-90-0-i-3.5-2-5	A B	90°	5.5 5.4	5.4	10410	A1035	15	3.6 3.6	3.6	1.7 1.8	7.0	22000 23200	22120	FP FP
5-12-90-0-i-3.5-2-10[e]	A B	90°	10.1 10.0	10.1	11600	A1035	15	3.5 3.5	3.5	2.5 1.5	6.8	46000 46000	46000	BY BY
5-8-180-0-i-2.5-2-7	A B	180°	7.4 7.1	7.3	9080	A1035	13	2.5 2.6	2.6	2.1 2.4	6.3	26700 35200	27110	FP/SS SB/FP
5-8-180-0-i-3.5-2-7	A B	180°	7.4 7.3	7.3	9080	A1035	15	3.6 3.4	3.5	1.9 2.0	7.1	34100 31400	30755	SS/FP FP/SS

[a]Notation described in Section 2.1 and Appendix A
*No failure of hook; equipment malfunction
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
[d]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio
[e]Not included in analysis in Chapters 4 and 5 due to yielding of hooked bars before anchorage failure

No. 5 Hooked Bars with One No. 3 Tie

Table 3.2 shows the results for 10 specimens with No. 5 hooked bars and one No. 3 tie confining the hooked bar. These specimens include 90° and 180° hooks placed inside the longitudinal column reinforcement. Concrete compressive strengths ranged from 5,310 to 9,300 psi, and average embedment lengths ranged from 5.1 to 7.9 in. Nominal side covers were 2.5 and 3.5 in. The tie was placed $8d_b$ from the top of the hooked bar ($7.5d_b$ from the center of the hooked bar). The average bar forces at failure ranged from 19,900 to 36,450 lb, corresponding to bar stresses at failure from 64,190 to 117,600 psi.

Table 3.2 No. 5 hooked bars with 1 No. 3 tie

Specimen[a]	**Hook**	**Bend Angle**	ℓ_{eh} **in.**	$\ell_{eh,avg}$ **in.**	f_{cm} **psi**	**Hook Bar Type**	b[b] **in.**	c_{so} **in.**	$c_{so,avg}$ **in.**	c_{th} **in.**	c_h **in.**	T_{ind} **lb**	T **lb**	**Failure Type**[c]
5-5-90-1#3-i-2.5-2-8†	A B	90°	8.0 7.6	7.8	5310	A1035	13	2.5 2.5	2.5	2.4 2.8	6.9	32900 37400	33135	FP SB/FB
5-5-90-1#3-i-2.5-2-6†	A B	90°	4.8 5.5	5.1	5800	A615	13	2.5 2.5	2.5	3.3 2.5	6.9	20000 29300	19915	SS SS/FP
5-8-90-1#3-i-2.5-2-6†	A B	90°	6.0 6.3	6.1	8450	A615	13	2.5 2.5	2.5	2.0 1.8	6.6	26200 27900	26575	FP SS
5-8-90-1#3-i-2.5-2-6(1)	A B	90°	6.1 5.6	5.9	9300	A1035	13	2.6 2.8	2.7	2.1 2.6	6.5	29300 25400	25400	FP/SS FP/SS
5-8-90-1#3-i-3.5-2-6†	A B	90°	6.0 6.0	6.0	8710	A1035	15	3.6 3.6	3.6	2.0 2.0	6.8	41400 31200	30085	FP/SS FP/SS
5-8-90-1#3-i-3.5-2-6(1)	A B	90°	6.3 6.3	6.3	9190	A1035	15	3.8 3.5	3.6	2.4 2.4	6.8	29000 26300	25905	FP/SS FP/SS
5-5-180-1#3-i-2.5-2-8†	A B	180°	8.0 7.8	7.9	5670	A1035	13	2.6 2.5	2.6	2.3 2.5	6.6	36600 39900	36450	SS SS/FP
5-5-180-1#3-i-2.5-2-6†	A B	180°	6.0 6.0	6.0	5800	A615	13	2.6 2.6	2.6	2.0 2.0	6.6	29100 24300	23915	SS/FP FP/SS
5-8-180-1#3-i-2.5-2-7	A B	180°	7.1 7.3	7.2	9300	A1035	13	2.5 2.5	2.5	2.4 2.3	6.5	34200 35400	32910	FP/SS FP/SS
5-8-180-1#3-i-3.5-2-7	A B	180°	7.1 6.8	6.9	9190	A1035	15	3.5 3.5	3.5	2.1 2.5	7.0	35800 28900	30500	FP FP

[a]Notation described in Section 2.1 and Appendix A
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

No. 5 Hooked Bars with One No. 4 Tie

Table 3.3 shows the results for six specimens with No. 5 hooked bars and one No. 4 tie confining the hooked bar. These specimens include 90° and 180° hooks placed inside the longitudinal column reinforcement. Concrete compressive strengths ranged from 5,310 to 9,300 psi, and average embedment lengths ranged from 5.5 to 8.0 in. Nominal side covers were 2.5 and 3.5 in. The tie was placed 8d_b from the top of the hooked bar (7.5d_b from the center of the hooked bar). The average bar forces at failure ranged from 21,500 to 38,400 lb, corresponding to bar stresses at failure from 69,400 to 123,900 psi.

Table 3.3 No. 5 hooked bars with 1 No. 4 tie

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]
5-5-90-1#4-i-2.5-2-8†	A B	90°	7.4 7.8	7.6	5310	A1035	13	2.5 2.5	2.5	2.8 2.4	6.9	35700 27500	27535	FP/SS SB
5-5-90-1#4-i-2.5-2-6†	A B	90°	5.3 5.8	5.5	5860	A615	13	2.5 2.5	2.5	2.8 2.3	6.6	21600 26800	21455	SS SS
5-8-90-1#4-i-2.5-2-6	A B	90°	5.9 6.0	6.0	9300	A1035	13	2.5 2.8	2.6	2.8 2.8	6.4	23900 27900	24290	FP FP/SS
5-8-90-1#4-i-3.5-2-6	A B	90°	6.0 7.0	6.5	9190	A1035	15	3.6 3.5	3.6	3.0 2.0	6.8	25300 25200	25240	FP/SS FP/SS
5-5-180-1#4-i-2.5-2-8†	A B	180°	8.0 8.0	8.0	5310	A1035	13	2.5 2.5	2.5	2.0 2.0	6.6	43100 38400	38420	FP/SS FP
5-5-180-1#4-i-2.5-2-6†	A B	180°	6.5 6.0	6.3	5670	A615	13	2.5 2.6	2.6	2.0 2.5	6.6	25300 22900	22975	FP/SS FP

[a]Notation described in Section 2.1 and Appendix A
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

No. 5 Hooked Bars with Two No. 3 Ties

Table 3.4 shows the results for 21 specimens with No. 5 hooked bars and two No. 3 ties confining the hooked bars. These specimens include 180° hooks placed outside the longitudinal column reinforcement and 90° and 180° hooks placed inside the longitudinal column reinforcement. Concrete compressive strengths ranged from 4,420 to 15,800 psi, and average embedment lengths ranged from 3.8 to 11.6 in. Nominal side covers were 1.5, 2.5, and 3.5 in. The two ties were spaced at approximately $8d_b$ for 90° hooks and $3d_b$ for 180° hooks with the first tie placed $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar). The average bar forces at failure ranged from 18,700 to 43,900 lbs, corresponding to bar stresses at failure from 60,300 to 141,600 psi. Testing was stopped on specimen 5-12-90-2#3-i-3.5-2-10 prior to concrete failure to prevent fracturing of the hook.

Table 3.4 No. 5 hooked bars with 2 No. 3 ties

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]
5-5-180-2#3-o-1.5-2-11.25†	A B	180°	11.6 11.5	11.6	4420	A1035	11	1.6 1.5	1.6	1.9 1.9	6.6	48300 43000	43050	FP/SB FP/SB
5-5-180-2#3-o-1.5-2-9.5†	B	180°	8.8	8.8	4520	A1035	11	1.6	1.6	2.4	6.6	20300	20300	FP/SB
5-5-180-2#3-o-2.5-2-9.5†	A B	180°	9.1 9.3	9.2	4420	A1035	13	2.5 2.5	2.5	2.1 2.0	6.6	35500 43900	43900	FP/SB FP
5-5-180-2#3-o-2.5-2-11.25†	A B	180°	11.1 11.4	11.3	4520	A1035	13	2.5 2.8	2.6	2.5 2.1	6.6	43600 42500	42325	FP FP/SB
5-5-90-2#3-i-2.5-2-8†	A B	90°	8.0 7.5	7.8	5860	A1035	13	2.5 2.5	2.5	2.0 2.5	6.6	37900 38900	37155	SS/FP SS/FP
5-5-90-2#3-i-2.5-2-6†	A B	90°	6.0 5.8	5.9	5800	A615	13	2.6 2.6	2.6	2.5 2.8	6.6	31800 29200	29445	FP/SS FP/SS
5-8-90-2#3-i-2.5-2-6†	A B	90°	6.0 6.0	6.0	8580	A1035	13	2.8 2.9	2.8	2.0 2.0	6.1	33500 30900	30640	FP/SS FP/SS
5-8-90-2#3-i-2.5-2-8†	A B	90°	8.3 8.5	8.4	8380	A1035	13	2.6 2.5	2.6	1.8 1.5	6.5	39800 40500	40170	FP/SS FP/SS
5-12-90-2#3-i-2.5-2-5	A B	90°	5.8 5.8	5.8	11090	A1035	13	2.5 2.8	2.6	3.0 3.0	6.5	25200 29400	24350	FP/SS FP
5-15-90-2#3-i-2.5-2-6	A B	90°	6.3 6.5	6.4	15800	A1035	13	2.4 2.4	2.4	1.9 1.7	6.6	42400 42900	42600	FP FB
5-15-90-2#3-i-2.5-2-4	A B	90°	3.5 4.0	3.8	15800	A1035	13	2.5 2.5	2.5	2.6 2.1	6.8	18700 21300	18700	FB FP
5-5-90-2#3-i-3.5-2-6	A B	90°	6.0 5.8	5.9	5230	A1035	15	3.4 3.4	3.4	2.3 2.5	6.5	21500 22400	21095	SS/FP SS/FP
5-5-90-2#3-i-3.5-2-8	A B	90°	7.9 7.5	7.7	5190	A1035	15	3.4 3.5	3.4	2.3 2.8	6.8	43700 45700	22830	FP FP
5-8-90-2#3-i-3.5-2-6†	A B	90°	6.5 6.0	6.3	8580	A1035	15	3.5 3.8	3.6	1.5 2.0	6.4	29900 30100	30035	FP FP/SS
5-8-90-2#3-i-3.5-2-8†	A B	90°	7.1 7.0	7.1	8710	A1035	15	3.5 3.5	3.5	2.9 3.0	6.6	38000 28600	28655	FP FP
5-12-90-2#3-i-3.5-2-5	A B	90°	5.6 5.3	5.4	10410	A1035	15	3.8 3.5	3.6	1.8 2.2	6.6	27900 28900	28365	FP FP
5-12-90-2#3-i-3.5-2-10[e]	A B	90°	10.8 10.6	10.7	11090	A1035	15	3.5 3.6	3.6	2.3 2.4	6.8	46000 46000	46000	BY BY
5-5-180-2#3-i-2.5-2-8†	A B	180°	8.0 8.0	8.0	5670	A1035	13	2.5 2.5	2.5	2.0 2.0	6.9	34000 34500	34080	FP/SS FP/SS
5-5-180-2#3-i-2.5-2-6†	A B	180°	5.8 5.5	5.6	5860	A615	13	2.6 2.6	2.6	2.0 2.3	6.6	26900 26900	26730	FP/SS FP
5-8-180-2#3-i-2.5-2-7	A B	180°	7.0 7.3	7.1	9080	A1035	13	2.5 2.5	2.5	2.3 2.1	6.4	34600 28700	29230	FP/SS FP/SS
5-8-180-2#3-i-3.5-2-7	A B	180°	6.8 6.9	6.8	9080	A1035	15	3.4 3.5	3.4	2.4 2.3	7.0	29300 32600	30930	FP/SS FP

[a]Notation described in Section 2.1 and Appendix A
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
[d]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio
[e]Not included in analysis in Chapters 4 and 5 due to yielding of hooked bars before anchorage failure

No. 5 Hooked Bars with Four No. 3 Ties

Table 3.5 shows the results for two specimens with No. 5 hooked bars and four No. 3 ties confining the hooked bar. These specimens include 90° hooks placed inside the longitudinal column reinforcement. The concrete compressive strengths for both specimens was 8,380 psi, and the average embedment lengths ranged from 7.7 to 8.4 in. Nominal side covers were 2.5 and 3.5 in. The four ties were spaced at approximately $3d_b$ with the first tie placed $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar). The average bar forces at failure ranged from 26,410 to 38,480 lb, corresponding to bar stresses at failure from 85,200 to 124,100 psi.

Table 3.5 No. 5 hooked bars with 4 No. 3 ties

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]
5-8-90-4#3-i-2.5-2-8†	A B	90°	7.9 7.5	7.7	8380	A1035	13	2.5 2.5	2.5	2.1 2.5	6.4	33400 27000	26410	FP/SS FP/SS
5-8-90-4#3-i-3.5-2-8†	A B	90°	8.6 8.3	8.4	8380	A1035	15	3.5 3.5	3.5	1.4 1.8	6.9	42500 39300	38480	FP SS/FP

[a]Notation described in Section 2.1 and Appendix A
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

No. 5 Hooked Bars with Five No. 3 Ties

Table 3.6 shows the results for 12 specimens with No. 5 hooked bars and five No. 3 ties confining the hooked bar. The ties in these specimens were spaced at $3d_b$, which allows the use of the 0.8 reduction factor in accordance with ACI 318-14 Section 25.4.3.2. This group of specimens included 90° hooked bars placed either inside or outside the longitudinal column reinforcement, but in all cases enclosed within ties (see Figure 2.3b). Concrete compressive strengths ranged from 4,930 to 15,800 psi, and average embedment lengths ranged from 4.0 to 11.1 in. Nominal side covers were 1.5, 2.5, and 3.5 in. The average bar forces at failure ranged from 21,700 to 39,200 lb, corresponding to bar stresses at failure of 70,000 to 126,500 psi. Testing of specimens 5-12-90-5#3-i-3.5-2-10 Hooks A and B and 5-15-90-5#3-i-2.5-2-5 Hook B was stopped at a load of 46,000 lb, which corresponds 148 ksi, close to the nominal 150-ksi tensile strength of the bar.

Table 3.6 No. 5 hooked bars with 5 No. 3 ties

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]
5-5-90-5#3-o-1.5-2-5†	B	90°	5.0	5.0	5205	A615	11	1.5	1.5	2.0	6.5	22000	22000	FP/SB
5-5-90-5#3-o-1.5-2-8†	A B	90°	8.0 7.8	7.9	5650	A1035	11	1.6 1.5	1.5	2.3 2.6	6.4	25200 30400	25110	FP/SB FP/SB
5-5-90-5#3-o-1.5-2-6.5†	A B	90°	6.5 6.5	6.5	5780	A1035	11	1.6 1.6	1.6	2.0 2.0	6.5	26200 20900	21710	FP/SB FP/SB
5-5-90-5#3-o-2.5-2-5†	A B	90°	5.2 5.1	5.2	4930	A615	13	2.6 2.6	2.6	1.9 1.9	6.6	22300 29500	22530	FP/SB FP/SB
5-5-90-5#3-o-2.5-2-8†	A	90°	7.5	7.5	5650	A1035	13	2.6	2.6	2.1	6.5	28400	28400	FP
5-5-90-5#3-i-2.5-2-7	A B	90°	5.6 7.0	6.3	5230	A1035	13	2.8 2.8	2.8	3.6 2.3	6.5	32100 31300	31695	FP FP/SS
5-12-90-5#3-i-2.5-2-5	A B	90°	5.1 5.8	5.4	10410	A1035	13	2.6 2.6	2.6	2.1 1.5	6.5	33900 34900	34420	FP/SS SS/FP
5-15-90-5#3-i-2.5-2-4	A B	90°	3.8 4.1	4.0	15800	A1035	13	2.4 2.5	2.4	2.2 1.9	6.6	31300 31300	31360	FP FP
5-15-90-5#3-i-2.5-2-5	A B	90°	5.0 5.1	5.1	15800	A1035	13	2.4 2.3	2.4	2.1 1.9	6.8	38600 46200	39200	FP BY
5-5-90-5#3-i-3.5-2-7	A B	90°	7.5 6.8	7.1	5190	A1035	15	3.4 3.5	3.4	2.0 2.8	7.0	44300 35200	36025	FP FP
5-12-90-5#3-i-3.5-2-5	A B	90°	5.3 4.8	5.0	11090	A1035	15	3.3 3.3	3.3	2.5 1.5	6.6	31500 31300	30440	FP FP
5-12-90-5#3-i-3.5-2-10[d]	A B	90°	11.0 11.3	11.1	11090	A1035	15	3.5 3.5	3.5	2.0 1.8	6.9	46000 46000	46000	BY BY

[a]Notation described in Section 2.1 and Appendix A
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
[d]Not included in analysis in Chapters 4 and 5 due to yielding of hooked bars before anchorage failure

3.3.2 No. 8 Hooked Bars

No. 8 Hooked Bars Without Transverse Reinforcement

Table 3.7 shows the results for 45 specimens with No. 8 hooked bars and no confining transverse reinforcement. Throughout the test program three heats of No. 8 A1035 Grade 120 hooked bars were used. The particular heat used for each test is denoted in the table and the bar deformation properties of these heats are given in Table 2.3. The specimens contained 90° hooked bars placed inside and outside the longitudinal column reinforcement and 180° hooked bars placed inside the longitudinal column reinforcement. Concrete compressive strengths ranged from 4,490 to 16,510 psi, and average embedment lengths ranged from 7.8 to 18.7 in. Nominal side covers were 2.5, 3.5, and 4 in. The average bar forces in the hooked bars at failure ranged from 27,600 to 95,400 lb, corresponding to bar stresses of 34,900 to 120,700 psi. Seven specimens (nine hooks total) exhibited tail kickout at failure.

Table 3.7 No. 8 hooked bars without transverse reinforcement

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[e] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
8-5-90-0-o-2.5-2-10a†	A B	90°	10.3 10.5	10.4	5270	A1035[a]	17	2.5 2.6	2.6	2.0 1.8	10.0	40600 46600	42300	FP/SS SS/FP
8-5-90-0-o-2.5-2-10b†	A B	90°	9.3 10.3	9.8	5440	A1035[a]	17	2.5 2.5	2.5	3.3 2.3	10.0	47900 30600	33700	FP/SS SS/FP
8-5-90-0-o-2.5-2-10c†	A B	90°	10.8 10.5	10.6	5650	A1035[a]	17	2.5 2.5	2.5	1.5 1.8	10.0	62700 54600	56000	FP/SS SS/FP/TK
8-8-90-0-o-2.5-2-8	A B	90°	8.6 8.3	8.4	8740	A1035[b]	17	2.8 2.5	2.6	1.8 2.1	9.0	44400 33200	33000	SB/TK SB/TK
8-8-90-0-o-3.5-2-8	A B	90°	7.6 8.0	7.8	8810	A1035[b]	19	3.5 3.6	3.6	2.4 2.0	9.8	35600 44500	35900	FP/SS SS/FP
8-8-90-0-o-4-2-8	A B	90°	8.1 8.3	8.2	8630	A1035[b]	20	4.5 3.8	4.1	2.5 2.4	9.8	37100 39200	37500	SS/FP SS
8-5-90-0-i-2.5-2-16†	A B	90°	16.0 16.8	16.4	4980	A1035[b]	17	2.8 2.8	2.8	1.8 1.4	9.5	83300 86100	83200	FP/SB FB/TK
8-5-90-0-i-2.5-2-9.5†	A B	90°	9.0 10.3	9.6	5140	A615	17	2.8 2.5	2.6	3.0 1.8	9.5	44600 65800	44500	FP SS
8-5-90-0-i-2.5-2-12.5†	A B	90°	13.3 13.3	13.3	5240	A615	17	2.8 2.8	2.8	1.3 1.3	9.8	65300 69900	65800	SS/B SS
8-5-90-0-i-2.5-2-18	A B	90°	19.5 17.9	18.7	5380	A1035[b]	17	2.5 2.5	2.5	0.8 2.4	10.5	100200 79800	80900	FB/SS/TK FB/SS/TK
8-5-90-0-i-2.5-2-13	A B	90°	13.3 13.5	13.4	5560	A1035[b]	17	2.5 2.5	2.5	2.0 1.8	9.8	73100 65200	65500	SS FP/SS
8-5-90-0-i-2.5-2-15(1)	A B	90°	14.5 15.3	14.9	5910	A1035[b]	17	2.5 2.6	2.5	2.8 2.0	9.6	64500 87300	63800	FB/SB SB
8-5-90-0-i-2.5-2-15	A B	90°	15.3 14.4	14.8	6210	A1035[b]	17	2.5 2.6	2.6	2.0 2.9	9.5	76300 80700	75500	SS/FP SB/FP
(2@3) 8-5-90-0-i-2.5-2-10‡	A B	90°	10.4 10.6	10.5	4490	A615	9	2.5 2.5	2.5	1.6 1.4	2.0	38900 41700	40300	FP FP
(2@5) 8-5-90-0-i-2.5-2-10‡	A B	90°	10.1 10.1	10.1	4490	A615	11	2.5 2.3	2.4	1.9 1.9	4.1	41900 38300	40100	FP FB/SS
8-8-90-0-i-2.5-2-8	A B	90°	8.9 8.0	8.4	7910	A1035[b]	17	2.8 2.9	2.8	1.1 2.0	8.6	54700 45200	45200	FP/TK FP/SS
8-8-90-0-i-2.5-2-10	A B	90°	9.8 9.5	9.6	7700	A1035[b]	17	2.8 2.9	2.8	2.3 2.5	9.0	50000 52900	51500	FP FP
8-8-90-0-i-2.5-2-8(1)	A B	90°	8.0 8.0	8.0	8780	A1035[b]	17	2.8 2.8	2.8	2.8 2.8	9.5	38000 37700	36800	FP/SS FP/SS

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
‡Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2
[g]Hooks placed in the middle of the column
[h]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio

Table 3.7 Cont. No. 8 hooked bars without transverse reinforcement

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[e] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
8-8-90-0-i-2.5sc-2tc-9‡	A B	90°	9.5 9.5	9.5	7710	A615	17	2.5 2.8	2.6	1.5 1.5	10.0	35500 34700	35100	FB FB
8-8-90-0-i-2.5sc-9tc-9[g]	A B	90°	9.3 9.0	9.1	7710	A615	17	2.8 2.8	2.8	8.8 9.0	10.0	38500 36800	37700	FB FB
(2@3) 8-8-90-0-i-2.5-9-9[g]	A B	90°	9.3 9.0	9.1	7510	A615	9	2.5 2.6	2.6	8.8 9.0	2.0	34000 27600	30700	FP FP
(2@4) 8-8-90-0-i-2.5-9-9[g]	A B	90°	9.9 10.0	9.9	7510	A615	10	2.6 2.5	2.5	8.1 8.0	3.1	32900 35500	34200	FP FP
8-12-90-0-i-2.5-2-9	A B	90°	9.0 9.0	9.0	11160	A1035[b]	17	2.8 2.6	2.7	2.4 2.4	9.6	50800 54800	49900	FP/SS SS/FP
8-12-90-0-i-2.5-2-12.5	A B	90°	12.9 12.8	12.8	11850	A1035[c]	17	2.6 2.6	2.6	1.7 1.8	10.1	66000 77400	67000	FB/SB FB/SB
8-12-90-0-i-2.5-2-12	A B	90°	12.1 12.1	12.1	11760	A1035[c]	17	2.5 2.4	2.5	1.9 1.9	9.8	70700 65800	65900	SB/FP FB/SS
8-15-90-0-i-2.5-2-8.5	A B	90°	8.8 8.9	8.8	15800	A1035[c]	17	2.5 2.5	2.5	2.0 1.9	10.0	43100 44100	43600	FP FP
8-15-90-0-i-2.5-2-13	A B	90°	12.8 12.8	12.8	15800	A1035[c]	17	2.4 2.5	2.4	2.1 2.0	9.9	77200 79000	78100	FB/SB FB
8-5-90-0-i-3.5-2-18	A B	90°	19.0 18.0	18.5	5380	A1035[b]	19	3.8 3.4	3.6	1.4 2.4	9.4	96000 105100	95400	FP/SS/TK FB/SS
8-5-90-0-i-3.5-2-13	A B	90°	13.4 13.4	13.4	5560	A1035[b]	19	3.6 3.4	3.5	1.9 1.9	9.4	69400 68300	68100	FP/SS SS/FP
8-5-90-0-i-3.5-2-15(1)	A B	90°	15.6 14.9	15.3	5180	A1035[c]	19	3.5 3.5	3.5	1.6 2.4	9.5	106200 85500	87700	SS SS/FP
8-5-90-0-i-3.5-2-15	A B	90°	15.4 15.1	15.3	6440	A1035[c]	19	3.3 3.4	3.3	1.8 2.0	10.1	71200 79400	70700	SS/FP SB
8-8-90-0-i-3.5-2-8	A B	90°	7.8 7.8	7.8	7910	A1035[b]	19	3.5 3.8	3.6	2.3 2.3	9.0	43700 44000	43800	SS/FP SS/FP
8-8-90-0-i-3.5-2-10	A B	90°	8.8 10.8	9.8	7700	A1035[b]	19	3.8 3.8	3.8	3.3 1.3	9.0	55200 71900	55600	FP/SS SS/FP
8-8-90-0-i-3.5-2-8	A B	90°	8.5 8.0	8.3	8780	A1035[b]	19	3.6 3.8	3.7	2.1 2.6	10.0	41200 42900	42000	FP FP
8-12-90-0-i-3.5-2-9	A B	90°	9.0 9.0	9.0	11160	A1035[b]	19	3.5 3.8	3.6	2.4 2.1	9.8	61400 68500	60200	FP FP/SS
8-8-90-0-i-4-2-8	A B	90°	7.6 8.0	7.8	8740	A1035[b]	20	4.5 3.9	4.2	2.9 2.5	9.5	37600 48700	37400	FP/SS FP
8-5-180-0-i-2.5-2-11†	A B	180°	11.0 11.0	11.0	4550	A615	15	3.0 2.8	2.9	2.0 2.0	9.8	45600 50500	46100	SS/FP SS
8-5-180-0-i-2.5-2-14†	A B	180°	14.0 14.0	14.0	4840	A1035[b]	15	2.8 2.6	2.7	2.0 2.0	9.8	49400 69400	49200	SS SS

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d] Notation described in Section 2.1 and Appendix A
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
‡ Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
[e] Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f] Failure types described in Section 3.2
[g] Hooks placed in the middle of the column
[h] Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio

Table 3.7 Cont. No. 8 hooked bars without transverse reinforcement

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b^e in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
(2@3) 8-5-180-0-i-2.5-2-10[h‡]	A B	180°	10.3 10.0	10.2	5260	A615	9	2.5 2.4	2.4	1.7 2.0	2.0	47600 56100	51800	FP FP
(2@5)8-5-180-0-i-2.5-2-10[h‡]	A B	180°	10.0 10.0	10.0	5260	A615	11	2.4 2.5	2.4	2.0 2.0	4.1	52300 54000	53200	FP FP
8-8-180-0-i-2.5-2-11.5	A B	180°	9.3 9.3	9.3	8630	A1035[b]	17	3.0 3.0	3.0	4.5 4.5	9.5	62800 80200	62800	FP/SB FP/SS
8-12-180-0-i-2.5-2-12.5	A B	180°	12.8 12.5	12.6	11850	A1035[c]	17	3.0 2.5	2.8	2.1 2.4	9.6	74800 92300	75200	FB/SB FP
8-5-180-0-i-3.5-2-11[†]	A B	180°	11.6 11.6	11.6	4550	A615	17	3.8 3.8	3.8	1.4 1.4	10.0	58600 60500	59300	FP/SS SS
8-5-180-0-i-3.5-2-14[†]	A B	180°	14.4 13.9	14.1	4840	A1035[b]	17	3.9 3.8	3.8	1.6 2.1	9.8	63700 78000	63500	SS FB/SS
8-15-180-0-i-2.5-2-13.5	A B	180°	13.8 13.5	13.6	16510	A1035[c]	17	2.5 2.5	2.5	2.0 2.3	10.0	90700 89100	89900	* FB/SB

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
*No failure; equipment malfunction
[†] Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[‡]Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2
[g]Hooks placed in the middle of the column
[h]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio

No. 8 Hooked Bars with One No. 3 Tie

Table 3.8 shows the results for seven specimens with No. 8 hooked bars and one No. 3 tie confining the hook. Specimens in this group contained 90° and 180° hooked bars placed inside the longitudinal column reinforcement. Concrete compressive strength ranged from 4,300 to 5,240 psi, and average embedment lengths ranged from 9.0 to 15.6 in. The nominal side covers were 2.5 and 3.5 in. The tie was placed at approximately $8d_b$ from the top of the hooked bar ($7.5d_b$ from the center of the hooked bar). The average bar forces at failure ranged from 49,000 to 76,000 lb, corresponding to bar stresses of 62,000 to 96,200 psi.

Table 3.8 No. 8 hooked bars with 1 No. 3 tie

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[e] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
8-5-90-1#3-i-2.5-2-16†	A B	90°	15.6 15.6	15.6	4810	A1035[b]	17	2.8 3.0	2.9	2.3 2.3	9.5	94600 73900	74810	FP/SS FP/SS
8-5-90-1#3-i-2.5-2-12.5†	A B	90°	12.5 12.5	12.5	5140	A1035[b]	17	2.6 2.8	2.7	2.1 2.1	9.8	73900 64800	64835	FP/SS SS/FP
8-5-90-1#3-i-2.5-2-9.5†	A B	90°	9.0 9.0	9.0	5240	A615	17	2.6 2.8	2.7	2.5 2.5	9.8	62000 55000	49035	SB FP/SS
8-5-180-1#3-i-2.5-2-11†	A B	180°	11.5 11.5	11.5	4300	A615	15	2.5 2.5	2.5	1.5 1.5	10.0	57300 69000	49730	SS/FP SS/FP
8-5-180-1#3-i-2.5-2-14†	A B	180°	14.8 15.0	14.9	4870	A1035[b]	15	2.8 2.9	2.8	1.3 1.0	9.9	67300 70900	69020	SS/FP FP/SS
8-5-180-1#3-i-3.5-2-11†	A B	180°	11.6 10.6	11.1	4550	A615	17	3.8 3.5	3.6	1.4 2.4	10.0	62900 56200	55390	SS SS
8-5-180-1#3-i-3.5-2-14†	A B	180°	15.6 14.5	15.1	4840	A1035[b]	17	3.6 3.6	3.6	0.9 2.0	10.0	78700 76900	75995	SS/FP SS/FP

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d] Notation described in Section 2.1 and Appendix A
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[e] Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f] Failure types described in Section 3.2

No. 8 Hooked Bars with One No. 4 Tie

Table 3.9 shows the results for one specimen with No. 8 hooked bars and one No. 4 tie confining the hook. This specimen contained a 180° hooked bar placed inside the longitudinal column reinforcement. The concrete compressive strength was 8,740 psi, and the average embedment length was 12.1 in. The nominal side cover was 2.5 in. The tie was placed at approximately $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar). The average bar force at failure was 72,200 lb, corresponding to a bar stress of 91,400 psi.

Table 3.9 No. 8 hooked bars with 1 No. 4 tie

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[e] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
8-8-180-1#4-i-2.5-2-11.5	A B	180°	12.0 12.3	12.1	8740	A1035[b]	17	2.9 2.8	2.8	2.0 1.8	9.5	72000 72500	72230	FP/SS FP/SS

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d] Notation described in Section 2.1 and Appendix A
[e] Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f] Failure types described in Section 3.2

No. 8 Hooked Bars with Two No. 3 Ties

Table 3.10 shows the results for 29 specimens with No. 8 hooked bars and two No. 3 ties confining the hook. Specimens in this group contained 90° and 180° hooked bars placed inside the longitudinal column reinforcement. Concrete compressive strength ranged from 4,300 to 15,800 psi, and average embedment lengths ranged from 6.1 to 17.3 in. The nominal side covers were 2.5 and 3.5 in. The two ties were spaced at approximately $8d_b$ for 90° hooks and $3d_b$ for 180° hooks with the first tie placed $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar). Two specimens, identified with "2#3vr" in the specimen designation, contained two No. 3 vertical stirrups as transverse reinforcement. For these specimens, the stirrups were spaced evenly along the embedment length at approximately $2.5d_b$. The average bar forces at failure ranged from 37,600 to 89,900 lb, corresponding to bar stresses of 47,600 to 113,800 psi.

Table 3.10 No. 8 hooked bars with 2 No. 3 ties

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[e] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
8-5-90-2#3-i-2.5-2-16†	A B	90°	15.0 15.8	15.4	4810	A1035[b]	17	2.8 2.9	2.8	2.9 2.1	9.5	80000 92800	79600	SS/FP FP
8-5-90-2#3-i-2.5-2-9.5†	A B	90°	9.0 9.3	9.1	5140	A615	17	2.5 2.5	2.5	2.6 2.3	10.0	54900 53600	53600	FP FP
8-5-90-2#3-i-2.5-2-12.5†	A B	90°	12.0 12.0	12.0	5240	A615	17	2.8 2.8	2.8	2.6 2.6	9.5	74100 76300	72100	FP FP/SS
8-5-90-2#3-i-2.5-2-8.5	A B	90°	8.9 9.6	9.3	5240	A1035[c]	17	3.0 3.0	3.0	1.8 1.1	9.1	52900 48400	50600	FP/SS SS
8-5-90-2#3-i-2.5-2-14	A B	90°	13.5 14.0	13.8	5450	A1035[c]	17	2.8 3.0	2.9	2.6 2.1	9.3	77000 77500	77000	SS/FP FP/SS
(2@3) 8-5-90-2#3-i-2.5-2-10‡	A B	90°	10.0 10.5	10.3	4760	A615	9	2.5 2.5	2.5	2.0 1.5	2.3	58000 46000	46800	FP FP
(2@5) 8-5-90-2#3-i-2.5-2-10‡	A B	90°	9.6 10.0	9.8	4760	A615	11	2.5 2.5	2.5	2.4 2.0	3.9	48400 48600	48500	FB FB
8-8-90-2#3-i-2.5-2-8	A B	90°	8.0 8.5	8.3	7700	A1035[b]	17	3.0 2.9	2.9	2.0 1.5	9.0	46200 55400	47900	FP/SS FP/SS
8-8-90-2#3-i-2.5-2-10	A B	90°	9.9 9.5	9.7	8990	A1035[b]	17	2.8 2.8	2.8	2.1 2.5	8.5	60700 67000	61000	FP FB
8-12-90-2#3-i-2.5-2-9	A B	90°	9.0 9.0	9.0	11160	A1035[b]	17	2.9 2.6	2.8	2.3 2.3	9.5	61800 60300	61000	FP/SS SS/FP

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d] Notation described in Section 2.1 and Appendix A
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
‡ Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
[e] Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f] Failure types described in Section 3.2
[g] Not included in the analysis in Chapters 4 and 5 due to high reinforcement ratio

Table 3.10 Cont. No. 8 hooked bars with 2 No. 3 ties

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[e] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
8-12-90-2#3-i-2.5-2-11	A	90°	10.5	10.9	12010	A1035[c]	17	2.8	2.8	2.4	9.5	68100	68700	FP
	B		11.3					2.8		1.6		79800		FP
8-12-90-2#3vr-i-2.5-2-11	A	90°	10.9	10.6	12010	A1035[c]	17	2.5	2.4	2.1	9.8	50700	52700	FP/SS
	B		10.4					2.3		2.6		66800		FP
8-15-90-2#3-i-2.5-2-6[g]	A	90°	5.8	6.1	15800	A1035[c]	17	2.5	2.4	2.3	9.9	37400	37600	FP
	B		6.4					2.4		1.8		37700		FP
8-15-90-2#3-i-2.5-2-11	A	90°	11.3	11.0	15800	A1035[c]	17	2.5	2.5	1.9	10.0	99000	83300	FB
	B		10.8					2.5		2.4		83600		FB
8-5-90-2#3-i-3.5-2-17	A	90°	17.5	17.3	5570	A1035[b]	19	3.3	3.4	1.8	10.1	102600	89900	SS
	B		17.0					3.5		2.3		88600		SS/FP
8-5-90-2#3-i-3.5-2-13	A	90°	13.8	13.6	5560	A1035[b]	19	3.1	3.4	1.5	10.3	81200	80400	SS/FP
	B		13.5					3.6		1.8		86900		SS/FP
8-8-90-2#3-i-3.5-2-8	A	90°	8.0	8.1	8290	A1035[b]	19	3.6	3.7	2.0	8.5	48300	48800	FP
	B		8.1					3.8		1.9		49300		FP
8-8-90-2#3-i-3.5-2-10	A	90°	8.8	8.8	8990	A1035[b]	19	3.6	3.7	3.3	8.5	54000	53900	SS
	B		8.8					3.8		3.3		53800		FP
8-12-90-2#3-i-3.5-2-9	A	90°	9.0	9.0	11160	A1035[b]	19	3.6	3.8	2.3	9.6	50300	49800	FP/SS
	B		9.0					4.0		2.4		49300		FP/SS
8-5-180-2#3-i-2.5-2-11[†]	A	180°	10.8	10.6	4550	A615	15	2.8	2.6	2.3	9.5	64200	60200	SS/FP
	B		10.5					2.5		2.5		61900		SS/FP
8-5-180-2#3-i-2.5-2-14[†]	A	180°	13.5	13.8	4870	A1035[b]	15	2.8	2.8	2.5	9.8	87100	76300	FP
	B		14.0					2.8		2.0		76900		FP/SS
(2@3) 8-5-180-2#3-i-2.5-2-10[g‡]	A	180°	10.3	10.3	5400	A615	9	2.5	2.5	1.8	2.0	57500	57700	FP
	B		10.3					2.5		1.8		58800		FP
(2@5) 8-5-180-2#3-i-2.5-2-10[g‡]	A	180°	10.3	10.0	5400	A615	11	2.5	2.5	1.8	4.0	63700	61900	FB
	B		9.8					2.5		2.3		60100		FB
8-8-180-2#3-i-2.5-2-11.5	A	180°	10.5	10.4	8810	A1035[b]	17	2.8	2.8	2.3	10.0	70100	58200	FB/SS
	B		10.3					2.8		2.5		59500		FP/SS
8-12-180-2#3-i-2.5-2-11	A	180°	11.1	10.8	12010	A1035[c]	17	2.5	2.6	2.1	9.6	73700	64700	FP
	B		10.4					2.6		2.8		66200		FB
8-12-180-2#3vr-i-2.5-2-11	A	180°	10.9	10.9	12010	A1035[c]	17	2.8	2.7	2.4	9.8	67100	65800	SS/FP
	B		10.9					2.6		2.4		87100		FB/SB
8-5-180-2#3-i-3.5-2-11[†]	A	180°	10.1	10.4	4300	A615	17	3.4	3.4	2.9	9.8	57200	55900	SS/FP
	B		10.6					3.5		2.4		54900		SS/FP
8-5-180-2#3-i-3.5-2-14[†]	A	180°	13.5	13.6	4870	A1035[b]	17	3.6	3.7	2.5	9.8	68300	63500	FP/SS
	B		13.6					3.8		2.4		90400		FP/SS
8-15-180-2#3-i-2.5-2-11	A	180°	11.1	11.1	15550	A1035[c]	17	2.8	2.8	2.1	9.8	79600	78900	FB/SS
	B		11.1					2.8		2.0		78300		FP

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
[†] Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[‡]Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2
[g]Not included in the analysis in Chapters 4 and 5 due to high reinforcement ratio

No. 8 Hooked Bars with Two No. 4 Ties

Table 3.11 shows the results for two specimens with No. 8 hooked bars and two No. 4 ties confining the hook. Specimens in this group contained 90° hooked bars placed inside the longitudinal column reinforcement. Concrete compressive strength for both specimens was 8,290 psi, and average embedment lengths ranged from 8.9 to 9.4 in. The nominal side covers were 2.5 and 3.5 in. The two ties were spaced at approximately $8d_b$ for 90° hooks with the first tie placed $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar). The average bar forces at failure ranged from 61,400 to 69,500 lb, corresponding to bar stresses of 77,700 to 87,900 psi.

Table 3.11 No. 8 hooked bars with 2 No. 4 ties

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b^{e} in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
8-8-90-2#4-i-2.5-2-10	A	90°	8.5	8.9	8290	A1035[b]	17	3.0	3.0	3.5	9.3	61400	61360	FP/SS
	B		9.3					3.0		2.8		71300		FP/SS
8-8-90-2#4-i-3.5-2-10	A	90°	9.0	9.4	8290	A1035[b]	19	3.8	3.8	3.0	9.1	69500	69465	SS/FP
	B		9.8					3.9		2.3		69500		FP/SS

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2

No. 8 Hooked Bars with Four No. 3 Ties

Table 3.12 shows the results for three specimens with No. 8 hooked bars and four No. 3 ties confining the hook. Specimens in this group contained 90° hooked bars placed inside the longitudinal column reinforcement. Concrete compressive strength ranged from 4,810 to 5,140 psi, and average embedment lengths ranged from 9.5 to 16.1 in. The nominal side cover was 2.5 in. The four ties were placed in two pairs; ties within a pair were spaced at approximately $3d_b$ and the spacing between pairs was $6d_b$. The first tie was placed $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar). The average bar forces at failure ranged from 54,900 to 90,400 lb, corresponding to bar stresses of 69,500 to 114,400 psi.

Table 3.12 No. 8 hooked bars with 4 No. 3 ties as confining transverse reinforcement

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b^e in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
8-5-90-4#3-i-2.5-2-16†	B A	90°	16.0 16.3	16.1	4810	A1035[b]	17	2.8 3.0	2.9	1.9 1.6	9.5	91800 97200	90430	FP/SS FP/SS
8-5-90-4#3-i-2.5-2-12.5†	A B	90°	11.9 11.9	11.9	4980	A1035[b]	17	2.5 2.5	2.5	2.0 2.0	10.0	83100 68600	68585	FP FP
8-5-90-4#3-i-2.5-2-9.5†	A B	90°	9.5 9.5	9.5	5140	A615	17	2.8 2.9	2.8	2.0 2.0	9.5	63300 54800	54915	FP FP/SS

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2

No. 8 Hooked Bars with Five No. 3 Ties

Table 3.13 shows the results of 40 specimens with No. 8 hooked bars and five No. 3 ties confining the hooks. Specimens in this group contained 90° hooked bars placed outside the longitudinal column reinforcement and 90° and 180° hooked bar placed inside the longitudinal column reinforcement. The ties in these specimens were spaced at $3d_b$, which allows the use of the 0.8 reduction factor in accordance with ACI 318-14 Section 25.4.3.2. Some specimens contained 4 No. 3 or 5 No. 3 vertical stirrups (see 4#3vr and 5#3vr in the table) also spaced at less than $3d_b$, with the first stirrup placed $2d_b$ from the back of the hook. Concrete compressive strengths ranged from 4,850 to 15,800 psi, and embedment lengths ranged from 6.3 to 15.8 in. Nominal side covers were 2.5, 3.5, or 4 in. The average bar forces at failure ranged from 39,100 to 90,000 lb, corresponding to ultimate bar stresses from 49,500 to 113,900 psi.

Table 3.13 No. 8 hooked bars with 5 No. 3 ties

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b^e in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
8-5-90-5#3-o-2.5-2-10a†	A B	90°	10.3 10.5	10.4	5270	A1035[a]	17	2.6 2.6	2.6	1.8 2.0	9.9	55700 55800	54255	SS SB
8-5-90-5#3-o-2.5-2-10b†	A B	90°	10.5 10.5	10.5	5440	A1035[a]	17	2.5 2.6	2.6	2.0 2.0	9.9	66400 69500	65590	FP/SB SB/FP
8-5-90-5#3-o-2.5-2-10c†	A B	90°	11.3 10.5	10.9	5650	A1035[a]	17	2.6 2.5	2.6	1.3 2.0	9.9	80600 57700	57700	SS/FP SS/FP

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
† Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
‡Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2
[g]Hooks placed in the middle of the column
[h]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio

Table 3.13 Cont. No. 8 hooked bars with 5 No. 3 ties

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[e] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
8-8-90-5#3-o-2.5-2-8	A B	90°	8.3 8.8	8.5	8630	A1035[b]	17	2.8 2.8	2.8	1.8 1.3	9.3	56100 66800	57980	FP/SS FB/SS
8-8-90-5#3-o-3.5-2-8	A B	90°	7.8 8.0	7.9	8810	A1035[b]	19	3.5 3.5	3.5	2.3 2.0	9.5	53900 56100	54955	FP FP/SS
8-8-90-5#3-o-4-2-8	A B	90°	8.5 8.0	8.3	8740	A1035[b]	20	3.9 4.5	4.2	1.5 2.0	10.0	39600 41500	39070	SS/FP FP
8-5-90-5#3-i-2.5-2-10b[†]	A B	90°	10.3 10.5	10.4	5440	A1035[a]	17	2.8 2.6	2.7	2.0 1.8	9.9	78800 66700	69715	FP/SS FP
8-5-90-5#3-i-2.5-2-10c[†]	A B	90°	10.5 10.5	10.5	5650	A1035[a]	17	2.5 2.5	2.5	2.0 2.0	10.0	68900 69600	68835	FP/SS FP/SS
8-5-90-5#3-i-2.5-2-15	A B	90°	15.3 15.8	15.5	4850	A1035[b]	17	2.8 2.5	2.6	1.9 1.4	9.9	77100 72600	73375	FP/SS FP/SS
8-5-90-5#3-i-2.5-2-13	A B	90°	13.8 13.5	13.6	5560	A1035[b]	17	2.5 2.4	2.4	1.5 1.8	10.3	93100 81300	82375	SS/FP FP/SS
8-5-90-5#3-i-2.5-2-12(1)	A B	90°	11.5 11.1	11.3	5090	A1035[c]	17	2.5 2.5	2.5	2.6 3.0	9.8	66700 75900	66365	SS/FP SS/FP
8-5-90-5#3-i-2.5-2-12	A B	90°	11.3 12.3	11.8	5960	A1035[c]	17	2.5 2.4	2.4	3.0 2.0	9.8	84900 72000	84900	SS SS
8-5-90-5#3-i-2.5-2-12(2)	A B	90°	12.4 12.0	12.2	5240	A1035[c]	17	2.5 2.6	2.6	1.8 2.1	9.0	72400 77400	71470	FP/SS FP/SS
8-5-90-5#3-i-2.5-2-8	A B	90°	7.8 7.4	7.6	5240	A1035[c]	17	2.8 2.9	2.8	2.6 2.9	9.0	48000 47000	47480	FP FP
8-5-90-5#3-i-2.5-2-10a[†]	B	90°	10.5	10.5	5270	A1035[a]	17	2.5	2.5	1.8	9.8	82800	82800	FP/SS
(2@3) 8-5-90-5#3-i-2.5-2-10[‡]	A B	90°	10.0 10.5	10.3	4805	A615	9	2.4 2.8	2.6	2.0 1.5	2.0	61500 58200	57900	FB/SS FB/SS
(2@5) 8-5-90-5#3-i-2.5-2-10[‡]	A B	90°	9.9 9.5	9.7	4805	A615	11	2.3 2.4	2.3	2.1 2.5	4.3	59700 52700	56000	FB FB
8-8-90-5#3-i-2.5-2-8	A B	90°	7.3 7.3	7.3	8290	A1035[b]	17	2.9 2.8	2.8	2.8 2.8	8.5	56000 51200	50265	FP FP
8-8-90-5#3-i-2.5-2-9[‡]	A B	90°	8.6 9.0	8.8	7710	A615	17	2.8 3.3	3.0	2.4 2.0	9.8	64800 64800	64390	FB FB
8-8-90-5#3-i-2.5-9-9[g‡]	A B	90°	9.0 9.3	9.1	7710	A615	17	2.5 2.8	2.6	9.0 8.8	10.0	62000 65200	63290	FB FB
(2@3) 8-8-90-5#3-i-2.5-9-9[g]	A B	90°	9.3 9.5	9.4	7440	A615	9	2.5 2.5	2.5	8.8 8.5	2.0	56500 61200	58790	FP FP
(2@4) 8-8-90-5#3-i-2.5-9-9[g]	A B	90°	8.9 9.1	9.0	7440	A615	10	2.5 2.5	2.5	9.1 8.9	3.3	55700 59300	57450	FB FB
8-12-90-5#3-i-2.5-2-9	A B	90°	9.0 9.0	9.0	11160	A1035[b]	17	2.5 2.6	2.6	2.5 2.5	9.5	66500 63100	64755	FP/SS FP/SS
8-12-90-5#3-i-2.5-2-10	A B	90°	9.0 9.9	9.4	11800	A1035[c]	17	2.6 2.3	2.4	3.2 2.3	9.9	66000 64600	64550	FB/SS SS/FP

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
[†] Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[‡]Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2
[g]Hooks placed in the middle of the column
[h]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio

Table 3.13 Cont. No. 8 hooked bars with 5 No. 3 ties

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b^e in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
8-12-90-5#3-i-2.5-2-12‡	A B	90°	12.2 12.3	12.2	11760	A1035[c]	17	2.4 2.5	2.4	2.0 1.9	10.0	90500 86500	87700	FB/SS SS/FP
8-12-90-5#3vr-i-2.5-2-10	A B	90°	10.3 10.2	10.2	11800	A1035[c]	17	2.5 2.4	2.4	1.7 1.7	9.8	59400 64100	60200	FP FP
8-12-90-4#3vr-i-2.5-2-10	A B	90°	10.6 10.3	10.4	11850	A1035[c]	17	2.5 2.5	2.5	1.8 2.1	9.0	80300 59300	59250	FP/SS FP
8-15-90-5#3-i-2.5-2-6[h]	A B	90°	6.5 6.1	6.3	15800	A1035[c]	17	2.6 2.6	2.6	1.8 2.2	9.8	48300 48700	48500	FP FP
8-15-90-5#3-i-2.5-2-10	A B	90°	10.6 9.7	10.1	15800	A1035[c]	17	2.4 2.4	2.4	1.6 2.4	9.9	111600 90200	90000	FB/SS FB/SS
8-5-90-5#3-i-3.5-2-15	A B	90°	15.8 15.8	15.8	4850	A1035[b]	19	3.6 3.5	3.5	1.3 1.3	10.3	81200 87100	80340	SS/FP SS/FP
8-5-90-5#3-i-3.5-2-13	A B	90°	13.3 13.0	13.1	5570	A1035[b]	19	3.4 3.5	3.4	2.1 2.4	10.4	89600 76000	77070	SS SS/FP
8-5-90-5#3-i-3.5-2-12(1)	A B	90°	12.8 12.3	12.5	5090	A1035[c]	19	3.5 3.4	3.5	1.6 2.1	9.8	78900 75900	76430	SS/FP SS
8-5-90-5#3-i-3.5-2-12	A B	90°	12.5 11.8	12.1	6440	A1035[c]	19	3.4 3.5	3.4	1.7 2.4	9.8	79200 79300	79150	FP FP/SS
8-8-90-5#3-i-3.5-2-8	A B	90°	8.0 8.0	8.0	7910	A1035[b]	19	3.5 3.6	3.6	2.0 2.0	8.9	55400 56200	55810	FP FP
8-12-90-5#3-i-3.5-2-9	A B	90°	9.0 9.0	9.0	11160	A1035[b]	19	3.3 3.4	3.3	2.5 2.5	9.5	68800 82200	67830	FP/SS FP/SS
(2@5) 8-5-180-5#3-i-2.5-2-10[h‡]	A B	180°	10.0 10.3	10.1	5540	A615	11	2.5 2.5	2.5	2.0 1.8	4.0	58100 72200	66640 66640	FB FB
8-12-180-5#3-i-2.5-2-10	A B	180°	9.9 9.6	9.8	11800	A1035[c]	17	2.3 2.8	2.5	2.3 2.6	9.9	63000 81400	64100	FP/SS FP
8-12-180-5#3vr-i-2.5-2-10	A B	180°	11.1 10.5	10.8	11800	A1035[c]	17	2.5 2.5	2.5	1.3 1.9	9.8	67500 68000	67800	FP FB
8-12-180-4#3vr-i-2.5-2-10	A B	180°	10.5 10.0	10.3	11850	A1035[c]	17	2.8 2.5	2.6	1.8 2.3	9.8	69700 68800	69200	FP FP
8-15-180-5#3-i-2.5-2-9.5	A B	180°	9.6 9.8	9.7	15550	A1035[c]	17	2.5 2.8	2.6	2.1 1.9	10.0	86000 86000	86000	SS FP/SS

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
[†] Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[‡]Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2
[g]Hooks placed in the middle of the column
[h]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio

No. 8 Hooked Bars with Four No. 4 Ties

Table 3.14 shows the results of six specimens with No. 8 hooked bars and four No. 4 ties confining the hooks. Specimens in this group contained 90° hooked bars placed inside the longitudinal column reinforcement. The ties in these specimens were spaced at $4d_b$ with No. 3 cross-ties in both directions in accordance with ACI 318-14 Section 18.8.3 for joints in special moment frames. Concrete compressive strengths ranged from 4,810 to 6,210 psi, and average embedment lengths ranged from 11.9 to 15.6 in. Nominal side covers were 2.5 and 3.5 in. The average bar forces at failure ranged from 90,800 to 99,800 lb, corresponding to ultimate bar stresses from 114,900 to 126,300 psi.

Table 3.14 No. 8 hooked bars with 4 No. 4 ties

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[e] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[f]
8-5-90-4#4s-i-2.5-2-15	A B	90°	15.6 15.6	15.6	4810	A1035[b]	17	3.0 2.9	2.9	1.6 1.6	9.1	93300 107700	93655	SS/FP FP/SS
8-5-90-4#4s-i-2.5-2-12(1)	A B	90°	12.3 12.5	12.4	5180	A1035[c]	17	2.5 2.6	2.6	2.1 1.9	10.0	100200 90100	90815	FP/SS FP/SS
8-5-90-4#4s-i-2.5-2-12	A B	90°	12.0 12.6	12.3	6210	A1035[c]	17	2.6 2.5	2.6	2.3 1.6	9.5	116400 99700	99755	FP/SS SS/FP
8-5-90-4#4s-i-3.5-2-15	A B	90°	15.5 15.1	15.3	4810	A1035[b]	19	4.1 4.0	4.1	1.8 2.1	9.5	106000 90200	90865	FP/SS SS/FP
8-5-90-4#4s-i-3.5-2-12(1)	A B	90°	12.0 11.9	11.9	5910	A1035[c]	19	3.8 3.5	3.6	2.3 2.4	9.8	115200 97400	95455	SS FP/SS
8-5-90-4#4s-i-3.5-2-12	A B	90°	12.0 12.5	12.3	5960	A1035[c]	19	3.8 3.5	3.6	2.4 1.9	9.0	103900 96900	98155	SS/FP FP/SS

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2

3.3.3 No. 11 Hooked Bars

No. 11 Hooked Bars Without Transverse Reinforcement

Table 3.15 shows the results for 23 specimens with No. 11 hooked bars without transverse reinforcement. The specimens had 90° and 180° hooked bars placed inside and outside the longitudinal column reinforcement. Concrete compressive strengths ranged from 4,910 to 16,180 psi, and average embedment lengths ranged from 13.9 to 26.0 in. Nominal side covers were 2.5 and 3.5 in. The average bar forces at failure ranged from 60,200 to 213,300 lb, corresponding to ultimate bar stresses of 38,600 to 136,700 psi. Thirteen of the 40 hooked bars in this group of 23 specimens exhibited tail kickout at failure. One specimen (11-15-90-0-i-2.5-2-11) had yielding of the column longitudinal reinforcement before anchorage failure of the hooked bars.

Table 3.15 No. 11 hooked bars without transverse reinforcement

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]
11-8-90-0-o-2.5-2-25	A B	90°	25.3 25.1	25.2	9460	A1035	21.5	2.6 2.9	2.8	2.3 2.3	13.6	194500 170700	174700	SB SB
11-8-90-0-o-2.5-2-17	A B	90°	16.8 16.4	16.6	9460	A1035	21.5	2.5 2.4	2.4	2.8 2.8	13.8	121400 105700	107200	SB/FB SB/TK
11-12-90-0-o-2.5-2-17	A B	90°	17.1 16.6	16.9	11800	A1035	21.5	2.5 2.5	2.5	2.2 2.7	13.8	123700 105800	105400	FB/TK FP/TK
11-12-180-0-o-2.5-2-17	A B	180°	16.9 17.3	17.1	11800	A1035	21.5	2.5 2.6	2.5	2.3 1.9	13.4	83300 90100	83500	SS/FP SB
11-5-90-0-i-2.5-2-14	A B	90°	13.5 15.3	14.4	4910	A615	21.5	2.8 2.8	2.8	2.5 0.8	13.3	67200 81400	66600	FP/SS SS
11-5-90-0-i-2.5-2-26	A B	90°	26.0 26.0	26.0	5360	A1035	21.5	2.5 2.9	2.7	2.1 2.1	13.3	165700 146800	148700	FB/SS FB/SS/TK
(2@5.35) 11-5-90-0-i-2.5-13-13[d]	A B	90°	14.0 13.9	13.9	5330	A615	14	2.6 2.6	2.6	12.0 12.1	6.2	58200 63000	60200	FP FP
11-8-90-0-i-2.5-2-17	A B	90°	17.3 18.0	17.6	9460	A1035	21.5	2.5 2.5	2.5	1.6 1.6	13.4	132000 141200	132100	FP/TK FB/TK
11-8-90-0-i-2.5-2-21	A B	90°	20.0 21.1	20.6	7870	A1035	21.5	2.5 2.8	2.6	3.4 2.3	13.0	127060 147900	125100	FP/TK FB
11-8-90-0-i-2.5-2-17	A B	90°	16.3 18.1	17.2	8520	A1035	21.5	2.5 2.5	2.5	3.0 1.1	13.5	105630 115170	104800	SS FP
11-12-90-0-i-2.5-2-17	A B	90°	16.1 16.9	16.5	11880	A1035	21.5	2.5 2.6	2.6	3.1 2.4	13.3	148400 120400	119700	SB SB/FP
11-12-90-0-i-2.5-2-17.5	A B	90°	17.6 17.8	17.7	13330	A1035	21.5	3.8 2.5	3.1	2.1 2.0	13.8	123600 125600	124600	SS/TK SS
11-12-90-0-i-2.5-2-25	A B	90°	24.9 24.4	24.6	13330	A1035	22	2.5 2.5	2.5	2.4 2.9	13.1	205100 198100	199700	SB SB
11-15-90-0-i-2.5-2-24	A B	90°	24.0 24.8	24.4	16180	A1035	21.5	2.5 2.5	2.5	2.0 1.3	13.5	212600 231300	213300	SB/TK SB/TK
11-15-90-0-i-2.5-2-11[e]	A B	90°	12.1 11.5	11.8	16180	A1035	21.5	2.4 2.8	2.6	1.0 1.6	13.0	48600 47700	48100	FL FL
11-15-90-0-i-2.5-2-10[‡]	A B	90°	9.5 9.5	9.5	14050	A615	21.5	2.8 2.7	2.7	2.5 2.5	13.6	52100 50900	51500	FP FP
11-15-90-0-i-2.5-2-15[‡]	A B	90°	14.0 14.0	14.0	14050	A1035	21.5	2.8 2.8	2.8	3.0 3.0	13.0	93300 91000	92200	SB SB
11-5-90-0-i-3.5-2-17	A B	90°	18.1 17.6	17.9	5600	A1035	23.5	4.0 3.9	3.9	1.8 2.5	13.1	105000 117600	108100	SS/TK SS
11-5-90-0-i-3.5-2-14	A B	90°	14.8 15.3	15.0	4910	A615	23.5	3.8 3.9	3.8	1.5 1.0	13.3	82600 69000	69500	FP/SS FP/SS/TK
11-5-90-0-i-3.5-2-26	A B	90°	26.3 25.8	26.0	5960	A1035	23.5	3.8 3.8	3.8	2.1 2.6	13.5	198300 181700	182300	SB/FB FB/SB
11-8-180-0-i-2.5-2-21	A B	180°	21.3 20.9	21.1	7870	A1035	21.5	2.9 2.4	2.7	1.8 2.2	13.0	137800 126800	128100	FB FB/SB
11-8-180-0-i-2.5-2-17	A B	180°	17.8 18.0	17.9	8520	A1035	21.5	2.4 2.5	2.4	1.4 1.1	13.8	101710 121270	100500	FP FB
11-12-180-0-i-2.5-2-17	A B	180°	16.6 16.6	16.6	11880	A1035	21.5	3.0 2.5	2.8	2.5 2.5	13.3	106700 108200	107500	SB/FP SS

[a]Notation described in Section 2.1 and Appendix A
[†] Specimens had constant 80 kip axial load, all other specimens were subjected to an axial stress of 280 psi
[‡]Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

[d]Hooks placed in the middle of the column
[e]Not included in analysis in Chapters 4 and 5 due to flexural failure of the column longitudinal steel

No. 11 Hooked Bars with One No. 4 Tie

Table 3.16 shows the results for two specimens with No. 11 hooked bars and one No. 4 tie as transverse reinforcement. These specimens contained 90° hooked bars placed inside the longitudinal column reinforcement. The concrete compressive strength for these specimens was 5,790 psi, and average embedment lengths were 17.7 and 17.8 in. Nominal side covers were 2.5 to 3.5 in. The tie was placed at approximately $5d_b$ from the top of the hooked bar ($4.5d_b$ from the center of the hooked bar). The average bar forces at failure ranged from 101,500 to 106,300 lb, corresponding to bar stresses of 65,100 to 68,100 psi. One of the 4 hooks in the group, 11-5-90-1#4-i-3.5-2-17 hook B, exhibited tail kickout at failure.

Table 3.16 No. 11 hooked bars with 1 No. 4 tie

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]
11-5-90-1#4-i-2.5-2-17	A B	90°	17.8 17.6	17.7	5790	A1035	21.5	2.8 2.8	2.8	1.8 2.0	13.1	99400 119700	101500	SS/FP FP/SS
11-5-90-1#4-i-3.5-2-17	A B	90°	17.8 17.8	17.8	5790	A1035	23.5	3.8 3.9	3.8	1.8 1.8	13.1	105700 108800	106270	SS SS/FP/TK

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

No. 11 Hooked Bars with Two No. 3 Ties

Table 3.17 shows the results for 11 specimens with No. 11 hooked bars and two No. 3 ties as transverse reinforcement. These specimens contained 90° hooked bars placed inside the longitudinal column reinforcement. Concrete compressive strengths ranged from 4,910 to 16,180 psi, and average embedment lengths ranged from 13.6 to 24.8 in. Nominal side covers were 2.5 to 3.5 in. The two ties were spaced at approximately $8.5d_b$ and the first tie was placed $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar). The average bar forces at failure ranged from 63,900 to 209,600 lb, corresponding to bar stresses of 41,000 to 134,400 psi. Two of the 16 hooks in the group (11-5-90-2#3-i-3.5-2-14 hook B and 11-5-90-2#3-i-3.5-2-17 hook A) exhibited tail kickout at failure. One specimen (11-15-90-2#3-i-2.5-2-10.5) exhibited yielding of the column longitudinal reinforcement before anchorage failure of the hooked bars. Testing was stopped on specimen 11-12-90-2#3-i-2.5-2-25 before fracture of the bars.

Table 3.17 No. 11 hooked bars with 2 No. 3 ties

Specimen[a]	**Hook**	**Bend Angle**	ℓ_{eh} **in.**	$\ell_{eh,avg}$ **in.**	f_{cm} **psi**	**Hook Bar Type**	b[b] **in.**	c_{so} **in.**	$c_{so,avg}$ **in.**	c_{th} **in.**	c_h **in.**	T_{ind} **lb**	T **lb**	**Failure Type**[c]
11-5-90-2#3-i-2.5-2-17	A B	90°	17.4 17.8	17.6	5600	A1035	22	2.5 2.6	2.6	2.3 1.8	13.4	108400 103200	100700	SS/FP SS/FP
11-5-90-2#3-i-2.5-2-14	A B	90°	13.5 13.8	13.6	4910	A615	22	2.8 2.9	2.8	2.5 2.3	13.3	77700 77200	77400	FP/SS SS
(2@5.35) 11-5-90-2#3-i-2.5-13-13[d]	A B	90°	13.9 13.8	13.8	5330	A615	14	2.7 2.6	2.6	12.1 12.3	6.2	68300 70100	69100	FP FP
11-12-90-2#3-i-2.5-2-17.5	A B	90°	18.0 17.5	17.8	13710	A1035	22	2.5 2.5	2.5	1.5 2.0	13.3	133200 129900	130400	SS SS
11-12-90-2#3-i-2.5-2-25[f]	A B	90°	25.0 24.5	24.8	13710	A1035	22	2.6 3.0	2.8	2.3 2.8	13.0	211000 211000	211000	BY BY
11-15-90-2#3-i-2.5-2-23	A B	90°	23.5 23.5	23.5	16180	A1035	22	2.8 2.8	2.8	1.5 1.5	13.0	232100 206900	209600	SB SB/FB
11-15-90-2#3-i-2.5-2-10.5[e]	A B	90°	11.8 10.5	11.1	16180	A1035	22	2.5 2.8	2.6	1.0 2.3	13.8	50600 49600	50100	FL FL
11-15-90-2#3-i-2.5-2-10[‡]	A B	90°	10.0 10.0	10.0	14045	A615	22	2.8 3.0	2.9	2.0 2.0	13.4	64300 63900	63900	FP FP
11-15-90-2#3-i-2.5-2-15[‡]	A B	90°	14.0 14.3	14.1	14045	A1035	22	2.6 2.6	2.6	3.0 2.8	13.6	115600 114800	115200	FP/SB FP/SB
11-5-90-2#3-i-3.5-2-17	A B	90°	17.5 17.8	17.6	7070	A1035	24	3.6 3.6	3.6	2.1 2.0	13.4	107800 111500	109600	SS/FP/TK SS
11-5-90-2#3-i-3.5-2-14	A B	90°	14.5 13.4	13.9	4910	A615	24	3.8 3.9	3.8	1.6 2.8	13.3	92700 81800	82300	FP/SS SS/FP/TK

[a]Notation described in Section 2.1 and Appendix A
[‡]Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
[d]Hooks placed in the middle of the column
[e]Not included in analysis in Chapters 4 and 5 due to flexural failure of the column longitudinal steel
[f]Not included in analysis in Chapters 4 and 5 due to yielding of hooked bars before anchorage failure

No. 11 Hooked Bars with Five No. 3 Ties

Table 3.18 shows the results for two specimens with No. 11 hooked bars and five No. 3 ties as transverse reinforcement. These specimens contained 90° hooked bars placed inside the longitudinal column reinforcement. The concrete compressive strength for these specimens was 4,910 psi, and average embedment lengths ranged from 13.9 to 14.6 in. Nominal side covers were 2.5 to 3.5 in. The five ties were spaced at approximately $3d_b$ and the first tie was placed $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar). The average bar forces at failure ranged from 95,200 to 98,000 lb, corresponding to bar stresses of 61,000 to 62,800 psi.

Table 3.18 No. 11 hooked bars with 5 No. 3 ties

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b^b in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]
11-5-90-5#3-i-2.5-2-14	A B	90°	14.3 13.5	13.9	4910	A615	21.5	2.8 2.9	2.8	1.8 2.5	13.4	105600 94100	95170	SS/FP SS/FP
11-5-90-5#3-i-3.5-2-14	A B	90°	14.6 14.5	14.6	4910	A615	23.5	3.9 3.9	3.9	1.4 1.5	13.1	101300 94700	97990	FP/SS SS/FP

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

No. 11 Hooked Bars with Six No. 3 Ties

The results for 24 specimens with No. 11 hooked bars and six No. 3 ties confining the hooks are shown in Table 3.19. The specimens contained 90° or 180° hooked bars placed inside and outside the longitudinal column reinforcement. The ties in these specimens were spaced at $3d_b$, which allows the use of the 0.8 reduction factor in accordance with ACI 318-14 Section 25.4.3.2. Concrete compressive strengths ranged from 5,280 to 16,180 psi, and average embedment lengths ranged from 13.9 to 22.3 in. Nominal side covers were 2.5 and 3.5 in. The average bar forces at failure ranged from 82,700 to 201,200 lb, corresponding to stresses of 53,000 to 129,000 psi. One specimen (11-15-90-6#3-i-2.5-2-9.5) exhibited yielding of the column longitudinal reinforcement before anchorage failure of the hooked bars and was not included in the analysis.

Table 3.19 No. 11 hooked bars with 6 No. 3 ties

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b^b in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]
11-8-90-6#3-o-2.5-2-16	A B	90°	15.9 16.5	16.2	9420	A1035	21.5	2.5 2.6	2.6	1.9 1.9	13.6	138900 134700	136800	SB/FB SB/FB
11-8-90-6#3-o-2.5-2-22	A B	90°	21.5 22.3	21.9	9120	A1035	21.5	2.5 2.6	2.6	2.5 2.5	13.5	186100 170500	170200	SB SB/FB
11-12-90-6#3-o-2.5-2-17	A B	90°	15.6 17.3	16.4	11800	A1035	21.5	2.5 2.4	2.4	3.6 2.0	13.8	116400 147300	115900	FB/SS SB/FB
11-12-180-6#3-o-2.5-2-17	A B	180°	16.6 16.4	16.5	11800	A1035	21.5	2.5 2.8	2.6	2.9 3.1	13.5	130000 113800	113100	SB FB/SS

[a]Notation described in Section 2.1 and Appendix A
‡Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
*No failure; load reached maximum capacity of jacks
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

[d]Hooks placed in the middle of the column
[e]Not included in analysis in Chapters 4 and 5 due to flexural failure of the column longitudinal steel

Table 3.19 Cont. No. 11 hooked bars with 6 No. 3 ties

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]
11-5-90-6#3-i-2.5-2-20	A B	90°	19.5 19.0	19.3	5420	A1035	21.5	2.6 2.6	2.6	2.8 3.3	12.9	153100 135000	136300	FP/SS FP/SS
(2@5.35) 11-5-90-6#3-i-2.5-13-13[d]	A B	90°	14.0 13.8	13.9	5280	A615	14	2.4 2.8	2.6	12.0 12.3	6.2	83800 96000	89700	FP FP
(2@5.35) 11-5-90-6#3-i-2.5-18-18[d]	A B	90°	19.3 19.5	19.4	5280	A1035	14	2.7 2.6	2.6	16.8 16.5	6.2	118500 128600	121600	FP FP
11-8-90-6#3-i-2.5-2-16	A B	90°	15.5 16.4	15.9	9120	A1035	21.5	2.5 2.5	2.5	2.3 2.3	13.4	147500 129700	133000	FP/SS FP/SS
11-8-90-6#3-i-2.5-2-22b	A B	90°	21.3 21.5	21.4	9420	A1035	21.5	2.5 2.6	2.6	2.7 2.7	13.5	205000 183200	184600	* SS
11-8-90-6#3-i-2.5-2-22a	A B	90°	21.9 22.0	21.9	9420	A1035	21.5	2.6 2.9	2.8	2.2 2.2	13.4	200000 191300	191000	* SB/FB
11-8-90-6#3-i-2.5-2-15	A B	90°	15.8 15.3	15.5	7500	A1035	21.5	2.8 2.5	2.6	1.5 2.0	13.5	142300 108000	108300	SS SS/FP
11-8-90-6#3-i-2.5-2-19	A B	90°	19.1 19.4	19.2	7500	A1035	21.5	2.5 2.6	2.6	2.0 1.7	13.5	182700 146100	145400	FB/SS FB/SS
11-12-90-6#3-i-2.5-2-17	A B	90°	17.1 16.5	16.8	12370	A1035	21.5	2.6 3.0	2.8	1.9 2.6	13.0	179700 162300	161600	FB/SB SP/SS
11-12-90-6#3-i-2.5-2-16	A B	90°	14.8 16.0	15.4	13710	A1035	22	2.5 2.5	2.5	3.3 2.0	13.0	115100 127500	115200	SS/FP SB/FB
11-12-90-6#3-i-2.5-2-22	A B	90°	21.9 21.5	21.7	13710	A1035	22	2.9 3.1	3.0	2.4 2.8	13.3	200100 199200	201200	SS/FB FB
11-15-90-6#3-i-2.5-2-22	A B	90°	22.3 22.4	22.3	16180	A1035	21.5	3.0 2.5	2.8	1.8 1.6	13.5	227500 195700	197800	FB/SS SB/FB
11-15-90-6#3-i-2.5-2-9.5[e]	A B	90°	9.0 10.3	9.6	16180	A1035	21.5	2.5 3.0	2.8	2.5 1.3	13.3	58200 56600	57400	FL FL
11-15-90-6#3-i-2.5-2-10a[‡]	A B	90°	9.5 10.0	9.8	14045	A615	21.5	2.6 2.8	2.7	2.5 2.0	13.4	83600 81800	82700	FP FP
11-15-90-6#3-i-2.5-2-10b[‡]	A B	90°	9.5 9.8	9.6	14050	A615	21.5	2.8 2.8	2.8	2.5 2.3	13.0	76600 74600	75600	FP FP
11-15-90-6#3-i-2.5-2-15[‡]	A B	90°	14.5 15.0	14.8	14045	A1035	21.5	2.6 2.6	2.6	2.5 2.0	13.6	145700 144900	145300	FP FP
11-5-90-6#3-i-3.5-2-20	A B	90°	20.5 20.3	20.4	5420	A1035	23.5	3.8 3.9	3.8	1.8 2.0	13.1	150200 135300	135800	SS/FP SS
11-8-180-6#3-i-2.5-2-15	A B	180°	15.1 15.5	15.3	7500	A1035	21.5	2.9 3.1	3.0	2.0 1.6	13.0	112400 111000	111700	SS SS
11-8-180-6#3-i-2.5-2-19	A B	180°	19.6 19.9	19.8	7870	A1035	21.5	2.9 2.9	2.9	1.5 1.3	13.3	170000 149000	149000	FB/SS FB/SS
11-12-180-6#3-i-2.5-2-17b	A B	108°	16.9 16.5	16.7	12370	A1035	21.5	2.6 2.8	2.7	2.9 3.3	13.5	123100 117600	116400	FP FP/SB
11-12-180-6#3-i-2.5-2-17a	A B	180°	16.8 16.8	16.8	12370	A1035	21.5	2.5 2.8	2.6	2.7 2.6	13.4	148900 173000	148700	FP/SS SB/FB

[a]Notation described in Section 2.1 and Appendix A
[‡]Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
*No failure; load reached maximum capacity of jacks
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
[d]Hooks placed in the middle of the column
[e]Not included in analysis in Chapters 4 and 5 due to flexural failure of the column longitudinal steel

No. 11 Hooked Bars with Five No. 4 Ties

The results for two specimens with No. 11 hooked bars and five No. 4 ties confining the hooks are shown in Table 3.20. The specimens contained 90° hooked bars placed inside the longitudinal column reinforcement. The ties in these specimens were spaced at 3.5d_b with No. 4 cross-ties in both directions in accordance with ACI 318-14 Section 18.8.3 for joints in special moment resisting frames. Concrete compressive strengths ranged from 5,420 to 5,960 psi, and average embedment lengths ranged from 19.5 to 20.1 in. Nominal side covers were 2.5 and 3.5 in. The average bar forces at failure ranged from 141,000 to 153,000 lb, corresponding to stresses of 90,400 to 98,100 psi.

Table 3.20 No. 11 hooked bars with 5 No. 4 ties

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]
11-5-90-5#4s-i-2.5-2-20	A	90°	20.0	20.1	5420	A1035	21.5	2.5	2.6	2.3	13.4	141400	141045	FP/SS
	B		20.3					2.8		2.0		161600		FP/SS
11-5-90-5#4s-i-3.5-2-20	A	90°	19.8	19.5	5960	A1035	23.5	3.8	3.8	2.3	13.1	186700	152965	SS/FP
	B		19.3					3.8		2.8		153500		FP/SS

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

3.3.4 No. 5 Hooked Bar Specimens with Multiple Hooks

No. 5 Multiple Hooked Bar Specimens Without Transverse Reinforcement

The results for 7 multiple hook specimens with No. 5 hooked bars without transverse reinforcement are shown in Table 3.21. The specimens contained three or four 90° hooked bars placed inside the longitudinal column reinforcement with a center-to-center spacing of approximately 4d_b or 6d_b. Concrete compressive strength ranged from 6,430 to 6,950 psi, and the average embedment lengths ranged from 5.2 to 9.0 in. The nominal side cover for all specimens was 2.5 in. The average bar forces at failure ranged from 14,500 to 28,400 lb, corresponding to stresses of 46,800 to 91,600 psi.

Table 3.21 No. 5 multiple hooked bar specimens without transverse reinforcement

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	Failure Type[c]
(4@4) 5-5-90-0-i-2.5-2-6	A	90°	5.4	5.2	6430	A1035	13	2.4	2.6	2.8	1.9	4	12200	14500	FP
	B		5.3					4.9		2.9	1.9		16800		FP
	C		4.8					5.1		3.4	1.8		15500		FP
	D		5.3					2.8		2.9			13700		FP
(4@4) 5-5-90-0-i-2.5-2-10	A	90°	9.0	9.0	6470	A1035	13	2.6	2.7	3.3	1.8	4	27900	28400	FP
	B		8.0					5.0		4.3	1.9		28600		FP
	C		9.3					5.0		3.0	1.6		44800		FP
	D		9.9					2.8		2.4	-		27600		FP
(4@4) 5-8-90-0-i-2.5-2-6	A	90°	6.3	5.9	6950	A1035	13	2.5	2.5	1.8	1.9	4	17300	15500	FP/SS
	B		5.8					5.0		2.3	1.6		17600		FP/SS
	C		5.8					5.0		2.3	1.9		14100		FP/SS
	D		6.0					2.5		2.0	-		14100		FP/SS
(4@6) 5-8-90-0-i-2.5-2-6	A	90°	6.0	5.9	6693	A1035	17	2.7	2.7	2.0	3.1	4	20600	19300	FP
	B		6.0					6.5		2.0	3.1		22500		FP
	C		5.8					6.5		2.3	3.1		22900		FP
	D		6.0					2.7		2.0	-		15100		FP
(4@6) 5-8-90-0-i-2.5-6-6[d]	A	90°	6.3	6.3	6693	A1035	17	2.5	2.6	5.8	3.1	4	16100	16100	FP/SS
	B		6.3					6.3		5.8	3.1		14700		FP/SS
	C		6.3					6.5		5.8	3.1		16500		FP/SS
	D		6.3					2.7		5.8	-		16800		FP/SS
(3@4) 5-8-90-0-i-2.5-2-6	A	90°	6.00	5.88	6950	A1035	11	2.56	2.63	2.00	1.8	3	18500	16800	FP
	B		5.63					5.56		2.38	1.9		17600		FP
	C		6.00					2.69		2.00	-		14700		FP
(3@6) 5-8-90-0-i-2.5-2-6	A	90°	6.38	6.00	6950	A1035	13	2.56	2.63	1.63	3.0	3	25500	24900	FP
	B		5.88					6.19		2.13	3.1		34900		FP
	C		5.75					2.69		2.25	-		23200		FP

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
[d]Hooks placed in the middle of the column

No. 5 Multiple Hooked Bar Specimens with Two No. 3 Ties

The results for two multiple hook specimens with No. 5 hooked bars and 2 No. 3 ties confining the hooked bars are shown in Table 3.22. The specimens contained four 90° hooked bars placed inside the longitudinal column reinforcement with a center-center spacing of approximately $4d_b$. The two ties were spaced at approximately $8d_b$ with the first tie placed $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar). The concrete compressive strength for both specimens was 6,430 psi, and the average embedment lengths were 6.3 and 8.0 in. The nominal side cover for both specimens was 2.5 in. The average bar forces at failure ranged from 21,400 to 26,000 lb, corresponding to stresses of 69,000 to 83,900 psi.

Table 3.22 No. 5 multiple hooked bar specimens with 2 No. 3 ties

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b^b in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	Failure Type[c]
(4@4) 5-5-90-2#3-i-2.5-2-6	A	90°	6.3	6.3	6430	A1035	13	2.5	2.5	1.9	1.9	4	22400	21400	FP
	B		6.1					5.0		2.0	1.9		22200		FP
	C		6.3					4.8		1.9	1.6		24000		FP
	D		6.4					2.5		1.8	-		21700		FP
(4@4) 5-5-90-2#3-i-2.5-2-8	A	90°	8.4	8.0	6430	A1035	13	2.5	2.5	1.8	1.9	4	24000	26000	FP
	B		7.8					5.0		2.4	1.9		31200		FP
	C		8.0					4.9		2.1	1.8		36000		FP
	D		7.8					2.5		2.4	-		23700		FP

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

No. 5 Multiple Hooked Bar Specimens with Five No. 3 Ties

Table 3.23 shows the results for 9 multiple hook specimens with No. 5 hooked bars and five No. 3 ties as confining transverse reinforcement. The specimens contained either three or four 90° hooked bars placed inside the longitudinal column reinforcement with a center-to-center spacing of approximately $6d_b$ or $4d_b$. The ties in these specimens were spaced at $3d_b$, which allows the use of the 0.8 reduction factor in accordance with ACI 318-14 Section 25.4.3.2. The concrete compressive strength ranged between 6,430 and 10,110 psi, and the average embedment lengths ranged from 5.5 to 7.1 in. Nominal side covers were 2.5 and 3.5 in. The average bar forces at failure ranged from 25,800 to 36,300 lb, corresponding to stresses of 83,200 to 117,100 psi.

Table 3.23 No. 5 multiple hooked bar specimens with 5 No. 3 ties

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b^b in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	Failure Type[c]
(3@6) 5-8-90-5#3-i-2.5-2-6.25	A	90°	5.0	5.5	10110	A1035	13	2.5	2.5	3.8	2.9	3	27100	25800	FP
	B		6.3					5.4		2.6	3.0		32400		FP
	C		5.3					2.5		3.6	-		26800		FP

[a]Notation described in Section 2.1 and Appendix A
[‡]Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

Table 3.23 Cont. No. 5 multiple hooked bar specimens with 5 No. 3 ties

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	Failure Type[c]
(3@4) 5-8-90-5#3-i-2.5-2-6‡	A	90°	6.0	6.1	6703	A1035	11	2.5	2.5	2.0	2.1	3	35800	34900	FP
	B		6.3					5.0		1.8	1.9		34700		FP
	C		6.0					2.5		2.0	-		34400		FP
(3@6) 5-8-90-5#3-i-2.5-2-6‡	A	90°	6.0	6.0	6703	A1035	13	2.5	2.5	2.0	3.4	3	37800	36300	FP
	B		6.0					5.0		2.0	3.1		34800		FP
	C		6.0					2.5		2.0	-		37500		FP
(4@4) 5-5-90-5#3-i-2.5-2-7	A	90°	6.6	7.1	6430	A1035	13	2.5	2.4	2.5	1.5	4	27300	27100	FP
	B		7.9					4.6		1.3	2.0		37000		FP
	C		7.5					4.6		1.6	1.6		29500		FP
	D		6.5					2.4		2.6	-		23000		FP
(4@4) 5-5-90-5#3-i-2.5-2-6	A	90°	6.0	6.3	6430	A1035	13	2.5	2.6	2.5	2.0	4	24900	25900	FP
	B		6.5					5.1		2.0	1.8		27200		FP
	C		6.6					5.0		1.9	1.8		26800		FP
	D		6.3					2.6		2.3	-		26600		FP
(4@6) 5-8-90-5#3-i-2.5-2-6‡	A	90°	6.0	6.0	6693	A1035	17	2.7	2.7	2.0	3.4	4	30300	28300	FP
	B		6.0					6.5		2.0	3.4		30100		FP
	C		6.0					6.5		2.0	3.1		27600		FP
	D		6.0					2.7		2.0	-		25300		FP
(4@6) 5-8-90-5#3-i-2.5-6-6[d]‡	A	90°	6.8	6.4	6693	A1035	17	2.5	2.6	1.3	3.1	4	32100	31200	FP
	B		6.0					6.5		2.0	3.1		29900		FP
	C		6.5					6.5		1.5	2.9		30800		FP
	D		6.3					2.7		1.8	-		31800		FP
(4@4) 5-8-90-5#3-i-2.5-2-6‡	A	90°	5.8	6.0	6703	A1035	17	2.5	2.5	2.3	1.9	4	28000	27500	FP
	B		5.5					5.0		2.5	1.9		27300		FP
	C		6.3					5.0		1.8	1.9		28600		FP
	D		6.5					2.5		1.5	-		26200		FP
(3@6) 5-8-90-5#3-i-3.5-2-6.25	A	90°	6.3	6.3	10110	A1035	15	3.5	3.6	2.1	2.6	3	36100	35300	FP
	B		6.3					6.6		2.1	3.3		33800		FP
	C		6.3					3.8		2.1	-		40800		FP

[a]Notation described in Section 2.1 and Appendix A
‡Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
[d]Hooks placed in the middle of the column

3.3.5 No. 8 Hooked Bar Specimens with Multiple Hooks

No. 8 Multiple Hooked Bar Specimens Without Transverse Reinforcement

The results for 15 multiple hook specimens with No. 8 hooked bars without transverse reinforcement are shown in

Table 3.24. The specimens contained three or four 90° or 180° hooked bars placed inside the longitudinal column reinforcement with a center-to-center spacing of 3d_b, 4d_b, 5d_b, or 5.5d_b. Concrete compressive strength ranged from 4,490 to 11,460 psi, and the average embedment lengths ranged from 7.9 to 16.0 in. The nominal side cover was 2.5 in. The average bar forces at failure ranged from 18,000 to 62,800 lb, corresponding to stresses of 22,800 to 79,500 psi.

Table 3.24 No. 8 multiple hooked bar specimens without transverse reinforcement

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[e] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	Failure Type[f]
	A		16.5					2.6		1.6	4.4		65300		FP
(3@5.5) 8-5-90-0-i-2.5-2-16	B	90°	15.8	16.1	6255	A1035[b]	17	8.0	2.7	2.4	4.5	3	103700	62800	FP
	C		16.0					2.8		2.1	-		46500		FP
	A		9.0					2.6		3.2	4.4		26800		FP
(3@5.5) 8-5-90-0-i-2.5-2-10	B	90°	9.4	9.4	6461	A1035[b]	17	7.9	2.6	2.8	4.4	3	57400	36100	FP
	C		9.8					2.5		2.4	-		26300		FP
	A		7.5					2.5		2.5	4.5		30500		FP
(3@5.5) 8-5-90-0-i-2.5-2-8‡	B	90°	8.0	7.8	5730	A615	17	8.0	2.5	2.0	4.5	3	23300	24400	FP
	C		8.0					2.5		2.0			19500		FP
	A		10.0					2.6		2.0	2.4		30670		FP
(3@3) 8-5-90-0-i-2.5-2-10	B	90°	10.3	10.1	4490	A615	12	5.5	2.6	1.8	2.3	3	43700	28500	FP
	C		10.0					2.5		2.0	-		21400		FP
	A		10.3					2.3		1.8	4.0		56500		FP
(3@5) 8-5-90-0-i-2.5-2-10	B	90°	10.1	10.1	4490	A615	16	7.3	2.4	1.9	4.3	3	46300	32200	FP
	C		10.0					2.5		2.0	-		55000		FP
	A		7.8					3.0		2.4	4.3		41000		FP
(3@5.5) 8-8-90-0-i-2.5-2-8	B	90°	8.8	7.9	8700	A1035[b]	17	8.2	2.9	1.4	3.4	3	41000	41000	FP
	C		7.3					2.8		2.9	-		41000		FP
	A		9.5					2.5		8.5	2.1		24600		FP
(3@3) 8-8-90-0-i-2.5-9-9[g]	B	90°	9.5	9.4	7510	A615	12	5.6	2.5	8.5	2.1	3	25000	47200	FP
	C		9.3					2.5		8.8			14700		FP
	A		9.3					2.5		8.8	3.0		29400		FP
(3@4) 8-8-90-0-i-2.5-9-9[g]	B	90°	9.3	9.3	7510	A615	14	6.5	2.5	8.8	3.1	3	27400	26400	FP
	C		9.3					2.5		8.8			22400		FP
	A		12.1					2.5		1.8	2.1		56500		SB
(3@3) 8-12-90-0-i-2.5-2-12‡	B	90°	12.1	12.1	11040	A1035[c]	12	5.4	2.5	1.9	2.0	3	46300	48000	FP
	C		12.2					2.4		1.8	-		55000		FP
	A		12.9					2.5		1.3	2.9		56800		FP/SS
(3@4) 8-12-90-0-i-2.5-2-12‡	B	90°	12.5	12.6	11440	A1035[c]	14	6.4	2.5	1.6	3.0	3	76100	55800	FP
	C		12.5					2.5		1.6	-		57700		FP/SS
	A		12.3					2.4		1.8	4.0		53300		FP
(3@5) 8-12-90-0-i-2.5-2-12‡	B	90°	12.0	12.2	11460	A1035[c]	16	7.4	2.4	2.0	4.0	3	66100	52400	FP
	C		12.3					2.5		1.8	-		60800		FP
	A		9.4					2.5		8.6	2.0		22200		FP
(4@3) 8-8-90-0-i-2.5-9-9[g]	B	90°	9.3	9.4	7510	A615	15	5.5	2.5	8.8	2.0	3	21200	18700	FP
	C		9.3					5.5		8.8	2.0		18300		FP
	D		9.6					2.5		8.4	-		13100		FP
	A		9.4					2.5		8.6	3.1		20400		FP
(4@4) 8-8-90-0-i-2.5-9-9[g]	B	90°	9.1	9.2	7510	A615	18	6.6	2.5	8.9	3.1	3	19000	18000	FP
	C		9.0					6.5		9.0	3.0		18400		FP
	D		9.1					2.5		8.9	-		14300		FP
	A		9.8					2.4		2.3	2.0		37000		FP
(3@3) 8-5-180-0-i-2.5-2-10[h]‡	B	180°	10.0	9.8	5260	A615	12	5.4	2.3	2.0	2.0	3	59800	47200	FP
	C		9.8					2.3		2.3	-		44900		FP
	A		10.0					2.5		2.0	4.3		41500		FP
(3@5) 8-5-180-0-i-02.5-2-10‡	B	180°	10.0	10.0	5260	A615	16	7.8	2.5	2.0	4.3	3	60400	45900	FP
	C		10.0					2.5		2.0	-		37900		FP

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2
[g]Hooks placed in the middle of the column
[h]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio

No. 8 Multiple Hooked Bar Specimens with Two No. 3 Ties

The results for 8 multiple hook specimens with No. 8 hooked bars and 2 No. 3 ties confining the hooked bars are shown in Table 3.25. The specimens contained three 90° or 180° hooked bars placed inside the longitudinal column reinforcement with a center-to-center spacing of $3d_b$, $5d_b$, or $5.5d_b$. The two ties were spaced at approximately $8d_b$ with the first tie placed $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar). The concrete compressive strength ranged from 4,760 to 6,460 psi, and the average embedment lengths ranged from 8.2 to 14.9 in. The nominal side cover was 2.5 in. The average bar forces at failure ranged from 32,400 to 65,300 lb, corresponding to stresses of 41,000 to 82,700 psi. All three hooked bars in specimen (3@5.5) 8-5-90-2#3-i-2.5-2-14 exhibited tail kickout at failure; inspection of the specimen after failure indicated that the tail cover was somewhat less than 2 in. for this specimen.

Table 3.25 No. 8 multiple hooked bar specimens with 2 No. 3 ties

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[e] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	Failure Type[f]
	A		14.6					2.8		1.5	4.4		66800		FP
(3@5.5) 8-5-90-2#3-i-2.5-2-14	B	90°	13.9	14.4	6460	A1035[b]	17	8.0	2.6	2.2	4.5	3	65800	57300	FP
	C		14.8					2.5		1.3	-		62300		FP
	A		9.8					2.5		0.9	4.3		25200		FP
(3@5.5) 8-5-90-2#3-i-2.5-2-8.5	B	90°	8.8	9.1	6460	A1035[b]	17	7.8	2.5	1.9	4.3	3	68700	40900	FP
	C		8.9					2.5		1.8	-		39200		FP
	A		14.7					2.8		1.7	4.2		58700		FP/TK
(3@5.5) 8-5-90-2#3-i-2.5-2-14(1)	B	90°	15.2	14.9	5450	A1035[c]	17	7.9	2.7	1.2	4.3	3	97100	65300	FP/TK
	C		14.8					2.6		1.6	-		70200		FP/TK
	A		7.3					2.3		3.5	4.5		36600		FP
(3@5.5) 8-5-90-2#3-i-2.5-2-8.5(1)	B	90°	8.9	8.2	5450	A1035[c]	17	7.9	2.5	1.8	4.3	3	43600	32400	FP
	C		8.4					2.6		2.3	-		35200		FP
	A		9.9					2.6		2.1	2.0		41000		FP
(3@3) 8-5-90-2#3-i-2.5-2-10	B	90°	10.1	10.0	4760	A615	12	5.6	2.6	1.9	2.0	3	41000	40700	FP
	C		10.0					2.5		2.0	-		37000		FP
	A		10.5					2.5		1.5	4.5		43300		FP
(3@5) 8-5-90-2#3-i-2.5-2-10	B	90°	10.6	10.5	4760	A615	16	8.0	2.6	1.4	3.9	3	54600	44700	FP
	C		10.4					2.8		1.6	-		42800		FP
	A		10.5					2.5		1.5	2.0		59800		FP
(3@3) 8-5-180-2#3-i-2.5-2-10[g‡]	B	180°	10.3	10.3	5400	A615	12	5.5	2.6	1.8	2.0	3	56100	54600	FP
	C		10.0					2.8		2.0	-		47800		FP

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2
[g]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio

Table 3.25 Cont. No. 8 multiple hooked bar specimens with 2 No. 3 ties

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b^e in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	Failure Type[f]
(3@5) 8-5-180-2#3-i-2.5-2-10‡	A	180°	9.6	9.7	5400	A615	16	2.5	2.4	2.4	4.2	3	59300	51500	FP
	B		9.8					7.8		2.3	4.2		49300		FP
	C		9.8					2.3		2.3	-		45800		FP

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2
[g]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio

No. 8 Multiple Hooked Bar Specimens with Five No. 3 Ties

Table 3.26 shows the results for 16 multiple hook specimens with No. 8 hooked bars and five No. 3 ties as transverse reinforcement. The specimens contained three or four 90° or 180° hooked bars placed inside the longitudinal column reinforcement with a center-to-center spacing of $3d_b$, $4d_b$, $5d_b$, or $5.5d_b$. The ties in these specimens were spaced at $3d_b$, which allows the use of the 0.8 reduction factor in accordance with ACI 318-14 Section 25.4.3.2. The concrete compressive strength ranged between 4,810 and 11,460 psi, and the average embedment lengths ranged from 7.7 to 12.3 in. The nominal side cover was 2.5 in. The average bar forces at failure ranged from 29,500 to 66,100 lb, corresponding to stresses of 37,300 to 83,700 psi.

Table 3.26 No. 8 multiple hooked bar specimens with 5 No. 3 ties

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b^e in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	Failure Type[f]
(3@5.5) 8-5-90-5#3-i-2.5-2-8	A	90°	8.0	8.0	6620	A1035[b]	17	2.5	2.5	2.2	4.1	3	30600	37100	FP
	B		8.1					7.6		2.1	4.5		47000		FP
	C		7.8					2.5		2.4	-		34100		FP
(3@5.5) 8-5-90-5#3-i-2.5-2-12	A	90°	12.4	12.2	6620	A1035[b]	17	2.5	2.5	1.8	4.3	3	60300	66100	FP
	B		12.1					7.8		2.1	4.5		110800		FP
	C		12.1					2.5		2.1	-		59300		FP
(3@5.5) 8-5-90-5#3-i-2.5-2-8(1)	A	90°	7.3	7.6	5660	A1035[c]	17	2.9	2.9	2.9	3.8	3	29800	31400	FP
	B		8.4					7.6		1.8	4.1		30200		FP
	C		7.3					2.9		2.9	-		34700		FP

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2
[g]Hooks placed in the middle of the column
[h]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio

Table 3.26 Cont. No. 8 multiple hooked bar specimens with 5 No. 3 ties

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[e] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	Failure Type[f]
(3@5.5) 8-5-90-5#3-i-2.5-2-12(1)	A	90°	11.4	12.0	5660	A1035[c]	17	2.5	2.6	2.8	4.3	3	55500	47900	FP
	B		12.5					7.8		1.7	4.5		74600		FP
	C		12.0					2.6		2.2	-		44400		FP
(3@5.5) 8-5-90-5#3-i-2.5-2-8(2)‡	A	90°	8.0	8.2	5730	A615	17	2.8	2.5	2.0	4.5	3	57000	48000	FP
	B		8.0					8.0		2.0	4.5		43300		FP
	C		8.5					2.3		1.5	-		43000		FP
(3@3) 8-5-90-5#3-i-2.5-2-10	A	90°	10.0	9.9	4810	A615	12	2.8	2.5	2.0	2.1	3	48000	47300	FP
	B		9.8					5.9		2.3	2.1		44000		FP
	C		9.9					2.3		2.1	-		48000		FP
(3@5) 8-5-90-5#3-i-2.5-2-10	A	90°	10.0	9.9	4850	A615	16	2.5	2.6	2.0	4.0	3	58900	61300	FP
	B		10.0					7.5		2.0	4.0		63400		FP
	C		9.8					2.8		2.3	-		69400		FP
(3@3) 8-8-90-5#3-i-2.5-9-9[g]	A	90°	9.5	9.3	7440	A615	12	2.5	2.5	8.5	2.0	3	43300	39800	FP
	B		9.0					5.5		9.0	2.0		49700		FP
	C		9.5					2.5		8.5	-		37200		FP
(3@4) 8-8-90-5#3-i-2.5-9-9[g]	A	90°	8.9	9.1	7440	A615	14	2.5	2.5	9.1	3.0	3	48500	36600	FP
	B		9.1					6.5		8.9	3.0		38600		FP
	C		9.3					2.5		8.8	-		32000		FP
(3@3) 8-12-90-5#3-i-2.5-2-12‡	A	90°	11.9	11.8	11040	A1035[c]	12	2.5	2.5	2.3	2.0	3	70400	62200	FP
	B		11.9					5.5		2.3	2.0		85000		FP
	C		11.6					2.5		2.5	-		62100		FP
(3@4) 8-12-90-5#3-i-2.5-2-12‡	A	90°	12.5	12.3	11440	A1035[c]	14	2.5	2.5	1.8	2.8	3	70700	64900	FP
	B		12.0					6.3		2.3	3.0		100000		FP
	C		12.5					2.5		1.8	-		63700		FP
(3@5) 8-12-90-5#3-i-2.5-2-12‡	A	90°	11.9	12.2	11460	A1035[c]	16	2.5	2.5	2.2	4.0	3	59400	64800	FP
	B		12.4					7.5		1.7	4.0		85500		FP
	C		12.3					2.5		1.8	-		69200		FP
(4@3) 8-8-90-5#3-i-2.5-9-9[g]	A	90°	9.3	9.3	7440	A615	15	2.5	2.5	8.8	2.0	4	32900	31400	FP
	B		9.3					5.5		8.8	2.3		38700		FP
	C		9.3					5.5		8.8	2.0		27300		FP
	D		9.3					2.5		8.8	-		26800		FP
(4@4) 8-8-90-5#3-i-2.5-9-9[g]	A	90°	9.5	9.5	7440	A615	18	2.5	2.5	8.5	3.0	4	33700	29500	FP
	B		9.5					6.5		8.5	3.0		30700		FP
	C		9.3					6.5		8.8	3.0		27900		FP
	D		9.6					2.5		8.4	-		25700		FP
(3@3) 8-5-180-5#3-i-2.5-2-10[h]‡	A	180°	10.1	9.9	5540	A615	12	2.8	2.8	1.9	2.0	3	50300	58900	FP
	B		9.9					5.8		2.1	2.0		67400		FP
	C		9.8					2.8		2.3	-		67000		FP
(3@5) 8-5-180-5#3-i-2.5-2-10‡	A	180°	9.9	9.7	5540	A615	16	2.3	2.5	2.1	3.8	3	55000	58700	FP
	B		9.8					7.0		2.3	4.0		60900		FP
	C		9.5					2.8		2.5	-		59900		FP

[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3
[d]Notation described in Section 2.1 and Appendix A
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[e]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[f]Failure types described in Section 3.2
[g]Hooks placed in the middle of the column
[h]Not included in analysis in Chapters 4 and 5 due to high reinforcement ratio

3.3.6 No. 11 Hooked Bar Specimens with Multiple Hooks

A total of four multiple hook specimens with No. 11 bars were tested. All four specimens were cast with the hook anchored in the middle of the column. The results for these specimens are shown in Table 3.27. The specimens contained three 90° hooked bars placed inside the longitudinal column reinforcement with a center-to-center spacing of $5.35d_b$. The concrete compressive strength was 5,330 psi, and the average embedment length ranged from 13.8 in. to 18.6 in. The nominal side cover was 2.5 in. One specimen was cast without transverse reinforcement, one specimen had 2 No. 3 bars confining the hooks, and two specimens had 6 No. 3 bars confining the hooks. For the specimen without transverse reinforcement, the average embedment length was 13.8 in. The average bar force at failure was 51,500 lb, corresponding to a stress of 33,000 psi. For the specimen with 2 No. 3 ties as confining reinforcement, the two ties were spaced at approximately $8d_b$ with the first tie placed $2d_b$ from the top of the hooked bar ($1.5d_b$ from the center of the hooked bar); the average embedment length of the hooks was 13.9 in. The average bar force at failure was 57,900 lb, corresponding to a stress of 37,100 psi. For the specimens with 6 No. 3 bars as confining reinforcement, the ties were spaced at $3d_b$ which allows the use of the 0.8 reduction factor in accordance with ACI 318-14 Section 25.4.3.2. The average embedment lengths ranged from 13.6 to 18.6 in. The average bar forces at failure ranged from 66,200 to 111,900 lb, corresponding to stresses of 42,400 to 71,700 psi.

Table 3.27 No. 11 multiple hooked bar specimens

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	Failure Type[c]
(3@5.35) 11-5-90-0-i-2.5-13-13[d]	A	90°	13.8	13.8	5330	A615	21.5	2.6	2.6	12.3	6.6	3	45400	51500	FP
	B		14.3					10.0		11.8	6.3		49900		FP
	C		13.5					2.6		12.5	-		59300		FP
(3@5.35) 11-5-90-2#3-i-2.5-13-13[d]	A	90°	14.0	13.9	5330	A615	21.5	2.6	2.6	12.0	6.1	3	50900	57900	FP
	B		14.0					10.0		12.0	6.1		58500		FP
	C		13.8					2.6		12.3	-		64500		FP
(3@5.35) 11-5-90-6#3-i-2.5-13-13[d]	A	90°	13.5	13.6	5280	A615	21.5	2.6	2.6	12.5	6.0	3	59600	66200	FP
	B		13.5					10.0		12.5	5.8		66000		FP
	C		13.8					2.7		12.3	-		72300		FP
(3@5.35) 11-5-90-6#3-i-2.5-18-18[d]	A	90°	18.6	18.6	5280	A1035	21.5	2.5	2.7	17.4	6.1	3	103300	111900	FP
	B		18.6					10.0		17.4	5.6		147800		FP
	C		18.6					2.8		17.4	-		113900		FP

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
[d]Hooks placed in the middle of the column

CHAPTER 4: ANALYSIS AND DISCUSSION

This chapter presents an analysis of the test results described in Chapter 3. The specimens in this study consisted of hooked bars embedded in beam-column joints with and without confining transverse reinforcement in the joint region, encompassing a wide range of concrete compressive strengths and reinforcing steel grades. The main objectives of the analysis were to understand the factors that control anchorage strength and to develop an equation to characterize the anchorage strength of hooked bars in beam-column joints as a function of those factors. The analysis presented in this Chapter serves as the basis for a simpler design equation presented in Chapter 5.

4.1 DESCRIPTION OF ANALYSIS

The analysis presented in this chapter involved multiple steps. First, test results from this and earlier studies were compared with anchorage strengths derived from the provisions for hooked bars in ACI 318-14. This comparison provided a frame of reference for the analysis and was helpful in identifying cases in which extrapolation of the current provisions could lead to overestimation of anchorage strength. Next, the test data were used to develop equations to characterize the relationship between bar force at failure and key parameters evaluated in the experimental program (embedment length, concrete compressive strength, bar diameter, bend angle, side cover, and amount of confining transverse reinforcement).

Iterative statistical analyses were conducted to quantify the effect of the key parameters. Where analysis showed that the effect of a given parameter was not statistically significant, the effect of that variable was omitted in subsequent calculations. The data set used for these analyses included test results from this study as well as data from tests performed by Marques and Jirsa (1975), Pinc et al. (1977), Hamad et al. (1993), Ramirez and Russell (2008), and Lee and Park (2010). Some specimens in the experimental program were omitted from the first evaluation data set and analyzed separately. Excluded from the first analysis were specimens with more than two hooked bars, hooked bars cast outside the column core (outside the longitudinal column reinforcement), hooked bars anchored outside the compression region of the column, and hooked bars anchored in columns with high reinforcement ratios (> 0.04). . The final sections of this chapter describe the separate analyses that were performed to investigate the effects of multiple hooks (more than two) anchored in the beam-column joint, hook placement (inside or outside the column core or outside the compression region of the column), and high column reinforcement ratio on anchorage strength. In addition, test results from Johnson and Jirsa (1981) were used to evaluate anchorage strength of hooked bars with short embedment lengths in walls. A list of calculated failure loads based on the analyses in this Chapter and Chapter 5, along with the test-to-calculated ratios, are given in Appendix C.

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

This concept is illustrated using the following equation:

$$Y = \gamma X + \beta_1 Z_1 + \beta_2 Z_2 + ... + \beta_n Z_n \tag{4.1}$$

In Eq. (4.1), Y represents the dependent variable and X represents the independent variable. As mentioned above, Y may represent the bar force at failure T and X may represent the embedment length ℓ_{eh}. The slope of the regression lines is γ and n represents the total number of dummy variables. The factors β_i (i from 1 to n) cause the intercept of the line to increase or decrease for each population (trend lines for bars of different size would all have different intercepts on the T axis). The terms Z_i are the dummy variables, which can have a value of either 1 or 0, acting as on/off switches for the intercept factors β_i. This method shows trend lines with the same slope but different intercepts for the individual populations (bars of different size), allowing common trends in different populations to be observed.

In addition to the using dummy variables analyses to determine trends within test data, Student's t-test was used to determine the statistical significance of differences between test parameters (such as the effect of hook bend angle on anchorage capacity). Based on the null hypothesis that the parameter being investigated has no effect on the result, Student's t-test determines, for a given significance level α, the probability that a difference between two sample means (x_1 and x_2) is due to chance and does not represent an actual difference between the two corresponding population means (μ_1 and μ_2). For example, a significance level of $\alpha = 0.05$ indicates that there is a 5% probability that there is no actual difference between the populations (or a 95% probability there is an actual difference) when the data show a difference in the sample means. A two-tailed test with unequal variances was used throughout this report (Wonnacott and Wonnacott 1977). This type of test implies that there is a probability $\alpha/2$ that $\mu_1 > \mu_2$ and a probability $\alpha/2$ that $\mu_1 < \mu_2$. Differences are generally considered to be statistically significant for values of α less than or equal to 0.05, although values as high a 0.20 are sometimes used, and not statistically significant for values of α greater than or equal to 0.20.

The method described above is used in the following sections to evaluate the effect of confining transverse reinforcement, side cover, hook bend angle, quantity and configuration of transverse reinforcement, spacing and number of hooked bars, and hook placement on anchorage strength.

4.2 COMPARISON WITH ACI 318-14

In Section 25.4.3.1(a) of ACI 318-14, the development length of a hooked bar ℓ_{dh} is expressed as a function of the yield strength of the reinforcement f_y, the compressive strength of the concrete f_c', and the bar diameter d_b. As shown in Eq. (4.2), the expression for ℓ_{dh} also includes factors for the effects of epoxy coating ψ_e, cover ψ_c, confining reinforcement ψ_r, and lightweight concrete λ. The development length ℓ_{dh} represents the minimum embedment length required to develop the yield strength of the bar. While ℓ_{dh} is an important parameter in the context of design, for the purposes of evaluating the test results it is more useful to derive the bar stress $f_{s,\mathrm{ACI}}$ as a function of the embedment length ℓ_{eh}. To obtain $f_{s,\mathrm{ACI}}$, the development length ℓ_{dh} in Eq. (4.2) is replaced by embedment length ℓ_{eh}, yield strength f_y is replaced by bar stress $f_{s,\mathrm{ACI}}$, the specified compressive strength f_c' is replaced by the measured compressive strength f_{cm}, and the equation is solved for $f_{s,ACI}$, as shown in Eq. (4.3). Because all the specimens in this study were constructed with uncoated bars and normalweight concrete, ψ_e and λ are taken as 1.0.

$$\ell_{dh} = \left(\frac{f_y \psi_e \psi_c \psi_r}{50\lambda\sqrt{f_c'}} \right) d_b \qquad (4.2)$$

$$f_{s,\mathrm{ACI}} = \frac{50\ell_{eh}\sqrt{f_{cm}}}{\psi_c \psi_r d_b} \qquad (4.3)$$

Figures 4.1 through 4.3 show the ratio of measured average bar stress at failure f_{su} to $f_{s,\mathrm{ACI}}$, plotted versus concrete compressive strength, measured on the day of the test. Each data point represents an individual test, and the trend lines are obtained using a dummy variables analysis with the data separated based on the size of the hooked bar. Figure 4.1 shows the results for No. 5, No. 6, No. 7, No. 8, No. 9, and No. 11 bars without confining transverse reinforcement in the joint region. Figures 4.2 and 4.3 , respectively, show the results for hooks with two No. 3 ties as confining transverse reinforcement and hooks with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement.

The values for ℓ_{eh} and f_{cm} used in Eq. (4.3) used to calculate $f_{s,\mathrm{ACI}}$ were those measured and not the nominal values. Each of these figures includes results from specimens with 2.5 in. and 3.5 in. clear side cover along with 90° and 180° bend angles. In the calculations, the 100 psi limit on $\sqrt{f_c'}$ (10,000 psi on f_c') was not applied.

The values of $f_{s,\mathrm{ACI}}$ shown in Figures 4.1 through 4.3 include the factor, ψ_c = 0.7 for No. 11 bars and smaller with at least 2.5 in. of clear cover to the side of the hook and 2 in. of clear cover to the tail of the hook. For hooked bars confined by stirrups or ties parallel to the bar being developed, and spaced no further than three bar diameters apart, ψ_r = 0.8. Because the nominal dimensions of the specimens provided at least a 2.5-in. side cover and a 2-in. tail cover, the 0.7 factor was applied to all calculations of $f_{s,\mathrm{ACI}}$, although some specimens, due to fabrication tolerances, had actual side and tail covers slightly less than 2.5 in. and 2 in., respectively.

Figure 4.1 includes results for 99 beam-column joint specimens without confining transverse reinforcement in the joint region. A summary of these specimens is presented in Table 4.1. Appendix D contains a complete list of all specimens included in this and all subsequent figures. Sixty-eight of the specimens are from the current investigation. As shown in the figure, the ratio of $f_{su}/f_{s,\text{ACI}}$ decreases as bar size and concrete compressive strength increase. These comparisons show that the current provisions for the development length of hooked bars result in estimates of anchorage strength that overestimate the influence of both bar size and compressive strength.

Table 4.1 Summary of Specimens Included in Figure 4.1

Number of Specimens	Size of Hooked Bars	Source
17	No. 5	Current investigation
3	No. 6	Ramirez & Russell (2008)
6	No. 7	Marques & Jirsa (1975)
2	No. 7	Lee & Park (2010)
2	No. 7	Hamad et al. (1993)
34	No. 8	Current investigation
2	No. 9	Pinc et al. (1977)
17	No. 11	Current investigation
4	No. 11	Ramirez & Russell (2008)
4	No. 11	Marques & Jirsa (1975)
4	No. 11	Pinc. Et al. (1977)
4	No. 11	Hamad et al. (1993)

Although test data for high strength concrete are not available for all bar sizes, the trend lines from the dummy variables analysis indicate that the ratio $f_{su}/f_{s,\text{ACI}}$ decreases with increasing compressive strength. The trend lines also show that $f_{su}/f_{s,\text{ACI}}$ decreases with bar size. The trend line for the ratio of $f_{su}/f_{s,\text{ACI}}$ falls below 1.0 for No. 6 hooked bars at approximately 13,500 psi, for No. 7 and No. 8 hooked bars at approximately 11,500 psi, for No. 9 hooked bars at approximately 8,000 psi, and for No. 11 hooked bars at approximately 6,000 psi. In the last two cases, the concrete compressive strength at which the $f_{su}/f_{s,\text{ACI}}$ ratio drops below 1.0 occurs below the 10,000 psi limit that corresponds to the 100 psi limit on $\sqrt{f_c'}$ in ACI 318-14. These results indicate that current code provisions for development length may result in unsafe designs for No. 9 or larger bars with concrete compressive strengths as low as 6,000 psi.

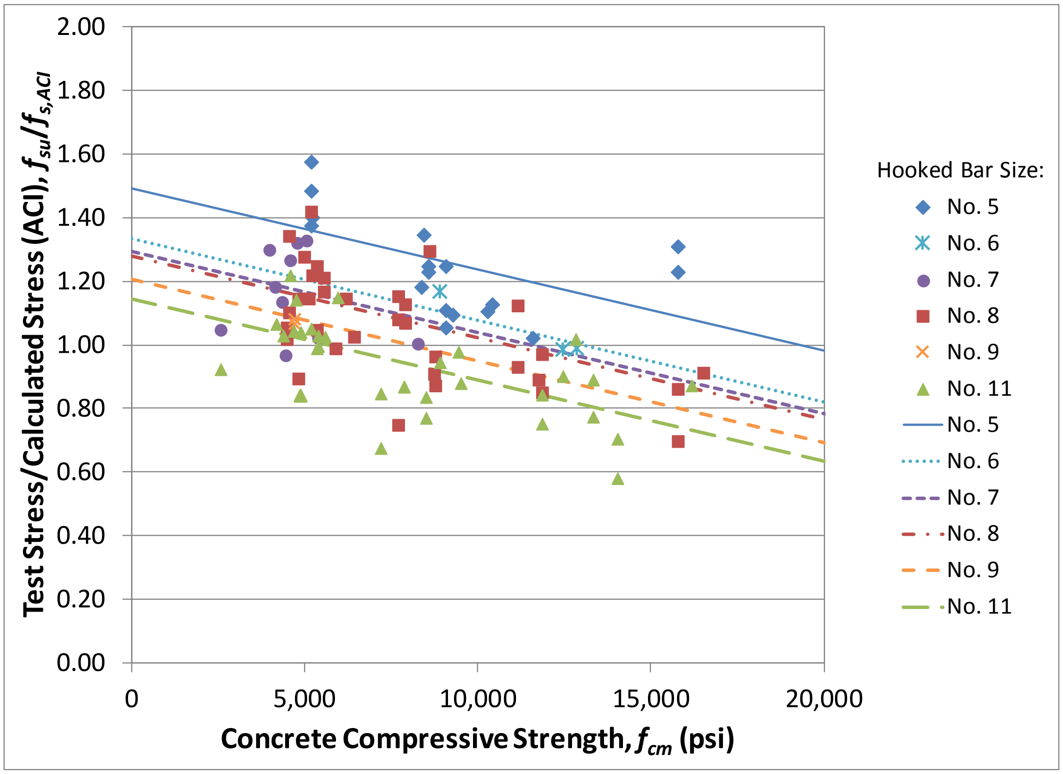


Figure 4.1 Ratio of test-to-calculated stress $f_{su}/f_{s,\mathrm{ACI}}$ versus f_{cm} for hooked bars without confining transverse reinforcement

Figure 4.2 shows the experimental results from this study for 50 beam-column joints with two hooked bars and two No. 3 column ties in the joint region. A summary of these specimens is presented in Table 4.2. As for the hooked bars without confining transverse reinforcement in the joint region, the ratio $f_{su}/f_{s,\mathrm{ACI}}$ decreases as bar size and concrete compressive strength increase. The values of $f_{su}/f_{s,\mathrm{ACI}}$ shown in Figure 4.2 are higher than those shown in Figure 4.1, an indication that the two ties in the joint region contribute to increased anchorage strength, an effect that is not accounted for in ACI 318-14 [Eq. (4.2) and (4.3)].

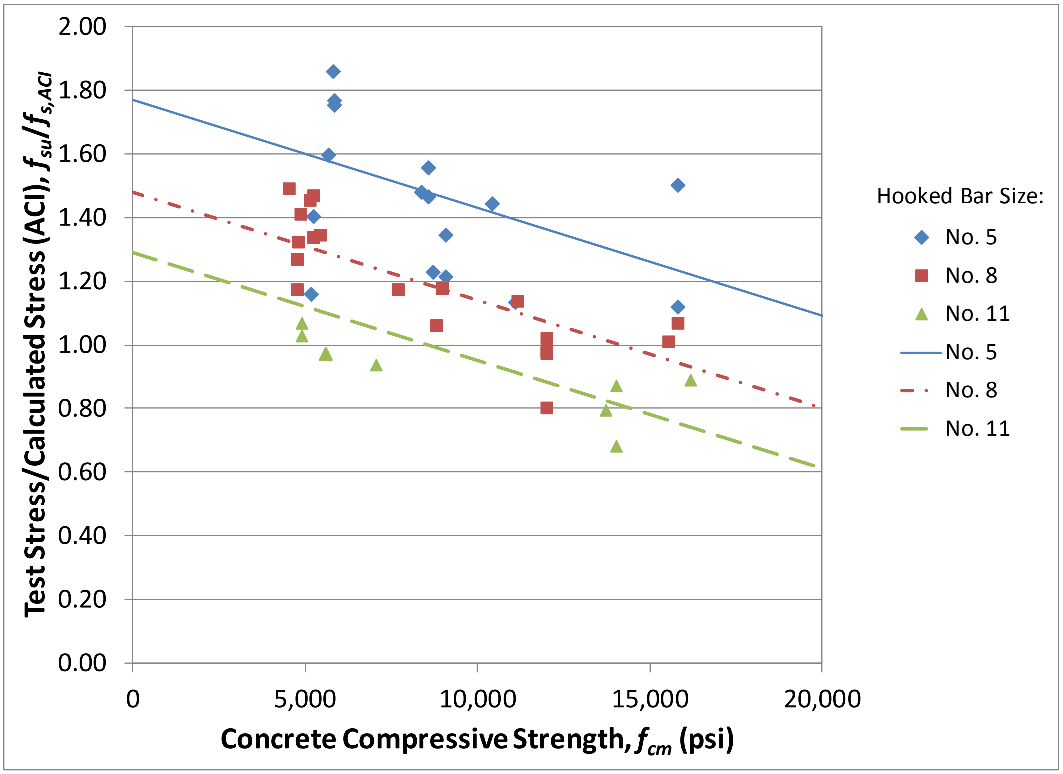


Figure 4.2 Ratio of test-to-calculated stress $f_{su}/f_{s,\mathrm{ACI}}$ versus f_{cm} for hooked bars confined by two No. 3 ties

Table 4.2 Summary of Specimens included in Figure 4.2

Number of Specimens	Size of Hooked Bars	Source
16	No. 5	Current investigation
26	No. 8	
8	No. 11	

As shown in Figure 4.2, the trend line for No. 8 bars drops below 1.0 for compressive strengths above approximately 14,500 psi, and for No. 11 bars for compressive strengths above approximately 9,000 psi. As for the hooked bars without confining transverse reinforcement in the joint region, these results indicate that the provisions for hooked bar development length in ACI 318-14 do not accurately reflect the effects of concrete compressive strength and bar diameter on anchorage strength, and can lead to unsafe estimates of development length for No. 11 hooked bars with concrete compressive strengths above 9,000 psi.

Figure 4.3 shows results for 59 beam column joints (53 from the current investigation) with No. 3 ties spaced less than or equal to $3d_b$ within the joint region. A summary of these specimens is presented in Table 4.3. The $3d_b$ spacing of the confining transverse reinforcement permits the use of the $\psi_r = 0.8$ factor for development length in Section 25.4.3.2 of ACI 318-14.

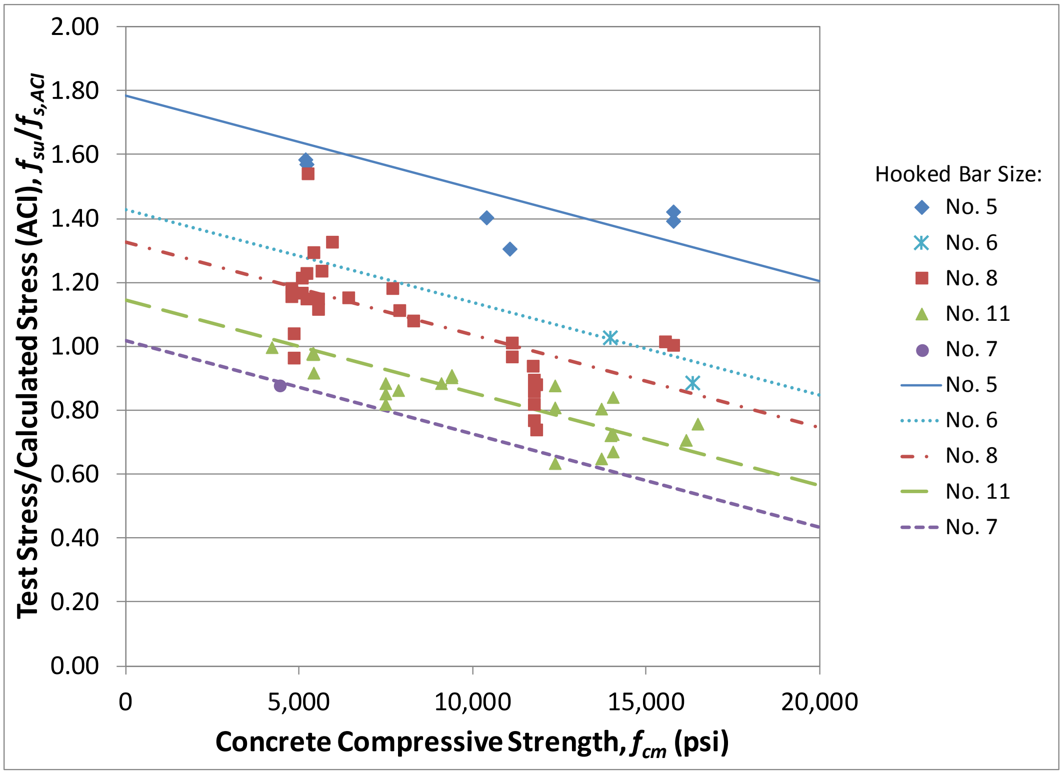


Figure 4.3 Ratio of test-to-calculated stress $f_{su}/f_{s,\mathrm{ACI}}$ versus f_{cm} for hooked bars with No. 3 ties spaced at $3d_b$

Table 4.3 Summary of Specimens included in Figure 4.3

Number of Specimens	Size of Hooked Bars	Source
6	No. 5	Current investigation
2	No. 6	Ramirez & Russell (2008)
1	No. 7	Lee & Park (2010)
29	No. 8	Current investigation
18	No. 11	Current investigation
2	No. 11	Ramirez & Russell (2008)
1	No. 11	Hamad et al. (1993)

As shown in Figure 4.3, the parallel trend lines from the dummy variables analysis have a negative slope and the intercepts of the trend lines decrease as bar size increases. An exception to this trend is the line corresponding to a single data point for No. 7 bars from the study by Lee and Park (2010), which is below the lines corresponding to No. 8 and No. 11 bars.

For the No. 6 hooked bars, the trend line for $f_{su}/f_{s,\mathrm{ACI}}$ reaches a value of 1.0 at a compressive strength of approximately 14,500 psi. For No. 8 and 11 hooked bars, the trend lines reach a value of 1.0 at respective concrete compressive strengths of approximately 11,000 and 5,000 psi. As previously stated, the development length provisions for hooked bars in ACI 318-14 limit the value of concrete compressive strength used in the calculations to a maximum of 10,000 psi. With one exception, Ramirez and Russell (2008) recommended allowing the use of higher concrete compressive strengths in the calculations in conjunction with the development length reduction factors that now appear in ACI 318-14 Section 25.4.3.2. Test results shown in Figure 4.3 indicate that this practice would produce unsafe designs for No. 8 hooked bars with concrete compressive strengths greater than 11,000 psi. For No. 11 bars, the results are of greater concern. Data trends show unsafe anchorage strengths for concrete compressive strengths as low as 5,000 psi when the 0.7 and 0.8 development length reduction factors are included in the calculations, as currently permitted by the provisions in ACI 318-14 Section 25.4.3.2. Ramirez and Russell (2008) also found these reduction factors to produce unconservative designs and recommended that the reduction factor permitted for hooked bars with at least 2.5 in. side cover be increased from 0.7 to 0.8.

There are similarities between the trends observed for specimens with No. 3 ties spaced at $3d_b$ within the joint region and specimens without confining transverse reinforcement. In both cases, the trend lines for $f_{su}/f_{s,\mathrm{ACI}}$ decrease with increasing bar size and concrete compressive strength, and in both instances, current design provisions can lead to unconservative designs for No. 11 bars with concrete compressive strengths as low as 5,000 psi. The observations presented in this section indicate that the provisions in ACI 318-14 for the design of hooked bars should be adjusted to more accurately represent the effects of concrete compressive strength and bar size.

4.3 ANALYSIS OF FACTORS CONTROLLING HOOK STRENGTH

In the analysis presented in Section 4.2, significant differences were found between the experimental data and anchorage strengths calculated with the design provisions ACI 318-14. Differing trends were identified for the effects of concrete compressive strength, bar size, and amount of confining transverse reinforcement on the anchorage strength of standard hooks in simulated beam-column joints. This section describes the results of analyses to develop an anchorage strength equation that accurately captures those trends for 90° and 180° standard hooks placed inside a column core.

A series of iterative analyses was conducted to determine the effects of key parameters on hooked bar anchorage strength using experimental results from this and other studies. The effects of hook bend angle, side cover, and absence of confining transverse reinforcement are discussed in Sections 4.3.1 through 4.3.3. The effect of tie orientation (parallel or perpendicular to the straight portion of the hooked bar) is discussed in Section 4.3.4. Two cases are addressed throughout the analyses: hooked bars without confining transverse reinforcement in the joint region and hooked bars with differing amounts of confining transverse reinforcement within the joint region. As described in Chapter 3, most specimens fell in one of three categories: specimens without confining transverse reinforcement in the joint region, specimens with two No. 3 ties as transverse reinforcement in the joint region, and specimens with No. 3 ties spaced at $3d_b$ within in the joint region. Other amounts of confining transverse reinforcement in the joint region that were evaluated in this study included one No. 3 tie, one No. 4 tie, two No. 4 ties, four No. 3 ties, five No. 3 ties, and reinforcement conforming to ACI 318-14 Section 18.8.3.

A similar approach was used to develop the characterizing equations for all cases. The first step consisted of using the subset of specimens without confining transverse reinforcement to perform a dummy variables analysis (as described earlier) to establish a relationship between the average bar force at failure T and the embedment length ℓ_{eh} for different bar sizes (No. 5, 6, 7, 8, 9, and 11). In all analyses, the average bar force at failure was defined as the peak load on the specimen divided by the number of hooked bars. This preliminary analysis provided a general understanding of the effect of embedment length, bar size, and concrete compressive strength on T.

In the second step in the analysis, the effect of concrete compressive strength was evaluated by normalizing the average bar force with respect to the measured concrete compressive strength to a power p_1, $T/f_{cm}^{p_1}$, and finding a relationship between that normalized value and the embedment length ℓ_{eh} multiplied by the bar diameter d_b to a power p_2. The powers p_1 and p_2 were modified to minimize the spread in the parallel lines obtained in the dummy variables analysis. The average intercept on the $T/f_{cm}^{p_1}$ axis was then used to obtain an expression for T as a function of embedment length ℓ_{eh}, bar diameter d_b, and concrete compressive strength f_{cm}. The resulting equation was then evaluated by plotting the ratio of the test-to-calculated average bar force at failure versus concrete compressive strength f_{cm} and then bar diameter d_b. For each of the two plots, a dummy variables analysis was performed with the data separated according to bar size. A positive slope of the trend lines from these dummy variables analyses would indicate that the effects of concrete compressive strength or hooked bar diameter were underestimated. Conversely, a negative slope of the trend lines from the dummy variables analysis would indicate that the effect of concrete compressive strength or bar diameter was overestimated. The powers p_1 or p_2 for concrete compressive strength or bar diameter, respectively, were then adjusted and the process repeated until the slope of the trend lines for both variables was approximately equal to zero. The optimized values of p_1 and p_2 were used in the final equation.

For purposes of comparison, the values of p_1 and p_2 in the ACI Code can be obtained by multiplying both sides of Eq. (4.3) by the nominal area of the bar $A_b = \pi d_b^2/4$ and substituting f_c' for f_{cm} to obtain the anchorage force in the hook.

$$T_h = f_{s,\text{ACI}} A_b = f_{s,\text{ACI}} \frac{\pi d_b^2}{4} = \frac{50\ell_{eh}\sqrt{f_c'}}{\psi_c \psi_r d_b}\frac{\pi d_b^2}{4} = \frac{39.27\ell_{eh}\sqrt{f_c'}d_b}{\psi_c \psi_r} \tag{4.4}$$

As demonstrated by Figures 4.1 through 4.3, both the power on f_c', $p_1 = 0.5$, and the power on d_b, $p_2 = 1.0$, are too high to properly characterize the role of either parameter on the anchorage strength of hooked bars.

For specimens with confining transverse reinforcement within the joint region, the bar force calculated with the equation characterizing the anchorage strength of specimens without confining transverse reinforcement T_c was subtracted from the average bar force at failure T. This difference was assumed to represent the contribution of the transverse reinforcement T_s to the anchorage capacity of the hooked bars. This difference was then plotted against a term representative of the amount of transverse reinforcement NA_{tr}/n, where N equals the number of legs of confining reinforcement parallel or perpendicular to the straight portion of the hooked bar, each leg with area A_{tr}, confining n hooked bars. N is taken as the number of legs parallel to the straight portion of the hooked bar along the length of the tail of a 90° hook or the number of legs perpendicular to the bar over the length being developed. As will be demonstrated, the results indicate that transverse reinforcement within a length equal to the tail of a 90° hook also serves as confining reinforcement for 180° hooks, even though the transverse reinforcement is outside the physical dimension of the hook. Based on the cracking patterns and failure modes described in Sections 3.1 and 3.2, the confining reinforcement appears to hold regions of the failing concrete together, not simply to prevent cracks in the plane of the hook from widening.

A dummy variables analysis was performed on the values of T_s to find the general effect of transverse reinforcement, bar diameter, and concrete compressive strength on anchorage force. To do this, the values of T_s were plotted versus the product the transverse reinforcement parameter NA_{tr}/n and bar diameter raised to a power p_3. Bar diameter was included because it was observed that larger hooked bars exhibited higher values of T_s for a given value of NA_{tr}/n. The average of the intercepts of the various trend lines with the $T - T_c$ axis was then used as the intercept of a single expression for T_s as a function of NA_{tr}/n and bar diameter d_b. The resulting equation was then checked by plotting the ratio of the measured values $T_{\text{test}} = T$ to the calculated values T_{calc}, where $T_{\text{calc}} = T_h = T_c + T_s$, versus concrete compressive strength f_{cm} and bar diameter d_b. A dummy variables analysis was again conducted with the data separated based on bar size. The power p_3 for bar diameter d_b was then adjusted and the process repeated until the slope of the dummy variables lines was approximately equal to zero, and the mean ratio of test-to-calculated strength $T_{\text{test}}/T_{\text{calc}}$ was approximately equal to 1.0. If the slope of the dummy variables lines for the $T_{\text{test}}/T_{\text{calc}}$-$f_{cm}$ plot was not zero, the power p_1 of f_{cm} in the equation for T_c was modified to obtain dummy variables lines with zero slope and a mean ratio of the test-to-calculated strength of 1.0.

4.3.1 Effect of Bend Angle

The analyses described in this and the following sections were, by necessity, iterative. A key step in any statistical analysis is the selection of the data to be included. For example, to determine the powers to be used for compressive strength and bar diameter first required the selection of the tests to be included in that determination. That selection, in turn, depended on whether the effects of hook bend angle and side clear concrete cover needed to be considered in the development of equations that characterized the anchorage strength of hooked bars. The initial steps, performed by Searle et al. (2014) on a smaller database than now available involved the determination of the appropriate power p_1 of f_{cm} for hooked bars with a 90° bend angle. Using that value of p_1, the anchorage strengths of hooked bars with bend angles of 90° and 180° and different values of side clear cover were compared, as will be described in this and the following section. Finding the differences in strengths not to be statistically significant, the test results for the 90° and 180° hooked bars with different values of side clear cover were combined and reanalyzed, producing a somewhat different value of p_1, which was again used to determine if the differences in anchorage strength of 90° and 180° hooked bars or hooked bars with different values of clear side cover were statistically significant.

In lieu of including the details of these iterative steps, only the final comparisons are included in this report. By necessity, some steps in the process must be presented before others. The insensitivity of hooked bar anchorage strength to bend angle and concrete clear cover are presented, respectively, in this section and in Section 4.3.2, using the values of p_1 established during the iterative statistical analyses of the test results in Sections 4.3.3 and 4.3.5.

To limit the effects of differences in concrete compressive strength and simplify the comparisons, the average bar forces at failure were normalized with respect to a reference concrete compressive strength of 5,000 psi by multiplying average bar forces at failure T by $\left(5000/f_{cm}\right)^{p_1}$ to give normalized average failure loads T_N. Based on the analyses in Sections 4.3.3 and 4.3.5, the power p_1 was taken as 0.29 for specimens without confining transverse reinforcement in the joint region and 0.26 for specimens with confining transverse reinforcement in the joint region.

Figure 4.4 shows the normalized average failure loads T_N as a function of embedment length. The specimens used for this comparison are summarized in Table 4.4. Figure 4.4 includes test results for 58 beam-column specimens (39 from the current study) containing No. 5, No. 7, No. 8, and No. 11 hooked bars without confining transverse reinforcement in the joint region, with bend angles of 90° and 180°, placed inside the column core. The solid lines correspond to trend lines for 90° hooked bars while the broken lines correspond to 180° hooked bars. Both trend lines and data points are color coded according to bar size. For each bar size, the range of embedment lengths is similar for 90° and 180° hooked bars. The embedment lengths ℓ_{eh} ranged from 6.31 to 21.1 in., and average bar forces at failure T ranged from 22,400 to 132,100 lb. The normalized average bar forces at failure ranged from 18,860 to 112,600 lb. The measured concrete compressive strengths ranged from 2,570 to 16,510 psi.

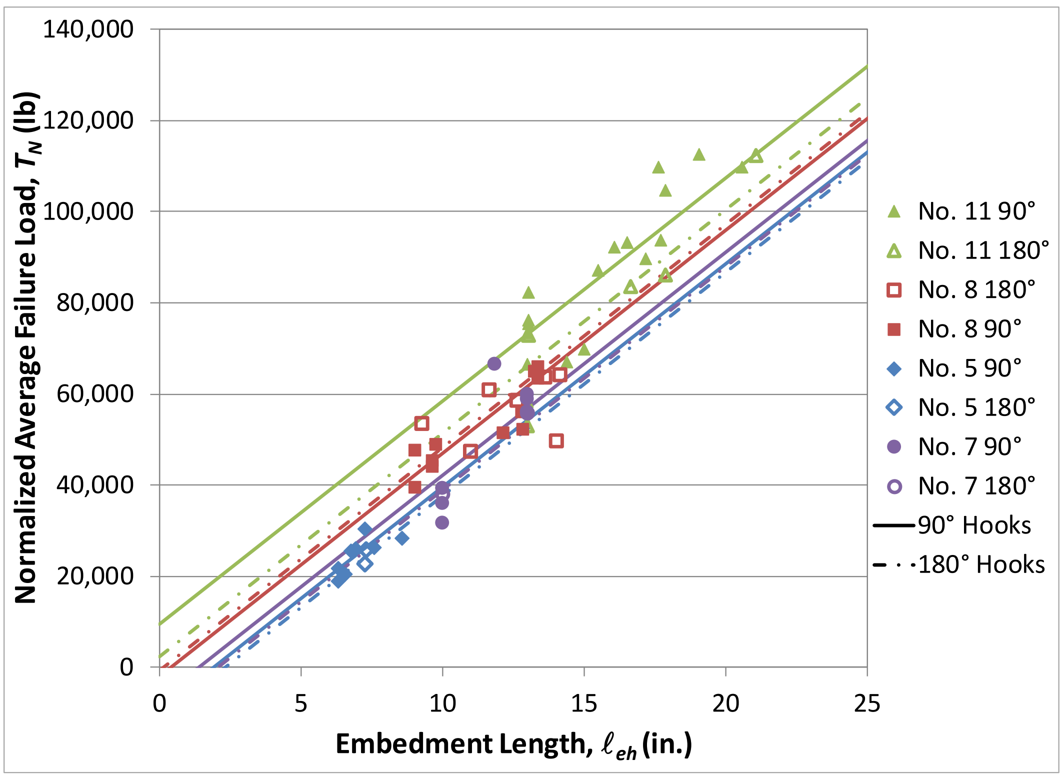


Figure 4.4 Normalized bar force at failure for hooked bars cast inside the column core and without confining transverse reinforcement

Table 4.4 Summary of Specimens included in Figure 4.4

Number of Specimens	Size of Hooked Bars	Hook Bend Angle	Source
8	No. 5	90˚	Current investigation
2	No. 5	180˚	
4	No. 7	90˚	Marques & Jirsa (1975)
2	No. 7	180˚	
1	No. 7	90˚	Lee & Park (2010)
2	No. 7	90˚	Hamad et al. (1993)
11	No. 8	90˚	Current investigation
7	No. 8	180˚	
8	No. 11	90˚	Current investigation
3	No. 11	180˚	
2	No. 11	90˚	Marques & Jirsa (1975)
1	No. 11	180˚	
3	No. 11	90˚	Pinc et al. (1977)
3	No. 11	90˚	Hamad et al. (1993)
1	No. 11	180˚	

As shown in Figure 4.4, an increase in embedment length is associated with an increase in the normalized average bar force at failure, as expected. The results in Figure 4.4 indicate that there is no clear correlation between anchorage strength and bend angle. For most bar sizes (No. 5, No. 7, and No. 11), the trend line corresponding to a 90° bend angle has a slightly higher intercept than the trend line corresponding to a 180° bend angle. The effect is opposite for No. 8 hooked bars, for which the trend line corresponding to a 90° bend angle has a slightly lower intercept than the trend line corresponding to a 180° bend angle. The results are compared using Student's t-test to compare intercepts with the T_N axis obtained by extending lines through each data point parallel to the dummy variables trend lines. Student's t-test indicates that the differences in anchorage strength between 90° and 180° hooked No. 5, No. 7, No. 8, and No. 11 bars are not statistically significant (α = 0.45, 0.48, 0.85, and 0.11, respectively) using α = 0.05 as the threshold for statistical significant.

Figure 4.5 compares the normalized anchorage strengths for 90° and 180° No. 5 and No. 8 hooked bars as a function of embedment length. The data in Figure 4.5, summarized in Table 4.5, includes 16 beam-column joint specimens tested in this study containing, 90° and 180° hooked bars with one No. 3 tie within the joint region as transverse reinforcement. The single tie was placed in the direction parallel to the straight portion of the hooked bars for both 90° and 180° hooks. A single tie with this orientation is insufficient to satisfy ACI Code requirements for the use of a development length reduction factor for hooked bars, and ties with this orientation, regardless of number or spacing, are not considered by the Code to increase the anchorage strength of 180° hooks. Contrary to this Code provisions, the ties placed parallel to the straight portion of the hooked bars increased anchorage strength with a similar effect for both 90° and 180° hooks. As with the specimens without confining transverse reinforcement, the range of embedment lengths was similar for 90° and 180° hooked bars for each bar size. The embedment lengths ℓ_{eh} ranged between 5.1 and 15.6 in., the average bar forces at failure T ranged between 19,900 and 76,000 lb, the normalized average bar forces at failure T_N ranged between 19,200 and 76,600 lb, and the measured concrete compressive strengths ranged from 4,810 to 9,300 psi. Similar to the trend observed in Figure 4.4, Figure 4.5 shows that there is an increase in average bar force at failure as embedment length increases, with little or no difference in anchorage strength as a function of bend angle. The dummy variables lines for the 90° and 180° No. 5 hooked bars nearly coincide. For the No. 8 bars, the dummy variables lines for the 90° and 180° hooked bars are very close to each other, with the hooks with a 180° bend angle exhibiting a slightly lower anchorage strength than the hooks with a 90° bend angle. Student's t-test confirms that the differences between the anchorage strengths of 90° and 180° hooks are not statistically significant for No. 5 and No. 8 bars (α = 0.92 and 0.53, respectively).

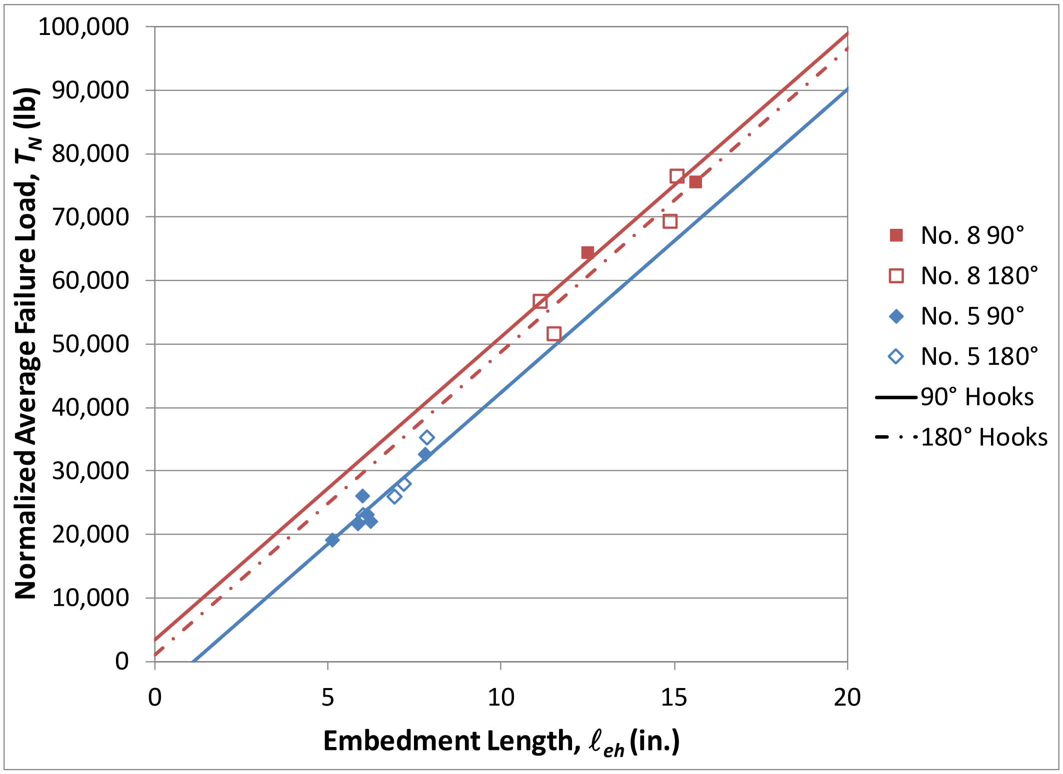


Figure 4.5 Normalized bar force at failure for hooked bars cast inside the column core and confined by one No. 3 tie

Table 4.5 Summary of Specimens included in Figure 4.5

Number of Specimens	Size of Hooked Bars	Hook Bend Angle	Source
6	No. 5	90°	Current Investigation
4	No. 5	180°	
2	No. 8	90°	
4	No. 8	180°	

Figure 4.6 compares the anchorage strengths of 90° and 180° No. 5 and No. 8 hooked bars with two No. 3 ties in the joint region as a function of embedment length. A summary of the specimens used in this analysis are presented in Table 4.6. The embedment lengths ℓ_{eh} ranged from 5.6 to 13.75 in., the average bar forces at failure T ranged from 21,100 to 83,300 lb, the normalized average bar forces sat failure T_N ranged from 19,800 to 78,200 lb, and the concrete compressive strengths ranged from 4,300 to 15,800 psi. The figure shows that the dummy variables trend lines for anchorage strength nearly coincide for the 90° and 180° No. 5 hooked bars, while the 180° No. 8 hooked bars had a slightly lower strength than the 90° No. 8 hooked bars. The results of a Student's t-test show that the differences in anchorage strength between 90°

and 180° No. 5 and No. 8 hooked bars are not statistically significant, with α = 0.82 and 0.62, respectively.

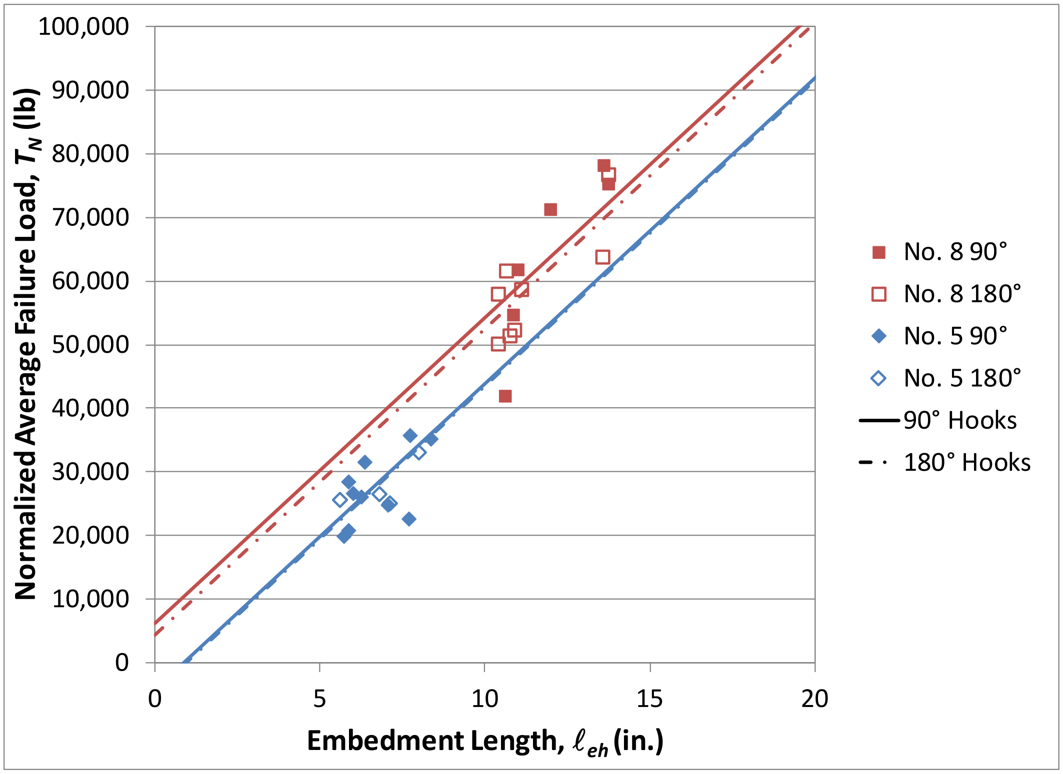


Figure 4.6 Normalized bar force at failure for hooked bars cast inside the column core with two No. 3 ties

Table 4.6 Summary of specimens included in Figure 4.6

Number of Specimens	Size of Hooked Bars	Hook Bend Angle	Source
10	No. 5	90°	Current Investigation
4	No. 5	180°	
6	No. 8	90°	
8	No. 8	180°	

Figure 4.7 compares the anchorage strengths of 90° and 180° No. 8 and No. 11 hooked bars with No. 3 ties spaced at 3db, which satisfies the requirements for the use of the 0.8 development length reduction factor in ACI 318-14 Section 25.4.3.2. The 20 specimens were tested in the current study. The specimens used for this comparison are summarized in Table 4.7. The embedment lengths ℓ_{eh} ranged from 9.4 to 20.4 in., the average bar forces at failure T ranged

from 60,200 to 161,600 lb, the normalized average bar forces at failure T_N ranged from 48,200 to 133,400 lb, and the concrete compressive strengths ranged from 5,420 to 15,800 psi. For both No. 11 and No. 8 hooked bars, the anchorage strength of 180° hooks was slightly lower than the strength of 90° hooks. Cracking and mode of failure were similar for hooked bars with the two bend angles. The results of Student's t-test, however, show that the differences in anchorage strength between 90° and 180° for No. 8 and No. 11 hooked bars are not statistically significant (α = 0.38 and 0.49, respectively).

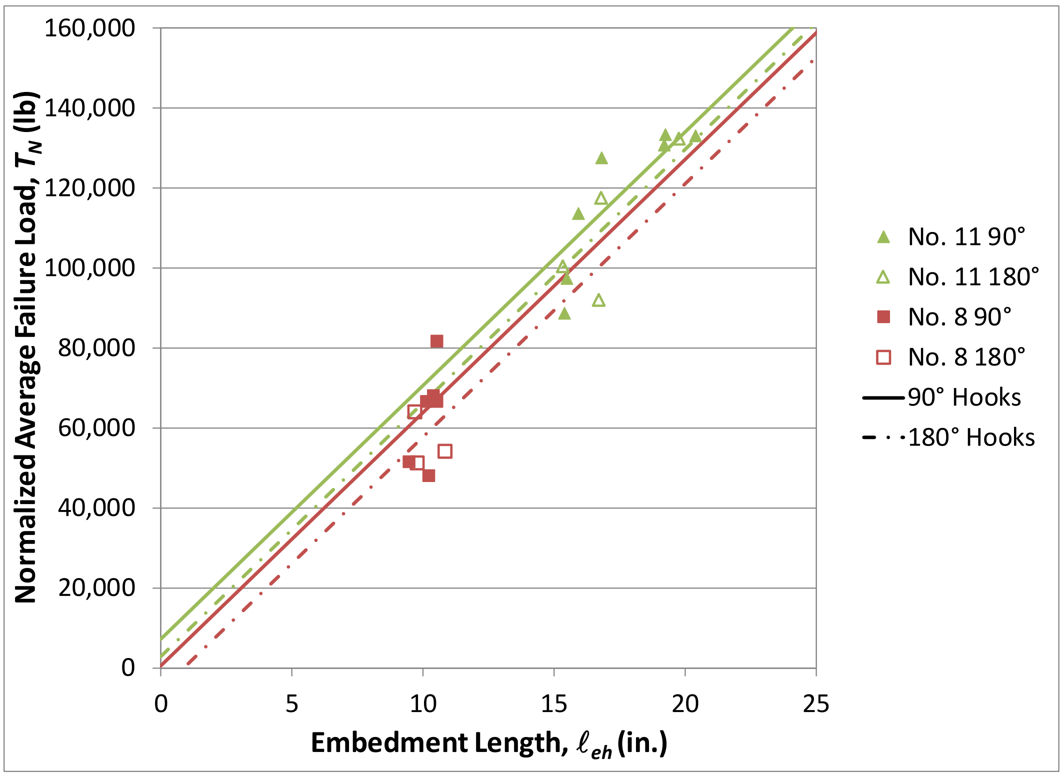


Figure 4.7 Normalized bar force at failure for hooked bars cast inside the column core with confining transverse reinforcement conforming to Section 25.4.3.2 of ACI 318-14

Table 4.7 Summary of specimens in Figure 4.7

Number of Specimens	Size of Hooked Bars	Hook Bend Angle	Source
6	No. 8	90°	Current Investigation
3	No. 8	180°	
7	No. 11	90°	
4	No. 11	180°	

Overall, although there were minor differences between the anchorage strengths of 90° and 180° hooks, none of the differences are statistically significant. Because 90° and 180° hooks provide similar anchorage strengths, results from tests of hooked bars with 90° and 180° were considered together in subsequent analyses.

4.3.2 Effect of Side Cover

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

Figure 4.8 shows the test results from this study for 39 No. 5 hooked bar beam-column joint specimens. All specimens in this analysis had hooked bars cast inside the column longitudinal bars. The nominal side covers were 2.5 (solid lines) and 3.5 in. (broken lines). Three different amounts of confining transverse reinforcement were investigated: no confining transverse reinforcement; two No. 3 ties within the joint region; and No. 3 ties spaced at $3d_b$ (satisfying the requirements for the 0.8 development length reduction factor in ACI 318-14 Section 25.4.3.2). A summary of these specimens is presented in

Table 4.8. The embedment lengths ℓ_{eh} ranged from 3.75 in. to 10.5 in. The average bar forces at failure T ranged from 18,700 to 42,600 lb, the normalized average bar forces at failure T_N ranged from 13,900 to 41,500 lb, and the concrete compressive strengths ranged from 5,190 to 15,800 psi. Figure 4.8 shows that, as expected, anchorage strength increased with increasing embedment length and amount of confining transverse reinforcement. Regardless of the amount of confining transverse reinforcement, the results indicate that there was a *decrease* in strength as the side cover increased from 2.5 in. to 3.5 in. Student's t-test, however, shows that this effect of side cover on anchorage strength is not statistically significant either for specimens without confining transverse reinforcement or for specimens with No. 3 ties spaced at $3d_b$ (α = 0.85 and 0.34, respectively). The value of α for specimens with two No. 3 ties is 0.08, just above the threshold value of 0.05 that indicates statistical significance.

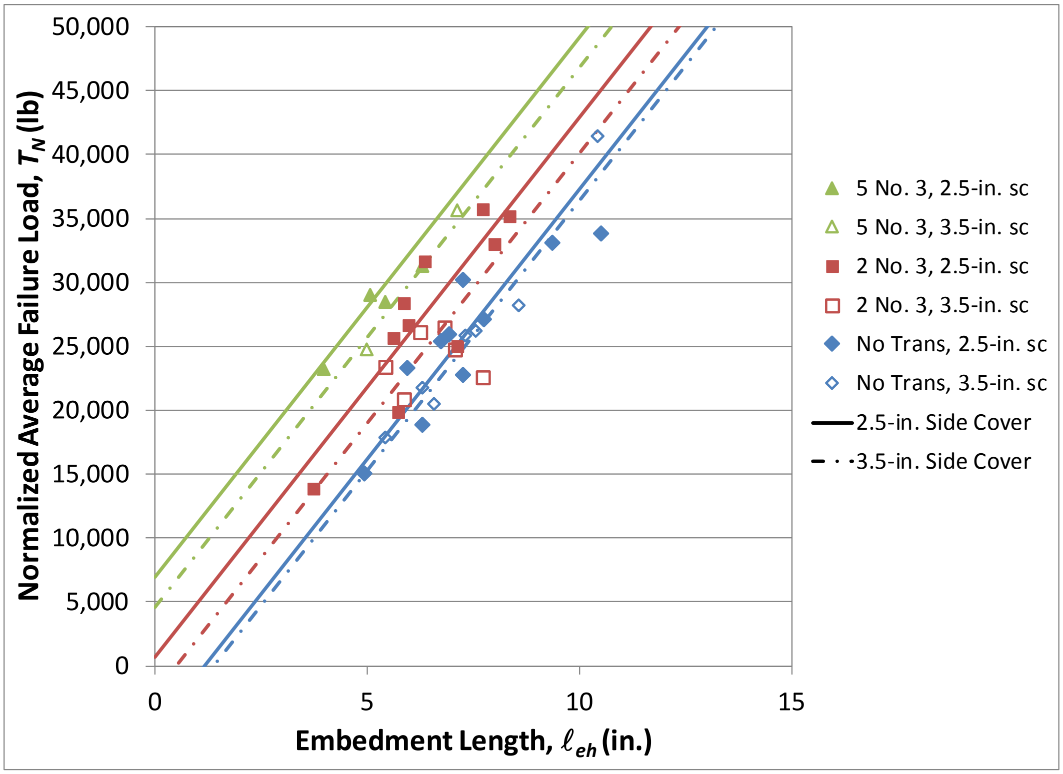


Figure 4.8 Normalized bar force at failure for No. 5 hooked bars cast inside the column core with different amounts of confining transverse reinforcement and side cover

Table 4.8 Summary of Specimens included in Figure 4.8

Number of Specimens	Size of Hooked Bars	Side Cover (in.)	Transverse Reinforcement	Source
10	No. 5	2.5	None	Current investigation
7	No. 5	3.5	None	
10	No. 5	2.5	Two No. 3	
6	No. 5	3.5	Two No. 3	
4	No. 5	2.5	No. 3 @ 3d_b	
2	No. 5	3.5	No. 3 @ 3d_b	

The results for 83 No. 8 hooked bar beam-column joint specimens from this study are shown in Figure 4.9, with the breakdown of these specimens presented in Table 4.9. The average embedment lengths ℓ_{eh} ranged from 6.1 to 18.7 in., the concrete compressive strengths ranged from 4,300 to 16,510 psi, the average bar forces at failure T ranged from 36,800 to 95,400 lb, and the normalized average bar forces at failure T_N ranged from 27,900 to 93,400 lb. As expected, anchorage strength increased with increasing embedment length and amount of transverse reinforcement. For No. 8 bars, increasing side cover from 2.5 in. to 3.5 in. led to increases in anchorage strength specimens without confining transverse reinforcement, and for specimens with No. 3 ties spaced at $3d_b$, increasing the side cover did not produce a change in the anchorage strength. For specimens with two No. 3 ties in the joint region, the specimens with 3.5-in. side cover had anchorage strengths that were slightly lower than those of specimens with 2.5-in. side cover. Student's t-test shows that the differences in anchorage strength associated with changes in cover for specimens with two No. 3 ties and No. 3 ties spaced at $3d_b$ are not statistically significant, with α equal to 0.68 and 0.80, respectively. The value of α for specimens without confining transverse reinforcement is 0.13.

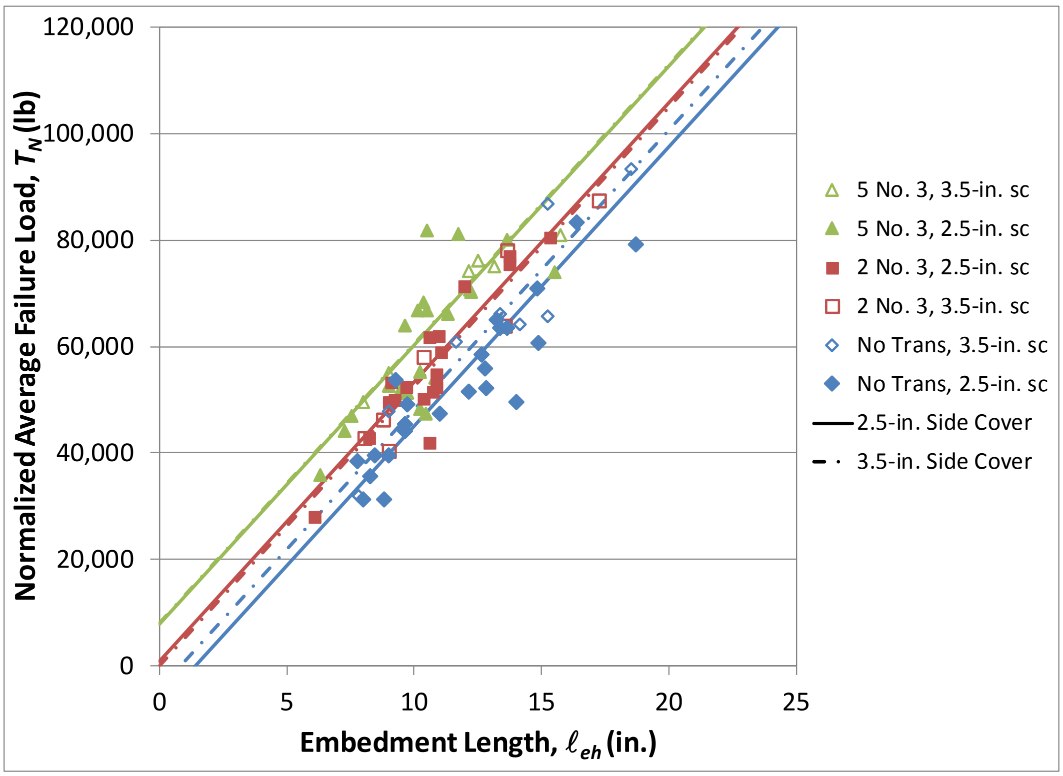


Figure 4.9 Normalized bar force at failure for No. 8 hooked bars cast inside the column core with different amounts of confining transverse reinforcement and side cover

Table 4.9 Summary of Specimens Included in Figure 4.9

Number of Specimens	Size of Hooked Bars	Side Cover (in.)	Transverse Reinforcement	Source
23	No. 8	2.5	None	Current investigation
8	No. 8	3.5	None	
18	No. 8	2.5	Two No. 3	
7	No. 8	3.5	Two No. 3	
21	No. 8	2.5	No. 3 @ 3d_b	
6	No. 8	3.5	No. 3 @ 3d_b	

Figure 4.10 shows the results for 36 No. 11 hooked bar beam-column joint specimens. A summary of these specimens is presented in Table 4.10. The average embedment lengths ℓ_{eh} ranged from 13.6 to 26.0 in., the concrete compressive strengths ranged from 4,910 to 16,180 psi, the average bar forces at failure T ranged from 66,600 to 213,300 lb, and the normalized average bar forces at failure T_N ranged from 66,900 to 173,200 lb. As for the No. 5 and No. 8 hooked bars, anchorage strength increased with embedment length and the amount of transverse reinforcement. For specimens without confining transverse reinforcement and specimens with two No. 3 ties, there was a small increase in anchorage strength as side cover increased from 2.5 to 3.5 in. For specimens with No. 3 ties spaced at 3d_b, there was a slight decrease in anchorage strength as side cover increased from 2.5 to 3.5 in. Student's t-test indicates that the differences in anchorage strength associated with changes in side cover for specimens without confining transverse reinforcement and specimens with two No. 3 ties are not statistically significant (α = 0.42 and 0.96, respectively). Student's t-test cannot be performed for the specimens with No. 3 ties spaced at 3d_b because there was only one specimen with 3.5-in. side cover.

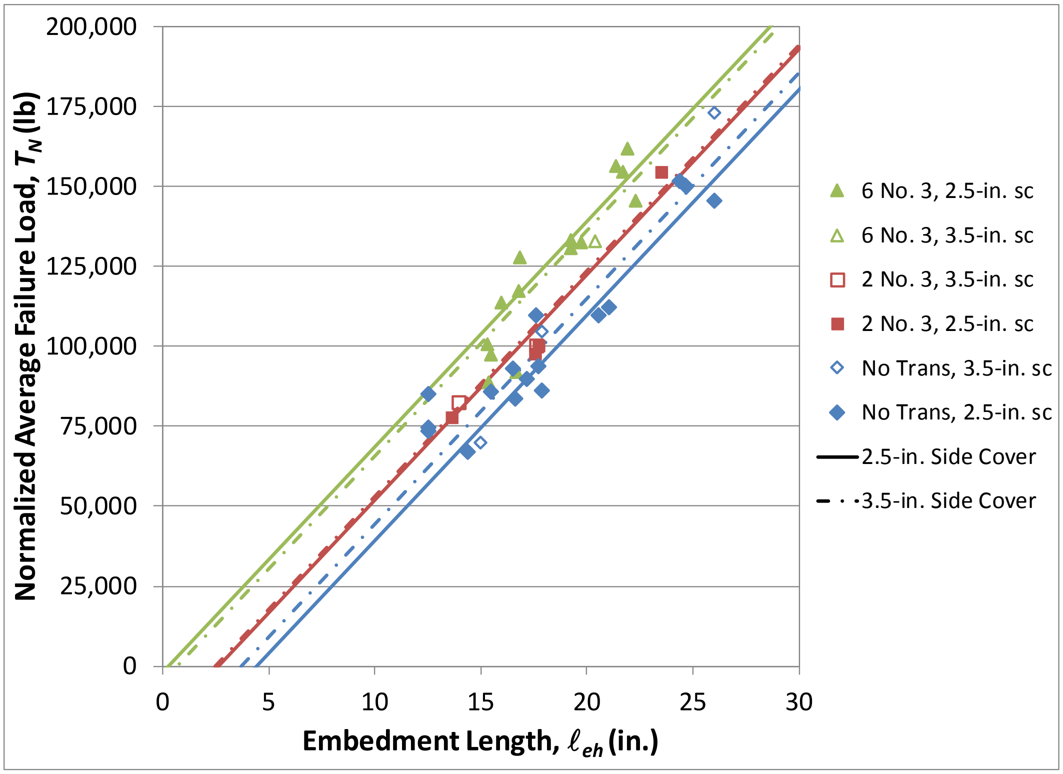


Figure 4.10 Normalized bar force at failure for No. 11 hooked bars cast inside the column core with different amounts of confining transverse reinforcement and side cover

Table 4.10 Summary of Specimens Included in Figure 4.10

Number of Specimens	Size of Hooked Bars	Side Cover (in.)	Transverse Reinforcement	Source
12	No. 11	2.5	None	Current investigation
3	No. 11	3.5	None	
4	No. 11	2.5	Two No. 3	
2	No. 11	3.5	Two No. 3	
14	No. 11	2.5	No. 3 @ 3d_b	
1	No. 11	3.5	No. 3 @ 3d_b	

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

2.5-in. side cover (α = 0.08), while the No. 8 specimens suggest that a hook with 3.5-in. side cover will have a greater anchorage capacity than a hook with 2.5-in. side cover (α = 0.13). These contradictory findings suggest that these differences, when considered in the context of the total population are not statistically significant, and may be the result of the relatively small population sizes for these two subsets of data. Overall, the results indicate that, in the current study, anchorage strength was not affected by differences in side cover in the range of 2.5 to 3.5 in. Because this range of side cover is typical for beam-column joints, side cover was omitted in subsequent analyses in this study.

4.3.3 Anchorage Strength of Hooks without Confining Transverse Reinforcement

The analyses described in Sections 4.3.1 and 4.3.2 showed that bend angle and side cover do not have a statistically significant effect on anchorage strength for the data set considered. Prior to performing those two analyses, test data from hooked bar specimens without confining transverse reinforcement in the joint region were evaluated to quantify the effects of concrete compressive strength and bar diameter on anchorage strength. As described at the beginning of Section 4.3, the dummy variables technique was used to establish the power p_1 for f_{cm} to determine the normalized bar force at failure T_N in Sections 4.3.1 and 4.3.2.

Figure 4.11 shows the results for 99 beam-column joint specimens without confining transverse reinforcement. The figure shows the average bar force at failure T as a function of embedment length ℓ_{eh}. A summary description of these specimens is presented in Table 4.1. The average bar forces at failure T ranged from 19,200 to 213,300 lb, the embedment lengths ℓ_{eh} ranged from 4.9 to 26.0 in., and the concrete compressive strengths ranged from 2,570 to 16,510 psi. The general trend shows that an increase in embedment length produces an increase in anchorage capacity. This representation of the data, however, does not show the effects of concrete compressive strength.

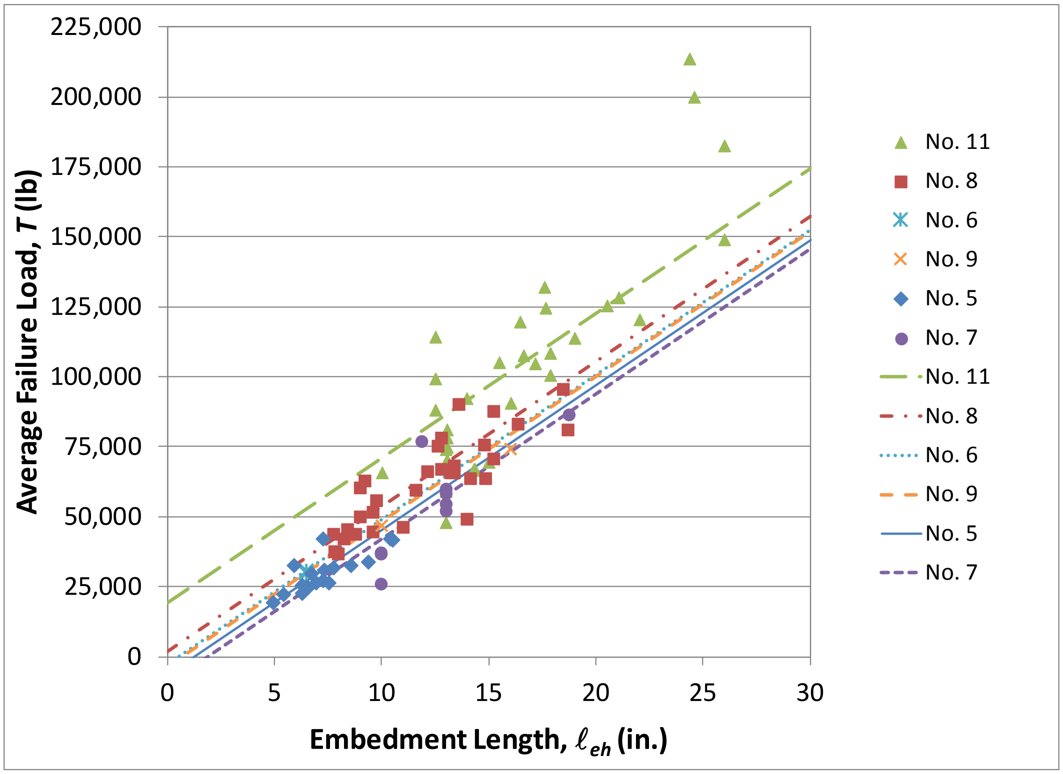


Figure 4.11 Average bar force at failure versus embedment length for hooked bars without confining transverse reinforcement

Using the process described in the beginning of Section 4.3, the results shown in Figure 4.11 were re-plotted with the load at failure normalized with respect to the compressive strength to the power p_1, $T/f_{cm}^{p_1}$. The value of p_1 was varied to obtain the linear relationship that minimized the scatter in $T/f_{cm}^{p_1}$ as a function of embedment length ℓ_{eh}. The average intercept of the individual dummy variables lines was used to develop Eq. (4.5), where T_c represents the calculated anchorage capacity of a hooked bar without confining transverse reinforcement.

$$\frac{T_c}{f_{cm}^{0.29}} = 420\ell_{eh} - 470 \tag{4.5}$$

Figures 4.12 and 4.13 show the results of this analysis. In Figure 4.12, the average bar force at failure T was normalized by $f_{cm}^{0.29}$ and plotted versus the embedment length. The dummy variables lines for the larger bars are above those for the smaller bars, indicating that, for a given embedment length, larger hooked bars are more effective anchors and, thus, provide greater anchorage strength.

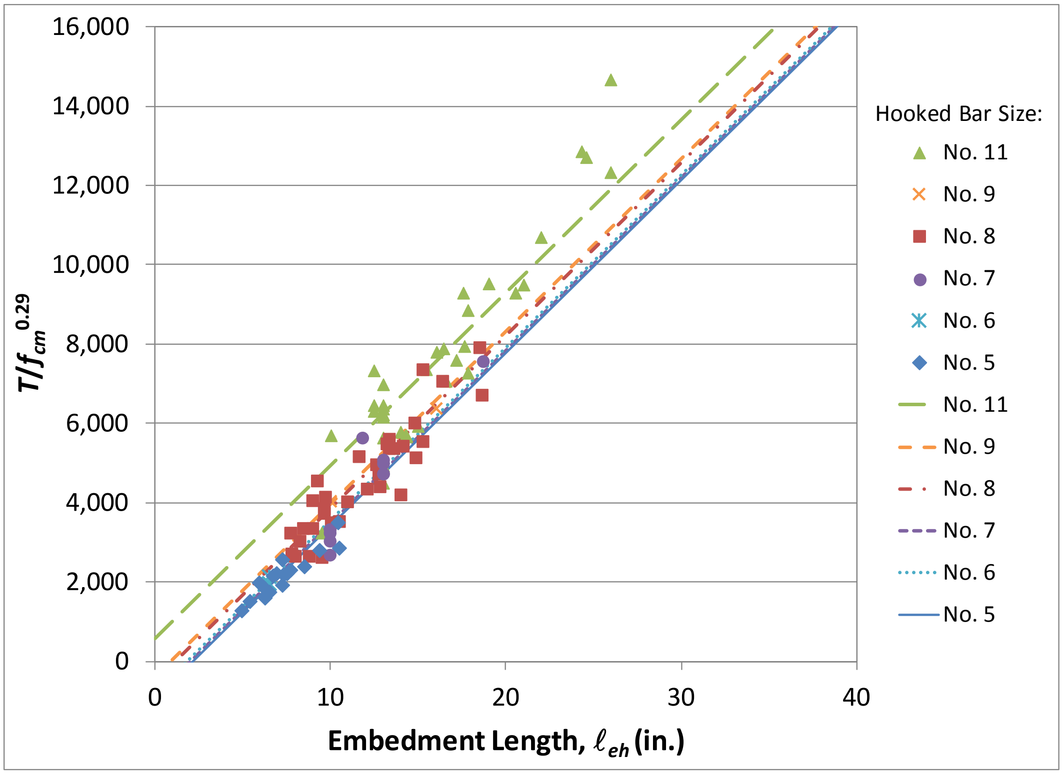


Figure 4.12 Average bar force at failure normalized to $f_c'^{0.29}$ versus embedment length for hooked bars without confining transverse reinforcement

In Figure 4.13, the ratios of the bar forces at failure to the bar forces calculated based on Eq. (4.5) are plotted with respect to f_{cm}. The mean ratio is 1.0, with a range from 0.644 to 1.46 and a standard deviation and coefficient of variation of 0.201. In the figure, the dummy variables lines are horizontal showing that the ratio of test-to-calculated failure load does not vary with concrete compressive strength. As suggested by Figure 4.12, the lines have a definite order, with the larger bar sizes giving higher ratios than the smaller bar sizes. The intercepts are 0.817 for No. 5 bars, 0.873 for No. 6 bars, 0.939 for No. 7 bars, 0.996 for No. 8 bars, 1.02 for No. 9 bars, and 1.19 for No. 11 bars.

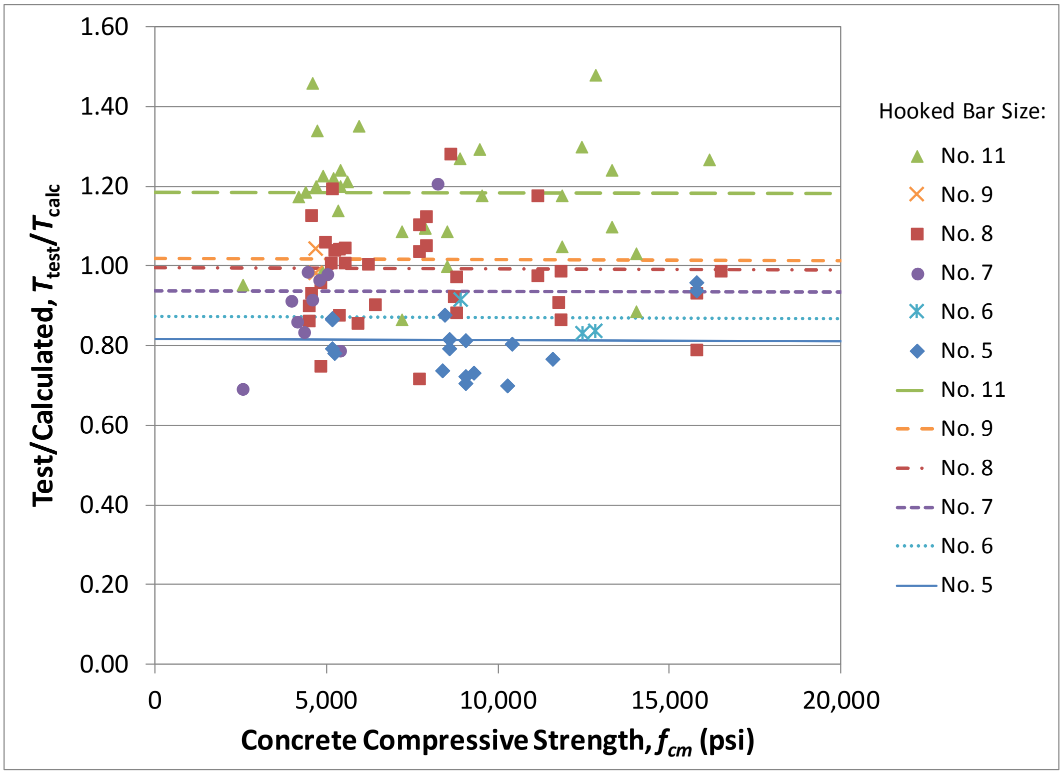


Figure 4.13 Ratio of test-to-calculated failure load versus concrete compressive strength for specimens without confining transverse reinforcement, with T_{calc} based on Eq. (4.5)

The next step in developing an equation to characterize hook strength was to determine the effect of bar diameter on anchorage strength for hooks without confining transverse reinforcement. The power $p_2 = 0.45$ is found by minimizing the spread in the intercepts normalized with respect to the data range (relative intercepts). The resulting dummy variables lines are very closely spaced as shown in Figure 4.14. Using the average intercept of the dummy variables lines, the descriptive equation for hooked bars without confining transverse reinforcement became

$$\frac{T_c}{f_{cm}^{0.29}} = 427\ell_{eh}d_b^{\,0.45} - 440 \tag{4.6}$$

The intercepts of the trend lines for each of the bar sizes evaluated are –351 for No. 5 hooked bars, –424 for No. 6 hooked bars, –493 for No. 7 hooked bars, –429 for No. 8 hooked bars, –571 for No. 9 hooked bars, and –371 for No. 11 hooked bars. These intercepts represent a major improvement when compared to those in Figure 4.12.

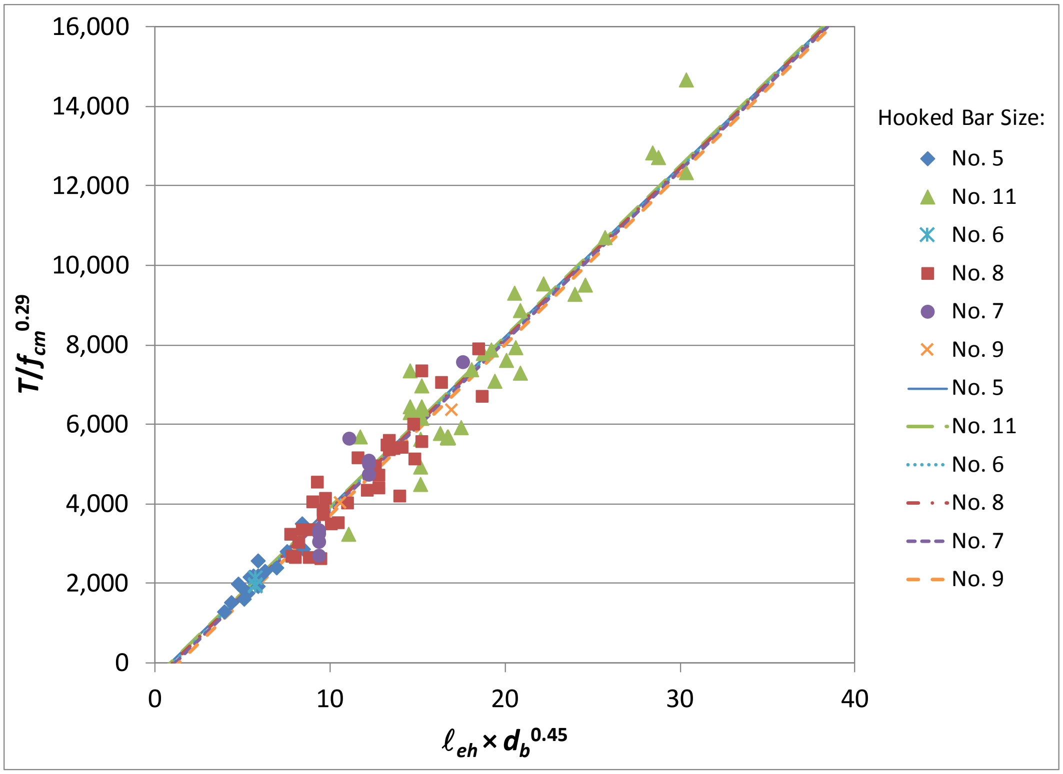


Figure 4.14 Average bar force at failure normalized to $f_{cm}^{0.29}$ versus embedment length and bar diameter for hooked bars without confining transverse reinforcement

The ratios of the bar forces at failure to the bar forces calculated based on Eq. (4.6) are plotted with respect to f_{cm} in Figure 4.15. The figure exhibits much less scatter than Figure 4.13 as a result of including the effect of the bar size in Eq. (4.6). The mean ratio is 1.0, the coefficient of variation is 0.120, and the ratios range from 0.723 to 1.30. The slopes of the dummy variables lines are approximately zero, indicating that $f_{cm}^{0.29}$ adequately captures the effect of concrete compressive strength on anchorage strength. The intercepts of the individual trend lines are 1.03 for No. 5 hooked bars, 0.98 for No. 6 hooked bars, 0.99 for No. 7 hooked bars, 0.99 for No. 8 hooked bars, 0.98 for No. 9 hooked bars, and 0.99 for No. 11 hooked bars.

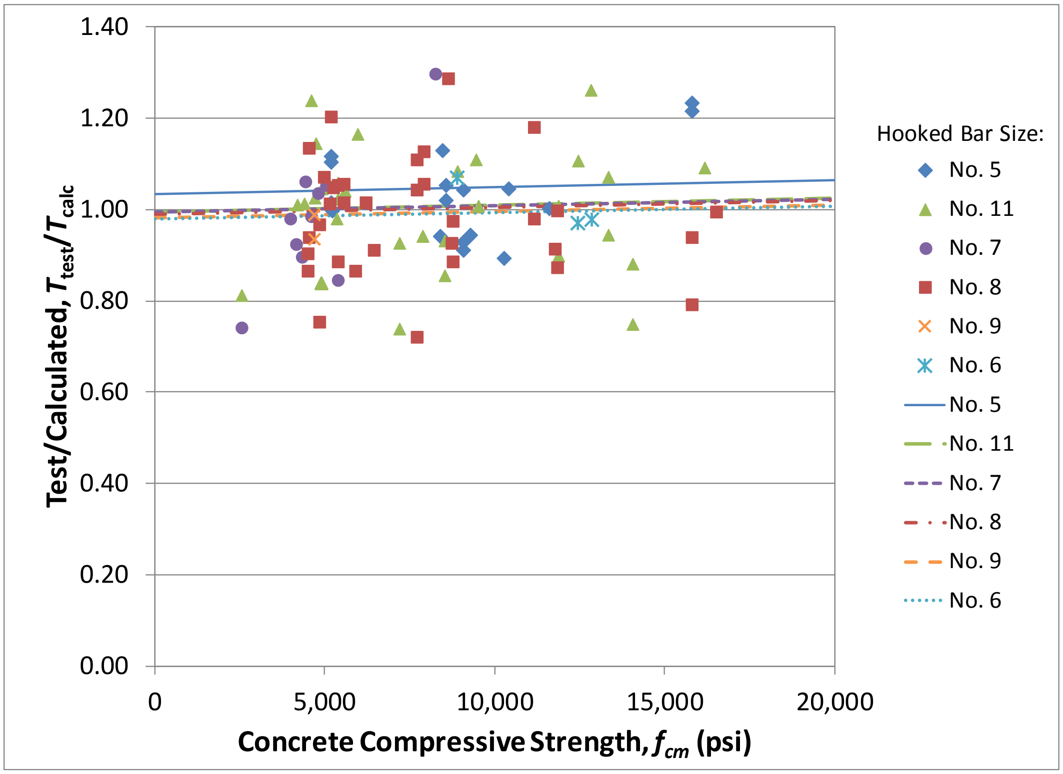


Figure 4.15 Ratio of test failure load to calculated failure load based on Eq. (4.6) versus concrete compressive strength for beam-column specimens without confining transverse reinforcement

Figure 4.16 shows the relationship between the ratio of test-to-calculated failure load [using Eq. (4.6)] and bar diameter d_b. The nearly zero slope of the dummy variables lines indicates that the effect of bar diameter on anchorage strength T is reasonably represented by $d_b^{0.45}$. The intercepts of the dummy variables trend lines are 1.04 for No. 5 hooked bars, 1.00 for No. 6 hooked bars, 1.00 for No. 7 hooked bars, 1.00 for No. 8 hooked bars, 0.96 for No. 9 hooked bars, and 1.01 for No. 11 hooked bars.

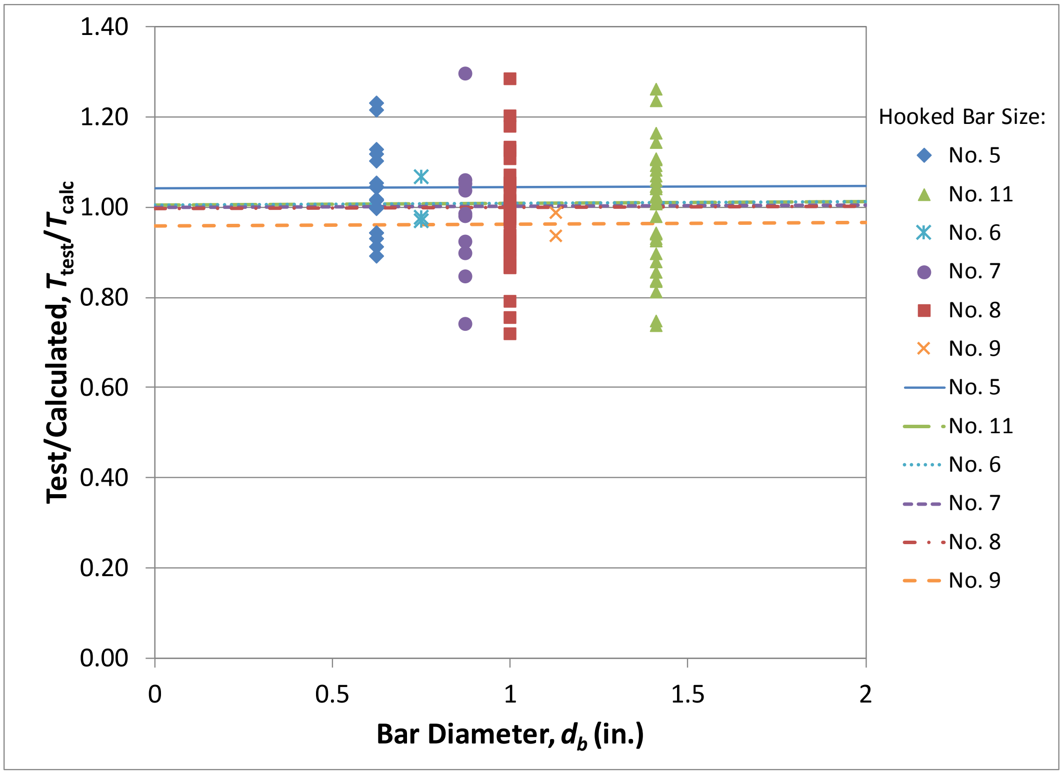


Figure 4.16 Ratio of measured to calculated bar force versus bar diameter for beam-column specimens without confining transverse reinforcement

Up to this point, all analyses performed were based on the assumption that the relationship between the anchorage strength of hooked bars and embedment length ℓ_{eh} is linear. The negative intercepts of the dummy variables lines indicate that this relationship may in fact be nonlinear in nature. There are several trends in the data that indicate a nonlinear relationship. For example, in Figure 4.14, three of the four data points corresponding to the greatest embedment lengths and highest anchorage forces deviate from the linear trend on the high side. To capture this behavior, the data were reanalyzed by raising the term $\ell_{eh} d_b^{0.45}$ to the power that minimized the sum of the squared differences $(1-T/T_c)^2$. The resulting equation is given by:

$$\frac{T_c}{f_{cm}^{0.29}} = 304\left(\ell_{eh} d_b^{\ 0.45}\right)^{1.10} = 304\ell_{eh}^{\ 1.10} d_b^{\ 0.50} \tag{4.7}$$

This nonlinear relationship, with a power of ℓ_{eh} greater than 1.0, is in concert with the failure modes, front breakout and blowout and side breakout and blowout, described in Chapter 3, that involve progressively more concrete as the embedment length increases. The average failure loads normalized to $f_{cm}^{0.29}$, calculated using Equation (4.7), are compared with the experimental data in Figure 4.17. The average test-to-calculated ratio based on Eq. (4.7) is 1.0 with a coefficient of variation of 0.119. The maximum and minimum ratios are, respectively, 1.32 and 0.73. These compare to the nearly identical respective values of for Eq. (4.6) of 1.0, 0.12, 0.723, and 1.30.

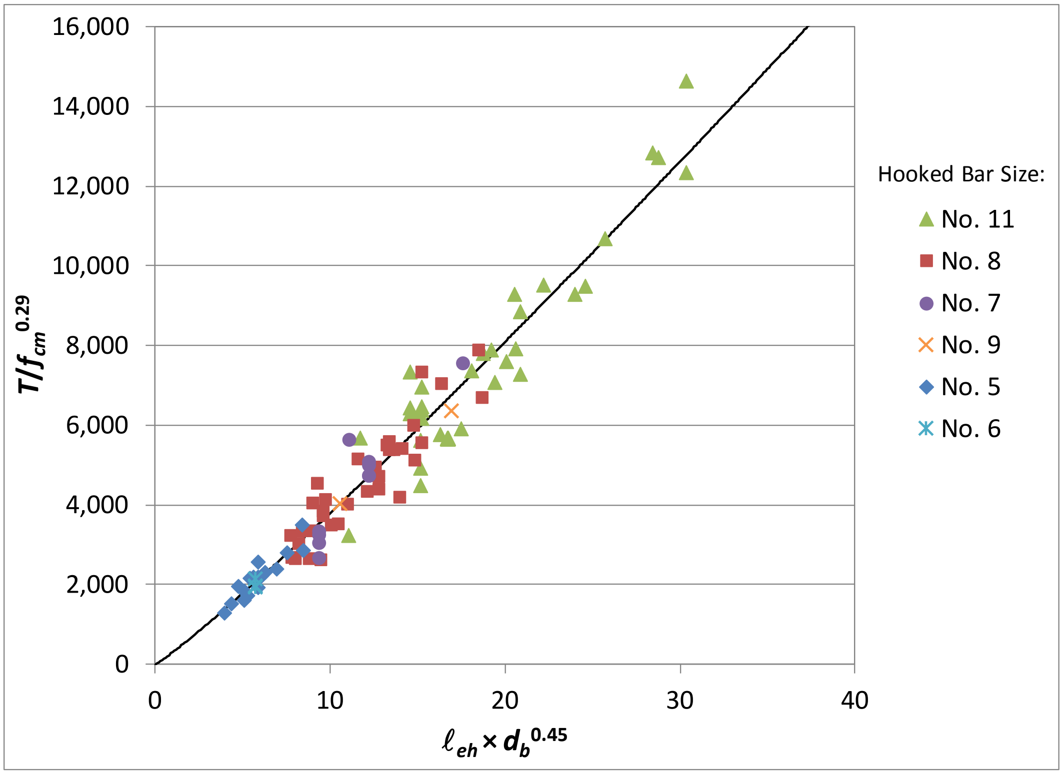


Figure 4.17 Average failure load normalized to $f_{cm}^{0.29}$ as a non-linear function of the product of embedment length and $d_b^{0.45}$ and compared to Eq. (4.7)

Because Eq. (4.7) provides a somewhat more accurate representation of the data than Eq. (4.6), Eq. (4.7) was used in subsequent calculations.

Equation (4.7) was developed for specimens without confining transverse reinforcement and is assumed to represent the contribution of the concrete to the anchorage capacity of hooked bars T_c. The following sections address the strength of specimens that contain transverse reinforcement in the region of the hook.

4.3.4 Effect of Orientation of Transverse Reinforcement

To take advantage of the 0.8 reduction factor for development length with 90° hooked bars, ACI 318-14 Section 25.4.3.2 requires confining reinforcement spaced at ≤ $3d_b$ and placed perpendicular or parallel to the straight portion of the bar being developed as illustrated for a cantilever in Figure 4.18, while for 180° hooked bars the reduction factor can only be applied for reinforcement oriented perpendicular (Figure 4.18a) to the straight portion of the bar being developed. Because confining reinforcement parallel to hooked bars is more convenient in a beam-column joint, it is important to determine if a parallel orientation yields comparable increases in anchorage strength to those provided by a perpendicular orientation for 180° hooks. This section evaluates the strength of both 90° and 180° hooked bars within simulated beam-column joints confined by ties oriented vertically and horizontally. The term "ties" is used to describe confining reinforcement oriented in either direction.

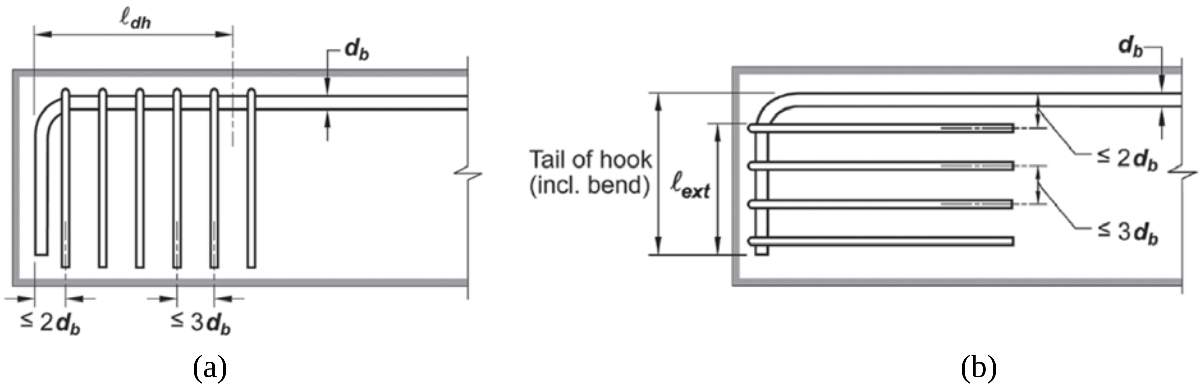


Figure 4.18 Ties or stirrups placed (a) perpendicular to the bar being developed and (b) parallel to the bar being developed in a cantilever beam (as shown for 90º hooks)

Test results for twelve beam-column joint specimens with 90° and 180° No. 8 hooked bars are summarized in Table 4.11. The respective cross-section dimensions for the specimens with 10-in., 11-in., and 12.5-in. embedment lengths were 17×12 in., 17×13 in., and 17×14.5 in. The nominal compressive strength for this test series was 12,000 psi, while the actual concrete compressive strengths ranged from 11,800 to 12,010 psi. The average embedment lengths ranged from 9.4 to 12.8 in., and the average failure loads ranged from 60,200 to 75,200 lb. Of the twelve specimens, six contained hooks with a 90° bend angle and six contained hooks with a 180° bend angle. For both sets of six, one specimen contained no confining transverse reinforcement, one contained two No. 3 ties placed horizontally (parallel to bar being developed), one contained two No. 3 ties placed vertically (perpendicular to bar being developed), one contained No. 3 ties spaced at $3d_b$ placed horizontally, and two contained No. 3 ties spaced at less than $3d_b$ placed vertically.

To take advantage of the 0.8 development length reduction factor in Section 25.4.3.2 of ACI 318-14, the maximum spacing is $3d_b$, regardless of whether they are placed horizontally or vertically (i.e., parallel or perpendicular to the straight portion of the bar). In the specimens with No. 8 hooked bars and ties placed horizontally along the tail of the hook, a minimum of five ties were needed to meet the $3d_b$ spacing requirement. Given the configuration of the specimens and the depth of the joint, only four ties were required to meet the $3d_b$ spacing requirement when the ties were placed vertically. To obtain an objective comparison between the effect of horizontal and vertical tie placement, two different configurations were used for specimens with vertical ties satisfying $3d_b$ maximum spacing requirement – one with four No. 3 ties to meet the $3d_b$ maximum spacing requirement for vertical ties and one with five No. 3 ties to match the area of transverse reinforcement used in the specimens with ties placed in the horizontal direction. The difference between the two configurations is shown in Figure 4.19. For specimens with 180° hook bend angles, the horizontal ties were placed throughout the hook region as defined by the bend and tail of a 90° hooked bar, as shown in Figure 4.20.

Table 4.11 Test results for series with horizontal and vertical ties

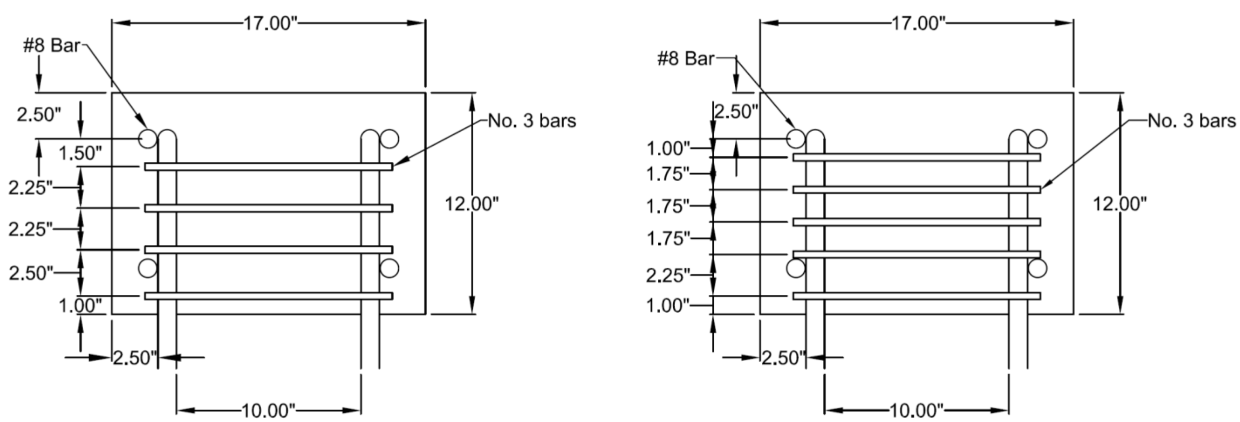
Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	T_{ind} lb	T lb	Failure Type
8-12-90-0-i-2.5-2-12.5	A B	90°	12.9 12.8	12.8	11850	2.6 2.6	2.6	1.7 1.8	10.1	0	-	-	66000 77400	66950	FB/SB FB/SB
8-12-90-2#3-i-2.5-2-11	A B	90°	10.5 11.3	10.9	12010	2.8 2.8	2.8	2.4 1.6	9.5	0.22	2	8	68100 79800	68700	FP FP
8-12-90-2#3vr-i-2.5-2-11	A B	90°	10.9 10.4	10.6	12010	2.5 2.3	2.4	2.1 2.6	9.8	0.22	2	2.67	50700 66800	52650	FP/SS FP
8-12-90-5#3-i-2.5-2-10	A B	90°	9.0 9.9	9.4	11800	2.6 2.3	2.4	3.2 2.3	9.9	0.55	5	3	66000 64600	64550	FB/SS SS/FP
8-12-90-4#3vr-i-2.5-2-10	A B	90°	10.6 10.3	10.4	11850	2.5 2.5	2.5	1.8 2.1	9.0	0.44	4	2.25	80300 59300	59250	FP/SS FP
8-12-90-5#3vr-i-2.5-2-10	A B	90°	10.3 10.2	10.2	11800	2.5 2.4	2.4	1.7 1.7	9.8	0.55	5	1.75	59400 64100	60200	FP FP

[d]Notation described in Section 2.1 and Appendix A

Table 4.11 Cont. Test results for series with horizontal and vertical ties

Specimen[d]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	T_{ind} lb	T lb	Failure Type
8-12-180-0-i-2.5-2-12.5	A B	180°	12.8 12.5	12.6	11850	3.0 2.5	2.8	2.1 2.4	9.6	0	-	-	74800 92300	75200	FB/SB FP
8-12-180-2#3-i-2.5-2-11	A B	180°	11.1 10.4	10.8	12010	2.5 2.6	2.6	2.1 2.8	9.6	0.22	2	8	73700 66200	64650	FP FB
8-12-180-2#3vr-i-2.5-2-11	A B	180°	10.9 10.9	10.9	12010	2.8 2.6	2.7	2.4 2.4	9.8	0.22	2	2.67	67100 87100	65800	SS/FP FB/SB
8-12-180-5#3-i-2.5-2-10	A B	180°	9.9 9.6	9.8	11800	2.3 2.8	2.5	2.3 2.6	9.9	0.55	5	3	63000 81400	64100	FP/SS FP
8-12-180-4#3vr-i-2.5-2-10	A B	180°	10.5 10.0	10.3	11850	2.8 2.5	2.6	1.8 2.3	9.8	0.44	4	2.25	69700 68800	69200	FP FP
8-12-180-5#3vr-i-2.5-2-10	A B	180°	11.1 10.5	10.8	11800	2.5 2.5	2.5	1.3 1.9	9.8	0.55	5	1.75	67500 68000	67800	FP FB

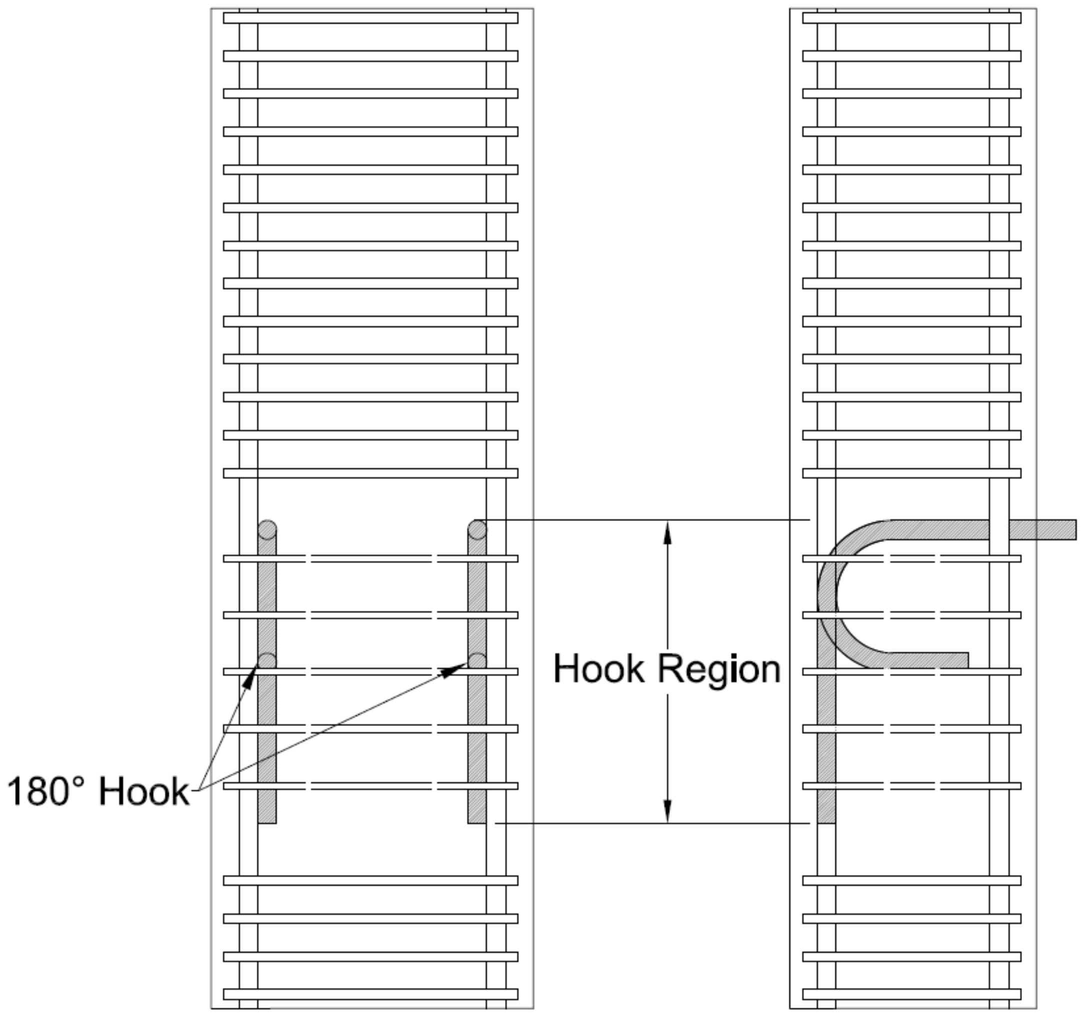
[d]Notation described in Section 2.1 and Appendix A



(a) (b)

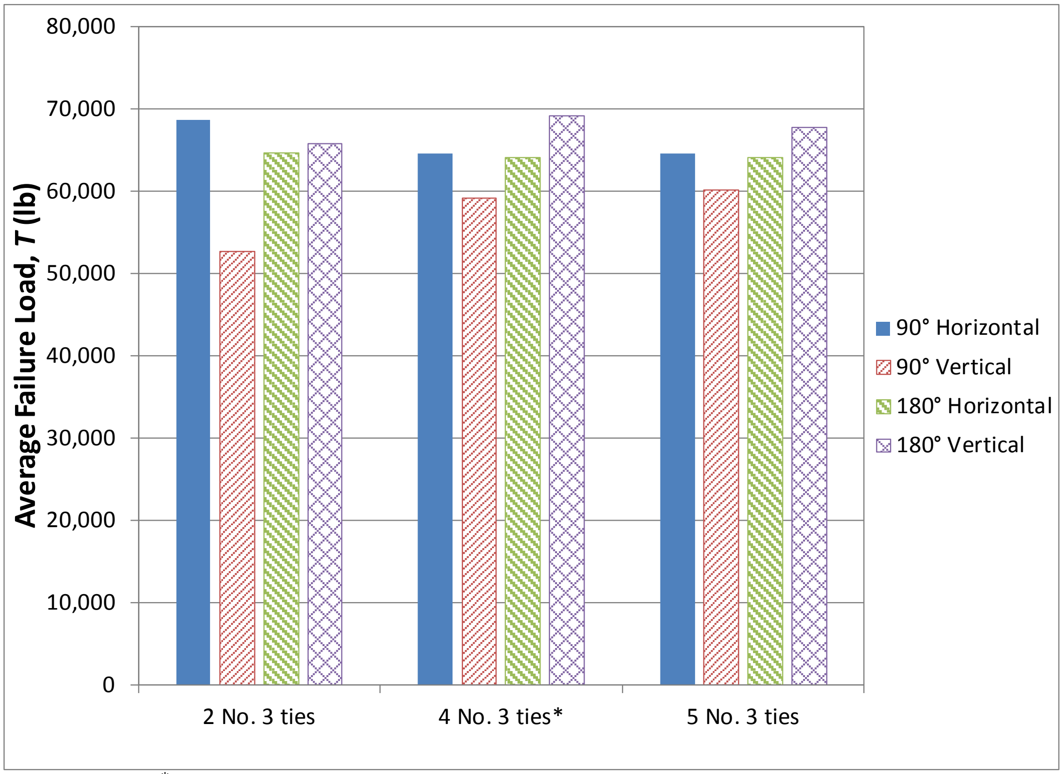
Figure 4.19 Plan view of hooked bars with vertical ties satisfying maximum spacing requirement in ACI 318-14 Section 25.4.3.2: (a) four No. 3 ties and (b) five No. 3 ties

The test results for specimens with two No. 3 ties and specimens with No. 3 ties spaced at $\leq 3d_b$ are shown in the bar graph in Figure 4.21. Each bar in the figure represents the average force in an individual hooked bar in a single specimen at the peak load sustained by the specimen. The first set of four bars shows the average failure loads of the 90° and 180° hooked bars confined by two No. 3 horizontal or vertical ties. As shown for these four specimens, the 90° hooks confined by horizontal ties performed better than the 90° hooks with the vertical ties – the average failure load for the hooked bars with horizontal ties was approximately 1.3 times the average failure load for the hooked bars with vertical stirrups. For the specimens with a 180° bend angle, configurations with vertical and horizontal ties had comparable strengths – the average failure load for the hooked bars with the vertical ties was 1.02 times the average failure load of the hooked bars with the horizontal ties.



(a) (b)

Figure 4.20 (a) Front and (b) side view for specimens with 90° and 180° hook bend angles

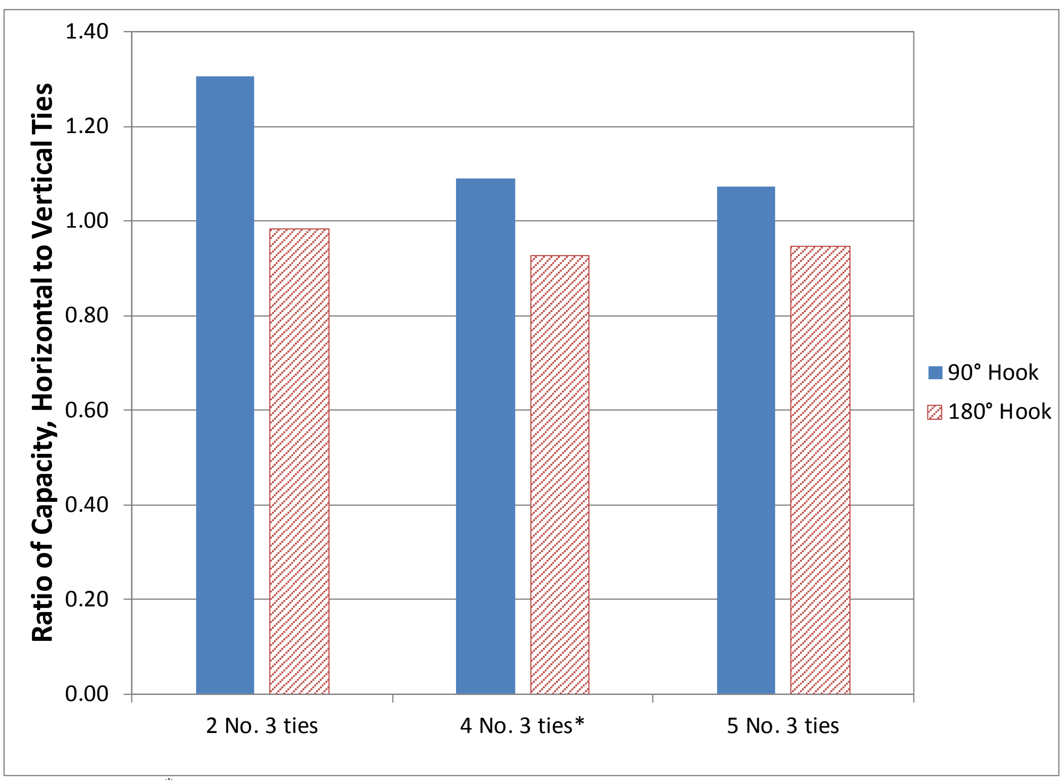


*Specimens with horizontal confining reinforcement had 5 No. 3 ties

Figure 4.21 Failure load for specimens containing No. 8 hooked bars with horizontal and vertical confining reinforcement and 90° and 180° bend angles

The second and third sets of four bars in Figure 4.21 show the results for specimens with ties spaced $\leq 3d_b$. Only two specimens were cast containing horizontal ties spaced $\leq 3d_b$. For ease of comparison, the first and third bars in these sets are duplicates and represent the same two specimens. Trends for specimens with ties spaced $\leq 3d_b$ are similar to those observed for specimens with two No. 3 ties. The 90° hooks with vertical ties failed at a lower load than those with horizontal ties, although the difference is significantly smaller than that observed for the specimens with two No. 3 ties. The failure load of the specimen with five No. 3 horizontal ties was, respectively, 1.09 and 1.07 times the failure loads of the specimens with four No. 3 vertical ties and five No. 3 vertical ties. For the 180° hook specimens, the opposite was true. Specimens with vertical ties failed at a higher load than the companion specimens with horizontal ties. The failure loads of the 180° hook specimens with four No. 3 vertical ties and five No. 3 vertical ties were, respectively, 1.08 and 1.06 times the failure load of the companion specimen with horizontal ties. The 180° hook specimen with five No. 3 horizontal ties had nearly identical strengths to the 90° hook specimen with horizontal ties and higher strengths than the 90° hook specimens with vertical ties, although current design provisions for hooked bars do not allow the use of the 0.8 reduction factor for development length for 180° hooks with horizontal ties.

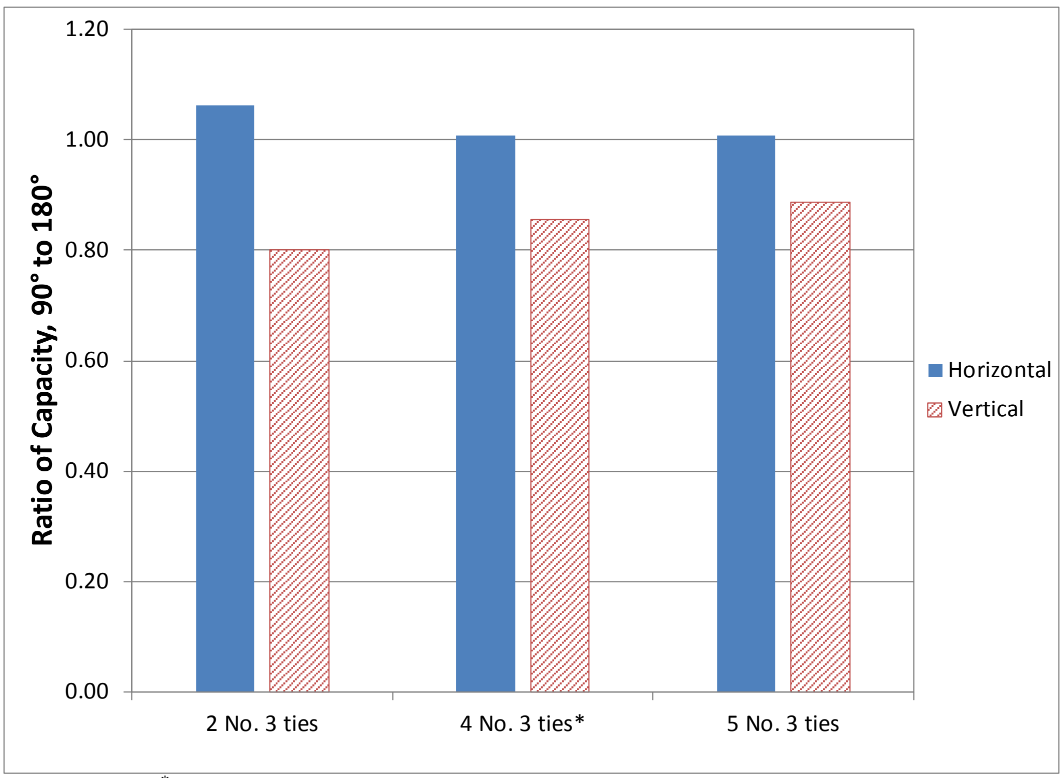
Figure 4.22 shows the ratio of the anchorage capacity of the hooked bars confined by horizontal ties to the anchorage capacity of hooked bars confined by vertical ties. This figure indicates that for 90° hooked bars, horizontal ties had a greater effect on anchorage strength than vertical ties, while for 180° hooked bars the opposite was true. This behavior may result because horizontal ties act similar to anchor reinforcement for the hooked bars and keep the concrete cone intact, while vertical ties may not be as efficient as the horizontal ties in acting as anchor reinforcement. Vertical ties, however, may be more efficient in limiting splitting of the concrete caused by slip of the hooked bars – splitting that may be greater for 180° hooked bars than for 90° hooked bars.



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

Figure 4.22 Ratio of anchorage strengths for No. 8 hooked bars with horizontal ties to No. 8 hooked bars with vertical ties

Figure 4.23 shows the ratio of anchorage strength of hooked bars with a 90° bend angle to that of hooked bars with a 180° bend angle with both tie orientations. The ratio for specimens with horizontal ties ranges from 1.01 to 1.06, while the ratio for specimens with vertical ties ranges from 0.80 to 0.89. For specimens with horizontal ties, the ratio of anchorage strengths is very close to 1.0, indicating that regardless of the number of ties in the specimens, placing the ties in the horizontal direction provided similar capacities for hooked bars with 90° and 180° bend angles. For specimens with vertical ties, the average anchorage strength ratio is approximately 0.85, showing that when vertical ties are used, the anchorage capacity attained with 90° hooks is lower than that attained with 180° hooks.



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

Figure 4.23 Ratio of anchorage strengths, No. 8 hooked bars with 90° bend angle to No. 8 hooked bars with 180° bend angle

Based on the failure modes described in Section 3.2, it appears that horizontal ties act to keep the concrete intact, serving to keep the concrete from being pulled out the front of the column, similar to anchor reinforcement. The force in the hooked bars tends to pull a section of concrete out the front of the column, but the ties act in direct opposition to that force. When vertical ties are used to confine 90° hooked bars, they help keep the concrete intact but no longer act as anchor reinforcement and, thus, are pulled through the front of the column with the cone of concrete, as shown in Figure 4.24.

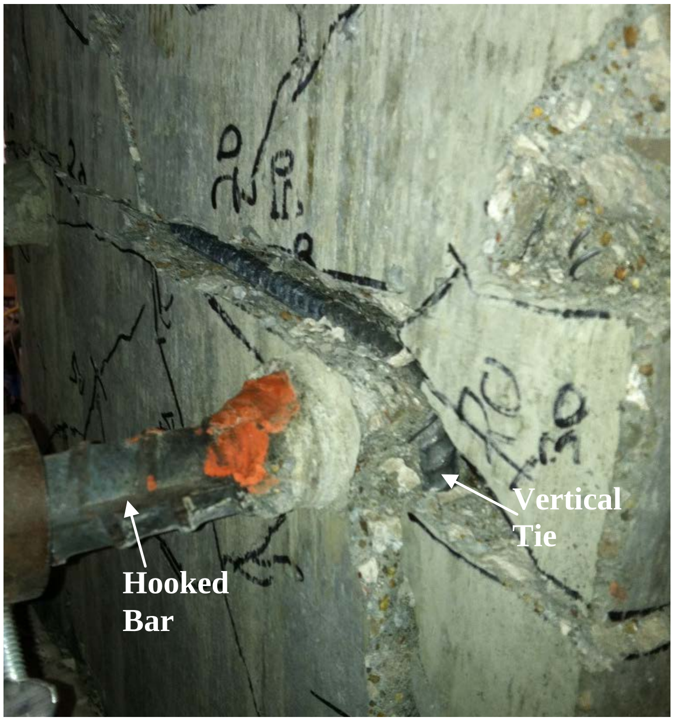


Figure 4.24 Vertical tie being pulled from the front of the column. Specimen 8-12-90-5#3vr-i-2.5-2-10 after failure

Because the anchorage strength of 180° hooks with horizontal ties was found to be similar to that of 90° hooks with either tie orientation, all subsequent specimens with 180° hooks were tested with horizontal ties. The hooks with vertical ties were included in the development of characterizing and design equations. For the term representing the contribution of the transverse reinforcement NA_{tr}/n, N was taken as the number of legs perpendicular to the bar over the length being developed.

4.3.5 Anchorage Strength of Hooked Bars Confined by Transverse Reinforcement

The analysis of hooked bar specimens with various amounts of confining transverse reinforcement is presented in this section. The general form of the equation used to quantify the effect of the confining transverse reinforcement is $T_h = T_c + T_s$, where T_h is the total calculated failure load, T_c is the concrete contribution given in Eq. (4.7), and T_s is the contribution of the confining transverse reinforcement. The analysis employed a dummy variables approach with $T_s = T - T_c$ serving as the basis of the analysis. A mathematical representation for the steel contribution T_s to anchorage strength T_h was investigated using a set of data generated by subtracting the calculated concrete contribution T_c from the average bar force at failure T for each specimen. This section describes the steps taken for this process and summarizes the results.

The nature of the failures described in Section 3.2 suggests that horizontal reinforcement may have acted as an anchor for the failure cone that was pulled out at failure by the hooked bars, which would imply that the anchorage strength should be proportional to the amount of transverse reinforcement in the direction of the bar being developed. In addition, the tests described in Section 4.3.4 indicate that transverse reinforcement oriented perpendicular to the straight portion of the hooked bar provides a similar increase in strength. The amount of transverse reinforcement per hooked bar is NA_{tr}/n, where N is the number of legs parallel to the straight length of the hooked bar along the length of the tail of a 90° hook or the number of legs perpendicular to the bar over the length being developed, A_{tr} is the area of one leg of transverse reinforcement, and n is the number of hooks being developed. For example, for a specimen with two No. 11 hooked bars and No. 3 ties spaced at $3d_b$ (this results in six No. 3 ties), the term $NA_{tr}/n = (12 \times 0.11)/2 = 0.66$ in.^{2} The range in NA_{tr}/n was 0.11 to 1.0 for the hooked bars discussed in this section. Due to the relatively small number of specimens (12) containing transverse reinforcement tested by other researchers and the inherent variability in the contribution of the transverse steel to the capacity of the hooked bars, only specimens that were tested in this study were used to develop T_s.

Figures 4.25a and 4.25b show, respectively, the relationships between the ratio of anchorage strength for hooks confined by transverse reinforcement to anchorage strength provided by concrete, T/T_c and the strength in excess of the concrete contribution, $T - T_c$, and the parameter NA_{tr}/n for 146 specimens with various amounts of confining transverse reinforcement. A summary of these specimens is presented in Table 4.12. The average bar forces at failure ranged from 18,700 to 209,600 lb, the average embedment lengths ranged from 3.75 to 23.5 in., and concrete compressive strengths ranged from 4,300 to 16,180 psi. In the figures, values of NA_{tr}/n of 0.55 for No. 5 and No. 8 bars and 0.66 for No. 11 bars correspond to No. 3 ties spaced at $3d_b$ (which qualify for a 0.8 reduction in development length in accordance with Section 25.4.3.2 in ACI 318-14), and values of 0.8 for No. 8 bars and 1.0 for No. 11 bars correspond to the higher quantities of transverse reinforcement required by ACI 318-14 Section 18.8.3 for joints in special moment frames. The trend lines in Figure 4.25a and 4.25b are, respectively, the best-fit lines and dummy variables based on bar size.

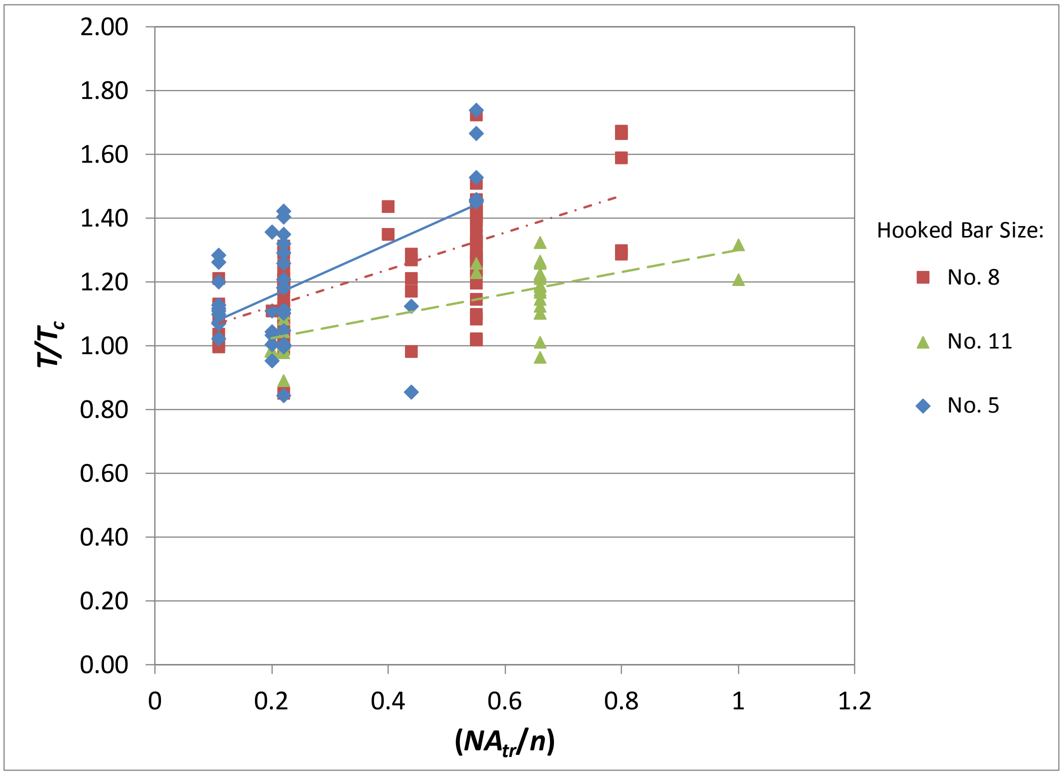


Figure 4.25a Ratio of anchorage strength for hooks confined by transverse reinforcement to anchorage strength provided by concrete, with T_c based on Eq. (4.7)

As shown in Figure 4.25a, T/T_c increases with an increase in NA_{tr}/n, with smaller bars exhibiting a greater relative increase in anchorage strength than the larger bars. Based on this comparison, it becomes clear that the increase in strength of hooked bars provided by confining transverse reinforcement spaced at $\leq 3d_b$ cannot be expressed as a single percentage of the strength without confinement T_c for all bar sizes as is implied by the use of the 0.8 reduction factor for development length in accordance with Section 25.4.3.2 of ACI 318-14.

Figure 4.25b shows that $T - T_c$ increases with an increase in NA_{tr}/n. The value of $T - T_c$ is about the same for the No. 8 and No. 11 hooked bars confined by No. 3 ties spaced at $3d_b$ and is also about the same for the No. 8 and No. 11 bars confined by the quantity of transverse reinforcement required for joints in special moment frames. $T - T_c$ for the No. 5 hooked bars confined by No. 3 ties spaced at $3d_b$ is less than that observed for the No. 8 and No. 11 bars. Accordingly, the No. 5 hooked bar dummy variables line has a lower intercept on the $T - T_c$ axis than the No. 8 and No. 11 hooked bars. There are, however, two No. 5 hooked bar results that are lower than expected, which may explain the lower intercept for the No. 5 dummy variables line. The intercept of the dummy variables line for the No. 8 hooked bars is greater than the No. 11 hooked bars, which may be a result of the relatively low number of No. 11 hooked bar results. If d_b were a major factor in the increase in capacity provided by the transverse reinforcement, it would be expected that the dummy variables lines appear in order of decreasing bar size. This trend is not observed in Figure 4.25. The spread in the intercepts, however, does suggest a small influence of d_b on the increase in capacity provided by the transverse reinforcement. An analysis similar to that used in Section 4.3.3 was used to investigate the effect of bar size on anchorage strength for specimens with confining transverse reinforcement. The transverse reinforcement parameter NA_{tr}/n was multiplied by the hooked bar diameter d_b to a power p_3. A least-squares approach was used to find the value of the power p_3 that would cause the range of intercepts for the various trend lines on the $T - T_c$ axis to be minimized and the average test-to-calculated ratio to be approximately 1.0.

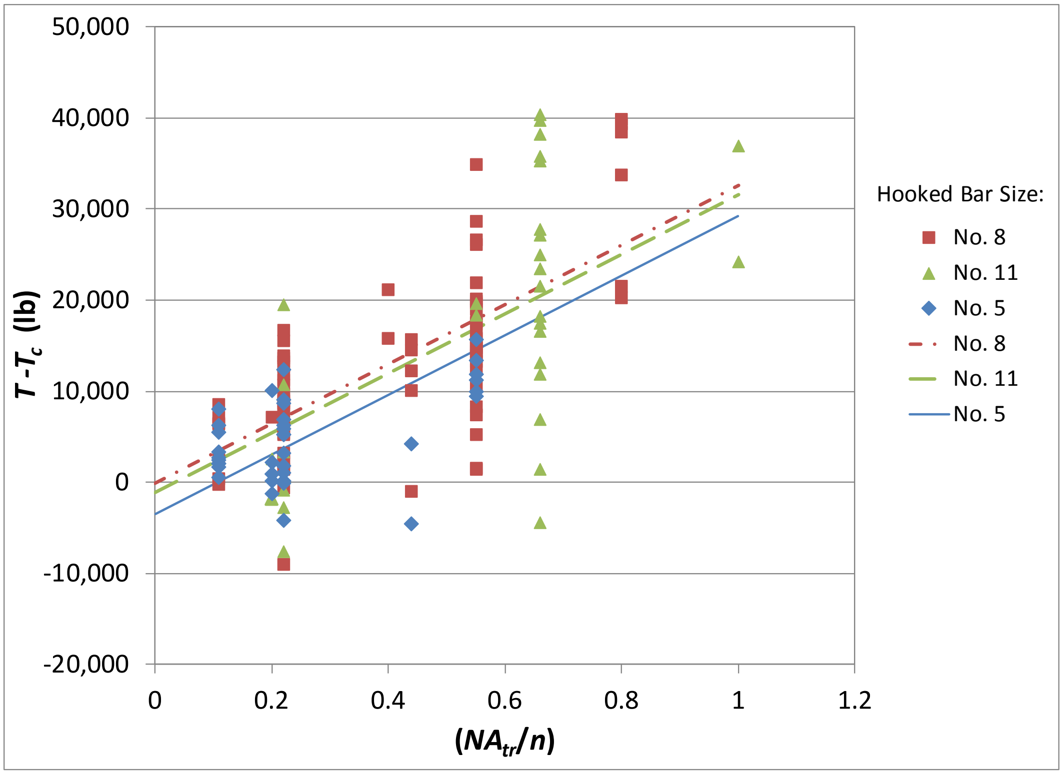


Figure 4.25b Anchorage strength in excess of the concrete contribution versus amount of transverse reinforcement, with T_c based on Eq. (4.7)

Table 4.12 Summary of specimens in Figure 4.25

Number of Specimens	Hooked Bar Size	Transverse Reinforcement	Source
10	No. 5	1 No. 3	Current Investigation
6		1 No. 4	
16		2 No. 3	
2		4 No. 3	
6		No. 3 ties at $3d_b$	
7	No. 8	1 No. 3	
1		1 No. 4	
26		2 No. 3	
2		2 No. 4	
3		4 No. 3	
29		No. 3 ties at $3d_b$	
6		4 No. 4	
2	No. 11	1 No. 4	
8		2 No. 3	
2		5 No. 3	
18		No. 3 ties at $3d_b$	
2		5 No. 4	

The results of this analysis are shown in Figures 4.26, 4.27, and 4.28. Figure 4.26 shows the relationship between $T - T_c$ and $\left(NA_{tr}/n\right)d_b^{0.20}$. The spread of the intercepts of the trend lines corresponding to the individual bar sizes is smaller with the addition of the d_b term, and the dummy variables lines do not appear in order of descending bar diameter. Using the average intercept of the dummy variables lines, the equation describing the effect of the confining transverse reinforcement is

$$T_s = 32,700 \frac{NA_{tr}}{n} d_b^{\,0.20} - 1785 \tag{4.8}$$

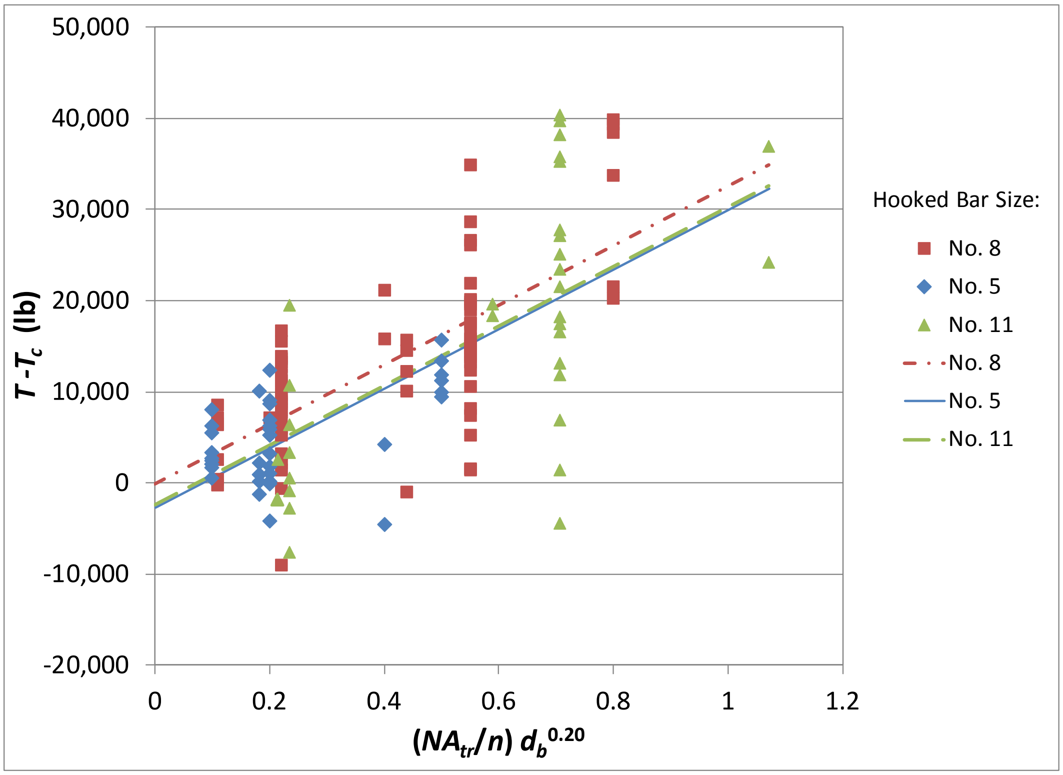


Figure 4.26 Anchorage strength in excess of the concrete contribution versus amount of transverse reinforcement and hooked bar diameter, with T_c based on Eq. (4.7)

Figure 4.27 shows the ratios of measured to the calculated bar force at failure T_{test}/T_{calc} versus the hooked bar diameter d_b, where $T_{calc} = T_c + T_s$ with T_c from Eq. (4.7) and T_s from Eq. (4.8). The test-to-calculated anchorage strength ratios range between 0.62 and 1.29. The intercepts of the trend lines are 0.99 for specimens with No. 5 bars, 1.03 for specimens with No. 8 bars, and 0.98 for specimens with No. 11 bars. The nearly zero slope of the lines suggests that

$d_b^{0.20}$ captures the effect of the hooked bar diameter on the anchorage capacity provided by confining transverse reinforcement. The mean ratio of the test-to-calculated ratio is 1.00, with a coefficient of variation of 0.109.

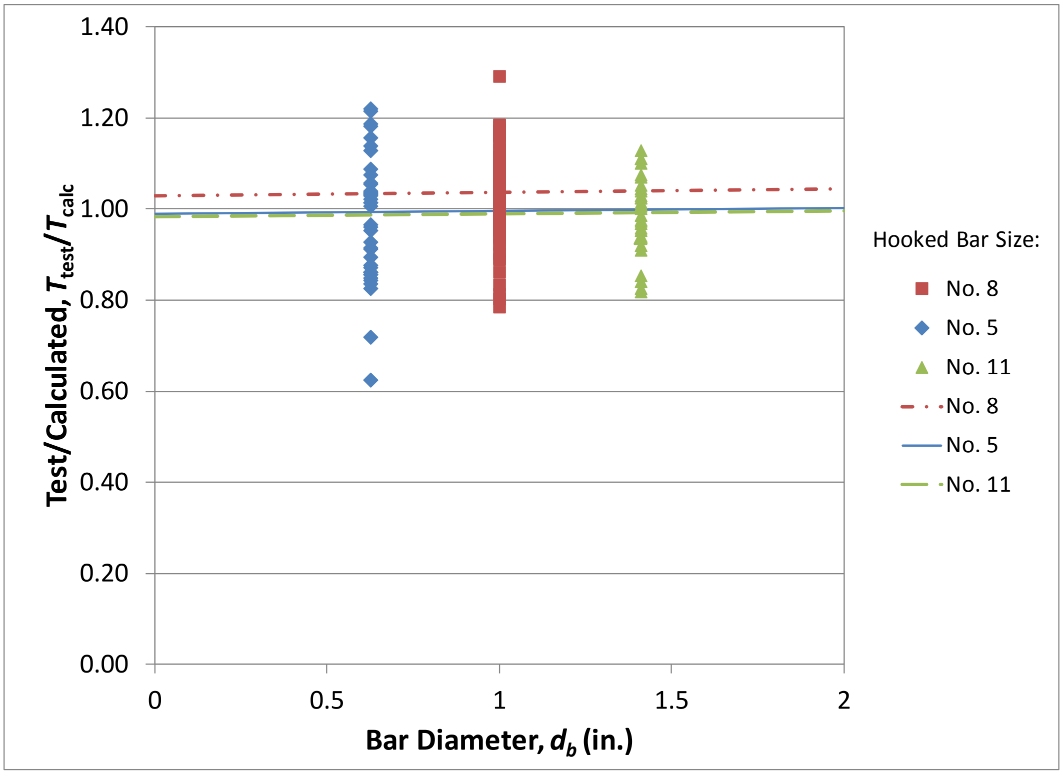


Figure 4.27 Test-to-calculated anchorage strength ratio versus bar diameter for hooked bars with confining transverse reinforcement, with T_{calc} based on Eq. (4.7) and (4.8)

Figure 4.28 shows the relationship between the test-to-calculated anchorage strength ratio and concrete compressive strength for the specimens with confining transverse reinforcement. The negative slope of the trend lines indicates that the effect of concrete compressive strength is overestimated by the parameter $f_{cm}^{0.29}$ in specimens with confining transverse reinforcement. This suggests, in turn, a lower relative concrete contribution as confining transverse reinforcement is added. For the test results shown in Figure 4.28 the concrete term, T_c, represents (on average) 84% of the capacity of the hooked bars. The intercepts of the trend lines are 1.04 for specimens with No. 5 bars, 1.08 for specimens with No. 8 hooked bars, and 1.06 for specimens with No. 11 hooked bars.

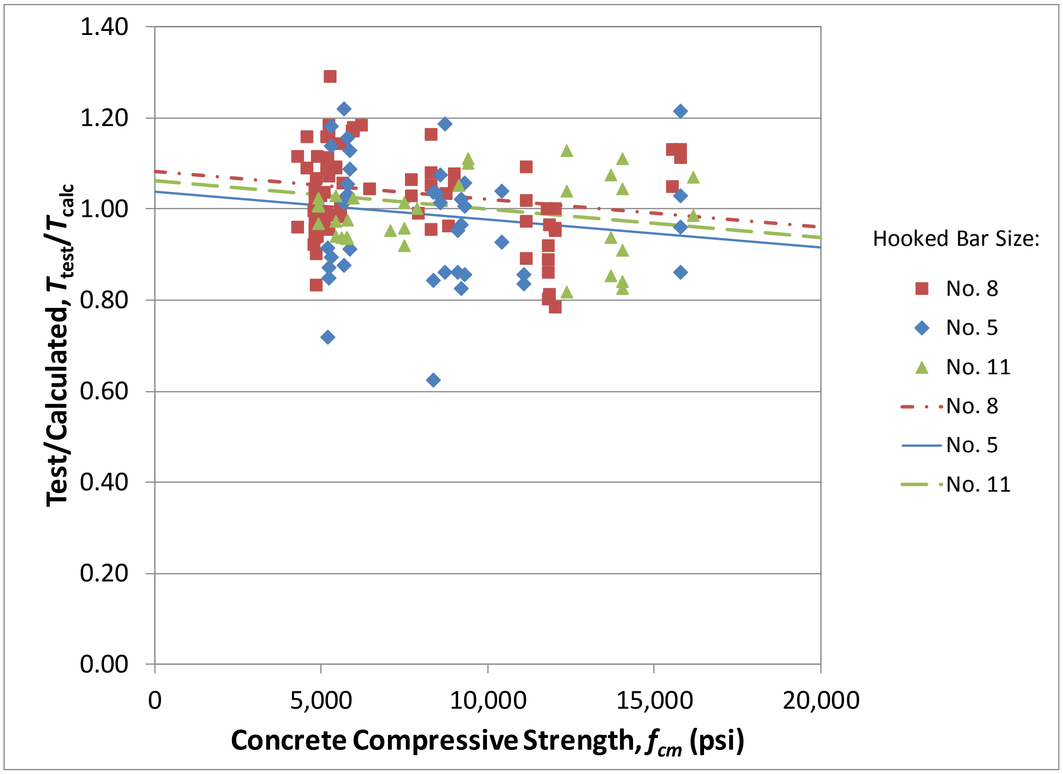


Figure 4.28 Test-to-calculated anchorage strength ratio versus concrete compressive strength for hooked bars with confining transverse reinforcement, based on Eq. (4.7) and (4.8)

Because concrete compressive strength had a lower effect on the anchorage strength of specimens with confining transverse reinforcement, and given that the contribution of the concrete T_c to the anchorage strength represents a large fraction of the total, the concrete term T_c was modified to account for this change in behavior. This process involved several iterative calculations. The first step was to determine the power p_1 that would produce a zero slope of the test-to-calculated ratio versus concrete compressive strength for the specimens with confining transverse reinforcement. The resulting expression representing the contribution of the concrete is given in Eq. (4.9).

$$\frac{T_c}{f_{cm}^{0.24}} = 486\ell_{eh}^{\ 1.09} d_b^{\ 0.49} \qquad (4.9)$$

T_c in Eq. (4.9), with a concrete compressive strength exponent p_1 equal to 0.24, was combined with the expression for T_s in Eq. (4.8) to calculate the total anchorage force T_h. The resulting anchorage strength ratio T_{test}/T_{calc} is plotted versus compressive strength in Figure 4.29. The figure shows that the dummy variables trend lines were nearly horizontal.

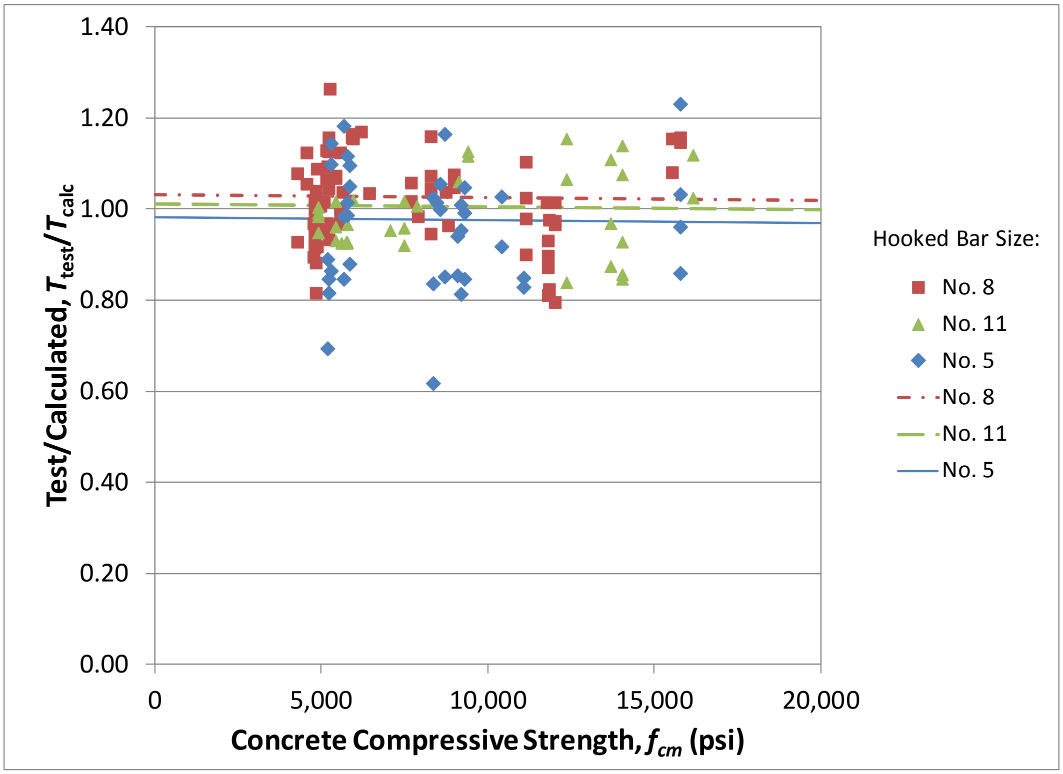


Figure 4.29 Test-to-calculated anchorage strength ratio versus concrete compressive strength for hooked bars with confining transverse reinforcement, with T_{calc} based on Eq. (4.8) and (4.9).

Figure 4.29 demonstrates that the parameter $f_{cm}^{0.24}$ adequately captures the effect of concrete compressive strength on anchorage strength for hooked bars with confining transverse reinforcement.

The relationship between the anchorage force in excess of the concrete contribution $T - T_c$ and the parameter $(NA_{tr}/n)d_b^{\,0.20}$ is plotted in Figure 4.30. The values of $T - T_c$ presented in Figure 4.30 were calculated using Eq. (4.8) and (4.9). . The intercepts of the dummy variables trend lines are -2,880, -363, and -638 for specimens with No. 5, 8, and 11 bars, respectively, and the spread of the intercepts corresponding to the different bar sizes is not as condensed as shown previously in Figure 4.26. This indicates that the exponent of 0.20 for the hooked bar diameter is not adequate when used in conjunction with an exponent of 0.24 for the concrete compressive strength.

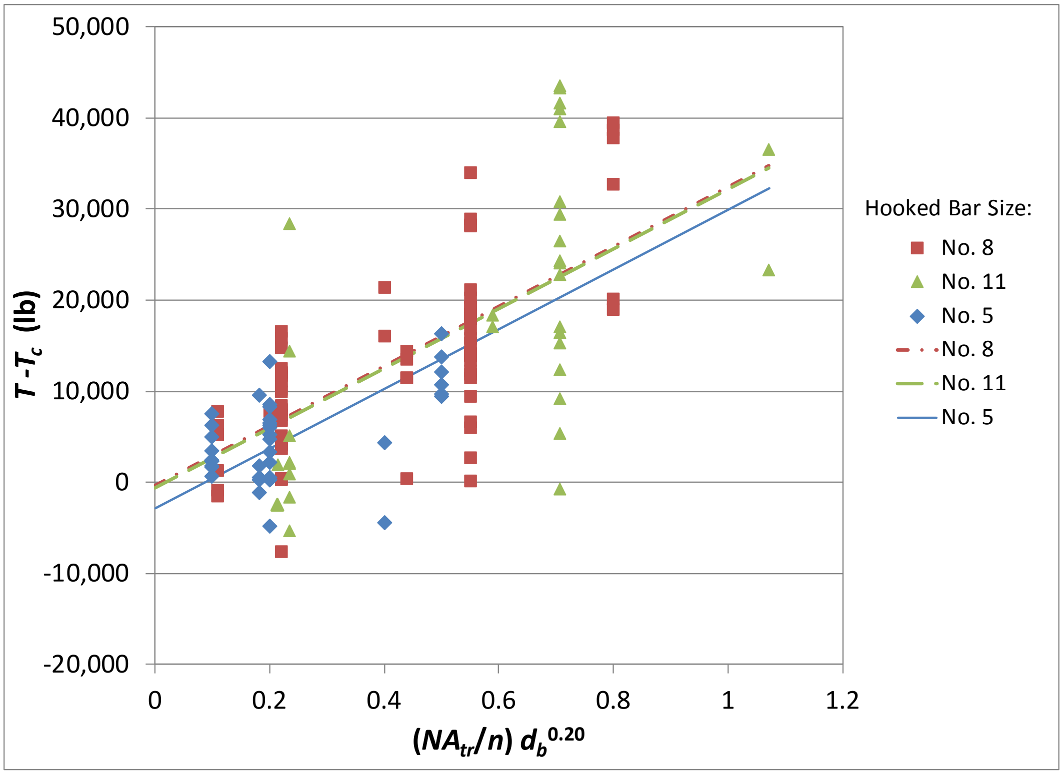


Figure 4.30 Anchorage strength in excess of the concrete contribution versus amount of confining transverse reinforcement and hooked bar diameter, with T_c based on Eq. (4.9)

The dummy variables analysis used to determine the exponent for d_b in Eq. (4.8) was repeated to account for the adjustment in the effect of concrete compressive strength on anchorage strength. Once again, an iterative analysis was performed to find the optimal relationship between $T - T_c$ and $(NA_{tr}/n)d_b^{p_3}$. The exponent of the bar diameter d_b in parameter $(NA_{tr}/n)d_b^{p_3}$ was modified until the spread of the intercepts of trend lines corresponding to the different bar sizes was minimized, and the mean test-to-calculated anchorage strength ratio was approximately equal to 1.0. The resulting equation for the steel contribution to anchorage strength is given in Eq. (4.10).

$$T_s = 32{,}600 \frac{NA_{tr}}{n} d_b^{\,0.40} - 1{,}400 \tag{4.10}$$

Figure 4.31 shows the relationship between the anchorage strength in excess of the concrete contribution $T - T_c$ and the parameter $(NA_{tr}/n)d_b^{\,0.40}$. The contribution of the concrete to anchorage strength was calculated using Eq. (4.9). The spread of the intercepts of the trend lines corresponding to each of the bar sizes is smaller than shown in Figure 4.30. The intercepts of the dummy variables trend lines are -2,150, -254, and -1,810 for specimens with No. 5, 8, and 11 bars, respectively.

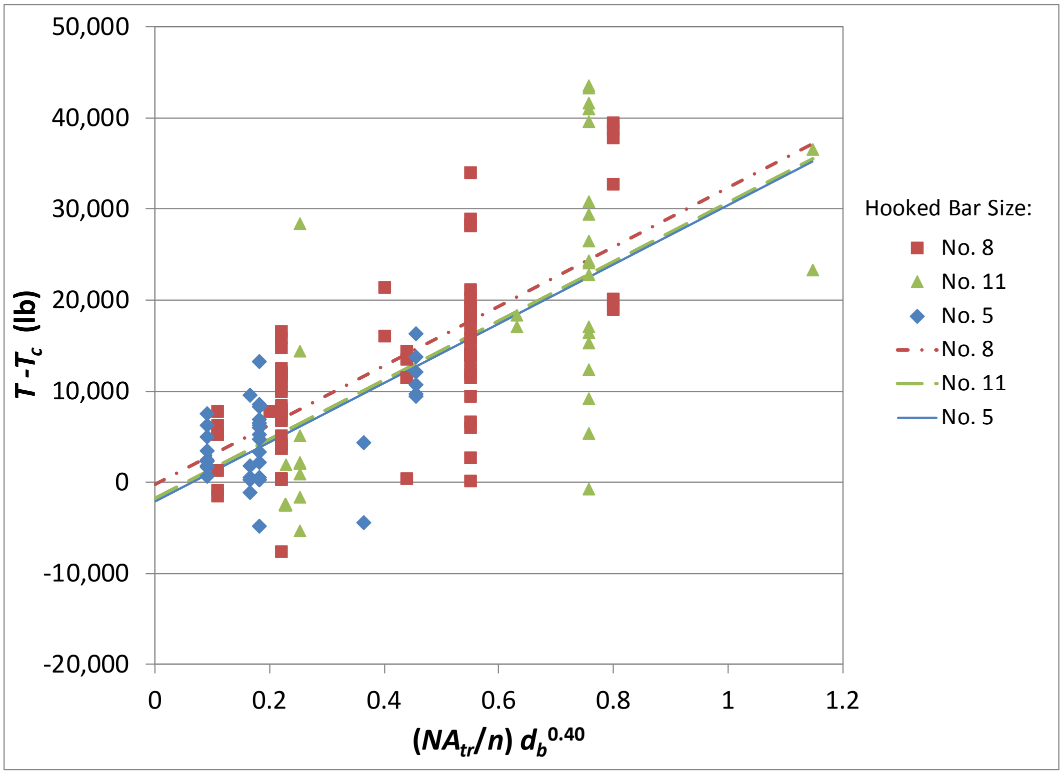


Figure 4.31 Anchorage strength in excess of the concrete contribution versus amount of confining transverse reinforcement and hooked bar diameter, with T_c based on Eq. (4.9)

As with the concrete contribution T_c, the negative intercepts of the dummy variables lines suggest that the relationship is not linear with respect to NA_{tr}/n. To capture this behavior, the data were reanalyzed by raising the term $(NA_{tr}/n)d_b^{0.40}$ to the power that minimized the sum of the squared differences $\left[(T-T_c)-T_s\right]^2$. The resulting equation is

$$T_s = 31{,}350\left(\frac{NA_{tr}}{n}d_b^{0.40}\right)^{1.11} = 31{,}350\left(\frac{NA_{tr}}{n}\right)^{1.11} d_b^{0.45} \qquad (4.11)$$

An equation for the anchorage strength of hooked bars with confining transverse reinforcement in exterior beam-column joints was obtained by adding the terms corresponding to the contributions of concrete and the confining transverse reinforcement given by Eq. (4.9) and (4.11).

$$T_h = 486 f_{cm}^{0.24} \ell_{eh}^{\ 1.09} d_b^{\ 0.49} + 31{,}350 \left(\frac{NA_{tr}}{n} \right)^{1.11} d_b^{\ 0.45} \tag{4.12}$$

Figure 4.32 shows the test-to-calculated anchorage strength ratio as a function of bar diameter based on Eq. (4.12). The dummy variables trend lines are nearly horizontal and the intercepts for trend lines corresponding to specimens with No. 5, 8, and 11 bars are 0.99, 1.02, and 0.99, respectively. The mean test-to-calculated strength ratio is 1.0, and the coefficient of variation and standard deviation are 0.105. The test-to-calculated anchorage strength ratio ranged between 0.642 and 1.28.

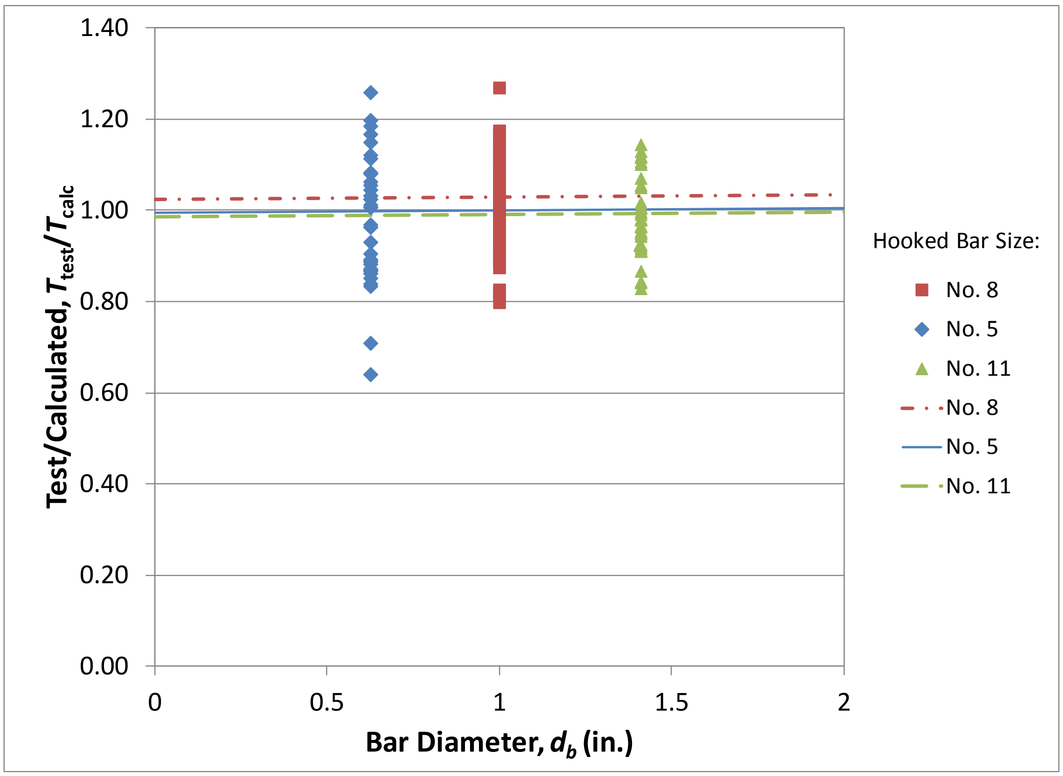


Figure 4.32 Test-to-calculated anchorage strength ratio versus bar diameter for hooked bars with confining transverse reinforcement, with T_{calc} based on Eq. (4.12)

The test-to-calculated anchorage strength ratio is plotted versus the concrete compressive strength in Figure 4.33. Anchorage strength was calculated using Eq. (4.12) for the data set of specimens with confining transverse reinforcement. Once again, the dummy variables trend lines are nearly horizontal, showing that the effect of concrete compressive strength is adequately represented by Eq. (4.12). The intercepts of the trend lines corresponding to specimens with No.

5, 8, and 11 bars are 1.00, 1.04, and 1.01, respectively. Using Eq. (4.12), T_c averages 83% of T_h, down from 84% when using $f_{cm}^{0.29}$ to characterize the influence of concrete compressive strength on the anchorage capacity of hooked bars confined by transverse reinforcement.

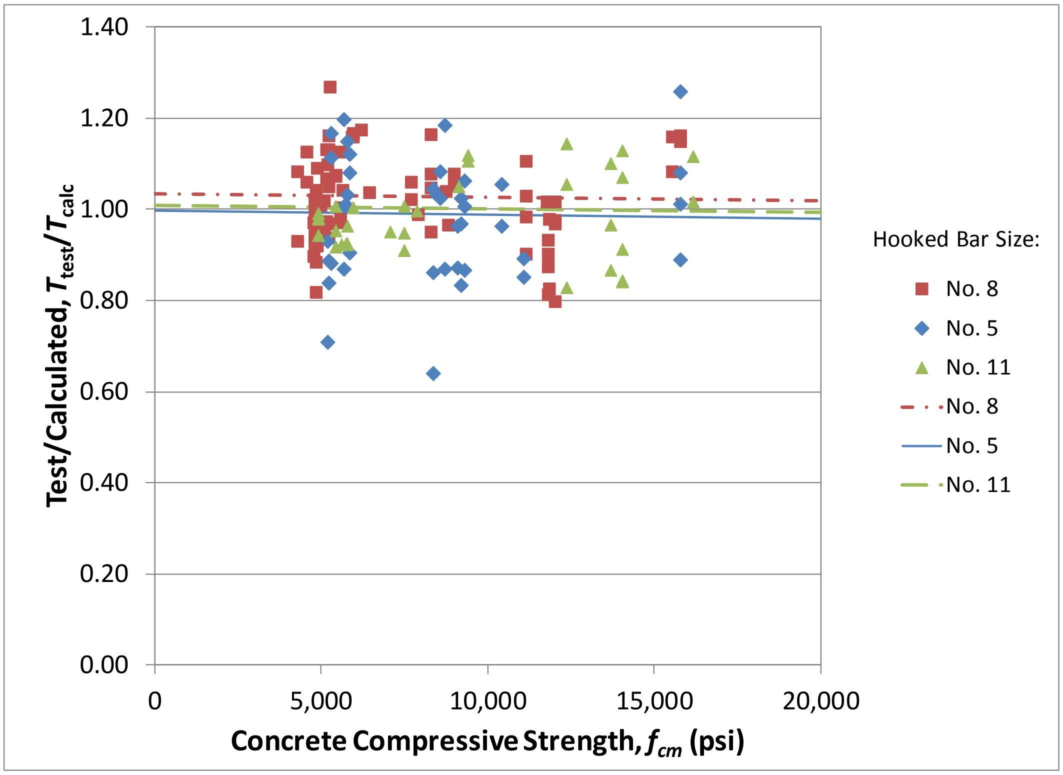


Figure 4.33 Test-to-calculated anchorage strength ratio versus concrete compressive strength for hooked bars with confining transverse reinforcement, with T_{calc} based on Eq. (4.12)

Figure 4.34 compares the anchorage forces measured in the tests to those calculated using Eq. (4.12). The dashed line represents cases in which the measured and calculated strengths are equal, while the solid line represents the best fit line for the data set. The fact that the solid line closely follows the dashed line indicates that Eq. (4.12) provides adequate estimates of anchorage strength for the entire range of tests.

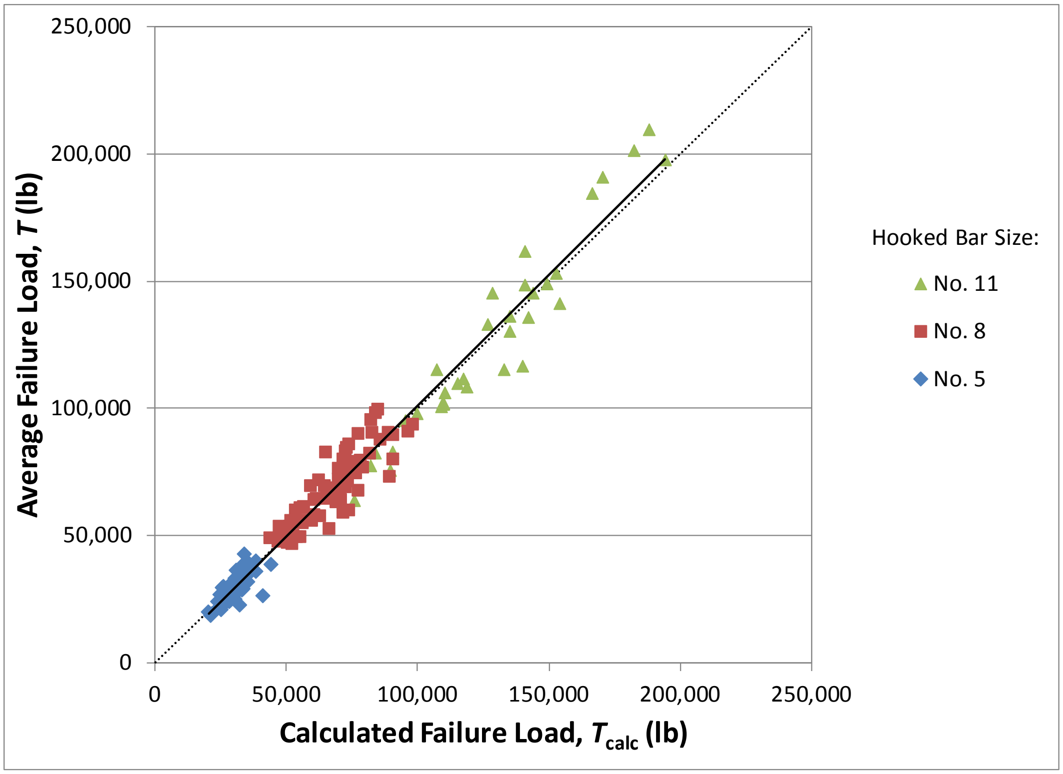


Figure 4.34 Measured versus calculated bar force at failure for hooked bars with confining transverse reinforcement, with T_{calc} based on Eq. (4.12)

As discussed in Section 4.3.4, transverse reinforcement that is oriented perpendicular to the straight portion of a hooked bar provides a lower anchorage capacity for hooked bars with a 90° bend angle than reinforcement oriented parallel to the straight portion of a hooked bar, while the two configurations provide similar anchorage capacities for hooked bars with a 180° bend angle. To further investigate this effect, the test-to-calculated ratios for the 90° and 180° hooked bars with horizontal and vertical ties (respectively, parallel and perpendicular to the straight portion of the hooked bar) compared in Section 4.3.4 are presented in Table 4.13. For this group of specimens, the test-to-calculated ratios are 1.00 or less. The table shows that the specimens with 90° hooked bars with vertical ties have test-to-calculated ratios lower than 180° hooked bars with vertical ties. On average, the 90° hooked bars with vertical ties have test-to-calculated ratios around 0.80 compared to values of 1.00 and 0.92 for 90° hooked bars with horizontal ties. The test-to-calculated ratios for 180° hooked bars with vertical ties ranges from 0.86 to 0.96 compared to a range of 0.89 to 0.95 for 180° hooked bars with horizontal ties.

Table 4.13 Test-to-calculated ratios for 90° and 180° hooked bars with horizontal and vertical ties, with calculation based on Eq. (4.12)

Transverse Reinforcement	Orientation	Hook Bend Angle	Test-to-Calculated Ratio
Two No. 3	Vertical	90°	0.78
Two No. 3	Vertical	180°	0.95
Four No. 3	Vertical	90°	0.81
Four No. 3	Vertical	180°	0.96
Five No. 3	Vertical	90°	0.80
Five No. 3	Vertical	180°	0.86
Two No. 3	Horizontal	90°	1.00
Two No. 3	Horizontal	180°	0.95
Five No. 3	Horizontal	90°	0.92
Five No. 3	Horizontal	180°	0.89

4.4 EFFECT OF MULTIPLE AND CLOSELY SPACED HOOKED BARS

Equation (4.12) was developed based on specimens with two hooked bars. Under this configuration, the majority of specimens had only a small range in center-to-center spacing between hooked bars, from $10d_b$ to $12d_b$. There are, however, many instances in construction in which flexural members contain more than two bars being anchored in a joint, and spacing between the bars can be as close as two bar diameters center-to-center. Although some of the two-hook specimens in this study had a center-to-center spacing as low as $3d_b$, they were comparatively few in number and did not address the case in which more than two hooked bars are anchored adjacent to each other. This section describes findings from tests in which three or four closely spaced hooked bars were anchored in a joint with center-to-center spacings of $3d_b$, $4d_b$, $5d_b$, $5.5d_b$, or $6d_b$ (see Sections 3.3.4 and 3.3.5).

Figure 4.35 shows the test-to-calculated ratios for specimens with both multiple hooked bars and two hooked bars without confining transverse reinforcement as a function of concrete compressive strength. The hollow symbols represent two-hook specimens, while the solid symbols represent the multiple-hook specimens. Figure 4.35 shows that, for the majority of multiple hooked bars, the anchorage capacity per bar was significantly lower (64 to 84%) than the average anchorage capacity per bar for specimens with only two hooked bars. Of the multiple-hooked bar specimens, only three specimens had test-to-calculated ratios near or above one. Figure 4.35 also shows that the decrease in capacity was more significant for the No. 8

hooked bars than it was for the No. 5 hooked bars. This behavior would be expected if joint shear were a controlling factor because force demands and column strains are much larger when the extra bars are added. An analysis of the joint shear, however, showed that all multiple and two-hook specimens without transverse reinforcement had joint shear stresses that were less than $15\sqrt{f_{cm}}$, the limit set for joint shear for this type of connection in ACI 352R-02. One of the limitations of this portion of study is that the number of tests with more than two hooked bars was small (15 specimens without confining transverse reinforcement and 25 with confining transverse reinforcement). The test parameters for the multiple-hook specimens with no confining transverse reinforcement are shown in Table 4.14.

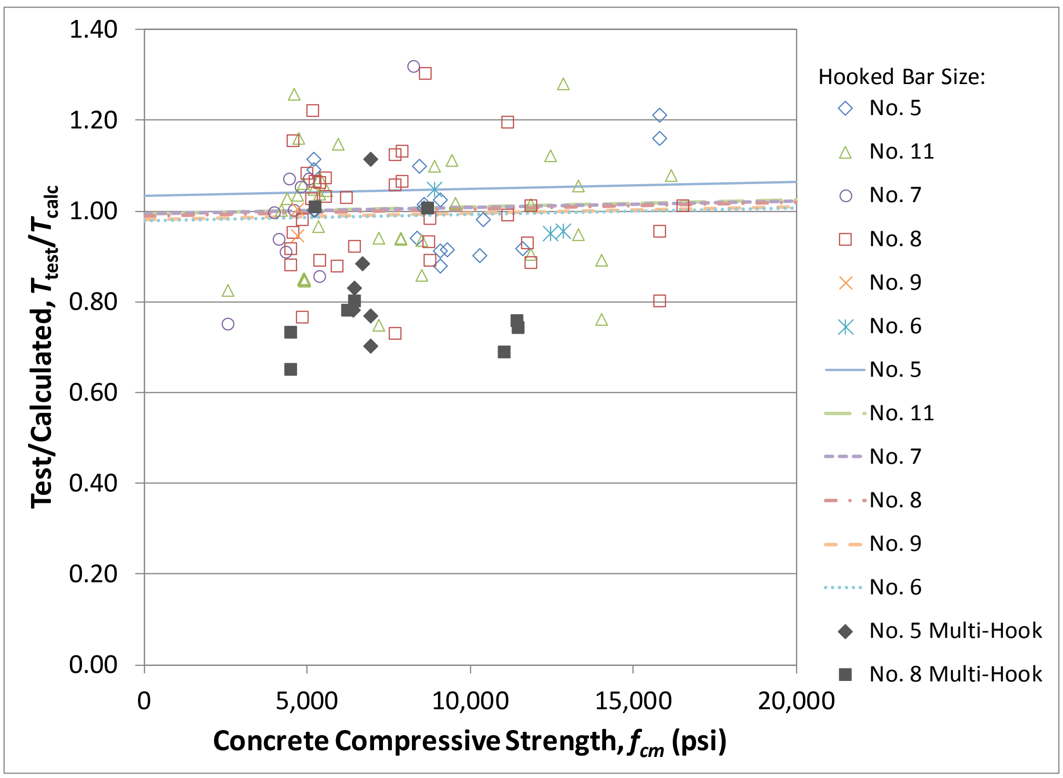


Figure 4.35 Test-to-calculated anchorage strength ratio versus concrete compressive strength for hooked bars without confining transverse reinforcement, with T_{calc} based on Eq. (4.12). Data points not identified as Multi-Hook represent specimens containing two hooked bars

Table 4.14 Test parameters for multiple-hook specimens with no confining transverse reinforcement included in Figures 4.35 and 4.36

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	T_{test}/T_{calc}	Failure Type[c]
(4@4) 5-5-90-0-i-2.5-2-6	A	90°	5.4	5.2	6430	13	2.4	2.6	2.8	1.9	4	12200	14500	0.78	FP
	B		5.3				4.9		2.9	1.9		16800			FP
	C		4.8				5.1		3.4	1.8		15500			FP
	D		5.3				2.8		2.9			13700			FP
(4@4) 5-5-90-0-i-2.5-2-10	A	90°	9.0	9	6470	13	2.6	2.7	3.3	1.8	4	27900	28400	0.83	FP
	B		8.0				5		4.3	1.9		28600			FP
	C		9.3				5		3	1.6		44800			FP
	D		9.9				2.8		2.4	-		27600			FP
(4@4) 5-8-90-0-i-2.5-2-6	A	90°	6.3	5.9	6950	13	2.5	2.5	1.8	1.9	4	17300	15500	0.70	FP/SS
	B		5.8				5		2.3	1.6		17600			FP/SS
	C		5.8				5		2.3	1.9		14100			FP/SS
	D		6.0				2.5		2	-		14100			FP/SS
(4@6) 5-8-90-0-i-2.5-2-6	A	90°	6.0	5.9	6693	17	2.7	2.7	2	3.1	4	20600	19300	0.88	FP
	B		6.0				6.5		2	3.1		22500			FP
	C		5.8				6.5		2.3	3.1		22900			FP
	D		6.0				2.7		2	-		15100			FP
(3@4) 5-8-90-0-i-2.5-2-6	A	90°	6.0	5.88	6950	11	2.6	2.63	2	1.8	3	18500	16800	0.77	FP
	B		5.6				5.6		2.4	1.9		17600			FP
	C		6.0				2.7		2	-		14700			FP
(3@6) 5-8-90-0-i-2.5-2-6	A	90°	6.38	6	6950	13	2.6	2.63	1.6	3	3	25500	24900	1.11	FP
	B		5.88				6.2		2.1	3.1		34900			FP
	C		5.75				2.7		2.3	-		23200			FP
(3@5.5) 8-5-90-0-i-2.5-2-16	A	90°	16.5	16.1	6255	17	2.6	2.7	1.6	4.4	3	65300	62800	0.78	FP
	B		15.8				8		2.4	4.5		103700			FP
	C		16.0				2.8		2.1	-		46500			FP
(3@5.5) 8-5-90-0-i-2.5-2-10	A	90°	9.0	9.4	6461	17	2.6	2.6	3.2	4.4	3	26800	36100	0.80	FP
	B		9.4				7.9		2.8	4.4		57400			FP
	C		9.8				2.5		2.4	-		26300			FP
(3@3) 8-5-90-0-i-2.5-2-10	A	90°	10.0	10.1	4490	12	2.6	2.6	2	2.4	3	30670	28500	0.65	FP
	B		10.3				5.5		1.8	2.3		43700			FP
	C		10.0				2.5		2	-		21400			FP
(3@5) 8-5-90-0-i-2.5-2-10	A	90°	10.3	10.1	4490	16	2.3	2.4	1.8	4	3	56500	32200	0.73	FP
	B		10.1				7.3		1.9	4.3		46300			FP
	C		10.0				2.5		2	-		55000			FP
(3@5.5) 8-8-90-0-i-2.5-2-8	A	90°	7.8	7.9	8700	17	3	2.9	2.4	4.3	3	41000	41000	1.01	FP
	B		8.8				8.2		1.4	3.4		41000			FP
	C		7.3				2.8		2.9	-		41000			FP
(3@3) 8-12-90-0-i-2.5-2-12‡	A	90°	12.1	12.1	11040	12	2.5	2.5	1.8	2.1	3	56500	48000	0.69	SB
	B		12.1				5.4		1.9	2		46300			FP
	C		12.2				2.4		1.8	-		55000			FP
(3@4) 8-12-90-0-i-2.5-2-12‡	A	90°	12.9	12.6	11440	14	2.5	2.5	1.3	2.9	3	56800	55800	0.76	FP/SS
	B		12.5				6.4		1.6	3		76100			FP
	C		12.5				2.5		1.6	-		57700			FP/SS

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table 4.14 Cont Test parameters for multiple-hook specimens with no confining transverse reinforcement included in Figures 4.35 and 4.36

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	$T_{\text{test}}/T_{\text{calc}}$	Failure Type[c]
(3@5) 8-12-90-0-i-2.5-2-12‡	A	90°	12.3	12.2	11460	16	2.4	2.4	1.8	4	3	53300	52400	0.74	FP
	B		12				7.4		2	4		66100			FP
	C		12.3				2.5		1.8	-		60800			FP
(3@5) 8-5-180-0-i-2.5-2-10‡	A	180°	10	10	5260	16	2.5	2.5	2	4.3	3	41500	45900	1.01	FP
	B		10				7.8		2	4.3		60400			FP
	C		10				2.5		2	-		37900			FP

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Figure 4.36 shows the test-to-calculated ratio for the multiple-hooked bar specimens as a function of center-to-center spacing, expressed in multiples of bar diameter d_b, for specimens without confining transverse reinforcement. For the specimens with two hooked bars, the dummy variables lines are nearly horizontal with respect to spacing, indicating that, when only two hooked bars are present, the spacing of the hooked bars has little influence on the anchorage capacity down to approximately $3d_b$ center-to-center spacing. For the multiple-hook specimens with low center-to-center spacing (all have a spacing of less than $6d_b$), the capacities of the hooked bars are significantly reduced–as low as 64% of the capacity of a hooked bar in a specimen containing two hooks. As bar spacing increases, this reduction becomes less severe, with the trend line indicating no reduction for specimens with spacing approximately greater than $8d_b$.

As shown in Figure 4.37, the addition of transverse reinforcement reduced the difference between the anchorage strength of two-hook and multiple-hook specimens, although the anchorage strength of multiple hook specimens was still approximately 80 to 85% of that corresponding to two-hook specimens. In five cases out of the 25 considered, the ratio of strength measured in the test to that calculated using Eq. (4.12) was greater than 1.0 for the multiple hook specimens. Table 4.15 shows the test parameters for the multiple-hook specimens shown in Figures 4.37 and 4.38.

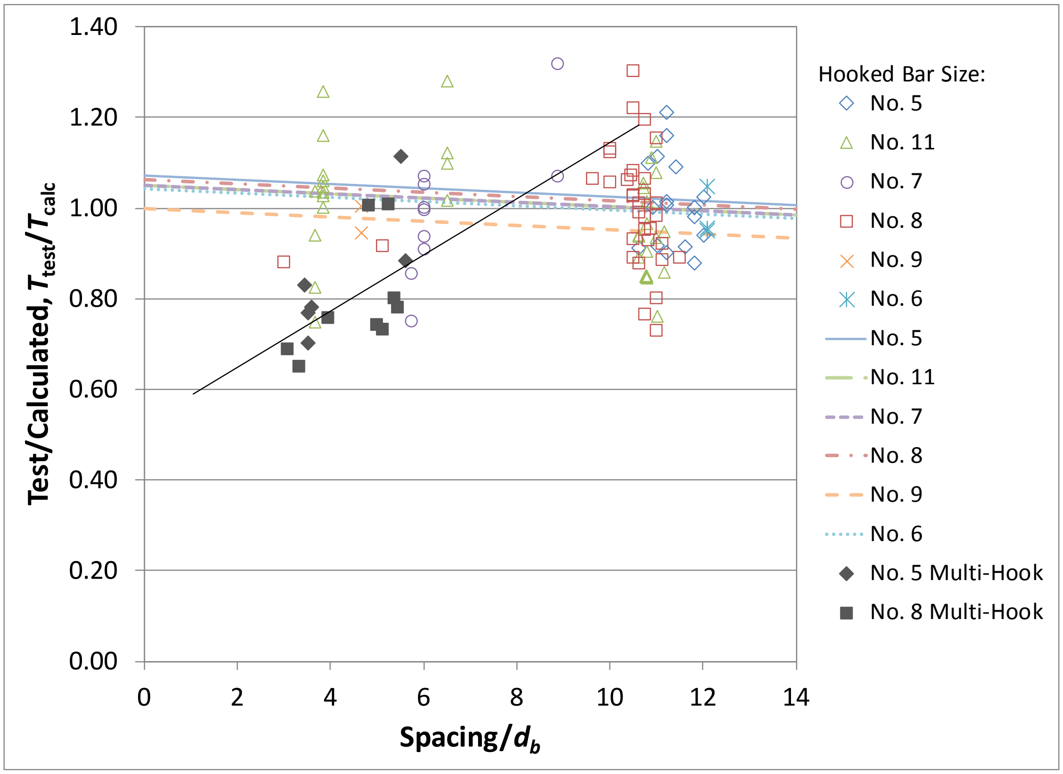


Figure 4.36 Test-to-calculated anchorage strength ratio versus center-to-center spacing for hooked bars without confining transverse reinforcement, with T_{calc} based on Eq. (4.12)

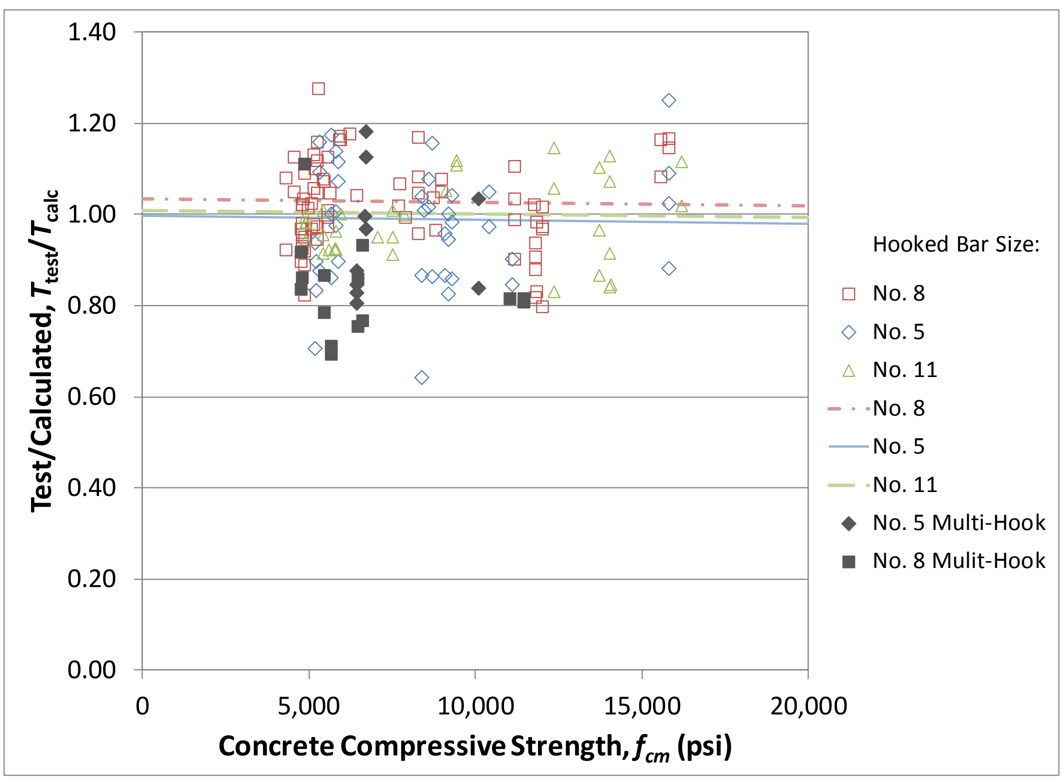


Figure 4.37 Test-to-calculated anchorage strength ratio versus concrete compressive strength for hooked bars with confining transverse reinforcement, with T_{calc} based on Eq. (4.12)

Table 4.15 Test parameters for multiple-hook specimens with confining transverse reinforcement included in Figures 4.35 and 4.36

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	T_{test}/T_{calc}	Failure Type[c]
(4@4) 5-5-90-2#3-i-2.5-2-6	A	90°	6.3	6.3	6430	13	2.5	2.5	1.9	1.9	4	22400	21400	0.84	FP
	B		6.1				5.0		2.0	1.9		22200			FP
	C		6.3				4.8		1.9	1.6		24000			FP
	D		6.4				2.5		1.8	-		21700			FP
(4@4) 5-5-90-2#3-i-2.5-2-8	A	90°	8.4	8	6430	13	2.5	2.5	1.8	1.9	4	24000	26000	0.8	FP
	B		7.8				5.0		2.4	1.9		31200			FP
	C		8.0				4.9		2.1	1.8		36000			FP
	D		7.8				2.5		2.4	-		23700			FP
(3@6) 5-8-90-5#3-i-2.5-2-6.25	A	90°	5.0	5.5	10110	13	2.5	2.5	3.8	2.9	3	27100	25800	0.84	FP
	B		6.3				5.4		2.6	3.0		32400			FP
	C		5.3				2.5		3.6	-		26800			FP
(3@4) 5-8-90-5#3-i-2.5-2-6‡	A	90°	6.0	6.1	6703	11	2.5	2.5	2.0	2.1	3	35800	34900	1.12	FP
	B		6.3				5.0		1.8	1.9		34700			FP
	C		6.0				2.5		2.0	-		34400			FP
(3@6) 5-8-90-5#3-i-2.5-2-6‡	A	90°	6.0	6	6703	13	2.5	2.5	2.0	3.4	3	37800	36300	1.18	FP
	B		6.0				5.0		2.0	3.1		34800			FP
	C		6.0				2.5		2.0	-		37500			FP
(4@4) 5-5-90-5#3-i-2.5-2-7	A	90°	6.6	7.1	6430	13	2.5	2.4	2.5	1.5	4	27300	27100	0.83	FP
	B		7.9				4.6		1.3	2.0		37000			FP
	C		7.5				4.6		1.6	1.6		29500			FP
	D		6.5				2.4		2.6	-		23000			FP
(4@4) 5-5-90-5#3-i-2.5-2-6	A	90°	6.0	6.3	6430	13	2.5	2.6	2.5	2.0	4	24900	25900	0.88	FP
	B		6.5				5.1		2.0	1.8		27200			FP
	C		6.6				5.0		1.9	1.8		26800			FP
	D		6.3				2.6		2.3	-		26600			FP
(4@6) 5-8-90-5#3-i-2.5-2-6‡	A	90°	6.0	6	6693	17	2.7	2.7	2.0	3.4	4	30300	28300	1.0	FP
	B		6.0				6.5		2.0	3.4		30100			FP
	C		6.0				6.5		2.0	3.1		27600			FP
	D		6.0				2.7		2.0	-		25300			FP
(4@4) 5-8-90-5#3-i-2.5-2-6‡	A	90°	5.8	6	6703	17	2.5	2.5	2.3	1.9	4	28000	27500	0.97	FP
	B		5.5				5.0		2.5	1.9		27300			FP
	C		6.3				5.0		1.8	1.9		28600			FP
	D		6.5				2.5		1.5	-		26200			FP
(3@6) 5-8-90-5#3-i-3.5-2-6.25	A	90°	6.3	6.3	10110	15	3.5	3.6	2.1	2.6	3	36100	35300	1.03	FP
	B		6.3				6.6		2.1	3.3		33800			FP
	C		6.3				3.8		2.1	-		40800			FP
(3@5.5) 8-5-90-2#3-i-2.5-2-14	A	90°	14.6	14.4	6460	17	2.8	2.6	1.5	4.4	3	66800	57300	0.75	FP
	B		13.9				8.0		2.2	4.5		65800			FP
	C		14.8				2.5		1.3	-		62300			FP
(3@5.5) 8-5-90-2#3-i-2.5-2-8.5	A	90°	9.8	9.1	6460	17	2.5	2.5	0.9	4.3	3	25200	40900	0.86	FP
	B		8.8				7.8		1.9	4.3		68700			FP
	C		8.9				2.5		1.8	-		39200			FP
(3@5.5) 8-5-90-2#3-i-2.5-2-14(1)	A	90°	14.7	14.9	5450	17	2.8	2.7	1.7	4.2	3	58700	65300	0.86	FP/TK
	B		15.2				7.9		1.2	4.3		97100			FP/TK
	C		14.8				2.6		1.6	-		70200			FP/TK

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Table 4.15 Cont Test parameters for multiple-hook specimens with confining transverse reinforcement included in Figures 4.35 and 4.36

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	$T_{\text{test}}/T_{\text{calc}}$	Failure Type[c]
	A		7.3				2.3		3.5	4.5		36600			FP
(3@5.5) 8-5-90-2#3-i-2.5-2-8.5(1)	B	90°	8.9	8.2	5450	17	7.9	2.5	1.8	4.3	3	43600	32400	0.78	FP
	C		8.4				2.6		2.3	-		35200			FP
	A		9.9				2.6		2.1	2.0		41000			FP
(3@3) 8-5-90-2#3-i-2.5-2-10	B	90°	10.1	10	4760	12	5.6	2.6	1.9	2.0	3	41000	40700	0.83	FP
	C		10.0				2.5		2.0	-		37000			FP
	A		10.5				2.5		1.5	4.5		43300			FP
(3@5) 8-5-90-2#3-i-2.5-2-10	B	90°	10.6	10.5	4760	16	8.0	2.6	1.4	3.9	3	54600	44700	0.92	FP
	C		10.4				2.8		1.6	-		42800			FP
	A		8.0				2.5		2.2	4.1		30600			FP
(3@5.5) 8-5-90-5#3-i-2.5-2-8	B	90°	8.1	8	6620	17	7.6	2.5	2.1	4.5	3	47000	37100	0.77	FP
	C		7.8				2.5		2.4	-		34100			FP
	A		12.4				2.5		1.8	4.3		60300			FP
(3@5.5) 8-5-90-5#3-i-2.5-2-12	B	90°	12.1	12.2	6620	17	7.8	2.5	2.1	4.5	3	110800	66100	0.93	FP
	C		12.1				2.5		2.1	-		59300			FP
	A		7.3				2.9		2.9	3.8		29800			FP
(3@5.5) 8-5-90-5#3-i-2.5-2-8(1)	B	90°	8.4	7.6	5660	17	7.6	2.9	1.8	4.1	3	30200	31400	0.69	FP
	C		7.3				2.9		2.9	-		34700			FP
	A		11.4				2.5		2.8	4.3		55500			FP
(3@5.5) 8-5-90-5#3-i-2.5-2-12(1)	B	90°	12.5	12	5660	17	7.8	2.6	1.7	4.5	3	74600	47900	0.71	FP
	C		12.0				2.6		2.2	-		44400			FP
	A		10.0				2.8		2.0	2.1		48000			FP
(3@3) 8-5-90-5#3-i-2.5-2-10	B	90°	9.8	9.9	4810	12	5.9	2.5	2.3	2.1	3	44000	47300	0.86	FP
	C		9.9				2.3		2.1	-		48000			FP
	A		10.0				2.5		2.0	4.0		58900			FP
(3@5) 8-5-90-5#3-i-2.5-2-10	B	90°	10.0	9.9	4850	16	7.5	2.6	2.0	4.0	3	63400	61300	1.11	FP
	C		9.8				2.8		2.3	-		69400			FP
	A		11.9				2.5		2.3	2.0		70400			FP
(3@3) 8-12-90-5#3-i-2.5-2-12‡	B	90°	11.9	11.8	11040	12	5.5	2.5	2.3	2.0	3	85000	62200	0.81	FP
	C		11.6				2.5		2.5	-		62100			FP
	A		12.5				2.5		1.8	2.8		70700			FP
(3@4) 8-12-90-5#3-i-2.5-2-12‡	B	90°	12.0	12.3	11440	14	6.3	2.5	2.3	3.0	3	100000	64900	0.81	FP
	C		12.5				2.5		1.8	-		63700			FP
	A		11.9				2.5		2.2	4.0		59400			FP
(3@5) 8-12-90-5#3-i-2.5-2-12‡	B	90°	12.4	12.2	11460	16	7.5	2.5	1.7	4.0	3	85500	64800	0.8	FP
	C		12.3				2.5		1.8	-		69200			FP

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
‡ Specimen contained A1035 Grade 120 for column longitudinal steel

Figure 4.38 shows the test-to-calculated ratio as a function of center-to-center spacing, expressed in multiples of bar diameter d_b, for the multiple-hooked bar specimens with transverse reinforcement. The decrease in capacity for specimens with lower center-to-center spacing is not as great as the decrease for the specimens with no confining transverse reinforcement, showing that the addition of transverse reinforcement reduces the adverse effects of spacings below $8d_b$.

Unlike the results for the specimens without confining transverse reinforcement shown in Figure 4.36, the dummy variables lines for two-hooked bar specimens slope upward, with the average intercept of the lines near 0.85. The three two-hooked bar specimens with low center-to-center spacing (3 to 5d_b) have test-to-calculated values that are representative of those for the multiple-hooked bar specimens, with an average value of approximately 0.90.

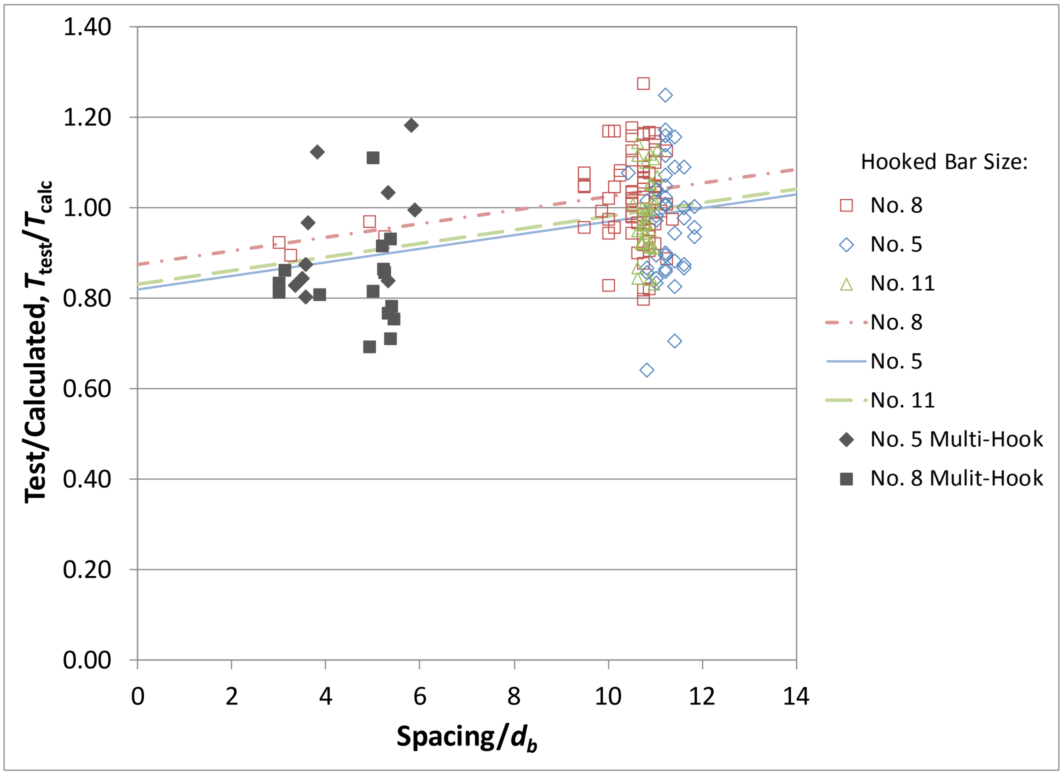


Figure 4.38 Test-to-calculated anchorage strength ratio versus center-to-center spacing for hooked bars with confining transverse reinforcement, with T_{calc} based on Eq. (4.12)

Because the use of multiple (more than two) hooked bars and closely spaced hooked bars causes a decrease in bar force at failure, there is a need to characterize the effect of multiple and closely spaced hooked bars. This will be addressed more fully in Chapter 5. Further testing is needed to understand how the nature of the failure changes when multiple hooked bars or closely spaced hooked bars are used.

4.5 EFFECT OF HOOK LOCATION

The effect of hook location, inside or outside the column core or outside compression region of the column, on anchorage strength is investigated in this section. Placement inside or outside the column core will be considered first.

Hooked bars placed outside the core were meant to represent hooked bars anchored in locations other than beam-column joints, such as in cantilevered beams. This effect was investigated through two different comparisons. The first consisted of a direct comparison of beam-column specimens with different hook placements cast in the same batch. The second comparison involved a dummy variables analysis to determine the differences between the anchorage strength of hooked bars cast inside the column core and hooked bars cast outside the core. This second analysis was conducted for specimens with No. 5 hooked bars without confining transverse reinforcement, two No. 3 ties, and No. 3 ties spaced at $3d_b$; No. 8 hooked bars without confining transverse reinforcement and No. 3 ties spaced at $3d_b$; and No. 11 hooked bars without confining transverse reinforcement and No. 3 ties spaced at $3d_b$. Student's t-test was used to determine if the differences in capacity were statistically significant. For comparisons in the same batch, the α value of the Student's t-test was calculated by comparing the failure load for each specimen. For comparisons of different batches, the α value of the Student's t-test was calculated by comparing intercepts with the T_N axis obtained by extending the lines through each data point parallel to the dummy variables trend lines. For this section, a value of α greater than 0.20 was considered to indicate that the differences in anchorage strength were not statistically significant. Given the small data set, it was considered that using the lower threshold value for α of 0.05 would be impractical.

The effect of hook location (inside or outside the column core) on anchorage capacity is shown in Figures 4.39 through 4.41. The vertical lines in the graphs show the range of the average bar stress at failure for the specimens. Figure 4.39 shows the results for three specimens that contained No. 8 hooked bars cast outside the column core with No. 3 ties spaced at $3d_b$ and three specimens that contained No. 8 hooked bars cast inside the column core with No. 3 ties spaced at $3d_b$. The specimens were cast at the same time using concrete with a nominal compressive strength of 5,000 psi. The side cover on the hooked bars was 2.5 in., and the nominal embedment length was 10 in. Figure 4.39 shows the average values and ranges of bar stress at failure in units of psi. The test parameters and measured strengths for these tests are shown in Table 4.16. These results show that the hooked bars placed inside the column core had a larger anchorage strength than hooked bars placed outside the column core, with respective average bar stresses at failure of 74,900 and 93,400 psi. The failure mode for the hooked bars cast outside the column core was predominantly a side failure while the failure mode for the hooked bars cast inside the core was front pullout. The results of Student's t-test indicate that for specimens with confining transverse reinforcement, the difference in anchorage strength between No. 8 hooked bars cast outside and inside the column core was statistically significant, with α = 0.065.

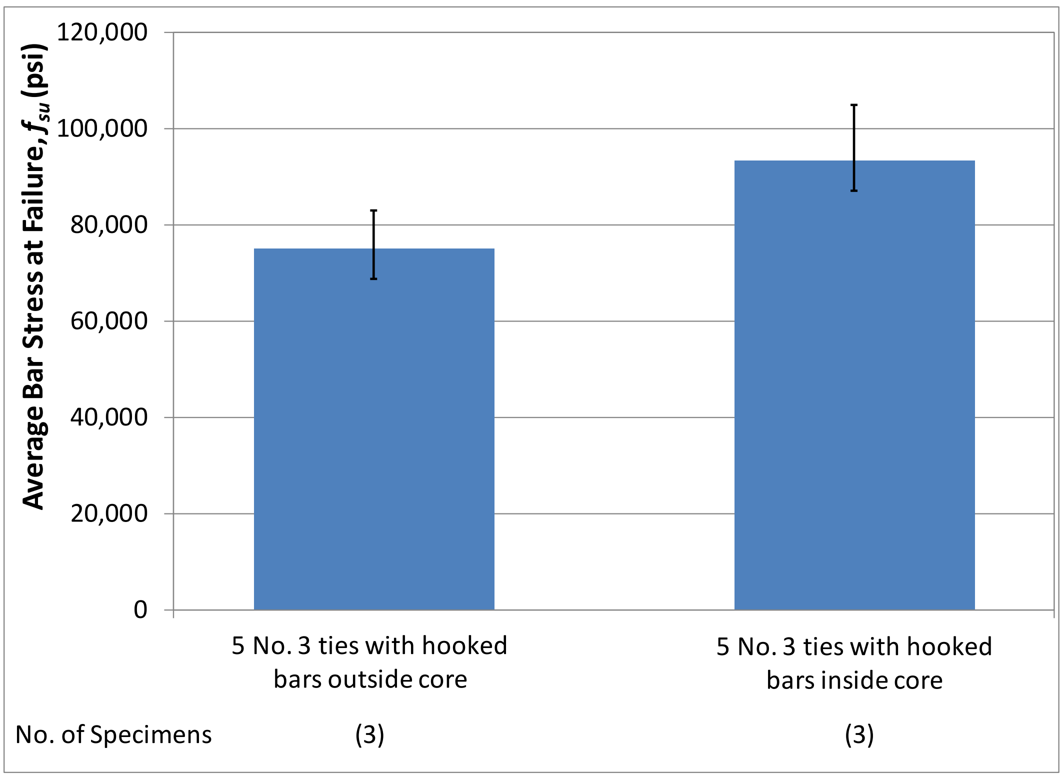


Figure 4.39 Anchorage strength for No. 8 hooked bars inside and outside the column core with No. 3 ties spaced at $3d_b$

Table 4.16 Test results for No. 8 hooked bars inside and outside the column core with No. 3 ties spaced at $3d_b$

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	b^b in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T lb	T_{avg} lb	$f_{su,avg}$ psi	Failure Type[c]
8-5-90-5#3-o-2.5-2-10a	A	90°	10.3	10.4	5270	A1035	17	2.6	2.6	1.8	9.9	55700	54300	68700	SS
	B	90°	10.5	10.4	5270	A1035	17	2.6	2.6	2.0	9.9	55800	54300	68700	SB
8-5-90-5#3-o-2.5-2-10b	A	90°	10.5	10.5	5440	A1035	17	2.5	2.6	2.0	9.9	66400	65600	83000	FP/SB
	B	90°	10.5	10.5	5440	A1035	17	2.6	2.6	2.0	9.9	69500	65600	83000	SB/FP
8-5-90-5#3-o-2.5-2-10c	A	90°	11.3	10.9	5650	A1035	17	2.6	2.6	1.3	9.9	80600	57700	73000	SS/FP
	B	90°	10.5	10.9	5650	A1035	17	2.5	2.6	2.0	9.9	57700	57700	73000	SS/FP
8-5-90-5#3-i-2.5-2-10a	B	90°	10.5	10.5	5270	A1035	17	2.5	2.5	1.8	9.8	82800	82800	104800	FP/SS
8-5-90-5#3-i-2.5-2-10b	A	90°	10.3	10.4	5440	A1035	17	2.8	2.7	2.0	9.9	78800	69700	88200	FP/SS
	B	90°	10.5	10.4	5440	A1035	17	2.6	2.7	1.8	9.9	66700	69700	88200	FP
8-5-90-5#3-i-2.5-2-10c	A	90°	10.5	10.5	5650	A1035	17	2.5	2.5	2.0	10.0	68900	68800	87100	FP/SS
	B	90°	10.5	10.5	5650	A1035	17	2.5	2.5	2.0	10.0	69600	68800	87100	FP/SS

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

Figure 4.40 shows the results for three specimens that contained No. 8 hooked bars cast outside the column core and three specimens that contained No. 8 hooked bars cast inside the column core. Both sets of specimens had no confining transverse reinforcement. The specimens were cast at the same time using concrete with a nominal compressive strength of 8,000 psi. All specimens had a nominal embedment length of 8 in. Figure 4.40 shows the range of the average bar stress at failure. For each hooked bar placement (inside and outside the column core), the three specimens had nominal side covers of 2.5, 3.5 and 4 in. The test parameters and measured strengths of these specimens are shown in Table 4.17. The measured bar stresses at failure for this series indicate that hooked bars placed inside the column core had a higher anchorage strength than hooked bars placed outside the column core, with respective average bar stresses a failure of 49,100 and 44,900 psi. As with the previous set of specimens, the failure mode for the hooks cast inside the core had front pullout failure, whereas the hooks cast outside the core had predominately side failure. The results of Student's t-test indicate that the difference in anchorage strength between the two groups is statistically significant with a value of α = 0.195.

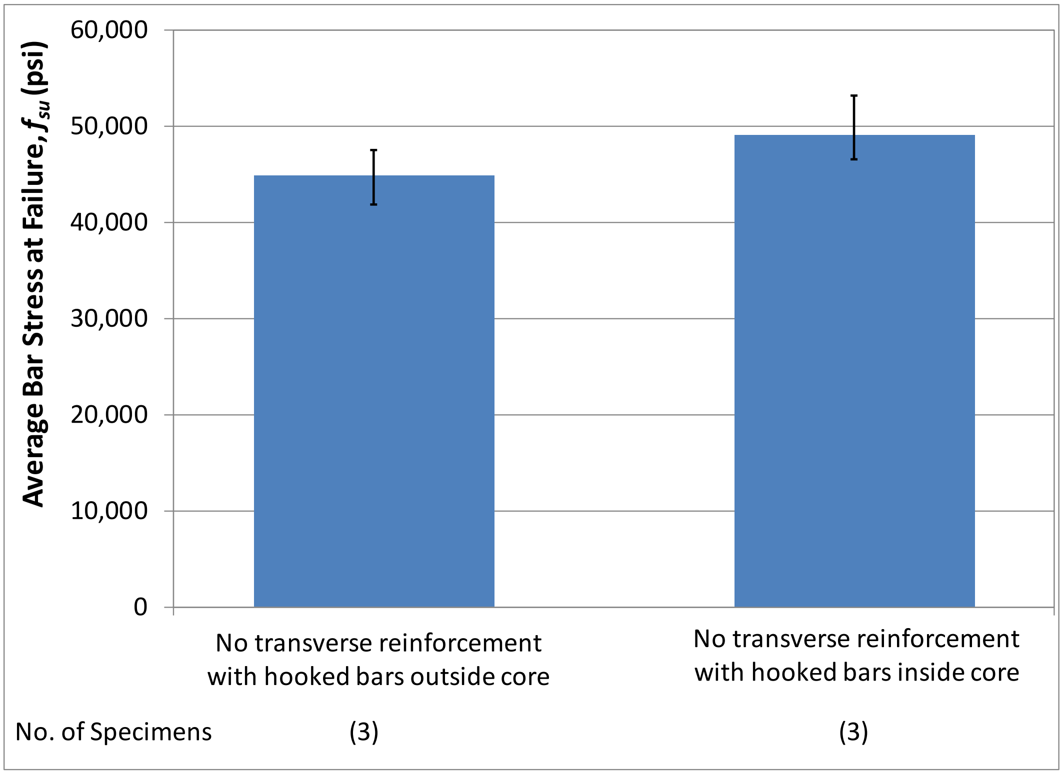


Figure 4.40 Anchorage strength for No. 8 hooked bars inside and outside the column core without confining transverse reinforcement

Table 4.17 Test results for No. 8 hooked bars inside and outside the column core without confining transverse reinforcement

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Hook Bar Type	B^b in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T lb	T_{avg} lb	$f_{su,avg}$ psi	Failure Type[c]
8-8-90-0-o-2.5-2-8	A	90°	8.6	8.4	8740	A1035	17	2.8	2.6	1.8	9.0	44400	33000	41800	SB/K
	B	90°	8.3	8.4	8740	A1035	17	2.5	2.6	2.1	9.0	33200	33000	41800	SB/K
8-8-90-0-o-3.5-2-8	A	90°	7.6	7.8	8810	A1035	19	3.5	3.6	2.4	9.8	35600	35900	45400	FP/SS
	B	90°	8.0	7.8	8810	A1035	19	3.6	3.6	2.0	9.8	44500	35900	45400	SS/FP
8-8-90-0-o-4-2-8	A	90°	8.1	8.2	8630	A1035	20	4.5	4.1	2.5	9.8	37100	37500	47500	SS/FP
	B	90°	8.3	8.2	8630	A1035	20	3.8	4.1	2.4	9.8	39200	37500	47500	SS
8-8-90-0-i-2.5-2-8	A	90°	8.0	8.0	8780	A1035	17	2.8	2.8	2.8	9.5	38000	36800	46600	FP/SS
	B	90°	8.0	8.0	8780	A1035	17	2.8	2.8	2.8	9.5	37700	36800	46600	FP/SS
8-8-90-0-i-3.5-2-8	A	90°	8.5	8.3	8780	A1035	19	3.6	3.7	2.1	10.0	41200	42000	53200	FP
	B	90°	8.0	8.3	8780	A1035	19	3.8	3.7	2.6	10.0	42900	42000	53200	FP
8-8-90-0-i-4-2-8	A	90°	7.6	7.8	8740	A1035	20	4.5	4.2	2.9	9.5	37600	37400	47400	FP/SS
	B	90°	8.0	7.8	8740	A1035	20	3.9	4.2	2.5	9.5	48700	37400	47300	FP

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

The results for nine No. 11 hooked bar specimens are shown in Figure 4.41. Of the nine specimens, two had hooked bars cast outside the core without confining transverse reinforcement, two had hooked bars cast inside the core without confining transverse reinforcement, two had hooked bars cast outside the core with No. 3 ties spaced at $3d_b$, and three had hooked bars cast inside the core with No. 3 ties spaced at $3d_b$. The specimens were cast at the same time and had a nominal concrete compressive strength of 12,000 psi, a nominal side cover on the hooked bars of 2.5 in., and a nominal embedment length of 17 in. The test parameters and measured anchorage strengths are presented in Table 4.18. Similar to the trends observed for specimens with No. 8 hooked bars, the No. 11 hooked bars cast inside the column core had greater anchorage strength than those cast outside the column core, with respective average bar stresses at failure of 72,800 and 53,500 psi for the hooked bars without confining transverse reinforcement and 91,200 and 73,400 psi for the hooked bars with confining transverse reinforcement. Student's t-test for the specimens with No. 3 ties spaced at $3d_b$ indicate that the difference between the anchorage strength of hooked bars cast inside the core and hooked bars cast outside the core is statistically significant, with a value of α = 0.174. For specimens without confining transverse reinforcement, a value of α = 0.298 indicates that the difference between the anchorage strength of hooked bars cast inside the core and hooked bars

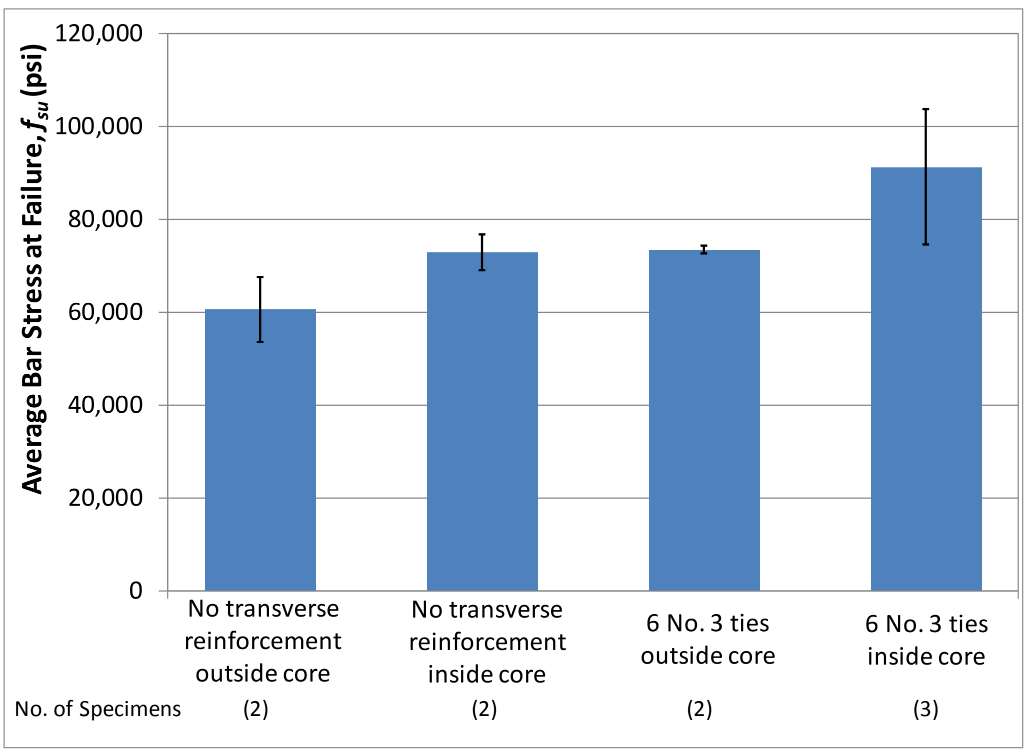


Figure 4.41 Anchorage strength for No. 11 hooked bars inside and outside the column core with confining transverse reinforcement spaced at $3d_b$ and without confining transverse reinforcement

Table 4.18 Test Results for Specimens with No. 11 Hooked Bars Inside and Outside Column Core with 12,000-psi Concrete and 17-in. Embedment Length

Specimen[a]	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_c' psi	Hook Bar Type	B^b in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T lb	T_{avg} lb	$f_{su,avg}$ psi	Failure Type[c]
11-12-180-0-o-2.5-2-17	A	180°	16.9	17.1	11800	A1035	21.5	2.5	2.5	2.3	13.4	83300	83500	53500	SS/FP
	B	180°	17.3	17.1	11800	A1035	21.5	2.6	2.5	1.9	13.4	90100	83500	53500	SB
11-12-90-0-o-2.5-2-17	A	90°	17.1	16.9	11800	A1035	21.5	2.5	2.5	2.2	13.8	123700	105400	67600	FB/TK
	B	90°	16.6	16.9	11800	A1035	21.5	2.5	2.5	2.7	13.8	105800	105400	67600	FP/TK
11-12-180-0-i-2.5-2-17	A	180°	16.6	16.6	11880	A1035	21.5	3.0	2.8	2.5	13.3	106700	107500	68900	SB/FP
	B	180°	16.6	16.6	11880	A1035	21.5	2.5	2.8	2.5	13.3	108200	107500	68900	SS
11-12-90-0-i-2.5-2-17	A	90°	16.1	16.5	11880	A1035	21.5	2.5	2.6	3.1	13.3	148400	119700	76700	SB
	B	90°	16.9	16.5	11880	A1035	21.5	2.6	2.6	2.4	13.3	120400	119700	76700	SB/FP
11-12-180-6#3-o-2.5-2-17	A	180°	16.6	16.5	11800	A1035	21.5	2.5	2.6	2.9	13.5	130000	113100	72500	SB
	B	180°	16.4	16.5	11800	A1035	21.5	2.8	2.6	3.1	13.5	113800	113100	72500	FB/SS
11-12-90-6#3-o-2.5-2-17	A	90°	15.6	16.4	11800	A1035	21.5	2.5	2.4	3.6	13.8	116400	115900	74300	FB/SS
	B	90°	17.3	16.4	11800	A1035	21.5	2.4	2.4	2.0	13.8	147300	115900	74300	SB/FB
11-12-180-6#3-i-2.5-2-17a	A	180°	16.9	16.7	12370	A1035	21.5	2.6	2.7	2.9	13.5	123100	116400	74600	FP
	B	180°	16.5	16.7	12370	A1035	21.5	2.8	2.7	3.3	13.5	117600	116400	74600	FP/SB
11-12-180-6#3-i-2.5-2-17b	A	180°	16.8	16.8	12370	A1035	21.5	2.5	2.6	2.7	13.4	148900	148700	95300	FP/SS
	B	180°	16.8	16.8	12370	A1035	21.5	2.8	2.6	2.6	13.4	173000	148700	95300	SB/FB
11-12-90-6#3-i-2.5-2-17	A	90°	17.1	16.8	12370	A1035	21.5	2.6	2.8	1.9	13.0	179700	161600	103600	FB/SB
	B	90°	16.5	16.8	12370	A1035	21.5	3.0	2.8	2.6	13.0	162300	161600	103600	SP/SS

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

cast outside the core is not statistically significant. The specimens in this series exhibit similar failure modes for both inside and outside the column core. The predominant failure mode for specimens without confining transverse reinforcement was a side failure, and the failure mode for specimens with transverse reinforcement was a front failure.

Figure 4.42 shows the anchorage strengths for eight No. 11 bar specimens with and without confining transverse reinforcement. Of the eight, two contained hooked bars cast outside the core without confining transverse reinforcement, one contained hooked bars cast inside the core without confining transverse reinforcement, two contained hooked bars cast outside the core with No. 3 ties spaced at $3d_b$, and three contain hooked bars cast inside the core with No. 3 ties spaced at $3d_b$. The specimens were cast at the same time and had a nominal concrete compressive strength of 8,000 psi and embedment lengths ranging from 15.9 to 25.2 in. The test parameters and measured anchorage strengths are presented in Table 4.19. Because the embedment lengths of the specimens in this series varied, a dummy variables analysis similar to that described earlier in this chapter was used to identify the differences between the anchorage strength of hooked bars cast inside the core and those cast outside the core. The dashed lines in

Figure 4.42 represent the specimens with hooked bars cast outside the core, and the solid lines represent the specimens with hooked bars cast inside the core. As shown in the figure, most of the hooked bars placed outside the column core exhibited lower strengths than the hooked bars cast inside the column core with a similar embedment length, regardless of the presence of confining transverse reinforcement. There was one exception (ℓ_{eh} approximately 15.9 in.) where the failure load of the hooked bars cast inside and outside the core were almost identical for the given embedment length. For this limited data set, Student's t-test shows that the difference in anchorage strength is not statistically significant for specimens with No. 3 ties spaced at $3d_b$ (α = 0.245), where α was calculated by comparing the intercepts of the f_{su} axis by extending the lines through each data point parallel to the dummy variables trend lines. Student's t-test cannot be performed for specimens without confining transverse reinforcement because only a single specimen is available for hooked bars outside the column core. Although the difference in the anchorage strength of No. 11 hooked bars placed inside and outside the column core was not statistically significant, there is enough statistical evidence to suggest that anchorage strength of hooked bars within the column core is greater than that of hooked bars placed outside of the core.

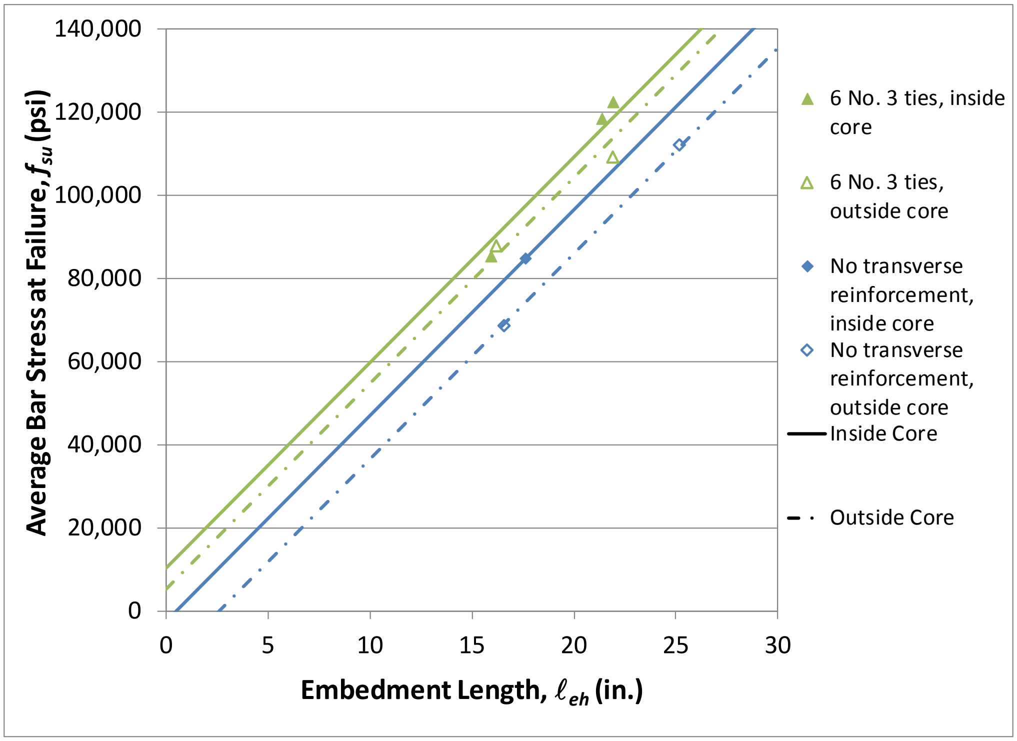


Figure 4.42 Anchorage strength for No. 11 hooked bars inside and outside the column core with confining transverse reinforcement spaced at $3d_b$ and without confining transverse reinforcement

Table 4.19 Test results for No. 11 hooked bars inside and outside the column core with 8,000 psi concrete and various embedment lengths

Specimen	Hook	Bend Angle	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f'_c psi	Hook Bar Type	b in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T lb	T_{avg} lb	$f_{su,avg}$ psi	Failure Type
11-8-90-6#3-o-2.5-2-22	A	90°	21.5	21.9	9120	A1035	21.5	2.5	2.6	2.9	13.5	186100	170200	109100	SB
	B	90°	22.3	21.9	9120	A1035	21.5	2.6	2.6	2.1	13.5	170500	170200	109100	SB/FB
11-8-90-6#3-o-2.5-2-16	A	90°	15.9	16.2	9420	A1035	21.5	2.5	2.6	2.3	13.6	138900	136800	87700	SB/FB
	B	90°	16.5	16.2	9420	A1035	21.5	2.6	2.6	1.6	13.6	134700	136800	87700	SB/FB
11-8-90-6#3-i-2.5-2-16	A	90°	15.5	15.9	9120	A1035	21.5	2.5	2.5	2.8	13.4	147500	133000	85300	FP/SS
	B	90°	16.4	15.9	9120	A1035	21.5	2.5	2.5	1.9	13.4	129700	133000	85300	FP/SS
11-8-90-6#3-i-2.5-2-22a	A	90°	21.3	21.4	9420	A1035	21.5	2.5	2.6	2.8	13.5	205000	184600	118300	Y
	B	90°	21.5	21.4	9420	A1035	21.5	2.6	2.6	2.6	13.5	183200	184600	118300	SS
11-8-90-6#3-i-2.5-2-22b	A	90°	21.9	21.9	9420	A1035	21.5	2.6	2.8	2.3	13.4	200000	191000	122400	Y
	B	90°	22.0	21.9	9420	A1035	21.5	2.9	2.8	2.2	13.4	191300	191000	122400	SB/FB
11-8-90-0-o-2.5-2-25	A	90°	25.3	25.2	9460	A1035	21.5	2.6	2.8	2.2	13.6	194500	174700	112000	SB
	B	90°	25.1	25.2	9460	A1035	21.5	2.9	2.8	2.3	13.6	170700	174700	112000	SB
11-8-90-0-o-2.5-2-17	A	90°	16.8	16.6	9460	A1035	21.5	2.5	2.4	2.6	13.8	121400	107200	68700	SB/FB
	B	90°	16.4	16.6	9460	A1035	21.5	2.4	2.4	2.9	13.8	105700	107200	68700	SB/TK
11-8-90-0-i-2.5-2-17	A	90°	17.3	17.6	9460	A1035	21.5	2.5	2.5	2.0	13.4	132000	132100	84700	FP/TK
	B	90°	18.0	17.6	9460	A1035	21.5	2.5	2.5	1.3	13.4	141200	132100	84700	FB/TK

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2

In addition to direct comparisons of measured anchorage strengths for specimens cast in the same concrete batch, an analysis was performed for all the hooked bars cast inside and outside the column core. A dummy variables analysis similar to that used to evaluate the effect of side cover on anchorage strength (Section 4.3.2) was used to investigate the effect of hooked bar location on anchorage strength.

Experimental results for 53 No. 5 hooked bar specimens are shown in Figure 4.43. A summary of specimens is presented in Table 4.20. The average bar force at failure ranged from 14,100 to 43,900 lb, and the average embedment length ranged from 4.75 to 11.6 in. The average normalized bar forces at failure (normalized with respect to f_{cm} = 5,000 psi using the 0.29 or 0.26 power as explained in Section 4.3.1) ranged from 14,100 to 45,300 lb, concrete compressive strengths ranged from 4,420 to 15,800 psi. Figure 4.43 shows the normalized average bar forces at failure T_N as a function of embedment length ℓ_{eh}. The dashed lines correspond to specimens with hooks cast outside the column core, while the solid lines correspond to hooks cast inside the column core. For specimens both without confining transverse reinforcement and specimens with No. 3 ties spaced at $3d_b$, the dashed line is below the solid line, indicating that the hooks cast outside the column core had a lower anchorage strength than those cast inside the core. Student's t-test indicates that the difference in the anchorage strength for these two configurations is statistically significant (α = 0.021 for specimens without confining transverse reinforcement and α = 0.0031 for specimens with No. 3 ties at $3d_b$). For specimens with two No. 3 ties, the dashed line is slightly above the solid line, which indicates that the hooks cast inside the core had a lower anchorage strength than those cast outside the core. For this set, however, the results may be skewed toward the hooked bars cast outside the core because the embedment lengths for most of these specimens was much larger than that of the specimens with hooked bars cast inside the core. In addition, Student's t-test shows that the difference in the anchorage strength between the hooks cast inside the core and outside the core is not statistically significant (α = 0.975) for the hooked bars confined by two No. 3 ties.

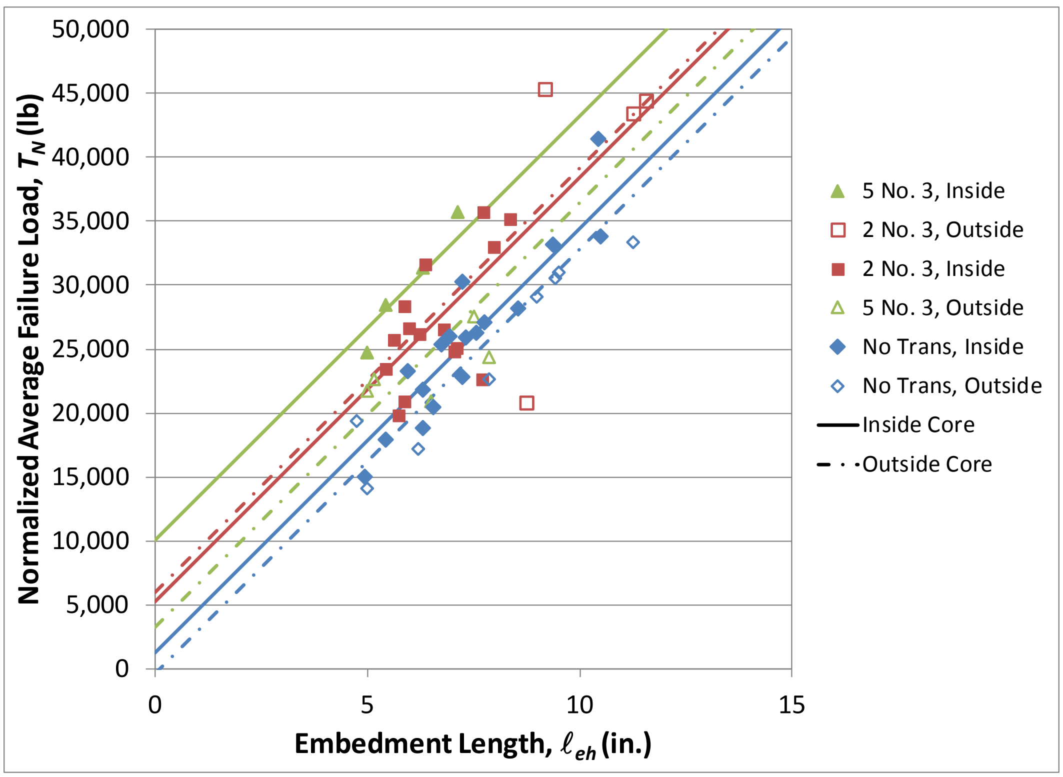


Figure 4.43 Anchorage strength for No. 5 hooked bars cast inside and outside the column core

Table 4.20 Summary of Specimens Included in Figure 4.43

Number of Specimens	Size of Hooked Bars	Hook Location	Transverse Reinforcement
17	No. 5	Inside Core	None
8	No. 5	Outside Core	None
15	No. 5	Inside Core	two No. 3
4	No. 5	Outside Core	two No. 3
4	No. 5	Inside Core	No. 3 @ $3d_b$
5	No. 5	Outside Core	No. 3 @ $3d_b$

Figure 4.44 shows the results for 75 No. 8 hooked bar specimens. A summary of these specimens is presented in Table 4.21. The average bar forces at failure ranged from 33,000 to 95,400 lb, the average normalized failure loads ranged from 28,100 to 93,400 lb, the average embedment lengths ranged from 7.25 to 18.7 in., and the concrete compressive strengths ranged from 4,490 to 16,510 psi. Figure 4.44 compares the normalized average bar forces at failure to embedment length. For specimens with and without confining transverse reinforcement, the dashed dummy variables trend lines (outside column core) are below the solid lines (inside column core), indicating that hooks cast outside the column core had lower anchorage strength than hooks cast inside the core. Student's t-test shows that the differences in anchorage strength are statistically significant (α = 0.170 for specimens without confining transverse reinforcement and α = 0.135 for specimens with No. 3 ties at $3d_b$).

Table 4.21 Summary of Specimens Included in Figure 4.44

Number of Specimens	Size of Hooked Bars	Hook Location	Transverse Reinforcement
34	No. 8	Inside Core	None
6	No. 8	Outside Core	None
29	No. 8	Inside Core	No. 3 @ $3d_b$
6	No. 8	Outside Core	No. 3 @ $3d_b$

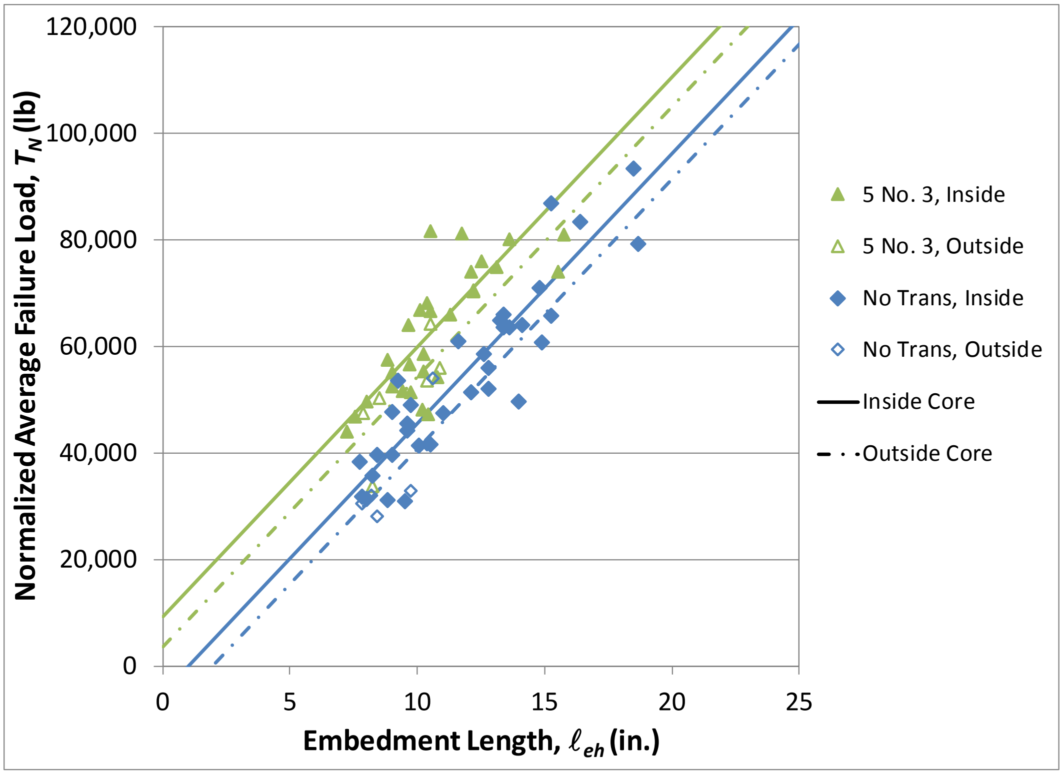


Figure 4.44 Anchorage strength for No. 8 hooked bars cast inside and outside the column core

Figure 4.45 shows the anchorage strength for 43 specimens with No. 11 hooked bars. A summary of these specimens is presented in Table 4.22. The average bar forces at failure ranged from 51,500 to 213,300 lb, average normalized bar forces at failure ranged from 38,200 to 173,200 lb, the average embedment lengths ranged from 9.50 to 26.0 in., and concrete compressive strengths ranged from 4,910 to 16,180 psi. Similar to the trends observed for No. 5 and No. 8 hooked bar specimens, the hooked bars cast outside the core had lower anchorage strength than the hooks cast inside the core. The value of α for specimens without confining transverse reinforcement was 0.198, just below the 0.20 threshold for identifying if a difference is statistically significant in a small data set. For specimens with No. 3 ties spaced at $3d_b$, the difference is not statistically significant (α = 0.232).

Table 4.22 Summary of Specimens Included in Figure 4.45

Number of Specimens	Size of Hooked Bars	Hook Location	Transverse Reinforcement
17	No. 11	Inside Core	None
4	No. 11	Outside Core	None
18	No. 11	Inside Core	No. 3 @ $3d_b$
4	No. 11	Outside Core	No. 3 @ $3d_b$

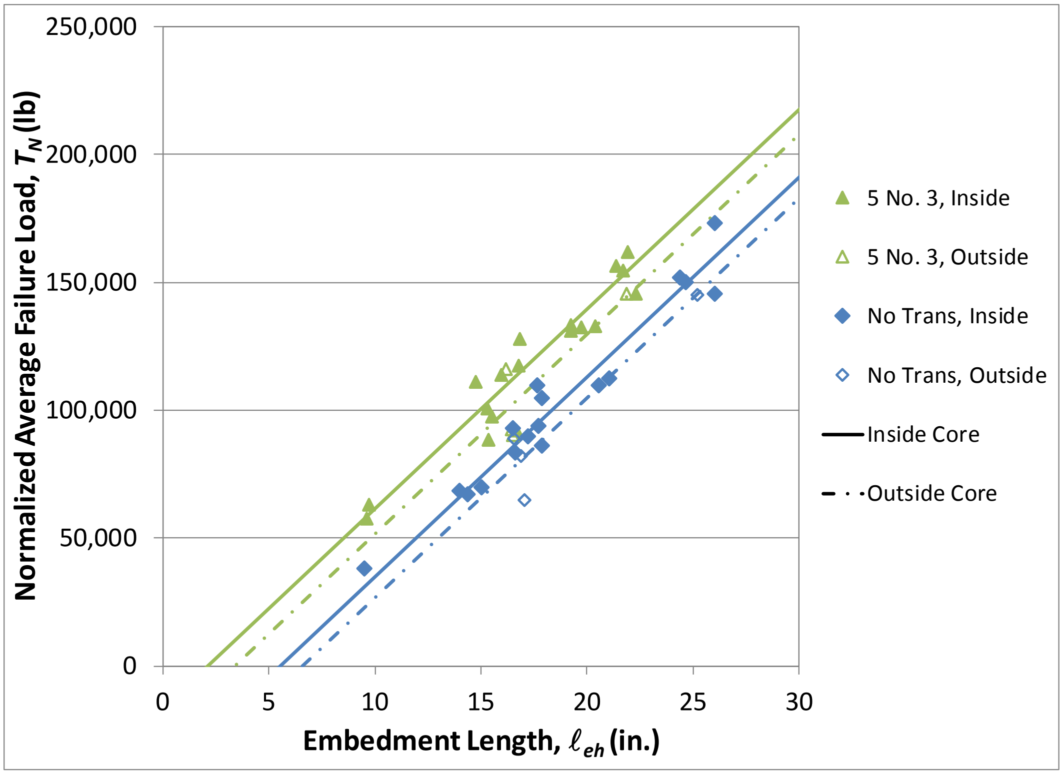


Figure 4.45 Anchorage strength No. 11 hooked bars cast inside and outside the column core

In addition to hooked bars cast outside the column core, hooked bars were cast outside the compression region of the column. These hooked bars were anchored in the middle of the column, as opposed to at the back face of the column. Upon analyzing the data, it was found that these specimens had lower test-to-calculated ratios than similar specimens where the hooked bars were anchored inside the compression region of the column. This reduction in strength is most likely due to the lack of confinement provided by the compression within the concrete when the column is under bending. The test-to-calculated ratios for No. 8 and No. 11 two-hook specimens with and without transverse reinforcement with hooked bars anchored in the middle of the column are shown in Table 4.23. The calculated value is based on Eq. (4.7) for hooked bars without confining transverse reinforcement and Eq. (4.12) for hooked bars with confining transverse reinforcement. The specimens without confining transverse reinforcement had test-to-calculated values ranging from 0.68 to 0.82. The specimens with confining transverse reinforcement had test-to-calculated ratios ranging from 0.82 to 1.02, indicating that the addition of transverse reinforcement lessens the adverse effects of anchoring the hooked bars in the middle of the column. The lowest test-to-calculated ratio for those specimens with transverse reinforcement corresponds to the specimen with 2 No. 3 ties as confining reinforcement. This would imply that the greater the amount of transverse reinforcement, the less adverse the effects of anchoring the hooked bar outside the compression region of the column.

Table 4.23 Test results for two-hooked bar specimens with hooked bars anchored in the middle of the column

Specimen[a]	Hook	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]	T/T_{calc}
8-8-90-0-i-2.5sc-9tc-9	A B	9.3 9	9.1	7710	17	2.8 2.8	2.8	8.8 9	10	38500 36800	37700	FB FB	0.82
(2@3) 8-8-90-0-i-2.5-9-9	A B	9.3 9	9.1	7510	9	2.5 2.6	2.6	8.8 9	2	34000 27600	30700	FP FP	0.67
(2@4) 8-8-90-0-i-2.5-9-9	A B	9.9 10	9.9	7510	10	2.6 2.5	2.5	8.1 8	3.1	32900 35500	34200	FP FP	0.68
8-8-90-5#3-i-2.5-9-9‡	A B	9 9.3	9.1	7710	17	2.5 2.8	2.6	9 8.8	10	62000 65200	63290	FB FB	1.02
(2@3) 8-8-90-5#3-i-2.5-9-9	A B	9.3 9.5	9.4	7440	9	2.5 2.5	2.5	8.8 8.5	2	56500 61200	58790	FP FP	0.93
(2@4) 8-8-90-5#3-i-2.5-9-9	A B	8.9 9.1	9	7440	10	2.5 2.5	2.5	9.1 8.9	3.3	55700 59300	57450	FB FB	0.94
(2@5.35) 11-5-90-0-i-2.5-13-13	A B	14 13.9	13.9	5330	14	2.6 2.6	2.6	12 12.1	6.2	58200 63000	60200	FP FP	0.77
(2@5.35) 11-5-90-2#3-i-2.5-13-13	A B	13.9 13.8	13.8	5330	14	2.7 2.6	2.6	12.1 12.3	6.2	68300 70100	69100	FP FP	0.82
(2@5.35) 11-5-90-6#3-i-2.5-13-13	A B	14 13.8	13.9	5280	14	2.4 2.8	2.6	12 12.3	6.2	83800 96000	89700	FP FP	0.87
(2@5.35) 11-5-90-6#3-i-2.5-18-18	A B	19.3 19.5	19.4	5280	14	2.7 2.6	2.6	16.8 16.5	6.2	118500 128600	121600	FP FP	0.9

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
‡Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement

In addition to the two-hook specimens, multiple-hook specimens were cast with the hooks anchored in the middle of the column. The results of these specimens are shown in Table 4.24. The same trends are observed for the multiple-hook specimens as for the two-hook specimens; however, the test-to-calculated ratios are lower than those observed for the two-hook specimens. These small test-to-calculated ratios result from combination of the reduction in anchorage capacity due to anchoring the hooked bars outside the compression region of the column and the close spacing of the hooked bars. The combined effects produced test-to-calculated ratios as low as 0.39 (specimen (4@4) 8-8-90-0-i-2.5-9-9 with four No. 8 hooked bars spaced at $4d_b$ without confining transverse reinforcement).

Table 4.24 Test results for multiple-hooked bar specimens with hooked bars anchored in the middle of the column

Specimen[a]	Hook	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	b[b] in.	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T lb	Failure Type[c]	T/T_{calc}
(4@6) 5-8-90-0-i-2.5-6-6	A	6.3	6.3	6693	17	2.5	2.6	5.8	3.1	4	16100	16100	FP/SS	0.70
	B	6.3				6.3		5.8	3.1		14700		FP/SS	
	C	6.3				6.5		5.8	3.1		16500		FP/SS	
	D	6.3				2.7		5.8	-		16800		FP/SS	
(4@6) 5-8-90-5#3-i-2.5-6-6‡	A	6.8	6.4	6693	17	2.5	2.6	1.3	3.1	4	32100	31200	FP	1.04
	B	6.0				6.5		2.0	3.1		29900		FP	
	C	6.5				6.5		1.5	2.9		30800		FP	
	D	6.3				2.7		1.8	-		31800		FP	
(3@3) 8-8-90-0-i-2.5-9-9	A	9.5	9.4	7510	12	2.5	2.5	8.5	2.1	3	24600	21400	FP	0.45
	B	9.5				5.6		8.5	2.1		25000		FP	
	C	9.3				2.5		8.8	-		14700		FP	
(3@4) 8-8-90-0-i-2.5-9-9	A	9.3	9.3	7510	14	2.5	2.5	8.8	3.0	3	29400	26400	FP	0.57
	B	9.3				6.5		8.8	3.1		27400		FP	
	C	9.3				2.5		8.8			22400		FP	
(4@3) 8-8-90-0-i-2.5-9-9	A	9.4	9.4	7510	15	2.5	2.5	8.6	2.0	3	22200	18700	FP	0.40
	B	9.3				5.5		8.8	2.0		21200		FP	
	C	9.3				5.5		8.8	2.0		18300		FP	
	D	9.6				2.5		8.4	-		13100		FP	
(4@4) 8-8-90-0-i-2.5-9-9	A	9.4	9.2	7510	18	2.5	2.5	8.6	3.1	3	20400	18000	FP	0.39
	B	9.1				6.6		8.9	3.1		19000		FP	
	C	9.0				6.5		9.0	3.0		18400		FP	
	D	9.1				2.5		8.9	-		14300		FP	
(3@3) 8-8-90-5#3-i-2.5-9-9	A	9.5	9.3	7440	12	2.5	2.5	8.5	2.0	3	43300	39800	FP	0.70
	B	9.0				5.5		9.0	2.0		49700		FP	
	C	9.5				2.5		8.5	-		37200		FP	
(3@4) 8-8-90-5#3-i-2.5-9-9	A	8.9	9.1	7440	14	2.5	2.5	9.1	3.0	3	48500	36600	FP	0.65
	B	9.1				6.5		8.9	3.0		38600		FP	
	C	9.3				2.5		8.8	-		32000		FP	
(4@3) 8-8-90-5#3-i-2.5-9-9	A	9.3	9.3	7440	15	2.5	2.5	8.8	2.0	4	32900	31400	FP	0.55
	B	9.3				5.5		8.8	2.3		38700		FP	
	C	9.3				5.5		8.8	2.0		27300		FP	
	D	9.3				2.5		8.8	-		26800		FP	
(4@4) 8-8-90-5#3-i-2.5-9-9	A	9.5	9.5	7440	18	2.5	2.5	8.5	3.0	4	33700	29500	FP	0.51
	B	9.5				6.5		8.5	3.0		30700		FP	
	C	9.3				6.5		8.8	3.0		27900		FP	
	D	9.6				2.5		8.4	-		25700		FP	
(3@5.35) 11-5-90-0-i-2.5-13-13	A	13.8	13.8	5330	21.5	2.6	2.6	12.3	6.6	3	45400	51500	FP	0.67
	B	14.3				10.0		11.8	6.3		49900		FP	
	C	13.5				2.6		12.5	-		59300		FP	
(3@5.35) 11-5-90-2#3-i-2.5-13-13	A	14.0	13.9	5330	21.5	2.6	2.6	12.0	6.1	3	50900	57900	FP	0.40
	B	14.0				10.0		12.0	6.1		58500		FP	
	C	13.8				2.6		12.3	-		64500		FP	
(3@5.35) 11-5-90-6#3-i-2.5-13-13	A	13.5	13.6	5280	21.5	2.6	2.6	12.5	6.0	3	59600	66200	FP	0.72
	B	13.5				10.0		12.5	5.8		66000		FP	
	C	13.8				2.7		12.3	-		72300		FP	
(3@5.35) 11-5-90-6#3-i-2.5-18-18	A	18.6	18.6	5280	21.5	2.5	2.7	17.4	6.1	3	103300	111900	FP	0.91
	B	18.6				10.0		17.4	5.6		147800		FP	
	C	18.6				2.8		17.4	-		113900		FP	

[a]Notation described in Section 2.1 and Appendix A

[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B

[c]Failure types described in Section 3.2

‡Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement

Additional testing may be warranted to more precisely define the effect of hook placement on anchorage strength. The trends in the data, however, indicate that hooks cast outside a core and outside the compression region of a column exhibit lower anchorage strengths than hooked bars cast inside the core. Close spacing of hooked bars causes a further decrease in the anchorage capacity. A design approach based on the available data is presented in Chapter 5.

4.6 EFFECT OF COLUMN REINFORCEMENT RATIO

The effect of the column reinforcement ratio on the anchorage capacity of hooked bars is investigated in this section. The specimens with high reinforcement ratios (ratios above 0.04) are compared using Eq. (4.7) and (4.12). The results and test-to-calculated ratios for specimens with high reinforcement ratios are shown in Table 4.25; test-to-calculated ratios are also shown in Figure 4.46 as a function of reinforcement ratio. As the reinforcement ratio increases the ratio of test-to-calculated increases, independent of the amount of confining transverse reinforcement. Most of the test-to-calculated ratios are above 1.0, indicating that the high amount of longitudinal steel may act as confinement for the hooked bars. This observation justifies the exclusion of this data set from use in the development of the characterizing and design equations.

Table 4.25 Test results for specimens with high reinforcement ratio

Specimen[a]	Hook	$\ell_{eh,avg}$ in.	f_{cm} psi	b[b] in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	T_{ind} lb	T lb	Failure Type[c]	Reinforcement Ratio	T/T_{calc}
(2@4) 5-8-90-0-i-2.5-2-6	A B	5.9	6950	8	3.2	2.3 2.0	1.9	23200 21700	22400	FP FP	0.049	1.02
(2@6) 5-8-90-0-i-2.5-2-6	A B	6.0	6950	9	2.6	2.0 2.0	3.1	25500 24000	24000	FP/SS FP/SS	0.042	1.07
(2@3) 8-5-180-0-i-2.5-2-10‡	A B	10.2	5260	9	2.4	1.7 2.0	2.0	47600 56100	51800	FP FP	0.059	1.12
(2@5)8-5-180-0-i-2.5-2-10‡	A B	10.0	5260	11	2.4	2.0 2.0	4.1	52300 54000	53200	FP FP	0.048	1.17
8-15-90-2#3-i-2.5-2-6	A B	6.1	15800	17	2.4	2.3 1.8	9.9	37400 37700	37600	FP FP	0.046	0.92
(2@3) 8-5-180-2#3-i-2.5-2-10‡	A B	10.3	5400	9	2.5	1.8 1.8	2.0	57500 58800	57700	FP FP	0.059	1.08
(2@5) 8-5-180-2#3-i-2.5-2-10‡	A B	10.0	5400	11	2.5	1.8 2.3	4.0	63700 60100	61900	FB FB	0.048	1.18
8-15-90-5#3-i-2.5-2-6	A B	6.3	15800	17	2.6	1.8 2.2	9.8	48300 48700	48500	FP FP	0.045	0.91
(2@5) 8-5-180-5#3-i-2.5-2-10‡	A B	10.1	5540	11	2.5	2.0 1.8	4.0	58100 72200	66640	FB FB	0.048	1.04

[a]Notation described in Section 2.1 and Appendix A
[b]Nominal depth of specimen is found by adding the nominal tail cover to the nominal embedment length. Actual depths can be found in the tables in Appendix B
[c]Failure types described in Section 3.2
‡Specimen contained ASTM A1035 Grade 120 longitudinal reinforcement

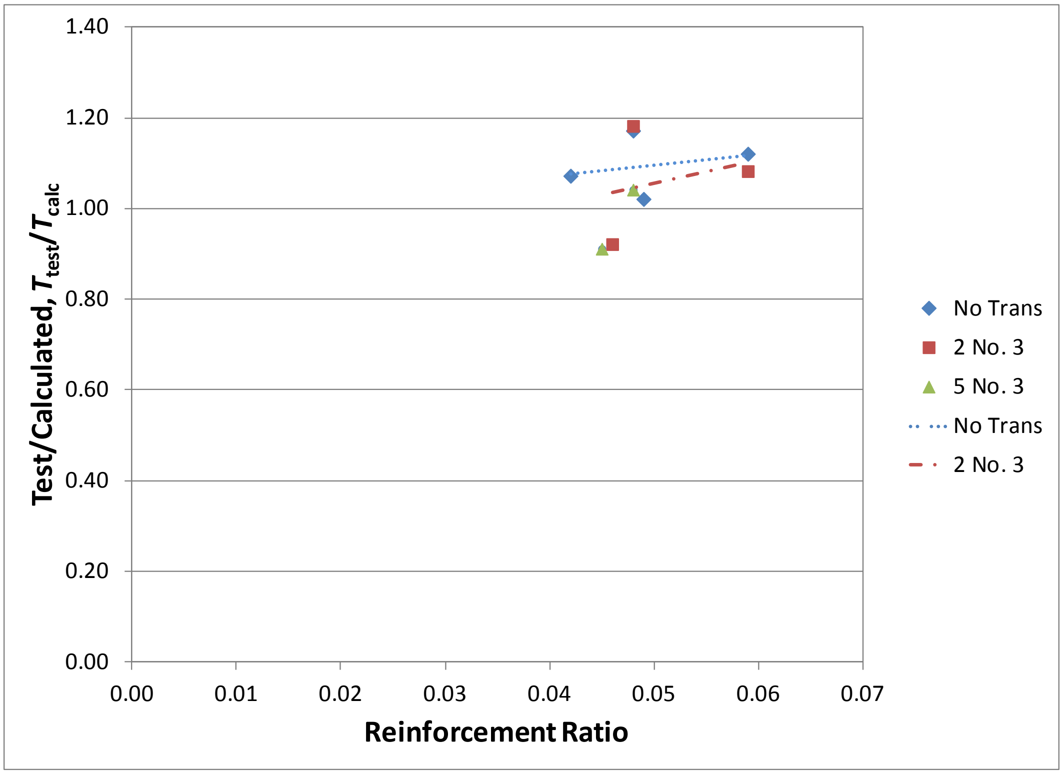


Figure 4.46 Test-to-calculated ratio versus reinforcement ratio for specimens with reinforcement ratios greater than 0.04, with T_{calc} based on Eq. (4.7) for specimens without transverse reinforcement and (4.12) for specimens with transverse reinforcement

4.7 HOOKED BARS IN WALLS

Oftentimes, hooked bars must be anchored in walls. In this case, the hooked bars could be considered as being located outside of a column core. The hooked bars in walls, however, have much higher side cover than the typical hooked bar in a beam-column joint. This section investigates whether the high side cover of hooked bars in walls provides sufficient confinement to avoid an increase in development length applied to a hooked bar outside a column core as discussed in Section 4.5. To evaluate this behavior, data from Johnson and Jirsa's (1981) tests of hooked bars in walls is compared using Eq. (4.7) developed for hooked bars without confining transverse reinforcement anchored in beam-column joints (Section 4.3.3). Most specimens were constructed with a single hooked bar in the middle of a short wall; however, four specimens were tested with three hooked bars spaced at either 11 or 22 in. The test results for the single hooked bars anchored in walls are listed in Table 4.26, while those for the multiple hooked bars are listed in Table 4.27.

Johnson and Jirsa tested thirty hooked bar wall specimens containing No. 4, 7, 9, and 11 hooked bars. Concrete compressive strengths ranged from 2,400 to 5,450 psi, and embedment lengths ranged from 2.0 to 7.0 in. All embedment lengths were shorter than the minimum lengths required in Section 25.4.3.1 of ACI 318-14. The failure loads ranged from 4.4 to 54.8 kips, corresponding to a range in stress of 14,200 to 60,000 psi. The side clear covers ranged from 11.3 to 11.75 in. for the single hooked bar specimens. The side covers for the multiple hooked bar specimens ranged from 13.3 to 24.6 in. Johnson and Jirsa also investigated the effect of the internal moment arm (distance between the hooked bar and the centroid of the compressive force applied against the wall during the test) on the anchorage capacity of hooked bars in walls. This parameter, listed as lever arm in Tables 4.26 and 4.27, ranged from 8 to 18 in.

Table 4.26 Test results for hooked bars in walls tested by Johnson and Jirsa (1981)

Specimen	f_{cm} psi	ℓ_{eh} in.	d_b in.	A_h in.^{2}	Lever Arm in.	T kips	f_s ksi	T_{calc} kips	T/T_{calc}
4-3.5-8-M	4500	2.0	0.5	0.2	8.0	4.4	22	5.28	0.83
4-5-11-M	4500	3.5	0.5	0.2	11.0	12	60	9.78	1.23
4-5-14-M	4500	3.5	0.5	0.2	14.0	9.8	49	9.78	1.00
7-5-8-L	2500	3.5	0.875	0.60	8.0	13	21.7	10.9	1.19
7-5-8-M	4600	3.5	0.875	0.60	8.0	16.5	27.5	13.0	1.27
7-5-8-H	5450	3.5	0.875	0.60	8.0	19.5	32.5	13.7	1.43
7-5-8-M	3640	3.5	0.875	0.60	8.0	14.7	24.5	12.2	1.21
7-5-14-L	2500	3.5	0.875	0.60	14.0	8.5	14.2	10.9	0.78
7-5-14-M	4100	3.5	0.875	0.60	14.0	11.2	18.7	12.6	0.89
7-5-14-H	5450	3.5	0.875	0.60	14.0	11.9	19.8	13.7	0.87
7-5-14-M	3640	3.5	0.875	0.60	14.0	11.3	18.8	12.2	0.93
7-7-8-M	4480	5.5	0.875	0.60	8.0	32	53.3	21.2	1.51
7-7-11-M	4480	5.5	0.875	0.60	11.0	27	45	21.2	1.27
7-7-14-M	5450	5.5	0.875	0.60	14.0	22	36.7	22.5	0.98
9-7-11-M	4500	5.5	1.128	1.0	11.0	30.8	30.8	24.1	1.28
9-7-14-M	5450	5.5	1.128	1.0	14.0	24.8	24.8	25.5	0.97
9-7-18-M	4570	5.5	1.128	1.0	18.0	22.3	22.3	24.3	0.92
7-8-11-M	5400	6.5	0.875	0.60	11.0	34.8	58	26.9	1.29
7-8-14-M	4100	6.5	0.875	0.60	14.0	26.5	44.2	24.9	1.07
9-8-14-M	5400	6.5	1.128	1.0	14.0	30.7	30.7	30.6	1.00
11-8.5-11-L	2400	7.0	1.41	1.56	11.0	37	23.7	29.3	1.26
11-8.5-11-M	4800	7.0	1.41	1.56	11.0	51.5	33.0	35.9	1.44
11-8.5-11-H	5450	7.0	1.41	1.56	11.0	54.8	35.1	37.2	1.47
11-8.5-14-L	2400	7.0	1.41	1.56	14.0	31	19.9	29.3	1.06
11-8.5-14-M	4750	7.0	1.41	1.56	14.0	39	25	35.8	1.09
11-8.5-14-H	5450	7.0	1.41	1.56	14.0	45.4	29.1	37.2	1.22

Table 4.27 Test results for multiple (three) hooked bars in walls tested by Johnson and Jirsa (1981)

Specimen	f_{cm} psi	ℓ_{eh} in.	d_b in.	A_h in.^{2}	Lever Arm in.	Spacing in.	T kips	f_s ksi	T_{calc} kips	T/T_{calc}
7-7-11-M	3800	5.5	0.875	0.60	24	11	24	40	20.2	1.19
7-7-11-L	3000	5.5	0.875	0.60	22.7	22	22.7	37.8	18.9	1.20
11-8.5-11-M	3800	7.0	1.41	1.56	38	11	38	24.4	33.5	1.13
11-8.5-11-L	3000	7.0	1.41	1.56	40	22	40	25.6	31.3	1.28

The results of Johnson and Jirsa (1981) tests are compared with Eq. (4.7) for hooked bars without confining transverse reinforcement. Tables 4.26 and 4.27 show the test-to-calculated ratios for these specimens. The ratios range from 0.78 to 1.51 with an average of 1.14. Since the center-to-center spacing of the multiple hooked bars was greater than $8d_b$, no correction was applied when calculating the expected failure load. Figure 4.47 compares the measured anchorage strengths with those calculated using Eq. (4.7). The dashed line is the 45° line, where anything above the line indicates Eq. (4.7) is conservative and anything below the line is unconservative. It can be seen that the majority of data points fall above the dashed line, including those for the multiple hooked bars. Of the points that fall below the line, the majority are No. 7 hooked bars, with the lowest having a test-to-calculated value of 0.78. This particular specimen had an embedment length of only 3.5 in., a concrete compressive strength of 2,400 psi, and a lever arm of 14 in. The development of the characterizing equation did not include specimens with concrete compressive strengths lower than 4,000 psi or embedment lengths lower than 4 in. Figure 4.47 also shows an increase in test-to-calculated ratio with an increase in bar diameter, with no No. 11 hooked bars below the dashed line.

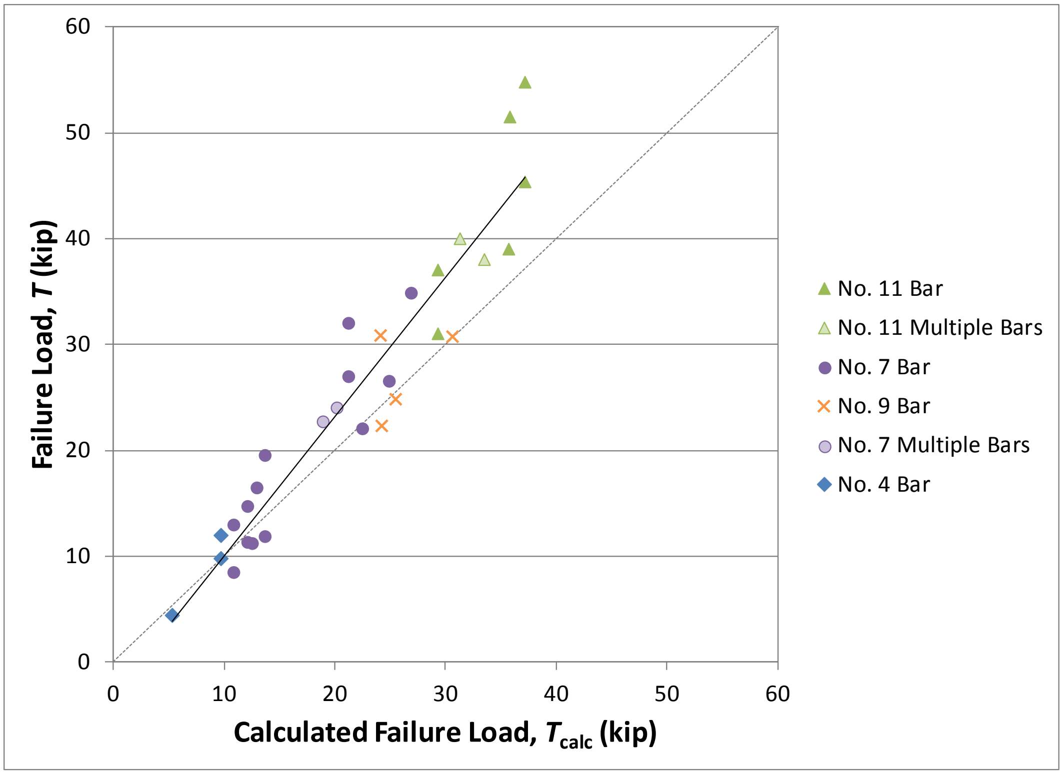


Figure 4.47 Comparison of test-to-calculated failure load for specimens tested by Johnson and Jirsa (1981)

Figure 4.48 shows the test-to-calculated ratios as a function of the internal moment arm. It can be seen that as the lever arm increases, the test-to-calculated ratio decreases. Of the eight specimens with test-to-calculated ratios less than 1.0, seven had a lever arm of 14 in. or more. This would indicate that beyond a certain lever arm, the compressive reaction no longer confines the hooked bar, possibly requiring an additional correction factor. The effect of larger lever arms, however, may actually be a function of the strut angle, where the strut angle is defined as the tangent of the embedment length to the lever arm. It would be reasonable to assume that an increase in the lever arm, corresponding to an increase in the strut angle, would have an adverse effect on the anchorage capacity of hooked bars; however, very little testing has been done to verify this hypothesis. Additional testing is needed to further understand the effect of strut angle on the anchorage capacity of hooked bars framing into both walls and beam-column joints with deep beams.

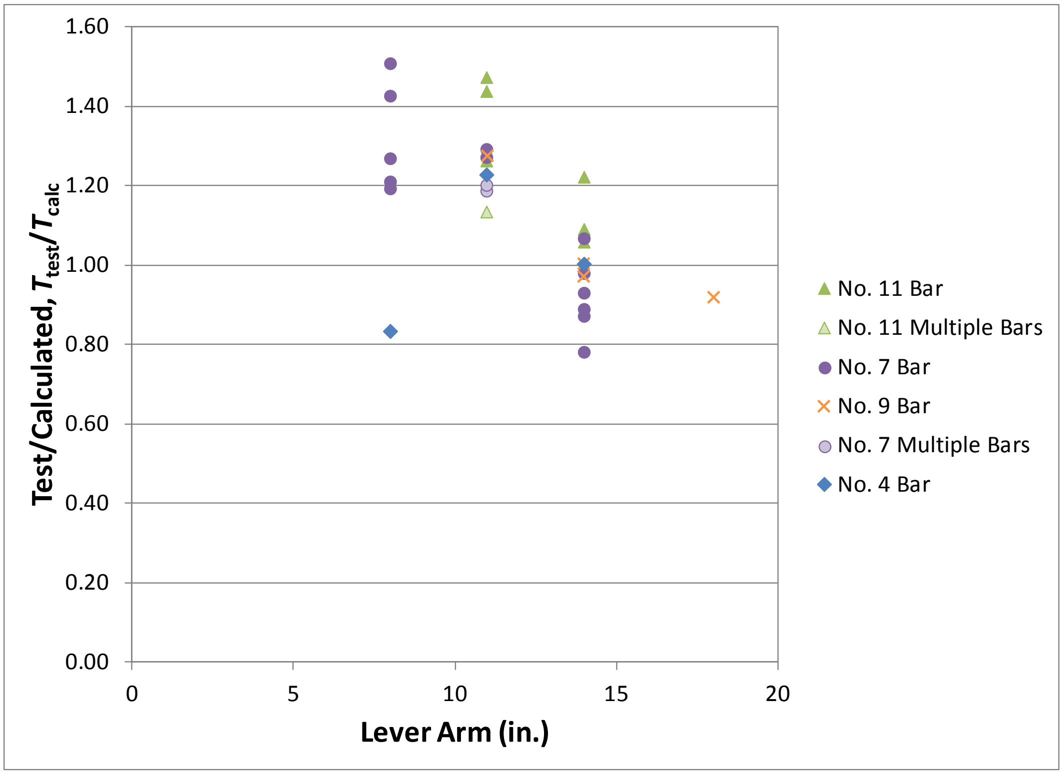


Figure 4.48 Test-to-calculated ratio versus internal moment arm, with T_{calc} based on Eq. (4.7)

It should be noted that the lowest test-to-calculated ratio for the hooked bars in walls is 0.78, whereas, the lowest test-to-calculated ratio for the dataset used to develop Eq. (4.7) is 0.73. In addition, the average test-to-calculated ratio for the dataset of hooked bars in walls is 1.14. These results indicate that Eq. (4.7) would be appropriate to characterize hooked bars in walls, and that high side cover is adequate to confine the hooked bars in a similar manner as the column core.

CHAPTER 5: DEVELOPMENT OF DESIGN EQUATION

The equations developed in Chapter 4 characterize the behavior and capacity of hooked bars based on a statistical analysis of test results. In contrast to these descriptive equations (the term used in this chapter), design equations must not only be reasonably accurate, they must also be easy to apply and give a low probability of predicting a capacity that is higher than the actual strength. In this chapter, equations are developed for use in design based on the observations in Chapter 4.

5.1 DESCRIPTIVE EQUATION

In Chapter 4, Eq. (4.7) and (4.12) were developed to characterize the anchorage capacity of hooked bars, respectively, without and with confining transverse reinforcement. The two equations, expressed here in terms of the anchorage force developed by hooked bars, apply to hooked bars with center-to-center spacing of at least 8 bar diameters.

$$T_c = 304 f_{cm}^{0.29} \ell_{eh}^{1.10} d_b^{0.50} \tag{4.7}$$

$$T_h = 486 f_{cm}^{0.24} \ell_{eh}^{1.09} d_b^{0.49} + 31{,}350 \left(\frac{NA_{tr}}{n} \right)^{1.11} d_b^{0.45} \tag{4.12}$$

where T_c is the anchorage capacity of a hooked bar without confining transverse reinforcement, T_h is the anchorage capacity of a hooked bar confined by transverse reinforcement, f_{cm} is the measured concrete compressive strength, ℓ_{eh} is the embedment length of the hooked bar, d_b is the diameter of the hooked bar, N is the number of legs of confining transverse reinforcement parallel or perpendicular to the straight portion of the hooked bar, A_{tr} is the area of each leg, and n is the number of confined hooked bars.

Several steps were taken to simplify Eq. (4.7) and (4.12) for use in design:

1. Anchorage capacity is assumed to be proportional to the embedment length ℓ_{eh} given that the powers of ℓ_{eh} in Eq. (4.7) and (4.12), 1.1 and 1.09, respectively, indicate that the relationship does not deviate substantially from one that is linear.

2. The power of the concrete compressive strength is assumed to be 0.25. This value is reasonably close to the values of 0.29 and 0.24 in Eq. (4.7) and (4.12), respectively, and matches the power of concrete compressive strength used in the best descriptive equations for straight development and lap splices (Darwin et al. 1996, Zuo and Darwin 1998, 2000, ACI 408R-03). A power less than 0.5 is justified based on the comparisons in Section 4.2, which indicate that using $\sqrt{f_c'}$ produces progressively unconservative comparisons with test results as compressive strength increases. On a more basic level, hook strength is governed by the combined effects of concrete tensile strength, which controls initial crack formation, and fracture energy, which controls crack propagation. While the tensile strength of concrete increases with the compressive strength to a power between approximately ½ and $^2/_3$, the fracture energy of concrete is independent of compressive strength (Darwin et al. 2001). The combined effect is a power below ½, as observed for both straight development and hooked bar anchorage strength.

3. A power for d_b of 0.5 is selected as a reasonable representation for the empirically derived powers of 0.5, 0.49, and 0.45 that appear in the two equations.

4. The power for the term NA_{tr}/n is assumed to be 1.0, because a power of 1.11, again, indicates only a small deviation from a linear relationship.

5.2 SIMPLIFIED DESCRIPTIVE EQUATION

The simplifications described above lead to a general form of the equation for T_h of

$$T_h = T_c + T_s = \mathrm{A}\ell_{eh} f_{cm}^{0.25} d_b^{0.5} + \mathrm{B}\frac{NA_{tr}}{n} d_b^{0.5} \tag{5.1}$$

where T_s is the anchorage capacity of a hooked bar contributed by confining transverse reinforcement.

The value of the coefficient A was selected so that the mean value of T_{test}/T_{calc} =1.0 when Eq. (5.1) is compared with the anchorage strengths for the database of specimens without confining transverse reinforcement. In this case, A = 548. With A fixed, the coefficient B was selected so that the mean value of T_{test}/T_{calc} = 1.0 when Eq. (5.1) was compared with the anchorage strengths for specimens with confining transverse reinforcement from the current study. As explained in Section 3.3.5, only specimens from the current study were included in this step because of the relatively small number of specimens (12) containing transverse reinforcement tested by other researchers and the inherent variability in the contribution of the transverse steel to the capacity of the hooked bars. This step yielded B = 27,100 and an equation for T_h.

$$T_h = 548\ell_{eh} f_{cm}^{0.25} d_b^{0.5} + 27{,}100 \frac{NA_{tr}}{n} d_b^{0.5} \tag{5.2}$$

The mean, maximum, minimum, R^2, *SD*, and *COV* values of T_{test}/T_{calc} for Eq. (5.2) are shown in Table 5.1. The mean value of T_{test}/T_{calc} are 1.0 for specimens without and with confining transverse reinforcement with coefficients of variation of 0.125 and 0.112.

Table 5.1 Statistical parameters for T_{test}/T_{calc} for Eq. (5.2)

Parameter	Specimens without confining transverse reinforcement	Specimens with confining transverse reinforcement	All specimens
Mean	1.000	1.000	1.000
Max	1.330	1.295	1.330
Min	0.713	0.640	0.640
R^2	0.944	0.959	0.953
SD	0.125	0.112	0.117
COV	0.125	0.112	0.117

To evaluate the performance of Eq. (5.1) as a function of concrete compressive strength, T_{test}/T_{calc}, with $T_{calc} = T_h$ from Eq. (5.2), is plotted versus concrete compressive strength for the specimens without and with transverse reinforcement within the hook region, respectively, in Figures 5.1 and 5.2. As expected, the slightly upward sloping best-fit line in Figure 5.1 shows that the power of 0.25 underestimates the effect of concrete compressive strength on the anchorage capacity of hooks without confining transverse reinforcement, while the slightly downward sloping best-fit line in Figure 5.2 shows that the concrete compressive strength to the 0.25 power somewhat overestimates the effect of concrete strength for hooks that are confined by transverse reinforcement.

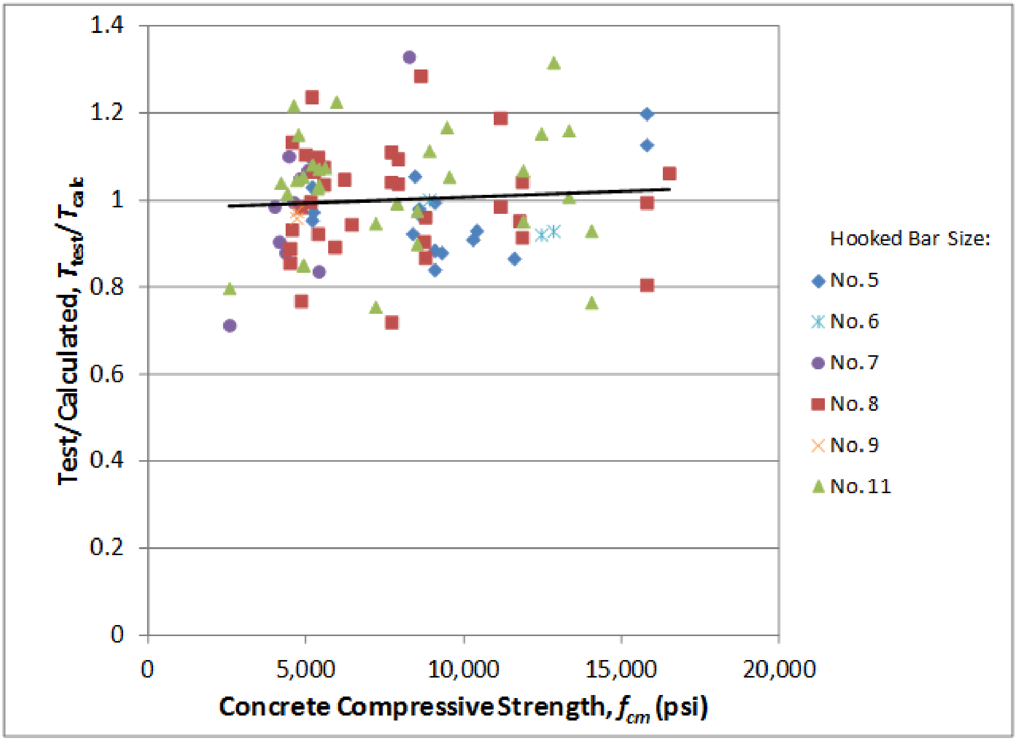


Figure 5.1 Ratio of test-to-calculated bar force versus concrete compressive strength for beam-column specimens without confining transverse reinforcement. T_{calc} based on Eq. (5.2)

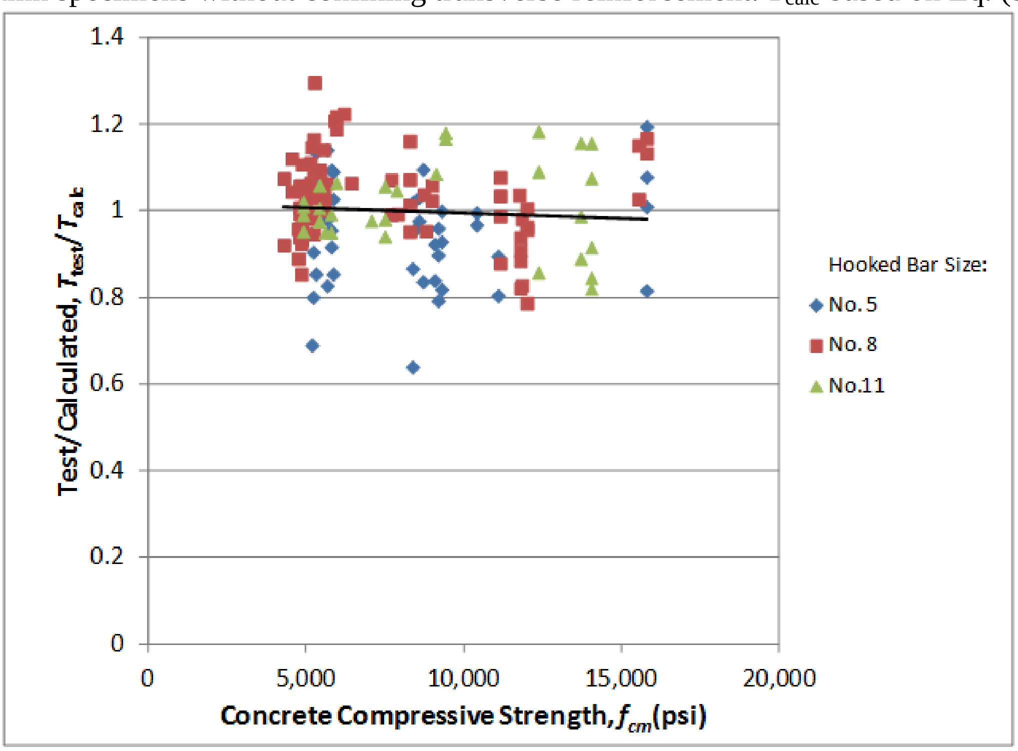


Figure 5.2 Ratio of test-to-calculated bar force versus concrete compressive strength for beam-column specimens with confining transverse reinforcement. T_{calc} based on Eq. (5.2)

In Figures 5.3 and 5.4, T_{test}/T_{calc}, with $T_{calc} = T_h$ from Eq. (5.2), is plotted versus embedment length for the specimens without and with confining transverse reinforcement, respectively. The upward sloping lines in the figures demonstrate that reducing the power of ℓ_{eh} from 1.0 underestimates the effect of embedment length on hook strength. The fact that T_{test}/T_{calc} is below 1.0 for shorter development lengths will be dealt with in the final version of the design equation.

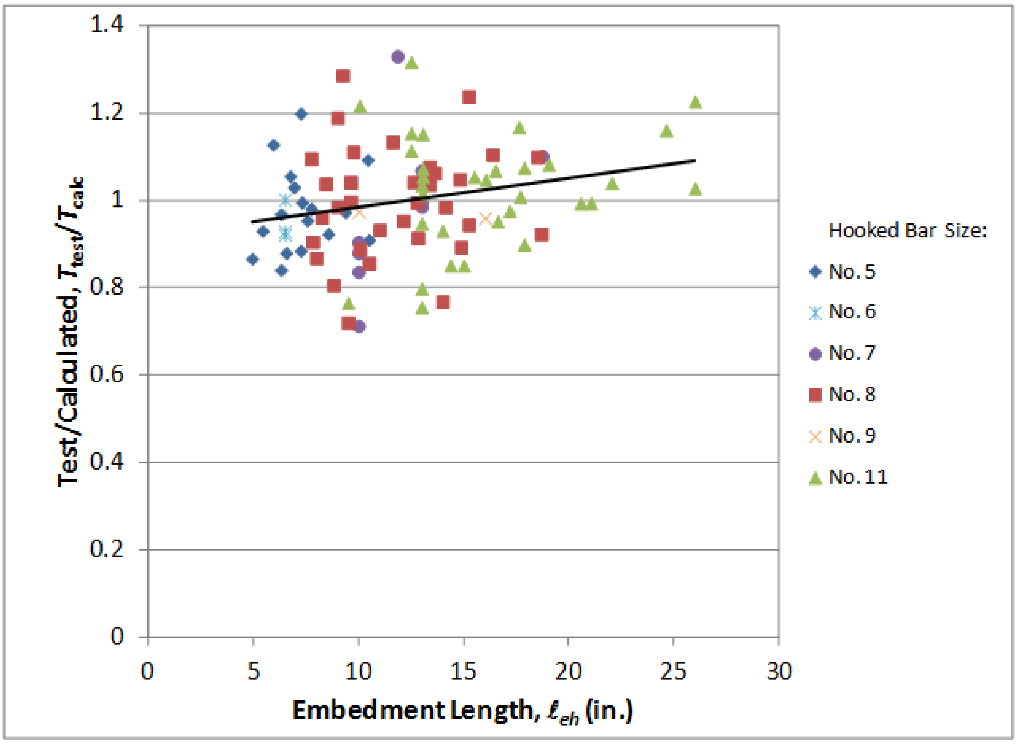


Figure 5.3 Ratio of test-to-calculated bar force versus embedment length for beam-column specimens without confining transverse reinforcement. T_{calc} based on Eq. (5.2)

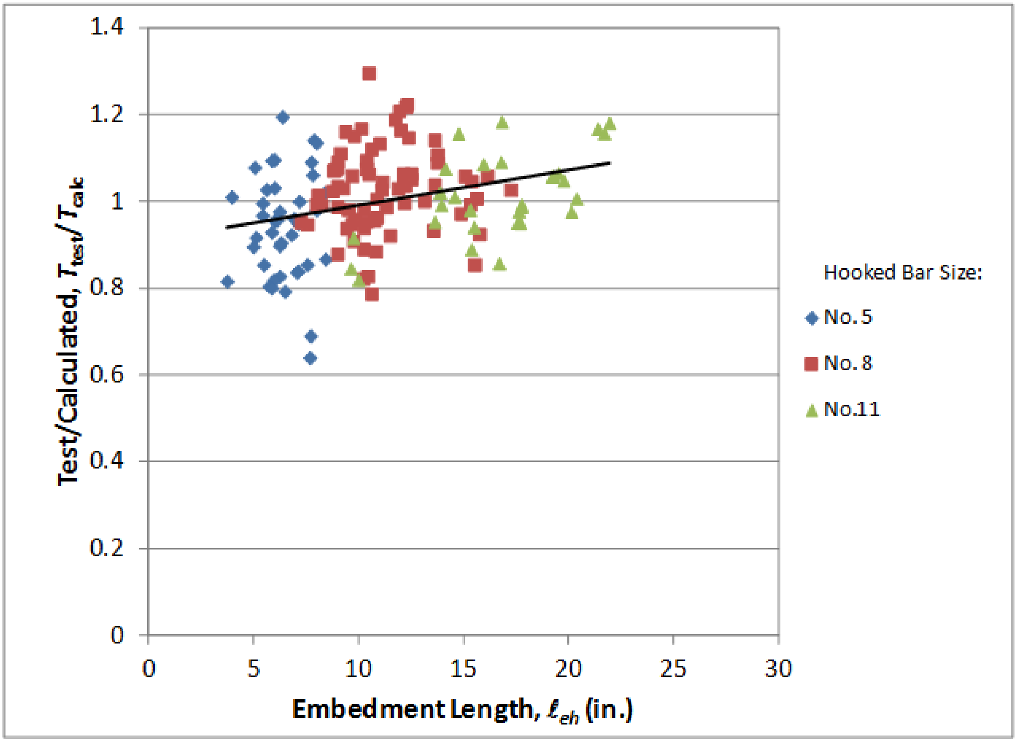


Figure 5.4 Ratio of test-to-calculated bar force versus embedment length for beam-column specimens with confining transverse reinforcement. T_{calc} based on Eq. (5.2)

Figures 5.5 and 5.6 show the effect of using a power of 0.5 for the bar diameter in the both terms in Eq. (5.2). The slightly upward sloping best-fit line in both figures indicates that the 0.5 power for d_b, when combined with the other simplifications in the equation, underestimates the effect of bar diameter on anchorage capacity for hooks with and without confining transverse reinforcement.

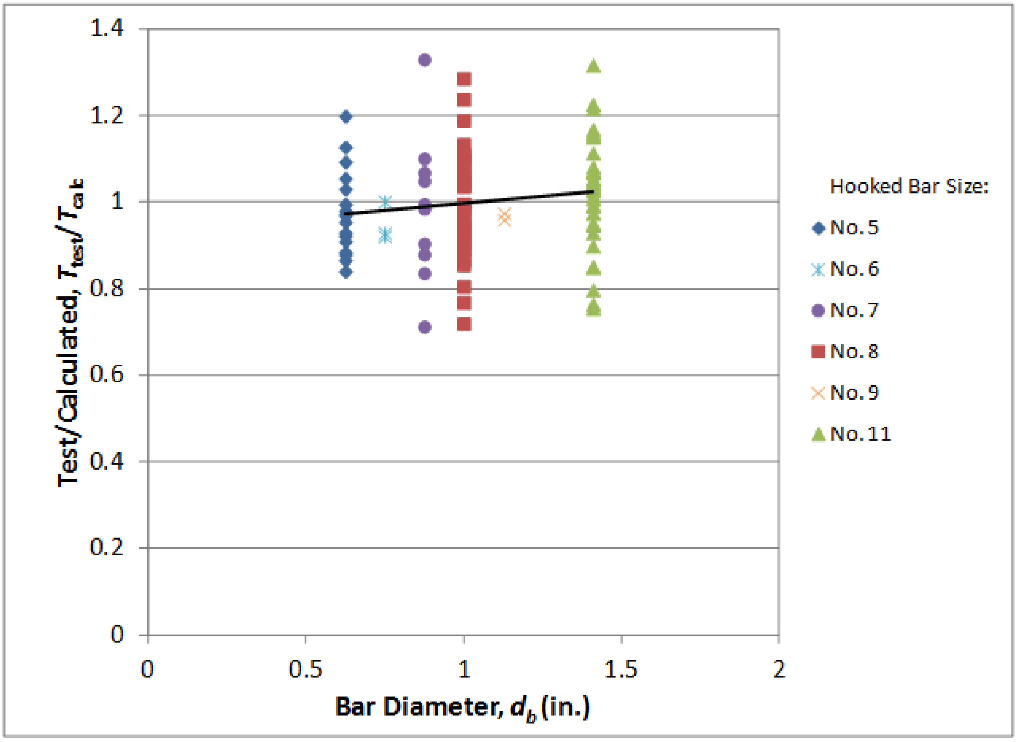


Figure 5.5 Ratio of test-to-calculated bar force versus bar diameter for hooks without confining transverse reinforcement. T_{calc} based on Eq. (5.2)

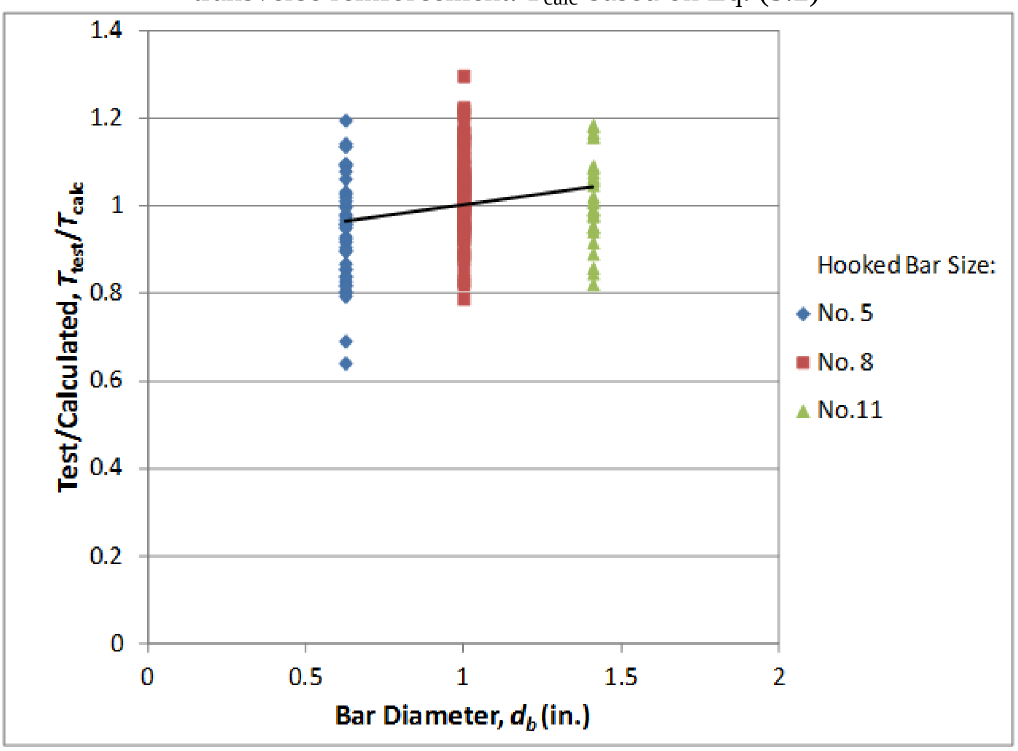


Figure 5.6 Ratio of test-to-calculated bar force versus bar diameter for hooks with confining transverse reinforcement. T_{calc} based on Eq. (5.2)

T_{test} is compared with $T_{calc} = T_h$ from Eq. (5.2) in Figures 5.7 and 5.8 for hooks without and with confining transverse reinforcement, respectively. As shown in both figures, Eq. (5.2) overestimates anchorage strength at lower forces (that is, for smaller bar sizes) and underestimates anchorage strength at higher forces for hooks both without and with confining transverse reinforcement.

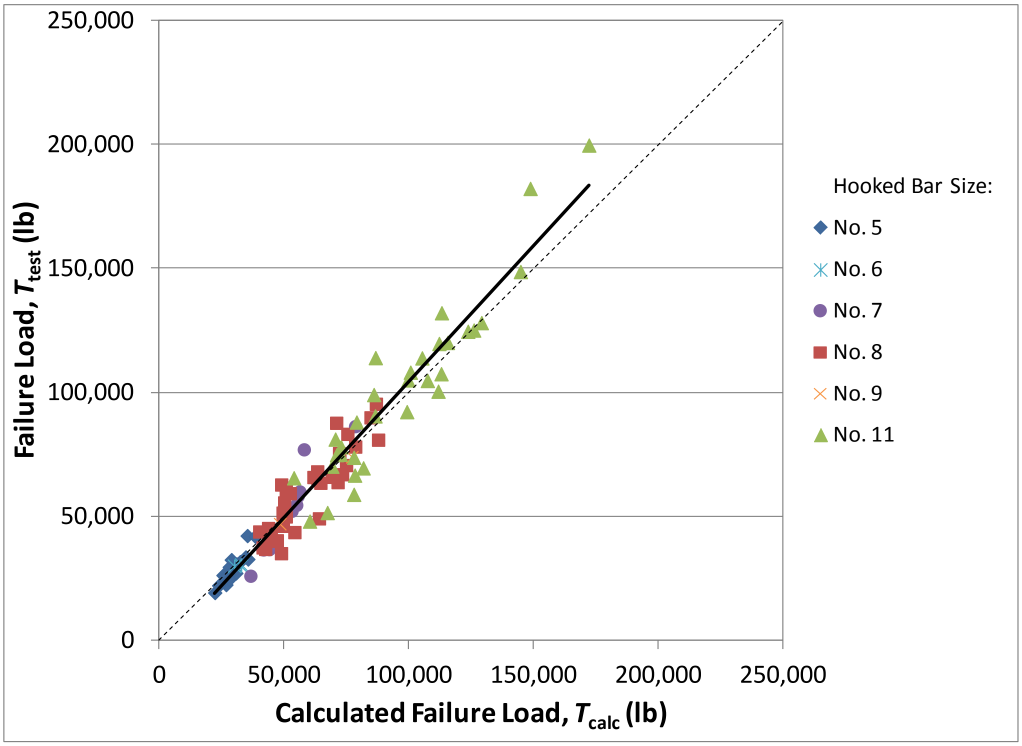


Figure 5.7 Comparison of the measured bar force at failure to the calculated bar force at failure for specimens without confining transverse reinforcement. T_{calc} based on Eq. (5.2)

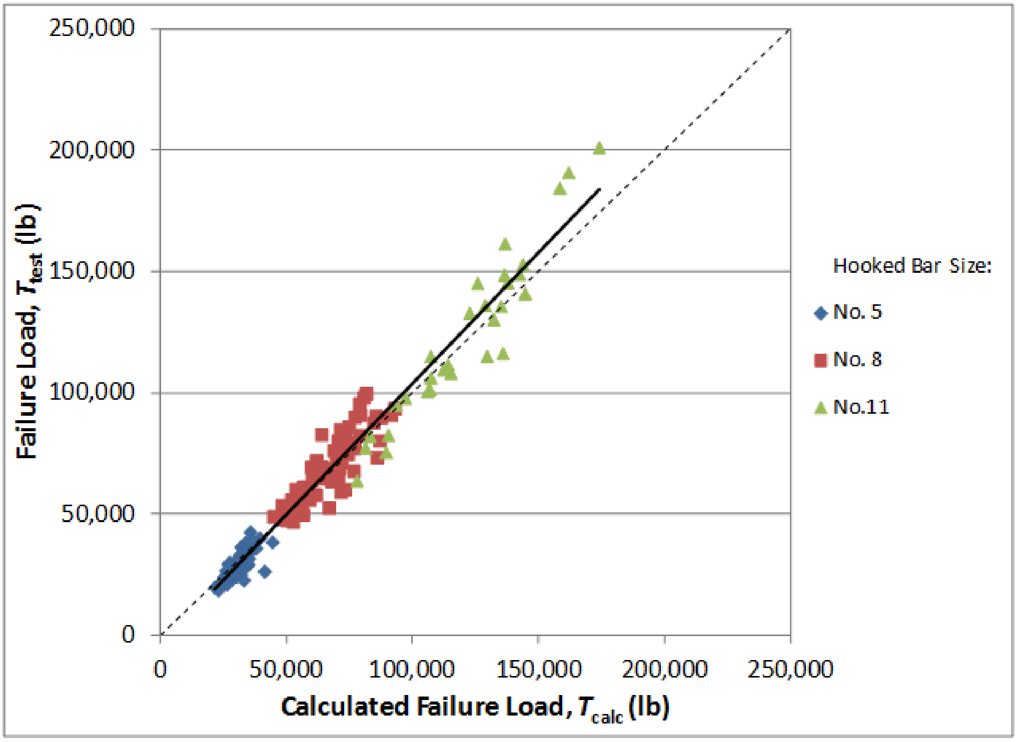


Figure 5.8 Comparison of the measured bar force at failure to the calculated bar force at failure for specimens with confining transverse reinforcement. T_{calc} based on Eq. (5.2)

5.3 CLOSELY SPACED HOOKED BARS

As discussed in Chapter 4, the anchorage capacity for specimens with multiple hooked bars is less than that for specimens with two hooked bars. As a result, the proposed equation overpredicts the capacity of closely spaced hooked bars, especially for specimens containing more than two hooked bars in a beam-column joint. The derivation of a correction factor for the use of closely spaced hooked bars is described in this section. Sixty-one specimens containing three or four No. 5, No. 8, or No. 11 hooked bars were tested. Of those, 42 were used in this analysis, 15 with no confining transverse reinforcement and 27 with confining transverse reinforcement. The 19 specimens not used for the derivation include 14 with hooked bars embedded outside the column compression region, which provide significantly lower hook capacities (Section 4.5), that must be dealt with separately in design and five with a column longitudinal reinforcement ratio of 0.04 or more that result in hook capacities that are significantly higher than the values for which Eq. (5.2) was derived (Section 4.6).

Figure 5.9 compares the values of T_{test}/T_{calc} for both two-hook and multiple-hook specimens for hooked bars without confining transverse reinforcement. As discussed in relation to Figure 4.36 in Section 4.4, Figure 5.9 indicates that without confining transverse reinforcement there is no effect of center-to-center spacing on the hook strength in specimens containing two hooked bars. For the specimens with more than two hooked bars, Figure 5.9 shows that center-to-center spacing plays a role in anchorage capacity—all but two specimens have a ratio of measured bar forces to calculated bar forces below 0.85.

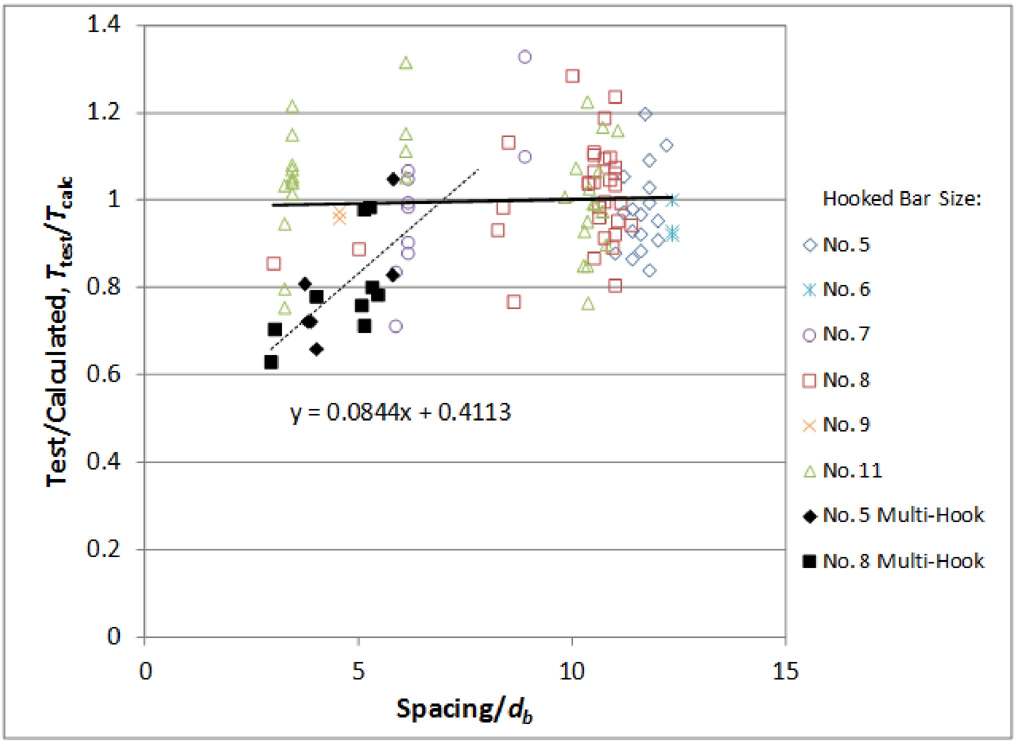


Figure 5.9 Comparison of the measured bar force at failure to the calculated bar force at failure for specimens without confining transverse reinforcement. T_{calc} based on Eq. (5.2)

A trend line was fit to the data points for the multiple-hook specimens in Figure 5.9 to establish a correction factor for the cases where closely spaced multiple hooks are used. This correction was only applied to the T_c term in Eq. (5.2) since the T_s term already takes into consideration the number of hooks by including the number of hooks n in the denominator of the term. The best-fit equation for the correction factor is expressed in terms of the average center-to-center spacing as a multiple of the bar diameter.

$$\frac{1}{\psi_m} = 0.0844\frac{s}{d_b} + 0.4133 \qquad \leq 1.0 \tag{5.3}$$

where ψ_m = development length correction factor for closely spaced hooks and s = average center-to-center hooked bar spacing

$1/\psi_m$ varies from 0.58 to 1.00 and ψ_m varies from 1.72 to 1.00 as the bar spacing s increases from 2 to 7 bar diameters. Values of $1/\psi_m$ and ψ_m are shown in Table 5.2

Table 5.2 Values of $1/\psi_m$ and ψ_m

s/d_b	2	3	4	5	6	≥ 7
$1/\psi_m$	0.58	0.66	0.75	0.83	0.92	1.00
ψ_m	1.72	1.50	1.34	1.20	1.09	1.00

Applying the correction factor for closely spaced hooks, the proposed descriptive equation becomes:

$$T_h = 548\ell_{eh} f_{cm}^{\ 0.25} d_b^{\ 0.5} \frac{1}{\psi_m} + 27{,}100\frac{NA_{tr}}{n} d_b^{\ 0.5} \tag{5.4}$$

Figure 5.10 compares the $T_{\text{test}}/T_{\text{calc}}$, with $T_{\text{calc}} = T_h$, from Eq. (5.4) to the center-to-center hooked bar spacing as a multiple of bar diameter d_b for hooked bars without confining transverse reinforcement. With the correction factor, the multiple-hook specimens have $T_{\text{test}}/T_{\text{calc}}$ ratios much closer to 1.0, suggesting that the correction factor accurately accounts for the effect of closely spaced multiple hooks.

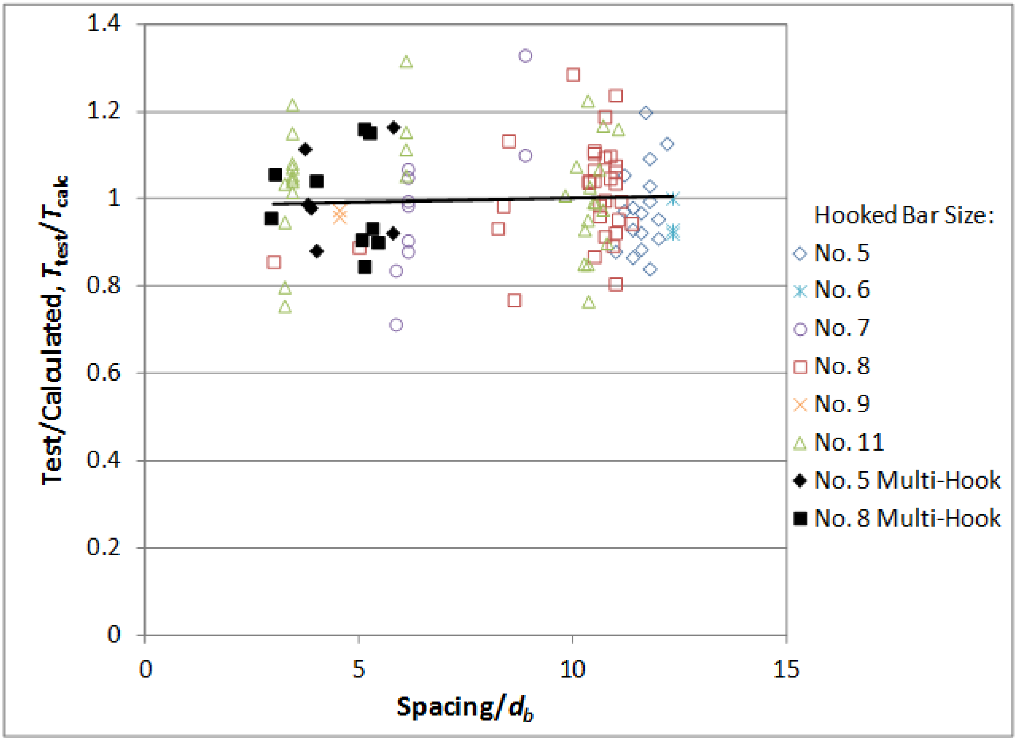


Figure 5.10 Ratio of test-to-calculated bar force versus center-to-center spacing between hooks for hooked bars without confining transverse reinforcement. T_{calc} based on Eq. (5.4)

5.4 CONVERSION TO DESIGN EQUATION

Equation (5.4) has a mean T_{test}/T_{calc} ratio of 1.0; therefore, an adjustment was needed to provide development lengths that would provide adequate anchorage strengths for the vast majority of conditions. To accomplish this, the equation was modified so that at least 95% of the T_{test}/T_{calc} ratios equaled or exceeded 1.0. To achieve this, the right side of Eq. (5.4) was divided by 1.31. The resulting equation is

$$T_h = 418\ell_{eh} f_{cm}^{\ 0.25} d_b^{\ 0.5} \frac{1}{\psi_m} + 20{,}687 \frac{NA_{tr}}{n} d_b^{\ 0.5} \tag{5.5}$$

Using Eq. (5.5) results in 3 out of 98 specimens without confining transverse reinforcement with T_{test}/T_{calc} below 1.0, with a low value of 0.933, and 2 out of 144 specimens with confining transverse reinforcement with T_{test}/T_{calc} below 1.0, with a low value of 0.833. In the latter case, the two low values represent hooked bars with less confining transverse reinforcement than required by Table 25.4.3.2 of ACI 318-14. For the multiple-hook specimens without transverse reinforcement, the average value of T_{test}/T_{calc} is 1.27, with no specimens having T_{test}/T_{calc} less than 1.0. For multiple-hook specimens with confining transverse reinforcement, the average value of T_{test}/T_{calc} is 1.35, also with no specimens with T_{test}/T_{calc} less than 1.0.

Obtaining a design equation for ℓ_{eh} involves substituting $f_s A_b = \pi f_s d_b^2/4$ for T_h in Eq. (5.5) and solving for ℓ_{eh}, which yields

$$\ell_{eh} = \left(0.00188 \frac{f_s d_b^{1.5}}{f_c'^{0.25}} - 49 \frac{NA_{tr}}{n f_{cm}^{0.25}}\right)\psi_m \quad (5.6)$$

To further simplify Eq. (5.6), the coefficient 0.00188 was conservatively rounded to 0.002. With this change the coefficient 49 was rounded to 50; while the latter change *increases* the effect of transverse reinforcement to *decrease* the embedment length, the overall equation is largely controlled by the first term with the result that these changes are conservative. The resulting equation is

$$\ell_{eh} = \left(0.002 \frac{f_s d_b^{1.5}}{f_c'^{0.25}} - 50 \frac{NA_{tr}}{n f_{cm}^{0.25}}\right)\psi_m \quad (5.7)$$

To check the safety of Eq. (5.7), the terms were rearranged to solve for T_h and the resulting equation is

$$T_h = 393 \ell_{eh} f_{cm}^{0.25} d_b^{0.5} \frac{1}{\psi_m} + 19{,}635 \frac{NA_{tr}}{n} d_b^{0.5} \quad (5.8)$$

Using Eq. (5.8) results in 1 out of 98 two-hook specimens without confining transverse reinforcement with T_{test}/T_{calc} below 1.0, with a low value of 0.991, and 2 out of 144 two-hook specimens with confining transverse reinforcement with T_{test}/T_{calc} below 1.0, with a low value of 0.889. None of the multiple-hook specimens produced a value T_{test}/T_{calc} below 1.0, as shown in Figures 5.11 and 5.12 for hooks without and with confining transverse reinforcement.

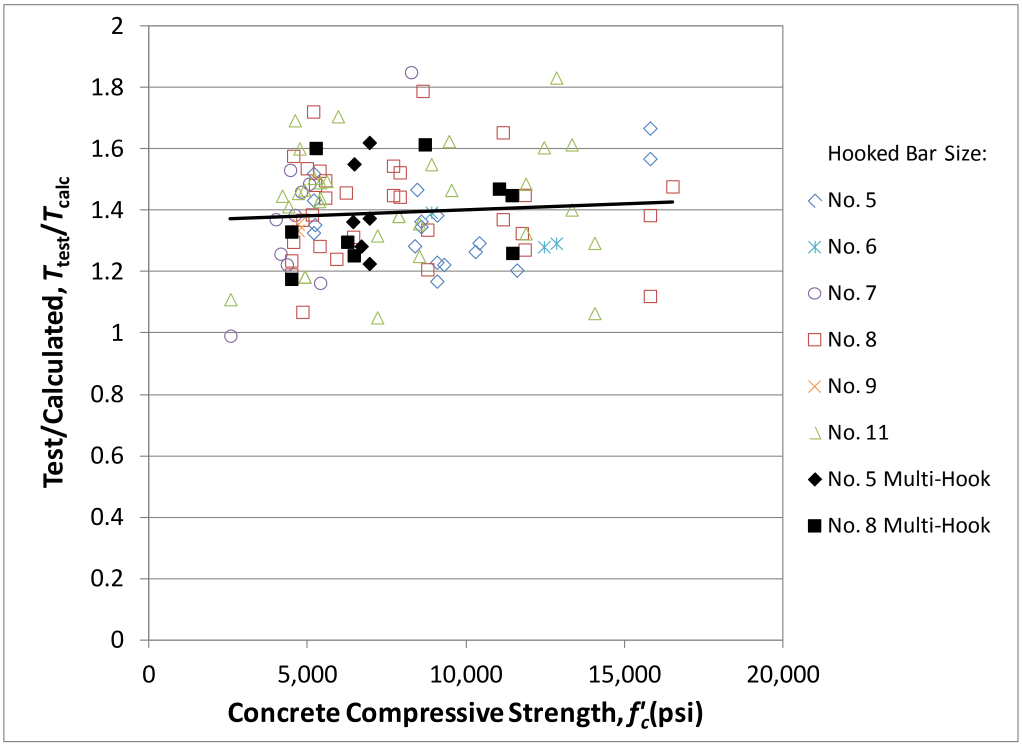


Figure 5.11 Ratio of test-to-calculated bar force versus concrete compressive strength for beam-column specimens without confining transverse reinforcement. T_{calc} based on Eq. (5.8)

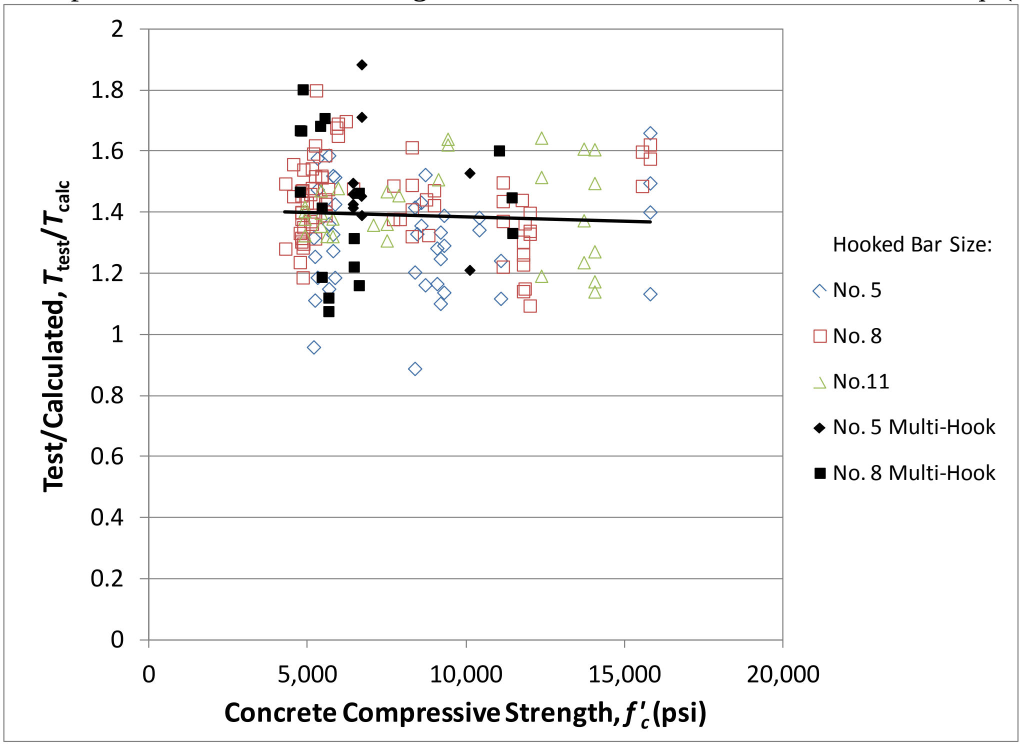


Figure 5.12 Ratio of test-to-calculated bar force versus concrete compressive strength for beam-column specimens with confining transverse. T_{calc} based on Eq. (5.8)

The failure load is compared to the load calculated using Eq. (5.8) for specimens without and with confining transverse reinforcement including two and multiple hooked bars, respectively, in Figures 5.13 and 5.14. The data points for the multiple-hook specimens are shown separately from those for the two-hook specimens. The figures illustrate the relative safety of Eq. (5.8).

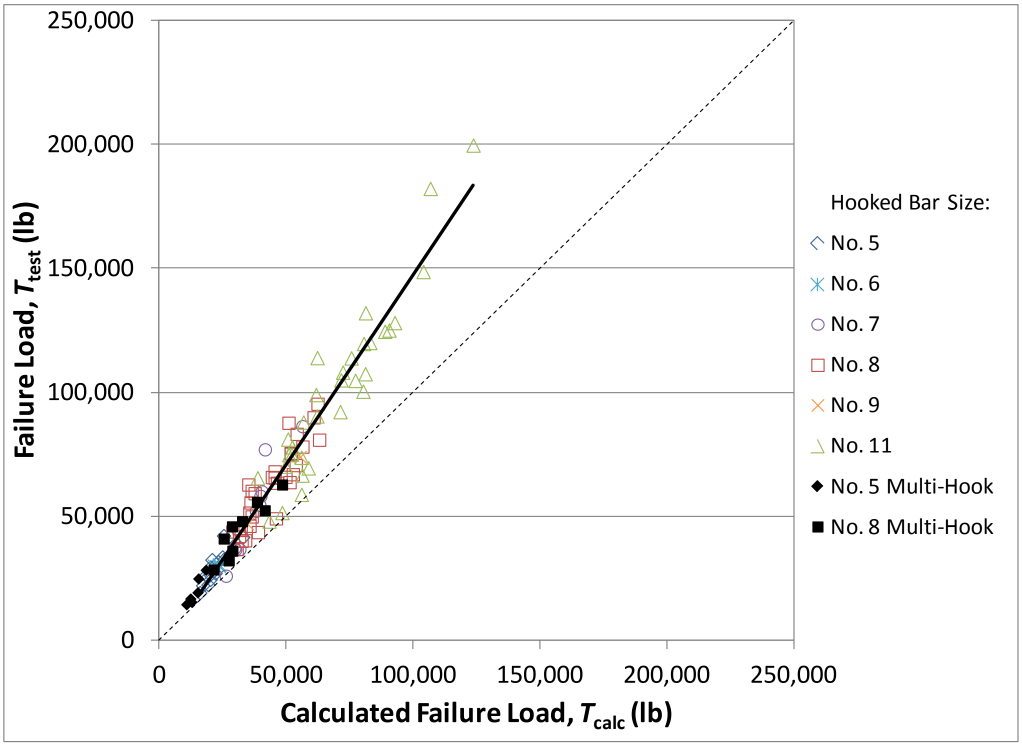


Figure 5.13 Measured versus calculated bar force at failure for hooked bars without confining transverse reinforcement, including multiple-hook specimens, with T_{calc} based on Eq. (5.8)

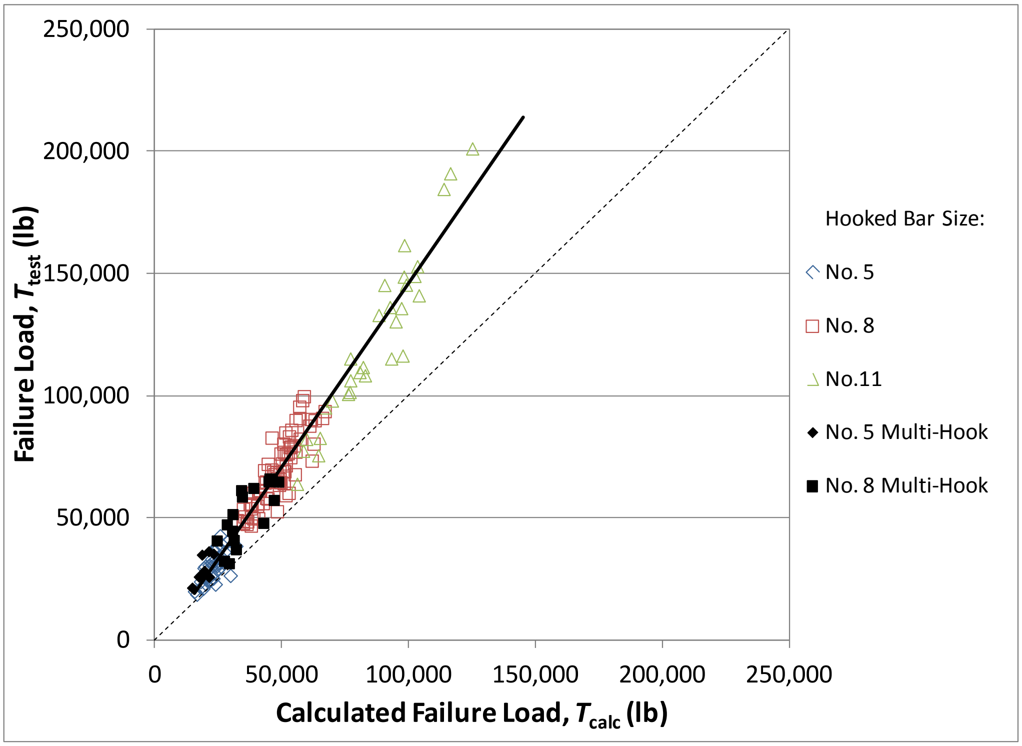


Figure 5.14 Measured versus calculated bar force at failure for hooked bars with confining transverse reinforcement, including multiple-hook specimens, with T_{calc} based on Eq. (5.8)

The mean, maximum, minimum, R^2, *SD*, and *COV* values of T_{test}/T_{calc} for Eq. (5.8) are shown in Table 5.3. The mean values of T_{test}/T_{calc} are 1.39 and 1.40 for two-hook and multiple-hook specimens without and with confining transverse reinforcement, respectively, with coefficients of variation of 0.123 and 0.119.

Table 5.3 Statistical parameters for T_{test}/T_{calc} for Eq. (5.8)

Parameter	Specimens without confining transverse reinforcement	Specimens with confining transverse reinforcement	All specimens
Mean	1.39	1.40	1.40
Max	1.85	1.88	1.88
Min	0.991	0.889	0.889
R^2	0.944	0.959	0.953
SD	0.171	0.167	0.168
COV	0.123	0.119	0.120

5.5 EQUATION FOR DEVELOPMENT LENGTH

For design, the embedment length ℓ_{eh} is replaced by development length ℓ_{dh}, the average measured compressive strength f_{cm} is replaced by the specified compressive strength f_c', and the stress in the hooked bar f_s is replaced by the specified yield strength f_y. With these substitutions, Eq. (5.7) becomes

$$\ell_{dh} = \left(0.002\frac{f_y d_b^{1.5}}{f_c'^{\,0.25}} - 50\frac{NA_{tr}}{nf_c'^{\,0.25}}\right)\psi_m \tag{5.9}$$

In Eq. (5.9), ℓ_{dh} for hooked bars without confining transverse reinforcement is a function of $d_b^{1.5}$, rather than being linearly related to either the bar diameter, as required by ACI 318-14 and the AASHTO LRFD Bridge Specifications, or the area of the bar, as earlier required in ACI 318-83. This relationship makes sense, not only because it is based on the test results, but because the bar force, which *does* increase linearly with the bar area, is resisted more effectively by hooked bars with larger diameters. This point is illustrated in Figures 4.4 through 4.8, which show that, for the same embedded length, larger diameter hooked bars carry a larger force at failure. The higher anchorage capacity of larger hooked bars is, however, not high enough to justify continuing to use a relationship in which development length ℓ_{dh} is proportional to bar diameter d_b. The factor for closely spaced hooks ψ_m modifies both terms within the parentheses.

When applying Eq. (5.9) to hooked bars confined by transverse reinforcement, ℓ_{dh} is obtained by reducing the development length required without confining transverse reinforcement, $0.002 f_s d_b^{1.5} / f_c'^{0.25}$, by a "length" provided by the confining transverse reinforcement $50NA_{tr} / nf_c'^{0.25}$, without a minimum value of transverse reinforcement, as required by Table 25.4.3.2 of ACI 318-14.

As an alternative, Eq. (5.9) can be expressed as

$$\ell_{dh} = \left(0.002\frac{f_y \psi_r \psi_m}{f_c'^{0.25}}\right) d^{1.5} \tag{5.10}$$

Where: $$\psi_r = \left(f_y d_b^{1.5} - 25{,}000 NA_{tr}/n\right) / \left(f_y d_b^{1.5}\right) \le 1.0 \tag{5.11}$$

ψ_r is the factor used to modify development length for hooked bars confined by transverse reinforcement and is equal 1.0 for hooked bars not confined by transverse reinforcement. The value of ψ_r increases as the area of each leg A_{tr} and number of legs N increase and decreases as the number of confined hooks n, hooked bar diameter d_b, and yield strength f_y increase. The values of ψ_r for specimens tested or analyzed in this study ranged between 0.72 and 0.97 for two-hook specimens with confining transverse reinforcement and between 0.77 and 0.96 for multiple-hook specimens with confining transverse reinforcement. Because of the lack of data, values of $\psi_r \leq 0.70$ are not recommended.

In the proposed design approach, the confining reinforcement can be perpendicular or parallel to the straight portion of the hooked bar for both 90° and 180° hooks. This is a departure from the provisions of the ACI Building Code, which does not consider parallel confining reinforcement in the calculation of development length for 180° hooks. Confining reinforcement perpendicular to the straight portion of a bar must be located within the development length ℓ_{dh}. Confining reinforcement parallel to the straight portion of the bar must enclose the bar extension beyond the hook, including the bend, corresponding to a 90° hook, as shown in Figure 5.15. As discussed in Chapter 4, the test results support the use of confining reinforcement in this region for both 90° and 180° hooks because it ties the concrete together and contributes to anchorage capacity.

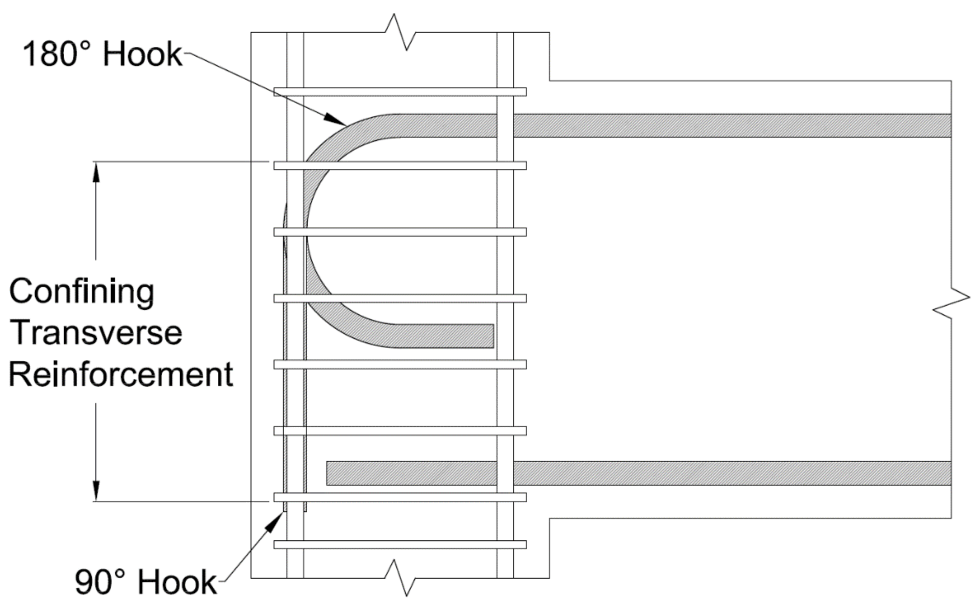


Figure 5.15 Transverse reinforcement providing confinement for 90° and 180° hooks

Tables 5.4a, 5.4b, and 5.4c show the values of ψ_r for f_y = 60,000, 80,000, and 100,000 psi, respectively, for hooked bars with sizes ranging from No. 3 though No. 11 when confined by No. 3 bars (A_{tr} = 0.11 in.). The values are expressed as a function of the number of confining legs per hook N/n ranging from 1 to 8. Values for N/n equal to 2 and 5 corresponding, respectively, to five hooked bars confined by transverse reinforcement spaced at $3d_b$ and two hooked bars confined by transverse reinforcement spaced at $3d_b$, are shown in bold. As shown in the tables, substantial reductions in ℓ_{dh} may be obtained in regions of high confinement. As proposed in Section 5.6, the designer will have the option of calculating the value of ψ_r based on Eq. (5.11) or selecting a value based on satisfying selected criteria.

Table 5.4a Values of ψ_r for hooked bars with f_y = 60,000 psi confined by No. 3 bars

Bar Designation No.	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Bar diameter, d_b, in.	0.375	0.500	0.625	0.750	0.875	1.00	1.128	1.270	1.410
N/n*									
1	0.80	0.87	0.91	0.93	0.94	0.95	0.96	0.97	0.97
2	--	**0.74**	**0.81**	**0.86**	**0.89**	**0.91**	**0.92**	**0.94**	**0.95**
3	--	--	0.72	0.79	0.83	0.86	0.89	0.90	0.92
4	--	--	--	0.72	0.78	0.82	0.85	0.87	0.89
5	--	--	--	--	**0.72**	**0.77**	**0.81**	**0.84**	**0.86**
6	--	--	--	--	--	0.73	0.77	0.81	0.84
7	--	--	--	--	--	--	0.73	0.78	0.81
8	--	--	--	--	--	--	--	0.74	0.78

*N = Number of legs of transverse reinforcement confining hooks – based on dimensions of 90° hooks for hooked bars with bend angles of 90° and 180°; n = Number of hooked bars being developed

-- Calculated value of ψ_r < 0.70

Table 5.4b Values of ψ_r for hooked bars with f_y = 80,000 psi confined by No. 3 bars

Bar Designation No.	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Bar diameter, d_b, in.	0.375	0.500	0.625	0.750	0.875	1.00	1.128	1.270	1.410
N/n*									
1	0.85	0.90	0.93	0.95	0.96	0.97	0.97	0.98	0.98
2	**0.70**	**0.81**	**0.86**	**0.89**	**0.92**	**0.93**	**0.94**	**0.95**	**0.96**
3	--	0.71	0.79	0.84	0.87	0.90	0.91	0.93	0.94
4	--	--	0.72	0.79	0.83	0.86	0.89	0.90	0.92
5	--	--	--	**0.74**	**0.79**	**0.83**	**0.86**	**0.88**	**0.90**
6	--	--	--	--	0.75	0.79	0.83	0.86	0.88
7	--	--	--	--	0.71	0.76	0.80	0.83	0.86
8	--	--	--	--	--	0.73	0.77	0.81	0.84

**N* = Number of legs of transverse reinforcement confining hooks – based on dimensions of 90° hooks for hooked bars with bend angles of 90° and 180°; *n* = Number of hooked bars being developed
-- Calculated value of $\psi_r < 0.70$

Table 5.4c Values of ψ_r for hooked bars with f_y = 100,000 psi confined by No. 3 bars

Bar Designation No.	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Bar diameter, d_b, in.	0.375	0.500	0.625	0.750	0.875	1.00	1.128	1.270	1.410
N/n*									
1	0.88	0.92	0.94	0.96	0.97	0.97	0.98	0.98	0.98
2	**0.76**	**0.84**	**0.89**	**0.92**	**0.93**	**0.95**	**0.95**	**0.96**	**0.97**
3	--	0.77	0.83	0.87	0.90	0.92	0.93	0.94	0.95
4	--	--	0.78	0.83	0.87	0.89	0.91	0.92	0.93
5	--	--	**0.72**	**0.79**	**0.83**	**0.86**	**0.89**	**0.90**	**0.92**
6	--	--	--	0.75	0.80	0.84	0.86	0.88	0.90
7	--	--	--	0.70	0.76	0.81	0.84	0.87	0.89
8	--	--	--	--	0.73	0.78	0.82	0.85	0.87

**N* = Number of legs of transverse reinforcement confining hooks – based on dimensions of 90° hooks for hooked bars with bend angles of 90° and 180°; *n* = Number of hooked bars being developed
-- Calculated value of $\psi_r < 0.70$

5.5.1 Hooked Bars Outside Column Core or Outside Compression Region

As shown in Section 4.5, hooked bars located outside of the column core exhibit about 20% lower strength than those located within the core. To address this in design, ℓ_{dh} should be increased by the factor ψ_o = 1/0.80 = 1.25 for hooked bars located outside a column core, with ψ_o = 1.0 for hooked bars located within a column core. With this factor and not including the effects of epoxy-coated reinforcement or lightweight concrete (added in Section 5.6), the final form of the expression for ℓ_{dh} for use in design is

$$\ell_{dh} = \left(0.002 \frac{f_y \psi_r \psi_m \psi_o}{f_c'^{0.25}} \right) d^{1.5} \tag{5.12}$$

Also as discussed in Section 4.5, hooked bars outside the compression region, not terminating at the far face of the column also tend to have lower anchorage strength. This case is treated the same as the hooked bars located outside of the column core. A total of 18 specimens had the hooked bars outside the column compression region, eight contained two hooked bars and 10 contained more than two hooked bars.

Figures 5.16 and 5.17 compare T_{test} with T_{calc} based Eq. (5.12) for hooked bars without and with confining transverse reinforcement, respectively. The test results for specimens with two hooked bars anchored outside the column core, two hooked bars anchored outside the column compression region, and multiple hooked bars anchored outside the column compression region are shown, along with test results for specimens with two hooked bars anchored within the column core. Application of ψ_o = 1.25 results in values for hooked bars outside the column core that conservatively track the trend of those inside the column core. For hooked bars outside the column core, none of the 20 specimens without confining transverse reinforcement and only one of the 19 specimens with confining transverse reinforcement have a $T_{\text{test}}/T_{\text{calc}}$ ratio below 1.0. The average, maximum and minimum values of $T_{\text{test}}/T_{\text{calc}}$ were 1.56, 1.95, and 1.26 for specimens with no transverse reinforcement and 1.49, 2.05, and 0.986 for specimens with transverse reinforcement.

Specimens with two hooked bars outside the column compression region had average, maximum and minimum values of $T_{\text{test}}/T_{\text{calc}}$ of 1.45, 1.64, and 1.15, while those with multiple hooked bars had average, maximum and minimum values of $T_{\text{test}}/T_{\text{calc}}$ of 1.61, 2.69, and 0.89; one specimen out of 19 had a $T_{\text{test}}/T_{\text{calc}}$ ratio less than 1.0. Both ψ_o and ψ_m were applied for specimens with multiple hooked bars located outside the column compression region.

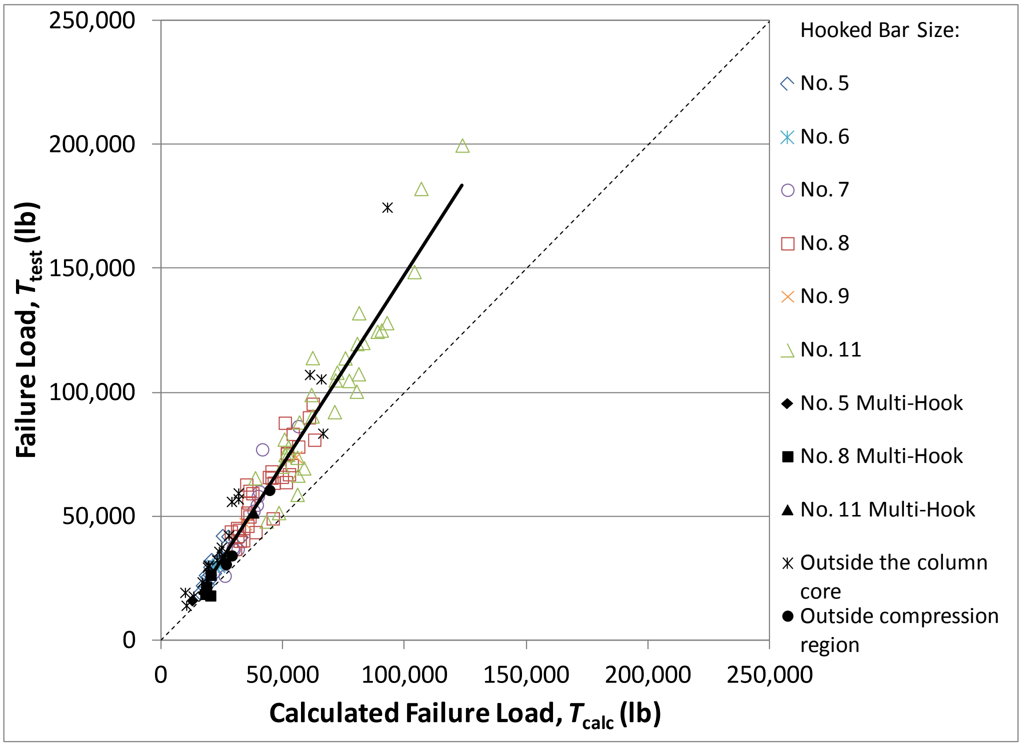


Figure 5.16 Measured versus calculated bar force at failure for hooked bars without confining transverse reinforcement, including hooks outside the column core and hooks outside the column compression region, with T_{calc} based on Eq. (5.12)

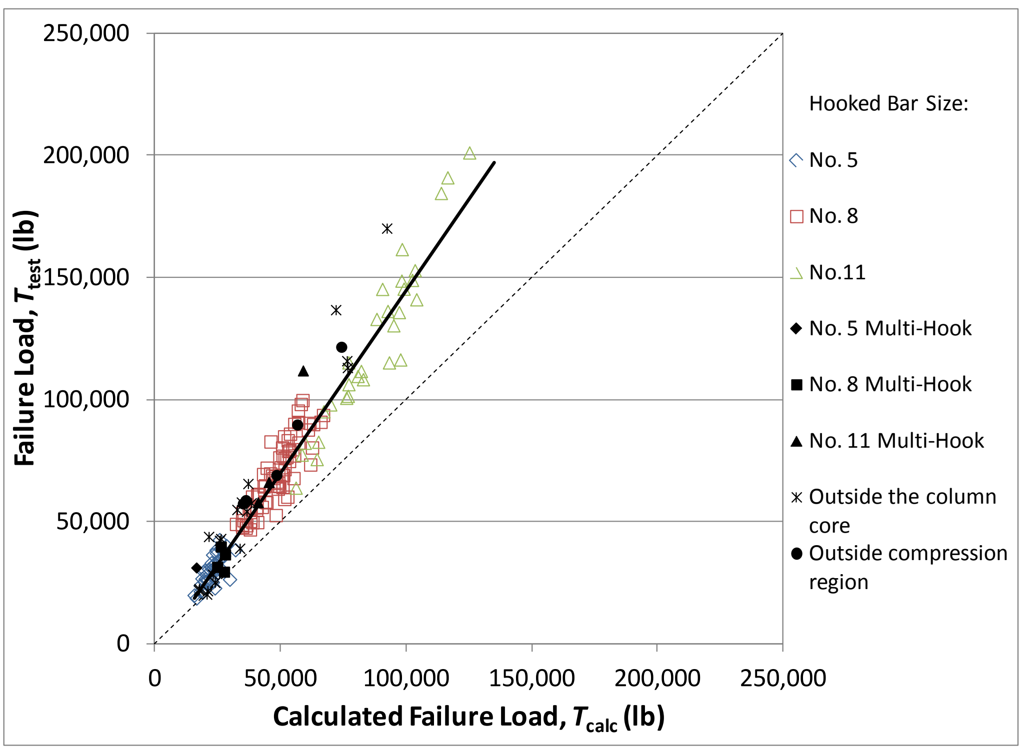


Figure 5.17 Measured versus calculated bar force at failure for hooked bars with confining transverse reinforcement, including hooks outside the column core and hooks outside the column compression region, with T_{calc} based on Eq. (5.12)

5.5.2 Hooked Bars in Walls

The study of hooked bars anchored in walls by Johnson and Jirsa (1981) was described in Chapters 1 and 4. As recommended in Section 4.7, the wide side cover should allow hooked bars anchored in walls to be treated as being anchored within a column core. For design, wide side cover will be treated as clear cover greater than 7 bar diameters, nominally the center-to-center spacing of $7d_b$ corresponding to $\psi_m = 1.0$.

The anchorage strengths of the hooked bars tested by Johnson and Jirsa (1981) are compared to calculated strengths based on Eq. (5.12) in Figure 5.18. The comparison includes 26 wall specimens with a single hooked bar and four wall specimens with three hooked bars. $\psi_o =$ 1.0 for all comparisons. With T_{calc} based on Eq. (5.12), the average, maximum and minimum values of T_{test}/T_{calc} were 1.43, 1.95, and 0.93. Two specimens out of 30 had a ratio of T_{test}/T_{calc} less than 1.0. Those specimens, however, had embedment lengths of just 2.5 and 3.5 in., much shorter than the embedment lengths used to develop Eq. (5.12) and much shorter than would be permitted in practice. The individual results are given in Table 5.5.

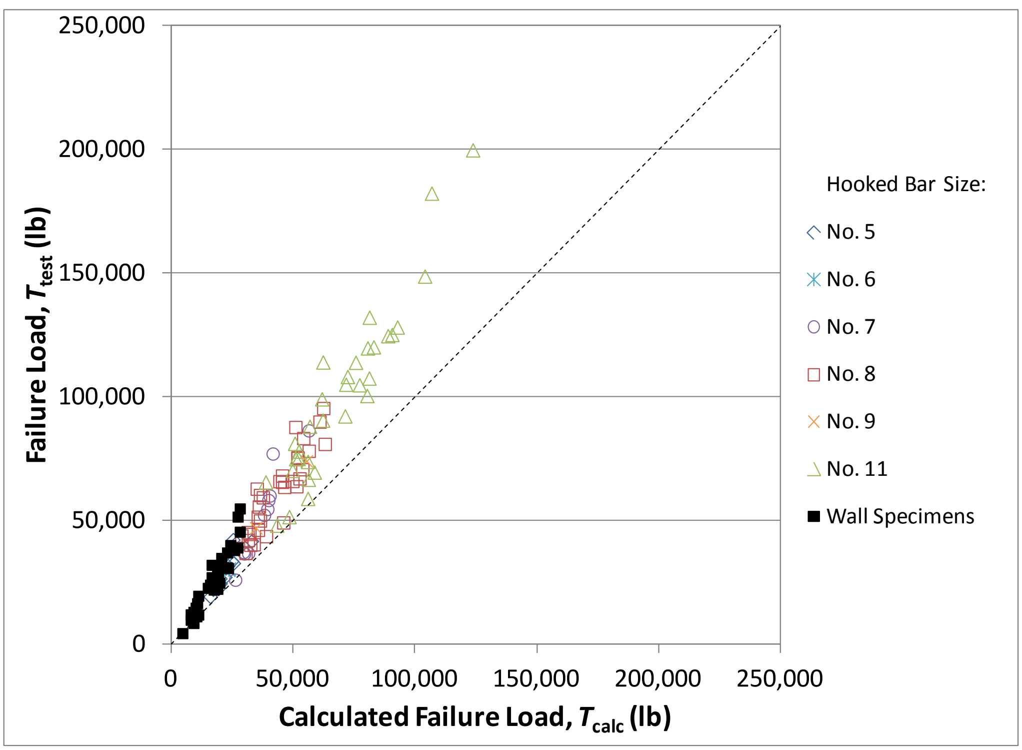


Figure 5.18 Measured versus calculated bar force at failure for hooked bars without confining transverse reinforcement, including hooks embedded in walls, with T_{calc} based on Eq. (5.12)

Table 5.5 Measured versus calculated bar force at failure for hooked bars in walls tested by Johnson and Jirsa (1981), with T_{calc} based on Eq. (5.12)

Specimen	T kips	T_{calc} kips	T/T_{calc}
4-3.5-8-M	4.4	4.6	0.96
4-5-11-M	12	8.0	1.50
4-5-14-M	9.8	8.0	1.23
7-5-8-L	13	9.1	1.43
7-5-8-M	16.5	10.6	1.55
7-5-8-H	19.5	11.1	1.76
7-5-8-M	14.7	10.0	1.47
7-5-14-L	8.5	9.1	0.93
7-5-14-M	11.2	10.3	1.09
7-5-14-H	11.9	11.1	1.07
7-5-14-M	11.3	10.0	1.13
7-7-8-M	32	16.6	1.93
7-7-11-M	27	16.6	1.63
7-7-14-M	22	17.4	1.26
9-7-11-M	30.8	18.8	1.64
9-7-14-M	24.8	19.8	1.26
9-7-18-M	22.3	18.9	1.18
7-8-11-M	34.8	20.5	1.70
7-8-14-M	26.5	19.2	1.38
9-8-14-M	30.7	23.3	1.32
11-8.5-11-L	37	22.9	1.62
11-8.5-11-M	51.5	27.2	1.89
11-8.5-11-H	54.8	28.1	1.95
11-8.5-14-L	31	22.9	1.35
11-8.5-14-M	39	27.2	1.44
11-8.5-14-H	45.4	28.1	1.61
7-7-11-M	24	15.9	1.51
7-7-11-L	22.7	15.0	1.51
11-8.5-11-M	38	25.7	1.48
11-8.5-11-L	40	24.2	1.65

5.6 PROPOSED CODE PROVISIONS

This section presents the proposed provisions for incorporation in the ACI Building Code. The section numbers are those that appear in ACI 318-14. Current criteria for epoxy-coated bars, lightweight concrete, and minimum development length are retained.

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 greater of (a) through (c):

(a) $\ell_{dh} = \left(\dfrac{f_y \psi_e \psi_r \psi_m \psi_o}{500\lambda f_c'^{0.25}} \right) d_b^{1.5}$

(b) $8d_b$

(c) 6 in.

25.4.3.2 For the calculation of ℓ_{dh}, modification factors shall be in accordance with Table 25.4.3.2a. Factor ψ_r 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
Confining reinforcement ψ_r	$\psi_r = \dfrac{f_y d_b^{1.5} - 25{,}000 N A_{tr}/n}{f_y d_b^{1.5}} > 0.7$ [1] or as given in Table 25.4.3.2b	
Placement ψ_o	Hooks terminating at the far face within a column core or at the far face of a wall with side cover $\geq 7d_b$	1.0
	Other	1.25
Closely spaced hooked bars ψ_m	For hooked bars spaced $< 7d_b$	[2] $\left(0.085\dfrac{s}{d_b} + 0.4\right)^{-1} \geq 1.0$
	For hooked bars spaced $\geq 7d_b$	1.0

[1] f_y is the yield strength and d_b is the nominal diameter of the hooked bars, N is the number of legs of transverse reinforcement confining the hooks – based on dimensions of 90° hooks, n is the number of hooked bars being developed.
[2] s is the center-to-center spacing of hooked bars.

Table 25.4.3.2b—Modification factor for confining reinforcement

Transverse reinforcement and hooked bar yield strength	Hooked Bar Size:		
	No. 6 and smaller	No. 7 to No. 11	No. 14 or No. 18
$N/n \geq 5$ and yield strength of the hooked bars $f_y \leq 80{,}000$ psi[1]	0.75	0.9	1.0
$2 \leq N/n < 5$ and yield strength of the hooked bars $f_y \leq 80{,}000$ psi	0.9	0.95	1.0
All other cases	1.0	1.0	1.0

[1]f_y is the yield strength of the hooked bars, N is the number of legs of transverse reinforcement confining hooks – based on dimensions of 90° hooks, n is the number of hooked bars being developed.

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 (d) 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_r shall be taken as 1.0 in calculating ℓ_{dh} in accordance with 25.4.3.1(a)

(d) 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

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

6.2 CONCLUSIONS

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

1. The provisions of ACI 318-14 overpredict the strength of larger hooked bars, the effect of concrete compressive strength, and the effect of transverse confining reinforcement on the anchorage capacity of hooked bars in tension.
2. The reduction factors as applied in Section 25.4.3.2 of ACI 318-14 for concrete cover and confining transverse reinforcement are unconservative.
3. Increasing concrete side cover from 2.5 to 3.5 in. does not increase the anchorage capacity of hooked bars.
4. Hooked bars with 90° and 180° bend angles produce similar anchorage capacities and can be used interchangeably. This includes hooked bars with a 180° bend angle confined by transverse reinforcement parallel to the straight portion of the bar spaced over the region required in Section 25.4.3.2 of ACI 318-14 to allow use of the 0.8 development length reduction factor for 90° hooks.
5. For hooked bars with a 90° bend angle, confining transverse reinforcement placed perpendicular to the straight portion of the bars results in lower anchorage capacity than confining transverse reinforcement with a similar spacing placed parallel to the straight portion of the bars.
6. The effect of concrete compressive strength on the anchorage capacity of hooked can be represented by the compressive strength to the 0.29 power for hooked bars not confined by transverse reinforcement and the compressive strength to the 0.24 power for hooked bars confined by transverse reinforcement.
7. Transverse reinforcement results in an incremental rather than percentage increase in the anchorage capacity of hooked bars.
8. For a given embedment length, the anchorage capacity of hooked bars increases with bar diameter; this effect is greater with the addition of confining transverse reinforcement.
9. If closely spaced, three or more hooked bars exhibit a decrease in force per bar compared to joints with just two hooked bars.
10. Hooked bars cast outside the column core exhibit lower anchorage capacity than hooked bars cast inside the core.

11. Hooked bars anchored in the middle of the column core exhibit lower anchorage capacity than hooked bars anchored on the far side of the column.
12. High longitudinal reinforcement ratios (> 0.04) in a column provide additional confinement to hooked bars, increasing their anchorage capacity.
13. The high side cover typically present for hooked bars in walls provides confinement similar to that provided to hooked bars inside a column core.
14. The proposed Code provisions in Section 5.6 provide a conservative basis for the development length of hooked bars.

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APPENDIX A: NOTATION

A_{cti} Total area of cross-ties inside the hook region
A_h Bar area of hook
A_s Area of longitudinal steel in the column
A_{tr} Total area of transverse steel inside hook region
b Column width
c_b Clear cover measured from the center of the hook to the side of the column
c_h Clear spacing between hooked bars, inside-to-inside spacing
c_{so} Clear cover measured from the side of the hook to the side of the column
$c_{so,avg}$ Average clear cover of the hooked bars
c_{th} Clear cover measured from the tail of the hook to the back of the column
d_b Nominal bar diameter of the hooked bar
d_{cto} Nominal bar diameter of cross-ties outside the hook region
d_s Nominal bar diameter of transverse reinforcing steel outside the hook region
d_{tr} Nominal bar diameter of transverse 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 25.4.3.1 of ACI 318-14
f_{su} Average peak stress in hooked bars at failure
$f_{su,\mathrm{ind}}$ Stress in hook at failure
f_{ys} Nominal yield strength of longitudinal reinforcing steel in the column
f_{yt} Nominal yield strength of transverse reinforcement
h_c Width of bearing member flange
h_{cl} Height measured from the center of the hook to the top of the bearing member flange
h_{cu} Height measured from the center of the hook to the bottom of the upper compression member
ℓ_{dh} Development length in tension of deformed bar with a standard hook, measured from the outside end of hook, point of tangency, toward critical section
ℓ_{eh} Embedment length measured from the back of the hook to the front of the column
$\ell_{eh,avg}$ Average embedment length of hooked bars
n Number of hooked bars confined by N legs
N Number of legs of confining transverse reinforcement in joint region
N_{cti} Total number of cross-ties used as supplemental reinforcement inside the hook region
N_{cto} Number of cross-ties used per layer as supplemental reinforcement outside the hook region and spaced at s_s
N_h Number of hooked bars loaded simultaneously
N_{tr} Number of stirrups/ties crossing the hook
R_r Relative rib area
s Center-to-center spacing of hooked bars, ties, or stirrups
s_{cti} Center-to-center spacing of cross-ties in the hook region
s_s Center-to-center spacing of stirrups/ties outside the hook region
s_{tr} Center-to-center spacing of transverse reinforcement in the hook region
T Average peak load on hooked bars
T_c Contribution of concrete to hooked bar anchorage capacity
T_{calc} Calculated hooked bar strength

T_h Hooked bar anchorage capacity
T_{ind} Peak load on the hooked bar at failure
T_N Load on hooked bar at failure multiplied by concrete compressive strength normalized to 5,000 psi
T_s Contribution of confining steel in joint region to hooked bar anchorage capacity
T_{test} Recorded load on hooked bar at failure
T_{total} Total peak load on hooked bars
α Student's t-test significance
λ Modification factor to reflect the reduced mechanical properties of lightweight concrete to normalweight concrete of the same compressive strength
ψ_c Factor for cover as defined in ACI 318-14 Section 25.4.3.2
ψ_e Epoxy coating factor as defined in ACI 318-14 Section 25.4.3.2
ψ_m Hooked bar spacing factor
ψ_o Factor for hooked bar location
ψ_r Factor for transverse reinforcement in the hook region

Failure types (described in Section 3.2)
FP Front Pullout
FB Front Blowout
SS Side Splitting
SB Side Blowout
TK Tail Kickout
FL Flexural Failure of column
BY Yield of hooked bars

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

APPENDIX B: COMPREHENSIVE TEST RESULTS

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	*Age* days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
1	5-5-90-0-o-1.5-2-5[†]	A B	90°	Horizontal	A615	5.0 5.0	5.0	4930	4	0.625	0.077	11	5.25	8.375
2	5-5-90-0-o-1.5-2-6.5[†]	A B	90°	Horizontal	A1035	6.5 5.9	6.2	5650	6	0.625	0.073	11	5.25	8.375
3	5-5-90-0-o-1.5-2-8[†]	B A	90°	Horizontal	A1035	7.9 4.8	7.9	5650	6	0.625	0.073	11	5.25	8.375
4	5-5-90-0-o-2.5-2-5	B A	90°	Horizontal	A615	4.8 9.0	4.8	4930	4	0.625	0.077	13	5.25	8.375
5	5-5-180-0-o-1.5-2-9.5[†]	A B	180°	Horizontal	A1035	9.6 9.3	9.4	4420	7	0.625	0.077	11	5.25	8.375
6	5-5-180-0-o-1.5-2-11.25[†]	A	180°	Horizontal	A1035	11.3	11.3	4520	8	0.625	0.077	11	5.25	8.375
7	5-5-180-0-o-2.5-2-9.5[†]	A B	180°	Horizontal	A1035	9.5 9.5	9.5	4520	8	0.625	0.077	13	5.25	8.375
8	5-5-90-0-i-2.5-2-10	A B	90°	Horizontal	A1035	9.4 9.4	9.4	5230	6	0.625	0.073	13	5.25	8.375
9	5-5-90-0-i-2.5-2-7	A B	90°	Horizontal	A1035	6.9 7.0	6.9	5190	7	0.625	0.073	13	5.25	8.375
10	5-8-90-0-i-2.5-2-6[†]	A B	90°	Horizontal	A615	6.8 6.8	6.8	8450	14	0.625	0.073	13	5.25	8.375
11	5-8-90-0-i-2.5-2-6(1)	A B	90°	Horizontal	A1035	6.1 6.5	6.3	9080	11	0.625	0.073	13	5.25	8.375
12	5-8-90-0-i-2.5-2-8[†]	A B	90°	Horizontal	A1035	8.0 7.5	7.8	8580	15	0.625	0.073	13	5.25	8.375
13	(2@4) 5-8-90-0-i-2.5-2-6	A B	90°	Horizontal	A1035	5.8 6.0	5.9	6950	18	0.625	0.073	8	5.25	8.375
14	(2@6) 5-8-90-0-i-2.5-2-6	A B	90°	Horizontal	A1035	6.0 6.0	6.0	6950	18	0.625	0.073	9	5.25	8.375
15	5-12-90-0-i-2.5-2-10	A B	90°	Horizontal	A1035	10.0 11.0	10.5	10290	14	0.625	0.073	13	5.25	8.375
16	5-12-90-0-i-2.5-2-5	A B	90°	Horizontal	A1035	5.1 4.8	4.9	11600	84	0.625	0.073	13	5.25	8.375
17	5-15-90-0-i-2.5-2-5.5	A B	90°	Horizontal	A1035	6.1 5.8	5.9	15800	62	0.625	0.073	13	5.25	8.375
18	5-15-90-0-i-2.5-2-7.5	A B	90°	Horizontal	A1035	7.3 7.3	7.3	15800	62	0.625	0.073	13	5.25	8.375
19	5-5-90-0-i-3.5-2-10	A B	90°	Horizontal	A1035	10.5 10.4	10.4	5190	7	0.625	0.073	15	5.25	8.375
20	5-5-90-0-i-3.5-2-7	A B	90°	Horizontal	A1035	7.5 7.6	7.6	5190	7	0.625	0.073	15	5.25	8.375
21	5-8-90-0-i-3.5-2-6[†]	A B	90°	Horizontal	A615	6.3 6.4	6.3	8580	15	0.625	0.073	15	5.38	8.375
22	5-8-90-0-i-3.5-2-6(1)	A B	90°	Horizontal	A1035	6.5 6.6	6.6	9300	13	0.625	0.073	15	5.25	8.375
23	5-8-90-0-i-3.5-2-8[†]	A B	90°	Horizontal	A1035	8.6 8.5	8.6	8380	13	0.625	0.060	15	5.25	8.375
24	5-12-90-0-i-3.5-2-5	A B	90°	Horizontal	A1035	5.5 5.4	5.4	10410	15	0.625	0.073	15	5.25	8.375
25	5-12-90-0-i-3.5-2-10	A B	90°	Horizontal	A1035	10.1 10.0	10.1	11600	84	0.625	0.073	15	5.25	8.375

*No failure of hook; equipment malfunction

[†] Specimens had constant 80 kip axial load

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

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

	Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	$f_{su,\ ind}$ ksi	f_{su} ksi	Slip at Failure in.	Failure Type
1	5-5-90-0-o-1.5-2-5†	A B	1.5 1.8	1.6	2.0 2.0	6.8	2	14100 19600	28140	14070	45500 63200	45400	- -	FP/SB FP/SB
2	5-5-90-0-o-1.5-2-6.5†	A B	1.5 1.6	1.6	2.0 2.8	6.6	2	20800 18200	35630	17815	67100 58700	57500	- -	FP FP/SB
3	5-5-90-0-o-1.5-2-8†	B A	1.5 2.5	1.5	2.1 2.1	6.6	2	23500 19500	23500	23500	75800 62900	75800	- -	SB FP/SB
4	5-5-90-0-o-2.5-2-5	B A	2.5 2.6	2.5	2.1 1.5	6.4	2	24000 30300	38570	19285	77400 97700	62200	- -	FP/SB SB
5	5-5-180-0-o-1.5-2-9.5†	A B	1.6 1.6	1.6	2.1 2.1	6.4	2	35200 30400	58970	29485	113500 98100	95100	- -	FP FP/SB
6	5-5-180-0-o-1.5-2-11.25†	A	1.8	1.8	2.3	6.6	2	32400	32400	32400	104500	104500	-	FP/SB
7	5-5-180-0-o-2.5-2-9.5†	A B	2.5 2.5	2.5	1.9 1.8	6.6	2	40400 24660	60260	30130	130300 79500	97200	- -	FP FP
8	5-5-90-0-i-2.5-2-10	A B	2.8 2.6	2.7	2.9 2.9	6.4	2	37400 32900	67170	33585	120600 106100	108300	- -	FP/SS FP/SS
9	5-5-90-0-i-2.5-2-7	A B	2.5 2.5	2.5	2.8 2.6	6.8	2	26600 26100	52530	26265	85800 84200	84700	- 0.192	FP/SS FP/SS
10	5-8-90-0-i-2.5-2-6†	A B	2.8 2.6	2.7	1.3 1.3	6.4	2	27600 32100	59140	29570	89000 103500	95400	- -	FB/SB SB/FB
11	5-8-90-0-i-2.5-2-6(1)	A B	2.5 2.5	2.5	2.6 2.3	7.0	2	21700 25000	44850	22425	70000 80600	72300	0.296 .330(.030)	FP FP
12	5-8-90-0-i-2.5-2-8†	A B	2.5 2.8	2.6	2.0 2.5	6.6	2	31900 35900	63350	31675	102900 115800	102200	- -	SS/FP SS/FP
13	(2@4) 5-8-90-0-i-2.5-2-6	A B	2.7 3.7	3.2	2.3 2.0	1.9	2 2	23200 21700	44700	22400	74800 73200	72300	- -	FP FP
14	(2@6) 5-8-90-0-i-2.5-2-6	A B	2.6 2.7	2.6	2.0 2.0	3.1	2 2	127060 147900	47900	24000	82300 77400	77400	- -	FP/SS FP/SS
15	5-12-90-0-i-2.5-2-10	A B	2.4 2.5	2.4	2.5 1.5	6.6	2	40800 42500	83310	41655	131600 137100	134400	0.191 -	SB FB/SB/TK
16	5-12-90-0-i-2.5-2-5	A B	2.6 2.6	2.6	2.1 2.5	6.5	2	19400 23170	38440	19220	62600 74700	62000	- -	FP/SS FP
17	5-15-90-0-i-2.5-2-5.5	A B	2.4 2.4	2.4	1.6 1.9	6.6	2	36200 32400	65000	32500	116800 104500	104800	- -	FP FB
18	5-15-90-0-i-2.5-2-7.5	A B	2.5 2.5	2.5	2.6 2.6	6.6	2	42000 42500	84400	42200	135500 137100	136100	- -	FB *
19	5-5-90-0-i-3.5-2-10	A B	3.5 3.5	3.5	1.8 1.9	6.5	2	43200 41100	83850	41925	139400 132600	135200	- -	SB/FP SB/FP
20	5-5-90-0-i-3.5-2-7	A B	3.4 3.5	3.4	1.3 1.1	7.0	2	27200 25900	53030	26515	87700 83500	85500	- -	SS FP/SS
21	5-8-90-0-i-3.5-2-6†	A B	3.6 3.5	3.6	1.8 1.6	6.6	2	25100 29100	50950	25475	81000 93900	82200	- -	FP/SS FP/SS
22	5-8-90-0-i-3.5-2-6(1)	A B	3.8 3.8	3.8	2.1 1.9	6.9	2	24400 27500	49080	24540	78700 88700	79200	0.152 .178(.150)	FP/SS FP/SS
23	5-8-90-0-i-3.5-2-8†	A B	3.6 3.5	3.6	1.4 1.5	7.1	2	39100 34300	65490	32745	126100 110600	105600	- -	FB/SS SS
24	5-12-90-0-i-3.5-2-5	A B	3.6 3.6	3.6	1.7 1.8	7.0	2	22000 23200	44240	22120	71000 74800	71400	- -	FP FP
25	5-12-90-0-i-3.5-2-10	A B	3.5 3.5	3.5	2.5 1.5	6.8	2	46000 46000	46000	46000	148400 148400	148400	- -	BY BY

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

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
1	5-5-90-0-o-1.5-2-5[†]	A B	60	-	-	-	-	0.88	4[1]	2.5	0.375	2.50	-	-	1.27	60
2	5-5-90-0-o-1.5-2-6.5[†]	A B	60	-	-	-	-	0.88	4[1]	2.5	0.375	2.50	-	-	1.89	60
3	5-5-90-0-o-1.5-2-8[†]	B A	60	-	-	-	-	0.88	4[1]	2.5	0.375	2.50	-	-	1.27	60
4	5-5-90-0-o-2.5-2-5	B A	60	-	-	-	-	0.88	4[1]	2.5	0.375	2.50	-	-	1.27	60
5	5-5-180-0-o-1.5-2-9.5[†]	A B	60	-	-	-	-	0.22	1[1]	4.0	0.375	4.00	-	-	1.27	60
6	5-5-180-0-o-1.5-2-11.25[†]	A	60	-	-	-	-	0.22	1[1]	4.0	0.375	4.0	-	-	1.27	60
7	5-5-180-0-o-2.5-2-9.5[†]	A B	60	-	-	-	-	0.22	1[1]	4.0	0.375	4.00	-	-	1.89	60
8	5-5-90-0-i-2.5-2-10	A B	60	-	-	-	-	0.33	3	3.0	0.375	3.00	-	-	1.89	60
9	5-5-90-0-i-2.5-2-7	A B	60	-	-	-	-	0.80	4	2.5	0.500	3.50	-	-	1.27	60
10	5-8-90-0-i-2.5-2-6[†]	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
11	5-8-90-0-i-2.5-2-6(1)	A B	60	-	-	-	-	0.66	6	3.0	0.500	3.00	-	-	1.27	60
12	5-8-90-0-i-2.5-2-8[†]	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
13	(2@4) 5-8-90-0-i-2.5-2-6	A B	60	-	-	-	-	-	-	-	0.375	3.00	-	-	3.16	60
14	(2@6) 5-8-90-0-i-2.5-2-6	A B	60	-	-	-	-	-	-	-	0.375	3.00	-	-	3.16	60
15	5-12-90-0-i-2.5-2-10	A B	60	-	-	-	-	0.11	1	7.0	0.375	5.00	-	-	1.89	60
16	5-12-90-0-i-2.5-2-5	A B	60	-	-	-	-	0.66	6	2.5	0.500	3.00	-	-	1.27	60
17	5-15-90-0-i-2.5-2-5.5	A B	60	-	-	-	-	-	-	-	0.375	2.50	-	-	1.27	60
18	5-15-90-0-i-2.5-2-7.5	A B	60	-	-	-	-	-	-	-	0.375	3.50	-	-	3.16	60
19	5-5-90-0-i-3.5-2-10	A B	60	-	-	-	-	0.33	3	3.0	0.375	3.00	-	-	1.89	60
20	5-5-90-0-i-3.5-2-7	A B	60	-	-	-	-	0.80	4	2.5	0.375	3.50	-	-	1.27	60
21	5-8-90-0-i-3.5-2-6[†]	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
22	5-8-90-0-i-3.5-2-6(1)	A B	60	-	-	-	-	0.66	6	3.0	0.500	3.00	-	-	1.27	60
23	5-8-90-0-i-3.5-2-8[†]	A B	60	-	-	-	-	0.80	4	4.0	0.500	4.00	-	-	1.27	60
24	5-12-90-0-i-3.5-2-5	A B	60	-	-	-	-	0.66	6	2.5	0.500	3.00	-	-	1.27	60
25	5-12-90-0-i-3.5-2-10	A B	60	-	-	-	-	0.11	1	7.0	0.375	5.00	-	-	1.89	60

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

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	*Age* days	d_b in.	R_r	*b* in.	h_{cl} in.	h_c in.
26	5-8-180-0-i-2.5-2-7	A B	180°	Horizontal	A1035	7.4 7.1	7.3	9080	11	0.625	0.073	13	5.25	8.375
27	5-8-180-0-i-3.5-2-7	A B	180°	Horizontal	A1035	7.4 7.3	7.3	9080	11	0.625	0.073	15	5.25	8.375
28	5-5-90-1#3-i-2.5-2-8[†]	A B	90°	Horizontal	A1035	8.0 7.6	7.8	5310	6	0.625	0.073	13	5.25	8.375
29	5-5-90-1#3-i-2.5-2-6[†]	A B	90°	Horizontal	A615	4.8 5.5	5.1	5800	9	0.625	0.060	13	5.25	8.375
30	5-8-90-1#3-i-2.5-2-6[†]	A B	90°	Horizontal	A615	6.0 6.3	6.1	8450	14	0.625	0.060	13	5.25	8.375
31	5-8-90-1#3-i-2.5-2-6(1)	A B	90°	Horizontal	A1035	6.1 5.6	5.9	9300	13	0.625	0.073	13	5.25	8.375
32	5-8-90-1#3-i-3.5-2-6[†]	A B	90°	Horizontal	A1035	6.0 6.0	6.0	8710	16	0.625	0.060	15	5.25	8.375
33	5-8-90-1#3-i-3.5-2-6(1)	A B	90°	Horizontal	A1035	6.3 6.3	6.3	9190	12	0.625	0.073	15	5.25	8.375
34	5-5-180-1#3-i-2.5-2-8[†]	A B	180°	Horizontal	A1035	8.0 7.8	7.9	5670	7	0.625	0.073	13	5.25	8.375
35	5-5-180-1#3-i-2.5-2-6[†]	A B	180°	Horizontal	A615	6.0 6.0	6.0	5800	9	0.625	0.060	13	5.25	8.375
36	5-8-180-1#3-i-2.5-2-7	A B	180°	Horizontal	A1035	7.1 7.3	7.2	9300	13	0.625	0.073	13	5.25	8.375
37	5-8-180-1#3-i-3.5-2-7	A B	180°	Horizontal	A1035	7.1 6.8	6.9	9190	12	0.625	0.073	15	5.25	8.375
38	5-5-90-1#4-i-2.5-2-8[†]	A B	90°	Horizontal	A1035	7.4 7.8	7.6	5310	6	0.625	0.073	13	9.25	8.375
39	5-5-90-1#4-i-2.5-2-6[†]	A B	90°	Horizontal	A615	5.3 5.8	5.5	5860	8	0.625	0.060	13	5.25	8.375
40	5-8-90-1#4-i-2.5-2-6	A B	90°	Horizontal	A1035	5.9 6.0	6.0	9300	13	0.625	0.073	13	5.25	8.375
41	5-8-90-1#4-i-3.5-2-6	A B	90°	Horizontal	A1035	6.0 7.0	6.5	9190	12	0.625	0.073	15	5.25	8.375
42	5-5-180-1#4-i-2.5-2-8[†]	A B	180°	Horizontal	A1035	8.0 8.0	8.0	5310	6	0.625	0.073	13	5.25	8.375
43	5-5-180-1#4-i-2.5-2-6[†]	A B	180°	Horizontal	A615	6.5 6.0	6.3	5670	7	0.625	0.060	13	5.25	8.375
44	5-5-180-2#3-o-1.5-2-11.25[†]	A B	180°	Horizontal	A1035	11.6 11.5	11.6	4420	7	0.625	0.077	11	5.25	8.375
45	5-5-180-2#3-o-1.5-2-9.5[†]	B	180°	Horizontal	A1035	8.8	8.8	4520	8	0.625	0.08	11	5.25	8.375
46	5-5-180-2#3-o-2.5-2-9.5[†]	A B	180°	Horizontal	A1035	9.1 9.3	9.2	4420	7	0.625	0.077	13	5.25	8.375
47	5-5-180-2#3-o-2.5-2-11.25[†]	A B	180°	Horizontal	A1035	11.1 11.4	11.3	4520	8	0.625	0.077	13	5.25	8.375
48	5-5-90-2#3-i-2.5-2-8[†]	A B	90°	Horizontal	A1035	8.0 7.5	7.8	5860	8	0.625	0.073	13	5.38	8.375
49	5-5-90-2#3-i-2.5-2-6[†]	A B	90°	Horizontal	A615	6.0 5.8	5.9	5800	9	0.625	0.060	13	5.25	8.375
50	5-8-90-2#3-i-2.5-2-6[†]	A B	90°	Horizontal	A1035	6.0 6.0	6.0	8580	15	0.625	0.073	13	5.25	8.375
51	5-8-90-2#3-i-2.5-2-8[†]	A B	90°	Horizontal	A1035	8.3 8.5	8.4	8380	13	0.625	0.073	13	5.25	8.375

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

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

	Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	$f_{su,\ ind}$ ksi	f_{su} ksi	Slip at Failure in.	Failure Type
26	5-8-180-0-i-2.5-2-7	A B	2.5 2.6	2.6	2.1 2.4	6.3	2	26700 35200	54220	27110	86100 113500	87500	0.194 .146(.016)	FP/SS SB/FP
27	5-8-180-0-i-3.5-2-7	A B	3.6 3.4	3.5	1.9 2.0	7.1	2	34100 31400	61510	30755	110000 101300	99200	0.251 .237(.021)	SS/FP FP/SS
28	5-5-90-1#3-i-2.5-2-8†	A B	2.5 2.5	2.5	2.4 2.8	6.9	2	32900 37400	66270	33135	106100 120600	106900	- -	FP SB/FB
29	5-5-90-1#3-i-2.5-2-6†	A B	2.5 2.5	2.5	3.3 2.5	6.9	2	20000 29300	39830	19915	64500 94500	64200	- -	SS SS/FP
30	5-8-90-1#3-i-2.5-2-6†	A B	2.5 2.5	2.5	2.0 1.8	6.6	2	26200 27900	53150	26575	84500 90000	85700	- -	FP SS
31	5-8-90-1#3-i-2.5-2-6(1)	A B	2.6 2.8	2.7	2.1 2.6	6.5	2	29300 25400	50800	25400	94500 81900	81900	- -	FP/SS FP/SS
32	5-8-90-1#3-i-3.5-2-6†	A B	3.6 3.6	3.6	2.0 2.0	6.8	2	41400 31200	60170	30085	133500 100600	97000	- -	FP/SS FP/SS
33	5-8-90-1#3-i-3.5-2-6(1)	A B	3.8 3.5	3.6	2.4 2.4	6.8	2	29000 26300	51810	25905	93500 84800	83600	0.239 0.158	FP/SS FP/SS
34	5-5-180-1#3-i-2.5-2-8†	A B	2.6 2.5	2.6	2.3 2.5	6.6	2	36600 39900	72900	36450	118100 128700	117600	- -	SS SS/FP
35	5-5-180-1#3-i-2.5-2-6†	A B	2.6 2.6	2.6	2.0 2.0	6.6	2	29100 24300	47830	23915	93900 78400	77100	- -	SS/FP FP/SS
36	5-8-180-1#3-i-2.5-2-7	A B	2.5 2.5	2.5	2.4 2.3	6.5	2	34200 35400	65820	32910	110300 114200	106200	0.373 .261(.035)	FP/SS FP/SS
37	5-8-180-1#3-i-3.5-2-7	A B	3.5 3.5	3.5	2.1 2.5	7.0	2	35800 28900	61000	30500	115500 93200	98400	0.205 0.238	FP FP
38	5-5-90-1#4-i-2.5-2-8†	A B	2.5 2.5	2.5	2.8 2.4	6.9	2	35700 27500	55070	27535	115200 88700	88800	- -	FP/SS SB
39	5-5-90-1#4-i-2.5-2-6†	A B	2.5 2.5	2.5	2.8 2.3	6.6	2	21600 26800	42910	21455	69700 86500	69200	- -	SS SS
40	5-8-90-1#4-i-2.5-2-6	A B	2.5 2.8	2.6	2.8 2.8	6.4	2	23900 27900	48580	24290	77100 90000	78400	0.25 0.22	FP FP/SS
41	5-8-90-1#4-i-3.5-2-6	A B	3.6 3.5	3.6	3.0 2.0	6.8	2	25300 25200	50480	25240	81600 81300	81400	- -	FP/SS FP/SS
42	5-5-180-1#4-i-2.5-2-8†	A B	2.5 2.5	2.5	2.0 2.0	6.6	2	43100 38400	76840	38420	139000 123900	123900	- -	FP/SS FP
43	5-5-180-1#4-i-2.5-2-6†	A B	2.5 2.6	2.6	2.0 2.5	6.6	2	25300 22900	45950	22975	81600 73900	74100	- -	FP/SS FP
44	5-5-180-2#3-o-1.5-2-11.25†	A B	1.6 1.5	1.6	1.9 1.9	6.6	2	48300 43000	86100	43050	155800 138700	138900	- -	FP/SB FP/SB
45	5-5-180-2#3-o-1.5-2-9.5†	B	1.6	1.6	2.4	6.6	2	20300	20300	20300	65500	65500	-	FP/SB
46	5-5-180-2#3-o-2.5-2-9.5†	A B	2.5 2.5	2.5	2.1 2.0	6.6	2	35500 43900	87800	43900	114500 141600	141600	- -	FP/SB FP
47	5-5-180-2#3-o-2.5-2-11.25†	A B	2.5 2.8	2.6	2.5 2.1	6.6	2	43600 42500	84650	42325	140600 137100	136500	- -	FP FP/SB
48	5-5-90-2#3-i-2.5-2-8†	A B	2.5 2.5	2.5	2.0 2.5	6.6	2	37900 38900	74310	37155	122300 125500	119900	- -	SS/FP SS/FP
49	5-5-90-2#3-i-2.5-2-6†	A B	2.6 2.6	2.6	2.5 2.8	6.6	2	31800 29200	58890	29445	102600 94200	95000	- -	FP/SS FP/SS
50	5-8-90-2#3-i-2.5-2-6†	A B	2.8 2.9	2.8	2.0 2.0	6.1	2	33500 30900	61280	30640	108100 99700	98800	- -	FP/SS FP/SS
51	5-8-90-2#3-i-2.5-2-8†	A B	2.6 2.5	2.6	1.8 1.5	6.5	2	39800 40500	80340	40170	128400 130600	129600	- -	FP/SS FP/SS

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

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
26	5-8-180-0-i-2.5-2-7	A B	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60
27	5-8-180-0-i-3.5-2-7	A B	60	-	-	-	-	0.22	2	4.0	0.500	3.00	-	-	1.27	60
28	5-5-90-1#3-i-2.5-2-8†	A B	60	0.38	0.1	1	5.00	0.44	4	6.0	0.375	4.00	-	-	1.27	60
29	5-5-90-1#3-i-2.5-2-6†	A B	60	0.38	0.1	1	5.00	0.44	4	6.0	0.375	4.00	-	-	1.27	60
30	5-8-90-1#3-i-2.5-2-6†	A B	60	0.38	0.1	1	5.00	0.80	4	6.0	0.500	4.00	-	-	1.27	60
31	5-8-90-1#3-i-2.5-2-6(1)	A B	60	0.38	0.1	1	6.00	0.66	6	3.0	0.500	3.00	-	-	1.27	60
32	5-8-90-1#3-i-3.5-2-6†	A B	60	0.38	0.1	1	5.00	0.80	4	6.0	0.500	4.00	-	-	1.27	60
33	5-8-90-1#3-i-3.5-2-6(1)	A B	60	0.38	0.1	1	6.00	0.66	6	3.0	0.500	3.00	-	-	1.27	60
34	5-5-180-1#3-i-2.5-2-8†	A B	60	0.38	0.1	1	4.00	-	-	-	0.375	4.00	-	-	1.27	60
35	5-5-180-1#3-i-2.5-2-6†	A B	60	0.38	0.1	1	4.00	-	-	-	0.375	4.00	-	-	1.27	60
36	5-8-180-1#3-i-2.5-2-7	A B	60	0.38	0.1	1	3.00	-	-	-	0.375	3.00	-	-	1.27	60
37	5-8-180-1#3-i-3.5-2-7	A B	60	0.38	0.1	1	3.00	-	-	-	0.375	3.00	-	-	1.27	60
38	5-5-90-1#4-i-2.5-2-8†	A B	60	0.5	0.2	1	5.00	0.44	4	6.0	0.375	4.00	-	-	1.27	60
39	5-5-90-1#4-i-2.5-2-6†	A B	60	0.5	0.2	1	5.00	0.44	4	6.0	0.375	4.00	-	-	1.27	60
40	5-8-90-1#4-i-2.5-2-6	A B	60	0.5	0.2	1	6.00	0.44	4	6.0	0.500	3.00	-	-	1.27	60
41	5-8-90-1#4-i-3.5-2-6	A B	60	0.5	0.2	1	6.00	0.44	4	6.0	0.500	3.00	-	-	1.27	60
42	5-5-180-1#4-i-2.5-2-8†	A B	60	0.5	0.2	1	4.00	-	-	-	0.375	4.00	-	-	1.27	60
43	5-5-180-1#4-i-2.5-2-6†	A B	60	0.5	0.2	1	4.00	-	-	-	0.375	4.00	-	-	1.27	60
44	5-5-180-2#3-o-1.5-2-11.25†	A B	60	0.38	0.2	2	2.00	-	-	-	0.375	4.00	-	-	1.89	60
45	5-5-180-2#3-o-1.5-2-9.5†	B	60	0.375	0.22	2	2.0	-	-	-	0.375	4.0	-	-	1.27	60
46	5-5-180-2#3-o-2.5-2-9.5†	A B	60	0.38	0.2	2	2.00	-	-	-	0.375	4.00	-	-	1.89	60
47	5-5-180-2#3-o-2.5-2-11.25†	A B	60	0.38	0.2	2	2.00	-	-	-	0.375	4.50	-	-	1.89	60
48	5-5-90-2#3-i-2.5-2-8†	A B	60	0.38	0.2	2	4.00	-	-	-	0.375	4.00	-	-	1.27	60
49	5-5-90-2#3-i-2.5-2-6†	A B	60	0.38	0.2	2	4.00	-	-	-	0.375	4.00	-	-	1.27	60
50	5-8-90-2#3-i-2.5-2-6†	A B	60	0.38	0.2	2	4.00	-	-	-	0.500	4.00	-	-	1.27	60
51	5-8-90-2#3-i-2.5-2-8†	A B	60	0.38	0.2	2	4.00	-	-	-	0.500	4.00	-	-	1.67	60

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

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	*Age* days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
52	5-12-90-2#3-i-2.5-2-5	A B	90°	Horizontal	A1035	5.8 5.8	5.8	11090	83	0.625	0.073	13	5.25	8.375
53	5-15-90-2#3-i-2.5-2-6	A B	90°	Horizontal	A1035	6.3 6.5	6.4	15800	61	0.625	0.073	13	5.25	8.375
54	5-15-90-2#3-i-2.5-2-4	A B	90°	Horizontal	A1035	3.5 4.0	3.8	15800	61	0.625	0.073	13	5.25	8.375
55	5-5-90-2#3-i-3.5-2-6	A B	90°	Horizontal	A1035	6.0 5.8	5.9	5230	6	0.625	0.073	15	5.25	8.375
56	5-5-90-2#3-i-3.5-2-8	A B	90°	Horizontal	A1035	7.9 7.5	7.7	5190	7	0.625	0.073	15	5.25	8.375
57	5-8-90-2#3-i-3.5-2-6†	A B	90°	Horizontal	A1035	6.5 6.0	6.3	8580	15	0.625	0.073	15	5.25	8.375
58	5-8-90-2#3-i-3.5-2-8†	A B	90°	Horizontal	A1035	7.1 7.0	7.1	8710	16	0.625	0.060	15	5.25	8.375
59	5-12-90-2#3-i-3.5-2-5	A B	90°	Horizontal	A1035	5.6 5.3	5.4	10410	15	0.625	0.073	15	5.25	8.375
60	5-12-90-2#3-i-3.5-2-10	A B	90°	Horizontal	A1035	10.8 10.6	10.7	11090	83	0.625	0.073	15	5.25	8.375
61	5-5-180-2#3-i-2.5-2-8†	A B	180°	Horizontal	A1035	8.0 8.0	8.0	5670	7	0.625	0.073	13	5.25	8.375
62	5-5-180-2#3-i-2.5-2-6†	A B	180°	Horizontal	A615	5.8 5.5	5.6	5860	8	0.625	0.060	13	5.25	8.375
63	5-8-180-2#3-i-2.5-2-7	A B	180°	Horizontal	A1035	7.0 7.3	7.1	9080	11	0.625	0.073	13	5.25	8.375
64	5-8-180-2#3-i-3.5-2-7	A B	180°	Horizontal	A1035	6.8 6.9	6.8	9080	11	0.625	0.073	15	5.25	8.375
65	5-8-90-4#3-i-2.5-2-8†	A B	90°	Horizontal	A1035	7.9 7.5	7.7	8380	13	0.625	0.060	13	5.25	8.375
66	5-8-90-4#3-i-3.5-2-8†	A B	90°	Horizontal	A1035	8.6 8.3	8.4	8380	13	0.625	0.060	15	5.25	8.375
67	5-5-90-5#3-o-1.5-2-5†	B	90°	Horizontal	A615	5.0	5.0	5205	5	0.625	0.077	11	5.25	8.375
68	5-5-90-5#3-o-1.5-2-8†	A B	90°	Horizontal	A1035	8.0 7.8	7.9	5650	6	0.625	0.077	11	5.25	8.375
69	5-5-90-5#3-o-1.5-2-6.5†	A B	90°	Horizontal	A1035	6.5 6.5	6.5	5780	7	0.625	0.073	11	5.25	8.375
70	5-5-90-5#3-o-2.5-2-5†	A B	90°	Horizontal	A615	5.2 5.1	5.2	4903	4	0.625	0.077	13	5.38	8.375
71	5-5-90-5#3-o-2.5-2-8†	A	90°	Horizontal	A1035	7.5	7.5	5650	6	0.625	0.077	13	5.25	8.375
72	5-5-90-5#3-i-2.5-2-7	A B	90°	Horizontal	A1035	5.6 7.0	6.3	5230	6	0.625	0.073	13	5.25	8.375
73	5-12-90-5#3-i-2.5-2-5	A B	90°	Horizontal	A1035	5.1 5.8	5.4	10410	15	0.625	0.073	13	5.25	8.375
74	5-15-90-5#3-i-2.5-2-4	A B	90°	Horizontal	A1035	3.8 4.1	4.0	15800	62	0.625	0.073	13	5.25	8.375
75	5-15-90-5#3-i-2.5-2-5	A B	90°	Horizontal	A1035	5.0 5.1	5.1	15800	62	0.625	0.073	13	5.25	8.375
76	5-5-90-5#3-i-3.5-2-7	A B	90°	Horizontal	A1035	7.5 6.8	7.1	5190	7	0.625	0.073	15	5.25	8.375
77	5-12-90-5#3-i-3.5-2-5	A B	90°	Horizontal	A1035	5.3 4.8	5.0	11090	83	0.625	0.073	15	5.25	8.375
78	5-12-90-5#3-i-3.5-2-10	A B	90°	Horizontal	A1035	11.0 11.3	11.1	11090	83	0.625	0.073	15	5.25	8.375

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

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

	Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	$f_{su,\ ind}$ ksi	f_{su} ksi	Slip at Failure in.	Failure Type
52	5-12-90-2#3-i-2.5-2-5	A	2.5	2.6	3.0	6.5	2	25200	48700	24350	81300	78500	-	FP/SS
		B	2.8		3.0			29400			94800		-	FP
53	5-15-90-2#3-i-2.5-2-6	A	2.4	2.4	1.9	6.6	2	42400	85300	42600	136800	137400	-	FP
		B	2.4		1.7			42900			138400		-	FB
54	5-15-90-2#3-i-2.5-2-4	A	2.5	2.5	2.6	6.8	2	18700	37300	18700	60300	60300	-	FB
		B	2.5		2.1			21300			68700		-	FP
55	5-5-90-2#3-i-3.5-2-6	A	3.4	3.4	2.3	6.5	2	21500	42190	21095	69400	68000	0.183	SS/FP
		B	3.4		2.5			22400			72300		-	SS/FP
56	5-5-90-2#3-i-3.5-2-8	A	3.4	3.4	2.3	6.8	2	43700	45660	22830	141000	73600	-	FP
		B	3.5		2.8			45700			147400		-	FP
57	5-8-90-2#3-i-3.5-2-6†	A	3.5	3.6	1.5	6.4	2	29900	60070	30035	96500	96900	-	FP
		B	3.8		2.0			30100			97100		-	FP/SS
58	5-8-90-2#3-i-3.5-2-8†	A	3.5	3.5	2.9	6.6	2	38000	57310	28655	122600	92400	-	FP
		B	3.5		3.0			28600			92300		-	FP
59	5-12-90-2#3-i-3.5-2-5	A	3.8	3.6	1.8	6.6	2	27900	56730	28365	90000	91500	-	FP
		B	3.5		2.2			28900			93200		0.349	FP
60	5-12-90-2#3-i-3.5-2-10	A	3.5	3.6	2.3	6.8	2	46000	92000	46000	148400	148400	-	BY
		B	3.6		2.4			46000			148400		-	BY
61	5-5-180-2#3-i-2.5-2-8†	A	2.5	2.5	2.0	6.9	2	34000	68160	34080	109700	109900	-	FP/SS
		B	2.5		2.0			34500			111300		-	FP/SS
62	5-5-180-2#3-i-2.5-2-6†	A	2.6	2.6	2.0	6.6	2	26900	53460	26730	86800	86200	-	FP/SS
		B	2.6		2.3			26900			86800		-	FP
63	5-8-180-2#3-i-2.5-2-7	A	2.5	2.5	2.3	6.4	2	34600	58460	29230	111600	94300	-	FP/SS
		B	2.5		2.1			28700			92600		.369(.081)	FP/SS
64	5-8-180-2#3-i-3.5-2-7	A	3.4	3.4	2.4	7.0	2	29300	61860	30930	94500	99800	-	FP/SS
		B	3.5		2.3			32600			105200		.329(.028)	FP
65	5-8-90-4#3-i-2.5-2-8†	A	2.5	2.5	2.1	6.4	2	33400	52820	26410	107700	85200	-	FP/SS
		B	2.5		2.5			27000			87100		-	FP/SS
66	5-8-90-4#3-i-3.5-2-8†	A	3.5	3.5	1.4	6.9	2	42500	76960	38480	137100	124100	-	FP
		B	3.5		1.8			39300			126800		-	SS/FP
67	5-5-90-5#3-o-1.5-2-5†	B	1.5	1.5	2.0	6.5	2	22000	22000	22000	71000	71000	-	FP/SB
68	5-5-90-5#3-o-1.5-2-8†	A	1.6	1.5	2.3	6.4	2	25200	50220	25110	81300	81000	-	FP/SB
		B	1.5		2.6			30400			98100		-	FP/SB
69	5-5-90-5#3-o-1.5-2-6.5†	A	1.6	1.6	2.0	6.5	2	26200	43420	21710	84500	70000	-	FP/SB
		B	1.6		2.0			20900			67400		-	FP/SB
70	5-5-90-5#3-o-2.5-2-5†	A	2.6	2.6	1.9	6.6	2	22300	45060	22530	71900	72700	-	FP/SB
		B	2.6		1.9			29500			95200		-	FP/SB
71	5-5-90-5#3-o-2.5-2-8†	A	2.6	2.6	2.1	6.5	2	28400	28400	28400	91600	91600	-	FP
72	5-5-90-5#3-i-2.5-2-7	A	2.8	2.8	3.6	6.5	2	32100	63390	31695	103500	102200	-	FP
		B	2.8		2.3			31300			101000		-	FP/SS
73	5-12-90-5#3-i-2.5-2-5	A	2.6	2.6	2.1	6.5	2	33900	68840	34420	109400	111000	0.292	FP/SS
		B	2.6		1.5			34900			112600		0.295	SS/FP
74	5-15-90-5#3-i-2.5-2-4	A	2.4	2.4	2.2	6.6	2	31300	62600	31360	101000	101200	0.603	FP
		B	2.5		1.9			31300			101000		0.378	FP
75	5-15-90-5#3-i-2.5-2-5	A	2.4	2.4	2.1	6.8	2	38600	78300	39200	124500	126500	-	FP
		B	2.3		1.9			46200			149000		-	BY
76	5-5-90-5#3-i-3.5-2-7	A	3.4	3.4	2.0	7.0	2	44300	72050	36025	142900	116200	-	FP
		B	3.5		2.8			35200			113500		-	FP
77	5-12-90-5#3-i-3.5-2-5	A	3.3	3.3	2.5	6.6	2	31500	60880	30440	101600	98200	-	FP
		B	3.3		1.5			31300			101000		-	FP
78	5-12-90-5#3-i-3.5-2-10	A	3.5	3.5	2.0	6.9	2	46000	46000	46000	148400	148400	-	BY
		B	3.5		1.8			46000			148400		-	BY

*No failure of hook; equipment malfunction

† Specimens had constant 80 kip axial load

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

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
52	5-12-90-2#3-i-2.5-2-5	A B	60	0.38	0.2	2	3.30	0.33	3	3.3	0.500	3.00	-	-	1.27	60
53	5-15-90-2#3-i-2.5-2-6	A B	60	0.38	0.2	2	3.00	-	-	-	0.375	2.75	-	-	3.16	60
54	5-15-90-2#3-i-2.5-2-4	A B	60	0.38	0.2	2	3.00	-	-	-	0.375	1.75	-	-	2.51	60
55	5-5-90-2#3-i-3.5-2-6	A B	60	0.38	0.2	2	3.50	0.11	1	3.5	0.375	3.50	-	-	1.27	60
56	5-5-90-2#3-i-3.5-2-8	A B	60	0.38	0.2	2	3.50	-	-	-	0.375	4.00	-	-	1.27	60
57	5-8-90-2#3-i-3.5-2-6†	A B	60	0.38	0.2	2	4.00	-	-	-	0.500	4.00	-	-	1.27	60
58	5-8-90-2#3-i-3.5-2-8†	A B	60	0.38	0.2	2	4.00	-	-	-	0.500	4.00	-	-	1.67	60
59	5-12-90-2#3-i-3.5-2-5	A B	60	0.38	0.2	2	3.33	0.33	3	3.3	0.500	3.00	-	-	1.27	60
60	5-12-90-2#3-i-3.5-2-10	A B	60	0.38	0.2	2	3.30	-	-	-	0.375	5.00	-	-	1.89	60
61	5-5-180-2#3-i-2.5-2-8†	A B	60	0.38	0.2	2	2.50	-	-	-	0.375	4.00	-	-	1.27	60
62	5-5-180-2#3-i-2.5-2-6†	A B	60	0.38	0.2	2	2.50	-	-	-	0.375	4.00	-	-	1.27	60
63	5-8-180-2#3-i-2.5-2-7	A B	60	0.38	0.2	2	2.00	-	-	-	0.375	3.00	-	-	1.27	60
64	5-8-180-2#3-i-3.5-2-7	A B	60	0.38	0.2	2	2.00	-	-	-	0.375	3.00	-	-	1.27	60
65	5-8-90-4#3-i-2.5-2-8†	A B	60	0.38	0.4	4	2.00	-	-	-	0.500	4.00	-	-	1.67	60
66	5-8-90-4#3-i-3.5-2-8†	A B	60	0.38	0.4	4	2.00	-	-	-	0.500	4.00	-	-	1.67	60
67	5-5-90-5#3-o-1.5-2-5†	B	60	0.375	0.55	5	2.00	-	-	-	0.375	2.50	-	-	1.27	60
68	5-5-90-5#3-o-1.5-2-8†	A B	60	0.38	0.6	5	2.50	-	-	-	0.375	2.50	-	-	1.27	60
69	5-5-90-5#3-o-1.5-2-6.5†	A B	60	0.38	0.6	5	2.50	-	-	-	0.375	2.50	-	-	1.89	60
70	5-5-90-5#3-o-2.5-2-5†	A B	60	0.38	0.6	5	2.00	-	-	-	0.375	2.50	-	-	1.27	60
71	5-5-90-5#3-o-2.5-2-8†	A	60	0.375	0.55	5	2.50	-	-	-	0.375	2.50	-	-	1.27	60
72	5-5-90-5#3-i-2.5-2-7	A B	60	0.38	0.6	5	1.75	-	-	-	0.500	3.50	-	-	1.27	60
73	5-12-90-5#3-i-2.5-2-5	A B	60	0.38	0.6	5	1.67	-	-	-	0.500	3.00	-	-	1.27	60
74	5-15-90-5#3-i-2.5-2-4	A B	60	0.38	0.6	5	1.75	-	-	-	0.375	1.75	-	-	2.51	60
75	5-15-90-5#3-i-2.5-2-5	A B	60	0.38	0.6	5	1.75	-	-	-	0.375	2.25	-	-	3.16	60
76	5-5-90-5#3-i-3.5-2-7	A B	60	0.38	0.6	5	1.75	-	-	-	0.500	3.50	-	-	1.27	60
77	5-12-90-5#3-i-3.5-2-5	A B	60	0.38	0.6	5	1.70	-	-	-	0.500	3.00	-	-	1.27	60
78	5-12-90-5#3-i-3.5-2-10	A B	60	0.38	0.6	5	1.70	-	-	-	0.375	5.00	-	-	1.89	60

*No failure of hook; equipment malfunction

† Specimens had constant 80 kip axial load

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

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
79	8-5-90-0-o-2.5-2-10a†	A B	90°	Horizontal	A1035[a]	10.3 10.5	10.4	5270	7	1	0.084	17	10.5	8.375
80	8-5-90-0-o-2.5-2-10b†	A B	90°	Horizontal	A1035[a]	9.3 10.3	9.8	5440	8	1	0.084	17	10.5	8.375
81	8-5-90-0-o-2.5-2-10c†	A B	90°	Horizontal	A1035[a]	10.8 10.5	10.6	5650	9	1	0.084	17	10.5	8.375
82	8-8-90-0-o-2.5-2-8	A B	90°	Horizontal	A1035[b]	8.6 8.3	8.4	8740	12	1	0.078	17	10.5	8.375
83	8-8-90-0-o-3.5-2-8	A B	90°	Horizontal	A1035[b]	7.6 8.0	7.8	8810	14	1	0.078	19	10.5	8.375
84	8-8-90-0-o-4-2-8	A B	90°	Horizontal	A1035[b]	8.1 8.3	8.2	8630	11	1	0.078	20	10.5	8.375
85	8-5-90-0-i-2.5-2-16†	A B	90°	Horizontal	A1035[b]	16.0 16.8	16.4	4980	7	1	0.078	17	10.5	8.375
86	8-5-90-0-i-2.5-2-9.5†	A B	90°	Horizontal	A615	9.0 10.3	9.6	5140	8	1	0.078	17	10.5	8.375
87	8-5-90-0-i-2.5-2-12.5†	A B	90°	Horizontal	A615	13.3 13.3	13.3	5240	9	1	0.078	17	10.5	8.375
88	8-5-90-0-i-2.5-2-18	A B	90°	Horizontal	A1035[b]	19.5 17.9	18.7	5380	11	1	0.078	17	10.5	8.375
89	8-5-90-0-i-2.5-2-13	A B	90°	Horizontal	A1035[b]	13.3 13.5	13.4	5560	11	1	0.078	17	10.5	8.375
90	8-5-90-0-i-2.5-2-15(1)	A B	90°	Horizontal	A1035[b]	14.5 15.3	14.9	5910	14	1	0.073	17	10.5	8.375
91	8-5-90-0-i-2.5-2-15	A B	90°	Horizontal	A1035[b]	15.3 14.4	14.8	6210	8	1	0.073	17	10.5	8.375
92	(2@3) 8-5-90-0-i-2.5-2-10‡	A B	90°	Horizontal	A615	10.4 10.6	10.5	4490	10	1	0.073	9	10.5	8.375
93	(2@5) 8-5-90-0-i-2.5-2-10‡	A B	90°	Horizontal	A615	10.1 10.1	10.1	4490	10	1	0.073	11	10.5	8.375
94	8-8-90-0-i-2.5-2-8	A B	90°	Horizontal	A1035[b]	8.9 8.0	8.4	7910	15	1	0.078	17	10.5	8.375
95	8-8-90-0-i-2.5-2-10	A B	90°	Horizontal	A1035[b]	9.8 9.5	9.6	7700	14	1	0.078	17	10.5	8.375
96	8-8-90-0-i-2.5-2-8(1)	A B	90°	Horizontal	A1035[b]	8.0 8.0	8.0	8780	13	1	0.078	17	10.5	8.375
97	8-8-90-0-i-2.5sc-2tc-9‡	A B	90°	Horizontal	A615	9.5 9.5	9.5	7710	25	1	0.073	17	10.5	8.375
98	8-8-90-0-i-2.5sc-9tc-9	A B	90°	Horizontal	A615	9.3 9.0	9.1	7710	25	1	0.073	17	10.5	8.375
99	(2@3) 8-8-90-0-i-2.5-9-9	A B	90°	Horizontal	A615	9.3 9.0	9.1	7510	21	1	0.073	9	10.5	8.375
100	(2@4) 8-8-90-0-i-2.5-9-9	A B	90°	Horizontal	A615	9.9 10.0	9.9	7510	21	1	0.073	10	10.5	8.375
101	8-12-90-0-i-2.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	17	10.5	8.375
102	8-12-90-0-i-2.5-2-12.5	A B	90°	Horizontal	A1035[c]	12.9 12.8	12.8	11850	39	1	0.073	17	10.5	8.375
103	8-12-90-0-i-2.5-2-12	A B	90°	Horizontal	A1035[c]	12.1 12.1	12.1	11760	34	1	0.073	17	10.5	8.375
104	8-15-90-0-i-2.5-2-8.5	A B	90°	Horizontal	A1035[c]	8.8 8.9	8.8	15800	61	1	0.073	17	10.5	8.375

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	$f_{su,\ ind}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
79	8-5-90-0-o-2.5-2-10a[a][†]	A B	2.5 2.6	2.6	2.0 1.8	10.0	2	40600 46600	84630	42315	51400 59000	53600	- 0.186	FP/SS SS/FP
80	8-5-90-0-o-2.5-2-10b[b][†]	A B	2.5 2.5	2.5	3.3 2.3	10.0	2	47900 30600	67300	33650	60600 38700	42600	- -	FP/SS SS/FP
81	8-5-90-0-o-2.5-2-10c[c][†]	A B	2.5 2.5	2.5	1.5 1.8	10.0	2	62700 54600	111950	55975	79400 69100	70900	- 0.132	FP/SS SS/FP/TK
82	8-8-90-0-o-2.5-2-8	A B	2.8 2.5	2.6	1.8 2.1	9.0	2	44400 33200	66030	33015	56200 42000	41800	0.153 0.113	SB/TK SB/TK
83	8-8-90-0-o-3.5-2-8	A B	3.5 3.6	3.6	2.4 2.0	9.8	2	35600 44500	71740	35870	45100 56300	45400	- -	FP/SS SS/FP
84	8-8-90-0-o-4-2-8	A B	4.5 3.8	4.1	2.5 2.4	9.8	2	37100 39200	75020	37510	47000 49600	47500	0.362 .(0.017)	SS/FP SS
85	8-5-90-0-i-2.5-2-16[†]	A B	2.8 2.8	2.8	1.8 1.4	9.5	2	83300 86100	166480	83240	105400 109000	105400	- -	FP/SB FB/TK
86	8-5-90-0-i-2.5-2-9.5[†]	A B	2.8 2.5	2.6	3.0 1.8	9.5	2	44600 65800	88970	44485	56500 83300	56300	- -	FP SS
87	8-5-90-0-i-2.5-2-12.5[†]	A B	2.8 2.8	2.8	1.3 1.3	9.8	2	65300 69900	131640	65820	82700 88500	83300	- -	SS/B SS
88	8-5-90-0-i-2.5-2-18	A B	2.5 2.5	2.5	0.8 2.4	10.5	2	100200 79800	161760	80880	126800 101000	102400	- 0.153	FB/SS/TK FB/SS/TK
89	8-5-90-0-i-2.5-2-13	A B	2.5 2.5	2.5	2.0 1.8	9.8	2	73100 65200	131080	65540	92500 82500	83000	- -	SS FP/SS
90	8-5-90-0-i-2.5-2-15(1)	A B	2.5 2.6	2.5	2.8 2.0	9.6	2	64500 87300	127530	63765	81600 110500	80700	- -	FB/SB SB
91	8-5-90-0-i-2.5-2-15	A B	2.5 2.6	2.6	2.0 2.9	9.5	2	76300 80700	150960	75480	96600 102200	95500		SS/FP SB/FP
92	(2@3) 8-5-90-0-i-2.5-2-10[‡]	A B	2.5 2.5	2.5	1.6 1.4	2.0	2	38900 41700	80600	40300	49241 52785	51013	0.2 -	FP FP
93	(2@5) 8-5-90-0-i-2.5-2-10[‡]	A B	2.5 2.3	2.4	1.9 1.9	4.1	2	41900 38300	80100	40100	53038 48481	50759	0.33 0	FP FB/SS
94	8-8-90-0-i-2.5-2-8	A B	2.8 2.9	2.8	1.1 2.0	8.6	2	54700 45200	90490	45245	69200 57200	57300	- -	FP/TK FP/SS
95	8-8-90-0-i-2.5-2-10	A B	2.8 2.9	2.8	2.3 2.5	9.0	2	50000 52900	102910	51455	63300 67000	65100	0.195 0.185	FP FP
96	8-8-90-0-i-2.5-2-8(1)	A B	2.8 2.8	2.8	2.8 2.8	9.5	2	38000 37700	73640	36820	48100 47700	46600	0.387 0.229	FP/SS FP/SS
97	8-8-90-0-i-2.5sc-2tc-9[‡]	A B	2.5 2.8	2.6	1.5 1.5	10.0	2	35500 34700	70	35100	44937 43924	44430	0.104 0	FB FB
98	8-8-90-0-i-2.5sc-9tc-9	A B	2.8 2.8	2.8	8.8 9.0	10.0	2	38500 36800	75	37700	48734 46582	47722	0.12 0.29	FB FB
99	(2@3) 8-8-90-0-i-2.5-9-9	A B	2.5 2.6	2.6	8.8 9.0	2.0	2	34000 27600	61300	30700	43038 34937	38861	 -	FP FP
100	(2@4) 8-8-90-0-i-2.5-9-9	A B	2.6 2.5	2.5	8.1 8.0	3.1	2	32900 35500	68400	34200	41646 44937	43291	0.018 0	FP FP
101	8-12-90-0-i-2.5-2-9	A B	2.8 2.6	2.7	2.4 2.4	9.6	2	50800 54800	99850	49925	64300 69400	63200	0.219	FP/SS SS/FP
102	8-12-90-0-i-2.5-2-12.5	A B	2.6 2.6	2.6	1.7 1.8	10.1	2	66000 77400	133900	66950	83500 98000	84700	0.295 0.266	FB/SB FB/SB
103	8-12-90-0-i-2.5-2-12	A B	2.5 2.4	2.5	1.9 1.9	9.8	2	70700 65800	131800	65900	89500 83300	83400	- 0.0119	SB/FP FB/SS
104	8-15-90-0-i-2.5-2-8.5	A B	2.5 2.5	2.5	2.0 1.9	10.0	2	43100 44100	87200	43600	54600 55800	55200	- -	FP FP

[†] Specimens had constant 80 kip axial load
[‡] Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_s ksi
79	8-5-90-0-o-2.5-2-10a[†]	A B	60	-	-	-	-	3.10	5	3.5	0.63	3.50	-	-	3.16	60
80	8-5-90-0-o-2.5-2-10b[†]	A B	60	-	-	-	-	3.10	5	3.5	0.63	3.50	-	-	3.16	60
81	8-5-90-0-o-2.5-2-10c[†]	A B	60	-	-	-	-	3.10	5	3.5	0.63	3.50	-	-	3.16	60
82	8-8-90-0-o-2.5-2-8	A B	60	-	-	-	-	2.00	10	3.0	0.50	1.75	-	-	3.16	60
83	8-8-90-0-o-3.5-2-8	A B	60	-	-	-	-	2.00	10	3.0	0.50	1.75	-	-	3.16	60
84	8-8-90-0-o-4-2-8	A B	60	-	-	-	-	2.00	10	3.0	0.50	1.75	-	-	3.16	60
85	8-5-90-0-i-2.5-2-16[†]	A B	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60
86	8-5-90-0-i-2.5-2-9.5[†]	A B	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60
87	8-5-90-0-i-2.5-2-12.5[†]	A B	60	-	-	-	-	2.00	10	3.0	0.50	3.00	-	-	3.16	60
88	8-5-90-0-i-2.5-2-18	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	1	3.78	60
89	8-5-90-0-i-2.5-2-13	A B	60	-	-	-	-	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60
90	8-5-90-0-i-2.5-2-15(1)	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60
91	8-5-90-0-i-2.5-2-15	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60
92	(2@3) 8-5-90-0-i-2.5-2-10[‡]	A B	60	-	-	-	-	-	-	-	0.38	5.00	-	-	3.16	120
93	(2@5) 8-5-90-0-i-2.5-2-10[‡]	A B	60	-	-	-	-	-	-	-	0.38	5.00	-	-	3.16	120
94	8-8-90-0-i-2.5-2-8	A B	60	-	-	-	-	1.60	8	4.0	0.50	1.75	-	-	3.16	60
95	8-8-90-0-i-2.5-2-10	A B	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60
96	8-8-90-0-i-2.5-2-8(1)	A B	60	-	-	-	-	1.60	8	4.0	0.50	1.50	-	-	3.16	60
97	8-8-90-0-i-2.5sc-2tc-9[‡]	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.16	60
98	8-8-90-0-i-2.5sc-9tc-9	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	4.74	60
99	(2@3) 8-8-90-0-i-2.5-9-9	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	4.74	60
100	(2@4) 8-8-90-0-i-2.5-9-9	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	4.74	60
101	8-12-90-0-i-2.5-2-9	A B	60	-	-	-	-	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60
102	8-12-90-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60
103	8-12-90-0-i-2.5-2-12	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.16	60
104	8-15-90-0-i-2.5-2-8.5	A B	60	-	-	-	-	-	-	-	0.38	4.00	-	-	3.78	60

[†] Specimens had constant 80 kip axial load
[‡] Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
105	8-15-90-0-i-2.5-2-13	A B	90°	Horizontal	A1035[c]	12.8 12.8	12.8	15800	61	1	0.073	17	10.5	8.375
106	8-5-90-0-i-3.5-2-18	A B	90°	Horizontal	A1035[b]	19.0 18.0	18.5	5380	11	1	0.078	19	10.5	8.375
107	8-5-90-0-i-3.5-2-13	A B	90°	Horizontal	A1035[b]	13.4 13.4	13.4	5560	11	1	0.078	19	10.5	8.375
108	8-5-90-0-i-3.5-2-15(2)	A B	90°	Horizontal	A1035[c]	15.6 14.9	15.3	5180	8	1	0.073	19	10.5	8.375
109	8-5-90-0-i-3.5-2-15(1)	A B	90°	Horizontal	A1035[c]	15.4 15.1	15.3	6440	9	1	0.073	19	10.5	8.375
110	8-8-90-0-i-3.5-2-8(1)	A B	90°	Horizontal	A1035[b]	7.8 7.8	7.8	7910	15	1	0.078	19	10.5	8.375
111	8-8-90-0-i-3.5-2-10	A B	90°	Horizontal	A1035[b]	8.8 10.8	9.8	7700	14	1	0.078	19	10.5	8.375
112	8-8-90-0-i-3.5-2-8(2)	A B	90°	Horizontal	A1035[b]	8.5 8.0	8.3	8780	13	1	0.078	19	10.5	8.375
113	8-12-90-0-i-3.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	19	10.5	8.375
114	8-8-90-0-i-4-2-8	A B	90°	Horizontal	A1035[b]	7.6 8.0	7.8	8740	12	1	0.078	20	10.5	8.375
115	8-5-180-0-i-2.5-2-11†	A B	180°	Horizontal	A615	11.0 11.0	11.0	4550	7	1	0.078	17	10.5	8.375
116	8-5-180-0-i-2.5-2-14†	A B	180°	Horizontal	A1035[b]	14.0 14.0	14.0	4840	8	1	0.078	17	10.5	8.375
117	(2@3) 8-5-180-0-i-2.5-2-10‡	A B	180°	Horizontal	A615	10.3 10.0	10.2	5260	15	1	0.073	9	10.5	8.375
118	(2@5)8-5-180-0-i-2.5-2-10‡	A B	180°	Horizontal	A615	10.0 10.0	10.0	5260	15	1	0.073	11	10.5	8.375
119	8-8-180-0-i-2.5-2-11.5	A B	180°	Horizontal	A1035[b]	9.3 9.3	9.3	8630	11	1	0.078	17	10.5	8.375
120	8-12-180-0-i-2.5-2-12.5	A B	180°	Horizontal	A1035[c]	12.8 12.5	12.6	11850	39	1	0.073	17	10.5	8.375
121	8-5-180-0-i-3.5-2-11†	A B	180°	Horizontal	A615	11.6 11.6	11.6	4550	7	1	0.078	17	10.5	8.375
122	8-5-180-0-i-3.5-2-14†	A B	180°	Horizontal	A1035[b]	14.4 13.9	14.1	4840	8	1	0.078	17	10.5	8.375
123	8-15-180-0-i-2.5-2-13.5	A B	180°	Horizontal	A1035[c]	13.8 13.5	13.6	16510	88	1	0.073	17	10.5	8.375
124	8-5-90-1#3-i-2.5-2-16†	A B	90°	Horizontal	A1035[b]	15.6 15.6	15.6	4810	6	1	0.078	17	10.5	8.375
125	8-5-90-1#3-i-2.5-2-12.5†	A B	90°	Horizontal	A1035[b]	12.5 12.5	12.5	5140	8	1	0.078	17	10.5	8.375
126	8-5-90-1#3-i-2.5-2-9.5†	A B	90°	Horizontal	A615	9.0 9.0	9.0	5240	9	1	0.078	17	10.5	8.375
127	8-5-180-1#3-i-2.5-2-11†	A B	180°	Horizontal	A615	11.5 11.5	11.5	4300	6	1	0.078	15	10.5	8.375
128	8-5-180-1#3-i-2.5-2-14†	A B	180°	Horizontal	A1035[b]	14.8 15.0	14.9	4870	9	1	0.078	15	10.5	8.375
129	8-5-180-1#3-i-3.5-2-11†	A B	180°	Horizontal	A615	11.6 10.6	11.1	4550	7	1	0.078	17	10.5	8.375
130	8-5-180-1#3-i-3.5-2-14†	A B	180°	Horizontal	A1035[b]	15.6 14.5	15.1	4840	8	1	0.078	17	10.5	8.375

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	$f_{su,\ ind}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
105	8-15-90-0-i-2.5-2-13	A B	2.4 2.5	2.4	2.1 2.0	9.9	2	77200 79000	156200	78100	97700 100000	98900	- -	FB/SB FB
106	8-5-90-0-i-3.5-2-18	A B	3.8 3.4	3.6	1.4 2.4	9.4	2	96000 105100	190740	95370	121500 133000	120700	0.181 -	FP/SS/TK FB/SS
107	8-5-90-0-i-3.5-2-13	A B	3.6 3.4	3.5	1.9 1.9	9.4	2	69400 68300	136200	68100	87800 86500	86200	- -	FP/SS SS/FP
108	8-5-90-0-i-3.5-2-15(2)	A B	3.5 3.5	3.5	1.6 2.4	9.5	2	106200 85500	175420	87710	134400 108200	111000	- -	SS SS/FP
109	8-5-90-0-i-3.5-2-15(1)	A B	3.3 3.4	3.3	1.8 2.0	10.1	2	71200 79400	141300	70650	90100 100500	89400		SS/FP SB
110	8-8-90-0-i-3.5-2-8(1)	A B	3.5 3.8	3.6	2.3 2.3	9.0	2	43700 44000	87690	43845	55300 55700	55500	0.144 0.156	SS/FP SS/FP
111	8-8-90-0-i-3.5-2-10	A B	3.8 3.8	3.8	3.3 1.3	9.0	2	55200 71900	111130	55565	69900 91000	70300	0.195 0.242	FP/SS SS/FP
112	8-8-90-0-i-3.5-2-8(2)	A B	3.6 3.8	3.7	2.1 2.6	10.0	2	41200 42900	84070	42035	52200 54300	53200	0.133 0.201	FP FP
113	8-12-90-0-i-3.5-2-9	A B	3.5 3.8	3.6	2.4 2.1	9.8	2	61400 68500	120480	60240	77700 86700	76300	 0.434	FP FP/SS
114	8-8-90-0-i-4-2-8	A B	4.5 3.9	4.2	2.9 2.5	9.5	2	37600 48700	74860	37430	47600 61600	47400	- -	FP/SS FP
115	8-5-180-0-i-2.5-2-11†	A B	3.0 2.8	2.9	2.0 2.0	9.8	2	45600 50500	92290	46145	57700 63900	58400	0.275 -	SS/FP SS
116	8-5-180-0-i-2.5-2-14†	A B	2.8 2.6	2.7	2.0 2.0	9.8	2	49400 69400	98300	49150	62500 87800	62200	0.088 0.096	SS SS
117	(2@3) 8-5-180-0-i-2.5-2-10‡	A B	2.5 2.4	2.4	1.7 2.0	2.0	2	47600 56100	103700	51800	60253 71013	65570	0 0.9	FP FP
118	(2@5)8-5-180-0-i-2.5-2-10‡	A B	2.4 2.5	2.4	2.0 2.0	4.1	2	52300 54000	106300	53200	66203 68354	67342		FP FP
119	8-8-180-0-i-2.5-2-11.5	A B	3.0 3.0	3.0	4.5 4.5	9.5	2	62800 80200	125600	62800	79500 101500	79500	- -	FP/SB FP/SS
120	8-12-180-0-i-2.5-2-12.5	A B	3.0 2.5	2.8	2.1 2.4	9.6	2	74800 92300	150400	75200	94700 116800	95200	0.193 0.242	FB/SB FP
121	8-5-180-0-i-3.5-2-11†	A B	3.8 3.8	3.8	1.4 1.4	10.0	2	58600 60500	118580	59290	74200 76600	75100	0.372 0.239	FP/SS SS
122	8-5-180-0-i-3.5-2-14†	A B	3.9 3.8	3.8	1.6 2.1	9.8	2	63700 78000	127010	63505	80600 98700	80400	- -	SS FB/SS
123	8-15-180-0-i-2.5-2-13.5	A B	2.5 2.5	2.5	2.0 2.3	10.0	2	90700 89100	179800	89900	114800 112800	113800	- -	- FB/SB
124	8-5-90-1#3-i-2.5-2-16†	A B	2.8 3.0	2.9	2.3 2.3	9.5	2	94600 73900	149620	74810	119700 93500	94700	- -	FP/SS FP/SS
125	8-5-90-1#3-i-2.5-2-12.5†	A B	2.6 2.8	2.7	2.1 2.1	9.8	2	73900 64800	129670	64835	93500 82000	82100	- -	FP/SS SS/FP
126	8-5-90-1#3-i-2.5-2-9.5†	A B	2.6 2.8	2.7	2.5 2.5	9.8	2	62000 55000	98070	49035	78500 69600	62100	- -	SB FP/SS
127	8-5-180-1#3-i-2.5-2-11†	A B	2.5 2.5	2.5	1.5 1.5	10.0	2	57300 69000	99460	49730	72500 87300	62900	0.088 0.341	SS/FP SS/FP
128	8-5-180-1#3-i-2.5-2-14†	A B	2.8 2.9	2.8	1.3 1.0	9.9	2	67300 70900	138040	69020	85200 89700	87400	- 0.123	SS/FP FP/SS
129	8-5-180-1#3-i-3.5-2-11†	A B	3.8 3.5	3.6	1.4 2.4	10.0	2	62900 56200	110780	55390	79600 71100	70100	0.434 0.216	SS SS
130	8-5-180-1#3-i-3.5-2-14†	A B	3.6 3.6	3.6	0.9 2.0	10.0	2	78700 76900	151990	75995	99600 97300	96200	0.232 0.227	SS/FP SS/FP

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_s ksi
105	8-15-90-0-i-2.5-2-13	A B	60	-	-	-	-	-	-	-	0.38	5.00	-	-	4.74	60
106	8-5-90-0-i-3.5-2-18	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	1	3.78	60
107	8-5-90-0-i-3.5-2-13	A B	60	-	-	-	-	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60
108	8-5-90-0-i-3.5-2-15(2)	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60
109	8-5-90-0-i-3.5-2-15(1)	A B	60	-	-	-	-	1.10	10	3.0	0.38	3.50	0.375	2	3.16	60
110	8-8-90-0-i-3.5-2-8(1)	A B	60	-	-	-	-	1.60	8	4.0	0.50	1.75	-	-	3.16	60
111	8-8-90-0-i-3.5-2-10	A B	60	-	-	-	-	1.60	8	4.0	0.63	3.50	-	-	3.16	60
112	8-8-90-0-i-3.5-2-8(2)	A B	60	-	-	-	-	1.60	8	4.0	0.50	1.50	-	-	3.16	60
113	8-12-90-0-i-3.5-2-9	A B	60	-	-	-	-	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60
114	8-8-90-0-i-4-2-8	A B	60	-	-	-	-	1.60	8	4.0	0.50	1.75	-	-	3.16	60
115	8-5-180-0-i-2.5-2-11†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
116	8-5-180-0-i-2.5-2-14†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
117	(2@3) 8-5-180-0-i-2.5-2-10‡	A B	60	-	-	-	-	-	-	-	0.50	4.00	-	-	6.32	120
118	(2@5)8-5-180-0-i-2.5-2-10‡	A B	60	-	-	-	-	-	-	-	0.50	4.00	-	-	6.32	120
119	8-8-180-0-i-2.5-2-11.5	A B	60	-	-	-	-	0.44	4	3.0	0.50	3.00	-	-	3.16	60
120	8-12-180-0-i-2.5-2-12.5	A B	60	-	-	-	-	-	-	-	0.50	2.25	-	-	3.16	60
121	8-5-180-0-i-3.5-2-11†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
122	8-5-180-0-i-3.5-2-14†	A B	60	-	-	-	-	0.44	4	3.5	0.50	3.50	-	-	3.16	60
123	8-15-180-0-i-2.5-2-13.5	A B	60	-	-	-	-	-	-	-	0.50	4.00	-	-	4.74	60
124	8-5-90-1#3-i-2.5-2-16†	A B	60	0.38	0.1	1	9.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
125	8-5-90-1#3-i-2.5-2-12.5†	A B	60	0.38	0.1	1	9.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
126	8-5-90-1#3-i-2.5-2-9.5†	A B	60	0.38	0.1	1	9.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
127	8-5-180-1#3-i-2.5-2-11†	A B	60	0.38	0.1	1	3.50	0.44	4	4.5	0.50	3.50	-	-	3.16	60
128	8-5-180-1#3-i-2.5-2-14†	A B	60	0.38	0.1	1	3.50	0.44	4	4.5	0.50	3.50	-	-	3.16	60
129	8-5-180-1#3-i-3.5-2-11†	A B	60	0.38	0.1	1	3.50	0.44	4	4.5	0.50	3.50	-	-	3.16	60
130	8-5-180-1#3-i-3.5-2-14†	A B	60	0.38	0.1	1	3.50	0.44	4	4.5	0.50	3.50	-	-	3.16	60

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
131	8-8-180-1#4-i-2.5-2-11.5	A B	180°	Horizontal	A1035[b]	12.0 12.3	12.1	8740	12	1	0.078	17	10.5	8.375
132	8-5-90-2#3-i-2.5-2-16†	A B	90°	Horizontal	A1035[b]	15.0 15.8	15.4	4810	6	1	0.078	17	10.5	8.375
133	8-5-90-2#3-i-2.5-2-9.5†	A B	90°	Horizontal	A615	9.0 9.3	9.1	5140	8	1	0.078	17	10.5	8.375
134	8-5-90-2#3-i-2.5-2-12.5†	A B	90°	Horizontal	A615	12.0 12.0	12.0	5240	9	1	0.078	17	10.5	8.375
135	8-5-90-2#3-i-2.5-2-8.5	A B	90°	Horizontal	A1035[c]	8.9 9.6	9.3	5240	6	1	0.073	17	10.5	8.375
136	8-5-90-2#3-i-2.5-2-14	A B	90°	Horizontal	A1035[c]	13.5 14.0	13.8	5450	7	1	0.073	17	10.5	8.375
137	(2@3) 8-5-90-2#3-i-2.5-2-10‡	A B	90°	Horizontal	A615	10.0 10.5	10.3	4760	11	1	0.073	9	10.5	8.375
138	(2@5) 8-5-90-2#3-i-2.5-2-10‡	A B	90°	Horizontal	A615	9.6 10.0	9.8	4760	11	1	0.073	11	10.5	8.375
139	8-8-90-2#3-i-2.5-2-8	A B	90°	Horizontal	A1035[b]	8.0 8.5	8.3	7700	14	1	0.078	17	10.5	8.375
140	8-8-90-2#3-i-2.5-2-10	A B	90°	Horizontal	A1035[b]	9.9 9.5	9.7	8990	17	1	0.078	17	10.5	8.375
141	8-12-90-2#3-i-2.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	17	10.5	8.375
142	8-12-90-2#3-i-2.5-2-11	A B	90°	Horizontal	A1035[c]	10.5 11.3	10.9	12010	42	1	0.073	17	10.5	8.375
143	8-12-90-2#3vr-i-2.5-2-11	A B	90°	Vertical	A1035[c]	10.9 10.4	10.6	12010	42	1	0.073	17	10.5	8.375
144	8-15-90-2#3-i-2.5-2-6	A B	90°	Horizontal	A1035[c]	5.8 6.4	6.1	15800	61	1	0.073	17	10.5	8.375
145	8-15-90-2#3-i-2.5-2-11	A B	90°	Horizontal	A1035[c]	11.3 10.8	11.0	15800	61	1	0.073	17	10.5	8.375
146	8-5-90-2#3-i-3.5-2-17	A B	90°	Horizontal	A1035[b]	17.5 17.0	17.3	5570	12	1	0.078	19	10.5	8.375
147	8-5-90-2#3-i-3.5-2-13	A B	90°	Horizontal	A1035[b]	13.8 13.5	13.6	5560	11	1	0.078	19	10.5	8.375
148	8-8-90-2#3-i-3.5-2-8	A B	90°	Horizontal	A1035[b]	8.0 8.1	8.1	8290	16	1	0.078	19	10.5	8.375
149	8-8-90-2#3-i-3.5-2-10	A B	90°	Horizontal	A1035[b]	8.8 8.8	8.8	8990	17	1	0.078	19	10.5	8.375
150	8-12-90-2#3-i-3.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	19	10.5	8.375
151	8-5-180-2#3-i-2.5-2-11†	A B	180°	Horizontal	A615	10.8 10.5	10.6	4550	7	1	0.078	17	10.5	8.375
152	8-5-180-2#3-i-2.5-2-14†	A B	180°	Horizontal	A1035[b]	13.5 14.0	13.8	4870	9	1	0.078	17	10.5	8.375
153	(2@3) 8-5-180-2#3-i-2.5-2-10‡	A B	180°	Horizontal	A615	10.3 10.3	10.3	5400	16	1	0.073	9	10.5	8.375
154	(2@5) 8-5-180-2#3-i-2.5-2-10‡	A B	180°	Horizontal	A615	10.3 9.8	10.0	5400	16	1	0.073	11	10.5	8.375
155	8-8-180-2#3-i-2.5-2-11.5	A B	180°	Horizontal	A1035[b]	10.5 10.3	10.4	8810	14	1	0.078	17	10.5	8.375

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	$f_{su,\ ind}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
131	8-8-180-1#4-i-2.5-2-11.5	A	2.9	2.8	2.0	9.5	2	72000	144460	72230	91100	91400	-	FP/SS
		B	2.8		1.8			72500			91800		.(0.013)	FP/SS
132	8-5-90-2#3-i-2.5-2-16†	A	2.8	2.8	2.9	9.5	2	80000	159260	79630	101300	100800	-	SS/FP
		B	2.9		2.1			92800			117500		-	FP
133	8-5-90-2#3-i-2.5-2-9.5†	A	2.5	2.5	2.6	10.0	2	54900	107240	53620	69500	67900	-	FP
		B	2.5		2.3			53600			67800		-	FP
134	8-5-90-2#3-i-2.5-2-12.5†	A	2.8	2.8	2.6	9.5	2	74100	144130	72065	93800	91200	-	FP
		B	2.8		2.6			76300			96600		-	FP/SS
135	8-5-90-2#3-i-2.5-2-8.5	A	3.0	3.0	1.8	9.1	2	52900	101100	50550	67000	64000		FP/SS
		B	3.0		1.1			48400			61300			SS
136	8-5-90-2#3-i-2.5-2-14	A	2.8	2.9	2.6	9.3	2	77000	153930	76965	97500	97400		SS/FP
		B	3.0		2.1			77500			98100			FP/SS
137	(2@3) 8-5-90-2#3-i-2.5-2-10‡	A	2.5	2.5	2.0	2.3	2	58000	104000	46800	73418	59241	0.21	FP
		B	2.5		1.5			46000			58228		-	FP
138	(2@5) 8-5-90-2#3-i-2.5-2-10‡	A	2.5	2.5	2.4	3.9	2	48400	97000	48500	61266	61392	0.23	FB
		B	2.5		2.0			48600			61519		0.108	FB
139	8-8-90-2#3-i-2.5-2-8	A	3.0	2.9	2.0	9.0	2	46200	95750	47875	58500	60600	-	FP/SS
		B	2.9		1.5			55400			70100		-	FP/SS
140	8-8-90-2#3-i-2.5-2-10	A	2.8	2.8	2.1	8.5	2	60700	122050	61025	76800	77200	0.186	FP
		B	2.8		2.5			67000			84800		0.152	FB
141	8-12-90-2#3-i-2.5-2-9	A	2.9	2.8	2.3	9.5	2	61800	122030	61015	78200	77200	0.345	FP/SS
		B	2.6		2.3			60300			76300		0.361	SS/FP
142	8-12-90-2#3-i-2.5-2-11	A	2.8	2.8	2.4	9.5	2	68100	137400	68700	86200	87000	0.181	FP
		B	2.8		1.6			79800			101000		0.165	FP
143	8-12-90-2#3vr-i-2.5-2-11	A	2.5	2.4	2.1	9.8	2	50700	105300	52650	64200	66600	-	FP/SS
		B	2.3		2.6			66800			84600		0.13	FP
144	8-15-90-2#3-i-2.5-2-6	A	2.5	2.4	2.3	9.9	2	37400	75100	37600	47300	47600	-	FP
		B	2.4		1.8			37700			47700		-	FP
145	8-15-90-2#3-i-2.5-2-11	A	2.5	2.5	1.9	10.0	2	99000	166600	83300	125300	105400	-	FB
		B	2.5		2.4			83600			105800		0.123	FB
146	8-5-90-2#3-i-3.5-2-17	A	3.3	3.4	1.8	10.1	2	102600	179830	89915	129900	113800	-	SS
		B	3.5		2.3			88600			112200		-	SS/FP
147	8-5-90-2#3-i-3.5-2-13	A	3.1	3.4	1.5	10.3	2	81200	160720	80360	102800	101700	-	SS/FP
		B	3.6		1.8			86900			110000		-	SS/FP
148	8-8-90-2#3-i-3.5-2-8	A	3.6	3.7	2.0	8.5	2	48300	97550	48775	61100	61700	0.31	FP
		B	3.8		1.9			49300			62400		.340(.147)	FP
149	8-8-90-2#3-i-3.5-2-10	A	3.6	3.7	3.3	8.5	2	54000	107770	53885	68400	68200	-	SS
		B	3.8		3.3			53800			68100		-	FP
150	8-12-90-2#3-i-3.5-2-9	A	3.6	3.8	2.3	9.6	2	50300	99550	49775	63700	63000	0.15	FP/SS
		B	4.0		2.4			49300			62400			FP/SS
151	8-5-180-2#3-i-2.5-2-11†	A	2.8	2.6	2.3	9.5	2	64200	120470	60235	81300	76200	0.26	SS/FP
		B	2.5		2.5			61900			78400		0.087	SS/FP
152	8-5-180-2#3-i-2.5-2-14†	A	2.8	2.8	2.5	9.8	2	87100	152560	76280	110300	96600	0.774	FP
		B	2.8		2.0			76900			97300		0.199	FP/SS
153	(2@3) 8-5-180-2#3-i-2.5-2-10‡	A	2.5	2.5	1.8	2.0	2	57500	115300	57700	72785	73038		FP
		B	2.5		1.8			58800			74430		0.288	FP
154	(2@5) 8-5-180-2#3-i-2.5-2-10‡	A	2.5	2.5	1.8	4.0	2	63700	123800	61900	80633	78354		FB
		B	2.5		2.3			60100			76076		0.263	FB
155	8-8-180-2#3-i-2.5-2-11.5	A	2.8	2.8	2.3	10.0	2	70100	116340	58170	88700	73600	0.261	FB/SS
		B	2.8		2.5			59500			75300		.25(.027)	FP/SS

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_s ksi
131	8-8-180-1#4-i-2.5-2-11.5	A B	60	0.5	0.2	1	3.00	0.44	4	3.0	0.50	3.00	-	-	3.16	60
132	8-5-90-2#3-i-2.5-2-16[†]	A B	60	0.38	0.2	2	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
133	8-5-90-2#3-i-2.5-2-9.5[†]	A B	60	0.38	0.2	2	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
134	8-5-90-2#3-i-2.5-2-12.5[†]	A B	60	0.38	0.2	2	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
135	8-5-90-2#3-i-2.5-2-8.5	A B	60	0.38	0.2	2	7.50	2.00	10	2.5	0.50	3.25	0.5	1	3.16	60
136	8-5-90-2#3-i-2.5-2-14	A B	60	0.38	0.2	2	6.00	0.88	8	3.0	0.50	3.50	0.5	1	3.16	60
137	(2@3) 8-5-90-2#3-i-2.5-2-10[‡]	A B	60	0.38	0.2	2	3.00	-	-	-	0.38	4.00	-	-	3.16	120
138	(2@5) 8-5-90-2#3-i-2.5-2-10[‡]	A B	60	0.38	0.2	2	3.00	-	-	-	0.38	5.00	-	-	3.16	120
139	8-8-90-2#3-i-2.5-2-8	A B	60	0.38	0.2	2	7.13	1.20	6	4.0	0.50	1.50	-	-	3.16	60
140	8-8-90-2#3-i-2.5-2-10	A B	60	0.38	0.2	2	7.13	1.20	6	4.0	0.63	3.50	-	-	3.16	60
141	8-12-90-2#3-i-2.5-2-9	A B	60	0.38	0.2	2	8.00	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60
142	8-12-90-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	2.00	-	-	3.16	60
143	8-12-90-2#3vr-i-2.5-2-11	A B	60	0.38	0.2	2	2.67	-	-	-	0.50	2.00	-	-	3.16	60
144	8-15-90-2#3-i-2.5-2-6	A B	60	0.38	0.2	2	6.00	-	-	-	0.38	2.75	-	-	6.32	60
145	8-15-90-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	5.50	-	-	-	0.38	4.00	-	-	6.32	60
146	8-5-90-2#3-i-3.5-2-17	A B	60	0.38	0.2	2	8.00	0.80	4	4.0	0.50	4.00	0.375	1	3.16	60
147	8-5-90-2#3-i-3.5-2-13	A B	60	0.38	0.2	2	8.00	0.44	4	4.0	0.50	3.00	-	-	3.16	60
148	8-8-90-2#3-i-3.5-2-8	A B	60	0.38	0.2	2	7.13	1.20	6	4.0	0.50	1.50	-	-	3.16	60
149	8-8-90-2#3-i-3.5-2-10	A B	60	0.38	0.2	2	7.13	1.20	6	4.0	0.63	3.50	-	-	3.16	60
150	8-12-90-2#3-i-3.5-2-9	A B	60	0.38	0.2	2	8.00	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60
151	8-5-180-2#3-i-2.5-2-11[†]	A B	60	0.38	0.2	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60
152	8-5-180-2#3-i-2.5-2-14[†]	A B	60	0.38	0.2	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60
153	(2@3) 8-5-180-2#3-i-2.5-2-10[‡]	A B	60	0.38	0.2	2	3.00	-	-	-	0.50	4.00	-	-	6.32	120
154	(2@5) 8-5-180-2#3-i-2.5-2-10[‡]	A B	60	0.38	0.2	2	3.00	-	-	-	0.50	4.00	-	-	6.32	120
155	8-8-180-2#3-i-2.5-2-11.5	A B	60	0.38	0.2	2		-	-	-	0.50	3.00	-	-	3.16	60

[†] Specimens had constant 80 kip axial load
[‡] Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
156	8-12-180-2#3-i-2.5-2-11	A B	180°	Horizontal	A1035[c]	11.1 10.4	10.8	12010	42	1	0.073	17	10.5	8.375
157	8-12-180-2#3vr-i-2.5-2-11	A B	180°	Vertical	A1035[b]	10.9 10.9	10.9	12010	42	1	0.073	17	10.5	8.375
158	8-5-180-2#3-i-3.5-2-11[†]	A B	180°	Horizontal	A1035[b]	10.1 10.6	10.4	4300	6	1	0.078	17	10.5	8.375
159	8-5-180-2#3-i-3.5-2-14[†]	A B	180°	Horizontal	A1035[b]	13.5 13.6	13.6	4870	9	1	0.078	17	10.5	8.375
160	8-15-180-2#3-i-2.5-2-11	A B	180°	Horizontal	A1035[b]	11.1 11.1	11.1	15550	87	1	0.073	17	10.5	8.375
161	8-8-90-2#4-i-2.5-2-10	A B	90°	Horizontal	A1035[b]	8.5 9.3	8.9	8290	16	1	0.078	17	10.5	8.375
162	8-8-90-2#4-i-3.5-2-10	A B	90°	Horizontal	A1035[b]	9.0 9.8	9.4	8290	16	1	0.078	19	10.5	8.375
163	8-5-90-4#3-i-2.5-2-16[†]	B A	90°	Horizontal	A1035[b]	16.0 16.3	16.1	4810	6	1	0.078	17	10.5	8.375
164	8-5-90-4#3-i-2.5-2-12.5[†]	A B	90°	Horizontal	A1035[b]	11.9 11.9	11.9	4980	7	1	0.078	17	10.5	8.375
165	8-5-90-4#3-i-2.5-2-9.5[†]	A B	90°	Horizontal	A615	9.5 9.5	9.5	5140	8	1	0.078	17	10.5	8.375
166	8-5-90-5#3-o-2.5-2-10a[†]	A B	90°	Horizontal	A1035[a]	10.3 10.5	10.4	5270	7	1	0.084	17	10.5	8.375
167	8-5-90-5#3-o-2.5-2-10b[†]	A B	90°	Horizontal	A1035[a]	10.5 10.5	10.5	5440	8	1	0.084	17	10.5	8.375
168	8-5-90-5#3-o-2.5-2-10c[†]	A B	90°	Horizontal	A1035[a]	11.3 10.5	10.9	5650	9	1	0.084	17	10.5	8.375
169	8-8-90-5#3-o-2.5-2-8	A B	90°	Horizontal	A1035[b]	8.3 8.8	8.5	8630	11	1	0.078	17	10.5	8.375
170	8-8-90-5#3-o-3.5-2-8	A B	90°	Horizontal	A1035[b]	7.8 8.0	7.9	8810	14	1	0.078	19	10.5	8.375
171	8-8-90-5#3-o-4-2-8	A B	90°	Horizontal	A1035[b]	8.5 8.0	8.3	8740	12	1	0.078	20	10.5	8.375
172	8-5-90-5#3-i-2.5-2-10b[†]	A B	90°	Horizontal	A1035[a]	10.3 10.5	10.4	5440	8	1	0.084	17	10.5	8.375
173	8-5-90-5#3-i-2.5-2-10c[†]	A B	90°	Horizontal	A1035[a]	10.5 10.5	10.5	5650	9	1	0.084	17	10.5	8.375
174	8-5-90-5#3-i-2.5-2-15	A B	90°	Horizontal	A1035[b]	15.3 15.8	15.5	4850	7	1	0.078	17	10.5	8.375
175	8-5-90-5#3-i-2.5-2-13	A B	90°	Horizontal	A1035[b]	13.8 13.5	13.6	5560	11	1	0.078	17	10.5	8.375
176	8-5-90-5#3-i-2.5-2-12(1)	A B	90°	Horizontal	A1035[c]	11.5 11.1	11.3	5090	7	1	0.073	17	10.5	8.375
177	8-5-90-5#3-i-2.5-2-12	A B	90°	Horizontal	A1035[c]	11.3 12.3	11.8	5960	7	1	0.073	17	10.5	8.375
178	8-5-90-5#3-i-2.5-2-12(2)	A B	90°	Horizontal	A1035[c]	12.4 12.0	12.2	5240	6	1	0.073	17	10.5	8.375
179	8-5-90-5#3-i-2.5-2-8	A B	90°	Horizontal	A1035[c]	7.8 7.4	7.6	5240	6	1	0.073	17	10.5	8.375
180	8-5-90-5#3-i-2.5-2-10a[†]	B	90°	Horizontal	A1035[a]	10.5	10.5	5270	7	1	0.08	17	10.5	8.375
181	(2@3) 8-5-90-5#3-i-2.5-2-10[‡]	A B	90°	Horizontal	A615	10.0 10.5	10.3	4805	12	1	0.073	9	10.5	8.375

[†] Specimens had constant 80 kip axial load
[‡] Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	c_{so}	$c_{so,avg}$	c_{th}	c_h	N_h	T_{ind}	T_{total}	T	$f_{su,\text{ ind}}$	f_{su}	Slip at Failure	Failure Type
			in.	in.	in.	in.		lb	lb	lb	psi	psi	in.	
156	8-12-180-2#3-i-2.5-2-11	A B	2.5 2.6	2.6	2.1 2.8	9.6	2	73700 66200	129300	64650	93300 83800	81800	- -	FP FB
157	8-12-180-2#3vr-i-2.5-2-11	A B	2.8 2.6	2.7	2.4 2.4	9.8	2	67100 87100	131600	65800	84900 110300	83300	- 0.369	SS/FP FB/SB
158	8-5-180-2#3-i-3.5-2-11†	A B	3.4 3.5	3.4	2.9 2.4	9.8	2	57200 54900	111740	55870	72400 69500	70700	0.167 0.212	SS/FP SS/FP
159	8-5-180-2#3-i-3.5-2-14†	A B	3.6 3.8	3.7	2.5 2.4	9.8	2	68300 90400	126930	63465	86500 114400	80300	- -	FP/SS FP/SS
160	8-15-180-2#3-i-2.5-2-11	A B	2.8 2.8	2.8	2.1 2.0	9.8	2	79600 78300	157800	78900	100800 99100	99900	- -	FB/SS FP
161	8-8-90-2#4-i-2.5-2-10	A B	3.0 3.0	3.0	3.5 2.8	9.3	2	61400 71300	122720	61360	77700 90300	77700	0.171 .285(.129)	FP/SS FP/SS
162	8-8-90-2#4-i-3.5-2-10	A B	3.8 3.9	3.8	3.0 2.3	9.1	2	69500 69500	138930	69465	88000 88000	87900	0.26 .181(.104)	SS/FP FP/SS
163	8-5-90-4#3-i-2.5-2-16†	B A	2.8 3.0	2.9	1.9 1.6	9.5	2	91800 97200	180860	90430	116200 123000	114500	- -	FP/SS FP/SS
164	8-5-90-4#3-i-2.5-2-12.5†	A B	2.5 2.5	2.5	2.0 2.0	10.0	2	83100 68600	137170	68585	105200 86800	86800	- -	FP FP
165	8-5-90-4#3-i-2.5-2-9.5†	A B	2.8 2.9	2.8	2.0 2.0	9.5	2	63300 54800	109830	54915	80100 69400	69500	- -	FP FP/SS
166	8-5-90-5#3-o-2.5-2-10a†	A B	2.6 2.6	2.6	1.8 2.0	9.9	2	55700 55800	108510	54255	70500 70600	68700	- 0.213	SS SB
167	8-5-90-5#3-o-2.5-2-10b†	A B	2.5 2.6	2.6	2.0 2.0	9.9	2	66400 69500	131180	65590	84100 88000	83000	0.203 0.235	FP/SB SB/FP
168	8-5-90-5#3-o-2.5-2-10c†	A B	2.6 2.5	2.6	1.3 2.0	9.9	2	80600 57700	115400	57700	102000 73000	73000	- -	SS/FP SS/FP
169	8-8-90-5#3-o-2.5-2-8	A B	2.8 2.8	2.8	1.8 1.3	9.3	2	56100 66800	115960	57980	71000 84600	73400	0.253 .237(.033)	FP/SS FB/SS
170	8-8-90-5#3-o-3.5-2-8	A B	3.5 3.5	3.5	2.3 2.0	9.5	2	53900 56100	109910	54955	68200 71000	69600	- .251(.249)	FP FP/SS
171	8-8-90-5#3-o-4-2-8	A B	3.9 4.5	4.2	1.5 2.0	10.0	2	39600 41500	78140	39070	50100 52500	49500	0.388 0.754	SS/FP FP
172	8-5-90-5#3-i-2.5-2-10b†	A B	2.8 2.6	2.7	2.0 1.8	9.9	2	78800 66700	139430	69715	99700 84400	88200	0.129 -	FP/SS FP
173	8-5-90-5#3-i-2.5-2-10c†	A B	2.5 2.5	2.5	2.0 2.0	10.0	2	68900 69600	137670	68835	87200 88100	87100	- -	FP/SS FP/SS
174	8-5-90-5#3-i-2.5-2-15	A B	2.8 2.5	2.6	1.9 1.4	9.9	2	77100 72600	146750	73375	97600 91900	92900	0.196 -	FP/SS FP/SS
175	8-5-90-5#3-i-2.5-2-13	A B	2.5 2.4	2.4	1.5 1.8	10.3	2	93100 81300	164750	82375	117800 102900	104300	- -	SS/FP FP/SS
176	8-5-90-5#3-i-2.5-2-12(1)	A B	2.5 2.5	2.5	2.6 3.0	9.8	2	66700 75900	132730	66365	84400 96100	84000	- -	SS/FP SS/FP
177	8-5-90-5#3-i-2.5-2-12	A B	2.5 2.4	2.4	3.0 2.0	9.8	2	84900 72000	156900	84900	107500 91100	107500		SS SS
178	8-5-90-5#3-i-2.5-2-12(2)	A B	2.5 2.6	2.6	1.8 2.1	9.0	2	72400 77400	142940	71470	91600 98000	90500		FP/SS FP/SS
179	8-5-90-5#3-i-2.5-2-8	A B	2.8 2.9	2.8	2.6 2.9	9.0	2	48000 47000	94960	47480	60800 59500	60100	 0.321	FP FP
180	8-5-90-5#3-i-2.5-2-10a†	B	2.5	2.5	1.8	9.8	2	82800	82800	82800	104800	104800	0.164	FP/SS
181	(2@3) 8-5-90-5#3-i-2.5-2-10‡	A B	2.4 2.8	2.6	2.0 1.5	2.0	2	61500 58200	119700	57900	77848 73671	73291	0.05 0.37	FB/SS FB/SS

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_s ksi
156	8-12-180-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	2.00	-	-	3.16	60
157	8-12-180-2#3vr-i-2.5-2-11	A B	60	0.38	0.2	2	2.67	-	-	-	0.50	2.00	-	-	3.16	60
158	8-5-180-2#3-i-3.5-2-11[†]	A B	60	0.38	0.2	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60
159	8-5-180-2#3-i-3.5-2-14[†]	A B	60	0.38	0.2	2	3.50	-	-	-	0.50	3.50	-	-	3.16	60
160	8-15-180-2#3-i-2.5-2-11	A B	60	0.38	0.2	2	5.00	-	-	-	0.50	4.00	-	-	4.74	60
161	8-8-90-2#4-i-2.5-2-10	A B	60	0.5	0.4	2	7.13	1.20	6	4.0	0.50	2.00	-	-	3.16	60
162	8-8-90-2#4-i-3.5-2-10	A B	60	0.5	0.4	2	7.13	1.20	6	4.0	0.50	2.00	-	-	3.16	60
163	8-5-90-4#3-i-2.5-2-16[†]	B A	60	0.38	0.4	4	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
164	8-5-90-4#3-i-2.5-2-12.5[†]	A B	60	0.38	0.4	4	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
165	8-5-90-4#3-i-2.5-2-9.5[†]	A B	60	0.38	0.4	4	3.00	2.00	10	3.0	0.50	3.00	-	-	3.16	60
166	8-5-90-5#3-o-2.5-2-10a[†]	A B	60	0.38	0.6	5	3.00	1.10	10	3.0	0.63	5.00	-	-	3.16	60
167	8-5-90-5#3-o-2.5-2-10b[†]	A B	60	0.38	0.6	5	3.00	1.10	10	3.0	0.63	5.00	-	-	3.16	60
168	8-5-90-5#3-o-2.5-2-10c[†]	A B	60	0.38	0.6	5	3.00	1.10	10	3.0	0.63	5.00	-	-	3.16	60
169	8-8-90-5#3-o-2.5-2-8	A B	60	0.38	0.6	5	3.00	2.00	10	3.0	0.50	1.75	-	-	3.16	60
170	8-8-90-5#3-o-3.5-2-8	A B	60	0.38	0.6	5	3.00	2.00	10	3.0	0.50	1.75	-	-	3.16	60
171	8-8-90-5#3-o-4-2-8	A B	60	0.38	0.6	5	3.00	2.00	10	3.0	0.50	1.75	-	-	3.16	60
172	8-5-90-5#3-i-2.5-2-10b[†]	A B	60	0.38	0.6	5	3.00	1.10	10	3.0	0.63	5.00	-	-	3.16	60
173	8-5-90-5#3-i-2.5-2-10c[†]	A B	60	0.38	0.6	5	3.00	1.10	10	3.0	0.63	5.00	-	-	3.16	60
174	8-5-90-5#3-i-2.5-2-15	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.375	2	3.16	60
175	8-5-90-5#3-i-2.5-2-13	A B	60	0.38	0.6	5	3.00	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60
176	8-5-90-5#3-i-2.5-2-12(1)	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.5	2	3.16	60
177	8-5-90-5#3-i-2.5-2-12	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.5	2	3.16	60
178	8-5-90-5#3-i-2.5-2-12(2)	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.375	1	3.16	60
179	8-5-90-5#3-i-2.5-2-8	A B	60	0.38	0.6	5	3.00	1.55	5	3.0	0.50	3.00	0.5	1	3.16	60
180	8-5-90-5#3-i-2.5-2-10a[†]	B	60	0.375	0.55	5	3.0	1.10	10	3.0	0.63	3.50	-	-	3.16	60
181	(2@3) 8-5-90-5#3-i-2.5-2-10[‡]	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	3.16	120

[†] Specimens had constant 80 kip axial load
[‡] Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
182	(2@5) 8-5-90-5#3-i-2.5-2-10‡	A B	90°	Horizontal	A615	9.9 9.5	9.7	4805	12	1	0.073	11	10.5	8.375
183	8-8-90-5#3-i-2.5-2-8	A B	90°	Horizontal	A1035[b]	7.3 7.3	7.3	8290	16	1	0.078	17	10.5	8.375
184	8-8-90-5#3-i-2.5-2-9‡	A B	90°	Horizontal	A615	8.6 9.0	8.8	7710	25	1	0.073	17	10.5	8.375
185	8-8-90-5#3-i-2.5-9-9‡	A B	90°	Horizontal	A615	9.0 9.3	9.1	7710	25	1	0.073	17	10.5	8.375
186	(2@3) 8-8-90-5#3-i-2.5-9-9	A B	90°	Horizontal	A615	9.3 9.5	9.4	7440	22	1	0.073	9	10.5	8.375
187	(2@4) 8-8-90-5#3-i-2.5-9-9	A B	90°	Horizontal	A615	8.9 9.1	9.0	7440	22	1	0.073	10	10.5	8.375
188	8-12-90-5#3-i-2.5-2-9	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	17	10.5	8.375
189	8-12-90-5#3-i-2.5-2-10	A B	90°	Horizontal	A1035[c]	9.0 9.9	9.4	11800	38	1	0.073	17	10.5	8.375
190	8-12-90-5#3-i-2.5-2-12‡	A B	90°	Horizontal	A1035[c]	12.2 12.3	12.2	11760	34	1	0.073	17	10.5	8.375
191	8-12-90-5#3vr-i-2.5-2-10	A B	90°	Vertical	A1035[c]	10.3 10.2	10.2	11800	38	1	0.073	17	10.5	8.375
192	8-12-90-4#3vr-i-2.5-2-10	A B	90°	Vertical	A1035[c]	10.6 10.3	10.4	11850	39	1	0.073	17	10.5	8.375
193	8-15-90-5#3-i-2.5-2-6	A B	90°	Horizontal	A1035[c]	6.5 6.1	6.3	15800	60	1	0.073	17	10.5	8.375
194	8-15-90-5#3-i-2.5-2-10	A B	90°	Horizontal	A1035[c]	10.6 9.7	10.1	15800	60	1	0.073	17	10.5	8.375
195	8-5-90-5#3-i-3.5-2-15	A B	90°	Horizontal	A1035[b]	15.8 15.8	15.8	4850	7	1	0.078	19	10.5	8.375
196	8-5-90-5#3-i-3.5-2-13	A B	90°	Horizontal	A1035[b]	13.3 13.0	13.1	5570	12	1	0.078	19	10.5	8.375
197	8-5-90-5#3-i-3.5-2-12(1)	A B	90°	Horizontal	A1035[c]	12.8 12.3	12.5	5090	7	1	0.073	19	10.5	8.375
198	8-5-90-5#3-i-3.5-2-12	A B	90°	Horizontal	A1035[c]	12.5 11.8	12.1	6440	9	1	0.073	19	10.5	8.375
199	8-8-90-5#3-i-3.5-2-8	A B	90°	Horizontal	A1035[b]	8.0 8.0	8.0	7910	15	1	0.078	19	10.5	8.375
200	8-12-90-5#3-i-3.5-2-9*	A B	90°	Horizontal	A1035[b]	9.0 9.0	9.0	11160	77	1	0.078	19	10.5	8.375
201	(2@5) 8-5-180-5#3-i-2.5-2-10‡	A B	180°	Horizontal	A615	10.0 10.3	10.1	5540	17	1	0.073	11	10.5	8.375
202	8-12-180-5#3-i-2.5-2-10	A B	180°	Horizontal	A1035[c]	9.9 9.6	9.8	11800	38	1	0.073	17	10.5	8.375
203	8-12-180-5#3vr-i-2.5-2-10	A B	180°	Vertical	A1035[c]	11.1 10.5	10.8	11800	38	1	0.073	17	10.5	8.375
204	8-12-180-4#3vr-i-2.5-2-10	A B	180°	Vertical	A1035[c]	10.5 10.0	10.3	11850	39	1	0.073	17	10.5	8.375
205	8-15-180-5#3-i-2.5-2-9.5	A B	180°	Horizontal	A1035[c]	9.6 9.8	9.7	15550	87	1	0.073	17	10.5	8.375
206	8-5-90-4#4s-i-2.5-2-15	A B	90°	Horizontal	A1035[b]	15.6 15.6	15.6	4810	6	1	0.078	17	10.5	8.375

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

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

	Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	$f_{su,\text{ ind}}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
182	(2@5) 8-5-90-5#3-i-2.5-2-10‡	A	2.3	2.3	2.1	4.3	2	59700	112400	56000	75570	70886	0.12	FB
		B	2.4		2.5			52700			66709		0.29	FB
183	8-8-90-5#3-i-2.5-2-8	A	2.9	2.8	2.8	8.5	2	56000	100530	50265	70900	63600	0.3	FP
		B	2.8		2.8			51200			64800		0.375 (.092)	FP
184	8-8-90-5#3-i-2.5-2-9‡	A	2.8	3.0	2.4	9.8	2	64800	129	64390	82025	81506	0.047	FB
		B	3.3		2.0			64800			82025		0	FB
185	8-8-90-5#3-i-2.5-9-9‡	A	2.5	2.6	9.0	10.0	2	62000	127	63290	78481	80114	0.05	FB
		B	2.8		8.8			65200			82532		0	FB
186	(2@3) 8-8-90-5#3-i-2.5-9-9	A	2.5	2.5	8.8	2.0	2	56500	117600	58790	71519	74418	0.082	FP
		B	2.5		8.5			61200			77468		-	FP
187	(2@4) 8-8-90-5#3-i-2.5-9-9	A	2.5	2.5	9.1	3.3	2	55700	114900	57450	70506	72722	0.117	FB
		B	2.5		8.9			59300			75063		0	FB
188	8-12-90-5#3-i-2.5-2-9	A	2.5	2.6	2.5	9.5	2	66500	129510	64755	84200	82000	0.224	FP/SS
		B	2.6		2.5			63100			79900		0.252	FP/SS
189	8-12-90-5#3-i-2.5-2-10	A	2.6	2.4	3.2	9.9	2	66000	129100	64550	83500	81700	0.44	FB/SS
		B	2.3		2.3			64600			81800		0.547	SS/FP
190	8-12-90-5#3-i-2.5-2-12‡	A	2.4	2.4	2.0	10.0	2	90500	175400	87700	114600	111000	-	FB/SS
		B	2.5		1.9			86500			109500		-	SS/FP
191	8-12-90-5#3vr-i-2.5-2-10	A	2.5	2.4	1.7	9.8	2	59400	120400	60200	75200	76200	0.236	FP
		B	2.4		1.7			64100			81100		0.246	FP
192	8-12-90-4#3vr-i-2.5-2-10	A	2.5	2.5	1.8	9.0	2	80300	118500	59250	101600	75000	0.123	FP/SS
		B	2.5		2.1			59300			75100		0.101	FP
193	8-15-90-5#3-i-2.5-2-6	A	2.6	2.6	1.8	9.8	2	48300	97000	48500	61100	61400	-	FP
		B	2.6		2.2			48700			61600		-	FP
194	8-15-90-5#3-i-2.5-2-10	A	2.4	2.4	1.6	9.9	2	111600	180000	90000	141300	113900	-	FB/SS
		B	2.4		2.4			90200			114200		0.407	FB/SS
195	8-5-90-5#3-i-3.5-2-15	A	3.6	3.5	1.3	10.3	2	81200	160680	80340	102800	101700	.214(.026)	SS/FP
		B	3.5		1.3			87100			110300		-	SS/FP
196	8-5-90-5#3-i-3.5-2-13	A	3.4	3.4	2.1	10.4	2	89600	154140	77070	113400	97600	-	SS
		B	3.5		2.4			76000			96200		-	SS/FP
197	8-5-90-5#3-i-3.5-2-12(1)	A	3.5	3.5	1.6	9.8	2	78900	152860	76430	99900	96700	-	SS/FP
		B	3.4		2.1			75900			96100		-	SS
198	8-5-90-5#3-i-3.5-2-12	A	3.4	3.4	1.7	9.8	2	79200	158300	79150	100300	100200		FP
		B	3.5		2.4			79300			100400		0.162	FP/SS
199	8-8-90-5#3-i-3.5-2-8	A	3.5	3.6	2.0	8.9	2	55400	111620	55810	70100	70600	-	FP
		B	3.6		2.0			56200			71100		-	FP
200	8-12-90-5#3-i-3.5-2-9*	A	3.3	3.3	2.5	9.5	2	68800	135660	67830	87100	85900		FP/SS
		B	3.4		2.5			82200			104100		0.415	FP/SS
201	(2@5) 8-5-180-5#3-i-2.5-2-10‡	A	2.5	2.5	2.0	4.0	2	58100	133300	66640	73544	84354		FB
		B	2.5		1.8			72200			91392		0.111	FB
202	8-12-180-5#3-i-2.5-2-10	A	2.3	2.5	2.3	9.9	2	63000	128200	64100	79700	81100	-	FP/SS
		B	2.8		2.6			81400			103000		0.339	FP
203	8-12-180-5#3vr-i-2.5-2-10	A	2.5	2.5	1.3	9.8	2	67500	135600	67800	85400	85800	-	FP
		B	2.5		1.9			68000			86100		0.321	FB
204	8-12-180-4#3vr-i-2.5-2-10	A	2.8	2.6	1.8	9.8	2	69700	138400	69200	88200	87600	-	FP
		B	2.5		2.3			68800			87100		-	FP
205	8-15-180-5#3-i-2.5-2-9.5	A	2.5	2.6	2.1	10.0	2	86000	171900	86000	108900	108900	-	SS
		B	2.8		1.9			86000			108900		-	FP/SS
206	8-5-90-4#4s-i-2.5-2-15	A	3.0	2.9	1.6	9.1	2	93300	187310	93655	118100	118600	0.21	SS/FP
		B	2.9		1.6			107700			136300		-	FP/SS

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_s ksi
182	(2@5) 8-5-90-5#3-i-2.5-2-10[‡]	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	3.16	120
183	8-8-90-5#3-i-2.5-2-8	A B	60	0.38	0.6	5	3.00	1.20	6	3.0	0.50	1.50	-	-	3.16	60
184	8-8-90-5#3-i-2.5-2-9[‡]	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	3.16	120
185	8-8-90-5#3-i-2.5-9-9[‡]	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	4.74	120
186	(2@3) 8-8-90-5#3-i-2.5-9-9	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	4.74	60
187	(2@4) 8-8-90-5#3-i-2.5-9-9	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	4.74	60
188	8-12-90-5#3-i-2.5-2-9	A B	60	0.38	0.6	5	3.00	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60
189	8-12-90-5#3-i-2.5-2-10	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	1.75	-	-	3.16	60
190	8-12-90-5#3-i-2.5-2-12[‡]	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	4.00	-	-	3.16	120
191	8-12-90-5#3vr-i-2.5-2-10	A B	60	0.38	0.6	5	1.75	-	-	-	0.50	1.75	-	-	3.16	60
192	8-12-90-4#3vr-i-2.5-2-10	A B	60	0.38	0.4	4	2.25	-	-	-	0.50	1.75	-	-	3.16	60
193	8-15-90-5#3-i-2.5-2-6	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	2.75	-	-	6.32	60
194	8-15-90-5#3-i-2.5-2-10	A B	60	0.38	0.6	5	3.00	-	-	-	0.38	3.00	-	-	6.32	60
195	8-5-90-5#3-i-3.5-2-15	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.375	2	3.16	60
196	8-5-90-5#3-i-3.5-2-13	A B	60	0.38	0.6	5	3.00	1.00	5	3.0	0.50	3.00	0.375	1	3.16	60
197	8-5-90-5#3-i-3.5-2-12(1)	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.5	2	3.16	60
198	8-5-90-5#3-i-3.5-2-12	A B	60	0.38	0.6	5	3.00	0.55	5	3.0	0.38	3.50	0.5	2	3.16	60
199	8-8-90-5#3-i-3.5-2-8	A B	60	0.38	0.6	5	3.00	1.20	6	3.0	0.50	1.50	-	-	3.16	60
200	8-12-90-5#3-i-3.5-2-9*	A B	60	0.38	0.6	5	3.00	0.88	8	4.0	0.50	4.00	0.375	2	3.16	60
201	(2@5) 8-5-180-5#3-i-2.5-2-10[‡]	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	4.00	-	-	6.32	120
202	8-12-180-5#3-i-2.5-2-10	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	1.75	-	-	3.16	60
203	8-12-180-5#3vr-i-2.5-2-10	A B	60	0.38	0.6	5	1.75	-	-	-	0.50	1.75	-	-	3.16	60
204	8-12-180-4#3vr-i-2.5-2-10	A B	60	0.38	0.4	4	2.25	-	-	-	0.50	1.75	-	-	3.16	60
205	8-15-180-5#3-i-2.5-2-9.5	A B	60	0.38	0.6	5	3.00	-	-	-	0.50	4.00	-	-	6.32	60
206	8-5-90-4#4s-i-2.5-2-15	A B	60	0.5	0.8	4	4.00	0.88	8	4.0	0.38	3.50	0.375	2	3.16	60

[†] Specimens had constant 80 kip axial load
[‡] Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
207	8-5-90-4#4s-i-2.5-2-12(1)	A B	90°	Horizontal	A1035[c]	12.3 12.5	12.4	5180	8	1	0.073	17	10.5	8.375
208	8-5-90-4#4s-i-2.5-2-12	A B	90°	Horizontal	A1035[c]	12.0 12.6	12.3	6210	8	1	0.073	17	10.5	8.375
209	8-5-90-4#4s-i-3.5-2-15	A B	90°	Horizontal	A1035[b]	15.5 15.1	15.3	4810	6	1	0.078	19	10.5	8.375
210	8-5-90-4#4s-i-3.5-2-12(1)	A B	90°	Horizontal	A1035[c]	12.0 11.9	11.9	5910	14	1	0.073	19	10.5	8.375
211	8-5-90-4#4s-i-3.5-2-12	A B	90°	Horizontal	A1035[c]	12.0 12.5	12.3	5960	7	1	0.073	19	10.5	8.375

[†] Specimens had constant 80 kip axial load
[‡] Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

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

[†] Specimens had constant 80 kip axial load
[‡] Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_s ksi
207	8-5-90-4#4s-i-2.5-2-12(1)	A B	60	0.5	0.8	4	4.00	1.60	8	4.0	0.50	3.50	0.5	1	3.16	60
208	8-5-90-4#4s-i-2.5-2-12	A B	60	0.5	0.8	4	4.00	1.60	8	4.0	0.50	3.50	0.5	1	3.16	60
209	8-5-90-4#4s-i-3.5-2-15	A B	60	0.5	0.8	4	4.00	0.88	8	4.0	0.38	3.50	0.375	2	3.16	60
210	8-5-90-4#4s-i-3.5-2-12(1)	A B	60	0.5	0.8	4	4.00	1.60	8	4.0	0.50	3.50	0.5	1	3.16	60
211	8-5-90-4#4s-i-3.5-2-12	A B	60	0.5	0.8	4	4.00	1.60	8	4.0	0.50	3.50	0.5	1	3.16	60

[†] Specimens had constant 80 kip axial load
[‡] Specimen contained A1035 Grade 120 for column longitudinal steel
[a] Heat 1, [b] Heat 2, [c] Heat 3 as described in Table 2.3

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
212	11-8-90-0-o-2.5-2-25	A B	90°	Horizontal	A1035	25.3 25.1	25.2	9460	9	1.41	0.085	21.5	19.5	8.375
213	11-8-90-0-o-2.5-2-17	A B	90°	Horizontal	A1035	16.8 16.4	16.6	9460	9	1.41	0.085	21.5	19.5	8.375
214	11-12-90-0-o-2.5-2-17	A B	90°	Horizontal	A1035	17.1 16.6	16.9	11800	36	1.41	0.085	21.5	19.5	8.375
215	11-12-180-0-o-2.5-2-17	A B	180°	Horizontal	A1035	16.9 17.3	17.1	11800	36	1.41	0.085	21.5	19.5	8.375
216	11-5-90-0-i-2.5-2-14	A B	90°	Horizontal	A615	13.5 15.3	14.4	4910	13	1.41	0.069	21.5	19.5	8.375
217	11-5-90-0-i-2.5-2-26	A B	90°	Horizontal	A1035	26.0 26.0	26.0	5360	6	1.41	0.085	21.5	19.5	8.375
218	(2@5.35) 11-5-90-0-i-2.5-13-13	A B	90°	Horizontal	A615	14.0 13.9	13.9	5330	11	1.41	0.085	14	19.5	8.375
219	11-8-90-0-i-2.5-2-17	A B	90°	Horizontal	A1035	17.3 18.0	17.6	9460	9	1.41	0.085	21.5	19.5	8.375
220	11-8-90-0-i-2.5-2-21	A B	90°	Horizontal	A1035	20.0 21.1	20.6	7870	6	1.41	0.085	21.5	19.5	8.375
221	11-8-90-0-i-2.5-2-17	A B	90°	Horizontal	A1035	16.3 18.1	17.2	8520	7	1.41	0.085	21.5	19.5	8.375
222	11-12-90-0-i-2.5-2-17	A B	90°	Horizontal	A1035	16.1 16.9	16.5	11880	35	1.41	0.085	21.5	19.5	8.375
223	11-12-90-0-i-2.5-2-17.5	A B	90°	Horizontal	A1035	17.6 17.8	17.7	13330	31	1.41	0.085	21.5	19.5	8.375
224	11-12-90-0-i-2.5-2-25	A B	90°	Horizontal	A1035	24.9 24.4	24.6	13330	34	1.41	0.085	21.5	19.5	8.375
225	11-15-90-0-i-2.5-2-24	A B	90°	Horizontal	A1035	24.0 24.8	24.4	16180	62	1.41	0.085	21.5	19.5	8.375
226	11-15-90-0-i-2.5-2-11	A B	90°	Horizontal	A1035	12.1 11.5	11.8	16180	63	1.41	0.085	21.5	19.5	8.375
227	11-15-90-0-i-2.5-2-10‡	A B	90°	Horizontal	A615	9.5 9.5	9.5	14050	76	1.41	0.085	21.5	19.5	8.375
228	11-15-90-0-i-2.5-2-15‡	A B	90°	Horizontal	A1035	14.0 14.0	14.0	14050	77	1.41	0.085	21.5	19.5	8.375
229	11-5-90-0-i-3.5-2-17	A B	90°	Horizontal	A1035	18.1 17.6	17.9	5600	24	1.41	0.085	23.5	19.5	8.375
230	11-5-90-0-i-3.5-2-14	A B	90°	Horizontal	A615	14.8 15.3	15.0	4910	13	1.41	0.069	23.5	19.5	8.375
231	11-5-90-0-i-3.5-2-26	A B	90°	Horizontal	A1035	26.3 25.8	26.0	5960	8	1.41	0.085	23.5	19.5	8.375
232	11-8-180-0-i-2.5-2-21	A B	180°	Horizontal	A1035	21.3 20.9	21.1	7870	6	1.41	0.085	21.5	19.5	8.375
233	11-8-180-0-i-2.5-2-17	A B	180°	Horizontal	A1035	17.8 18.0	17.9	8520	7	1.41	0.085	21.5	19.5	8.375
234	11-12-180-0-i-2.5-2-17	A B	180°	Horizontal	A1035	16.6 16.6	16.6	11880	35	1.41	0.085	21.5	19.5	8.375
235	11-5-90-1#4-i-2.5-2-17	A B	90°	Horizontal	A1035	17.8 17.6	17.7	5790	25	1.41	0.085	21.5	19.5	8.375
236	11-5-90-1#4-i-3.5-2-17	A B	90°	Horizontal	A1035	17.8 17.8	17.8	5790	25	1.41	0.085	23.5	19.5	8.375
237	11-5-90-2#3-i-2.5-2-17	A B	90°	Horizontal	A1035	17.4 17.8	17.6	5600	24	1.41	0.085	21.5	19.5	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

*No failure; load reached maximum capacity of jacks

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

	Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T lb	T_{Total} lb	T_{avg} lb	f_{su} psi	$f_{su,avg}$ psi	Slip at Failure in.	Failure Type
212	11-8-90-0-o-2.5-2-25	A B	2.6 2.9	2.8	2.2 2.3	13.6	2	194500 170700	349400	174700	124700 109400	112000	- -	SB SB
213	11-8-90-0-o-2.5-2-17	A B	2.5 2.4	2.4	2.6 2.9	13.8	2	121400 105700	214400	107200	77800 67800	68700	- -	SB/FB SB/TK
214	11-12-90-0-o-2.5-2-17	A B	2.5 2.5	2.5	2.2 2.7	13.8	2	123700 105800	210800	105400	79300 67800	67600	0.143 -	FB/TK FP/TK
215	11-12-180-0-o-2.5-2-17	A B	2.5 2.6	2.5	2.3 1.9	13.4	2	83300 90100	167000	83500	53400 57800	53500	- -	SS/FP SB
216	11-5-90-0-i-2.5-2-14	A B	2.8 2.8	2.8	2.5 0.8	13.3	2	67200 81400	133180	66590	43100 52200	42700	0.139 -	FP/SS SS
217	11-5-90-0-i-2.5-2-26	A B	2.5 2.9	2.7	2.1 2.1	13.3	2	165700 146800	297450	148725	106200 94100	95300	- -	FB/SS FB/SS/TK
218	(2@5.35) 11-5-90-0-i-2.5-13-13	A B	2.6 2.6	2.6	12.0 12.1	6.2	2	58200 63000	121200	60600	37308 40385	38846	0.2 -	FP FP
219	11-8-90-0-i-2.5-2-17	A B	2.5 2.5	2.5	2.0 1.3	13.4	2	132000 141200	264100	132100	84600 90500	84700	- -	FP/TK FB/TK
220	11-8-90-0-i-2.5-2-21	A B	2.5 2.8	2.6	3.4 2.3	13.0	2	127060 147900	250250	125120	81400 94800	80200	- -	FP/TK FB
221	11-8-90-0-i-2.5-2-17	A B	2.5 2.5	2.5	3.0 1.1	13.5	2	105630 115170	209560	104780	67700 73800	67200	- -	SS FP
222	11-12-90-0-i-2.5-2-17	A B	2.5 2.6	2.6	3.1 2.4	13.3	2	148400 120400	239400	119700	95100 77200	76700	- -	SB SB/FP
223	11-12-90-0-i-2.5-2-17.5	A B	3.8 2.5	3.1	2.1 2.0	13.8	2	123600 125600	249240	124620	79200 80500	79900	- 0.25	SS/TK SS
224	11-12-90-0-i-2.5-2-25	A B	2.5 2.5	2.5	2.4 2.9	13.1	2	205100 198100	399490	199745	131500 127000	128000	- -	SB SB
225	11-15-90-0-i-2.5-2-24	A B	2.5 2.5	2.5	2.0 1.3	13.5	2	212600 231300	426500	213300	136300 148300	136700	- -	SB/TK SB/TK
226	11-15-90-0-i-2.5-2-11	A B	2.4 2.8	2.6	1.0 1.6	13.0	2	48600 47700	96300	48100	31200 30600	30800	- 0.252	FP/TK FP
227	11-15-90-0-i-2.5-2-10‡	A B	2.8 2.7	2.7	2.5 2.5	13.6	2	52100 50900	103	51500	33397 32628	33013	- -	FP FP
228	11-15-90-0-i-2.5-2-15‡	A B	2.8 2.8	2.8	3.0 3.0	13.0	2	93300 91000	184	92200	59808 58333	59103	- -	SB SB
229	11-5-90-0-i-3.5-2-17	A B	4.0 3.9	3.9	1.8 2.5	13.1	2	105000 117600	216240	108120	67300 75400	69300	0.187 -	SS/TK SS
230	11-5-90-0-i-3.5-2-14	A B	3.8 3.9	3.8	1.5 1.0	13.3	2	82600 69000	139030	69515	52900 44200	44600	- -	FP/SS FP/SS/TK
231	11-5-90-0-i-3.5-2-26	A B	3.8 3.8	3.8	2.1 2.6	13.5	2	198300 181700	364510	182255	127100 116500	116800	- -	SB/FB FB/SB
232	11-8-180-0-i-2.5-2-21	A B	2.9 2.4	2.7	1.8 2.2	13.0	2	137800 126800	256250	128125	88300 81300	82100	- -	FB FB/SB
233	11-8-180-0-i-2.5-2-17	A B	2.4 2.5	2.4	1.4 1.1	13.8	2	101710 121270	200910	100450	65200 77700	64400	- -	FP FB
234	11-12-180-0-i-2.5-2-17	A B	3.0 2.5	2.8	2.5 2.5	13.3	2	106700 108200	214900	107500	68400 69400	68900	0.156 -	SB/FP SS
235	11-5-90-1#4-i-2.5-2-17	A B	2.8 2.8	2.8	1.8 2.0	13.1	2	99400 119700	203000	101500	63700 76700	65100	- -	SS/FP FP/SS
236	11-5-90-1#4-i-3.5-2-17	A B	3.8 3.9	3.8	1.8 1.8	13.1	2	105700 108800	212540	106270	67800 69700	68100	- -	SS SS/FP/TK
237	11-5-90-2#3-i-2.5-2-17	A B	2.5 2.6	2.6	2.3 1.8	13.4	2	108400 103200	201390	100695	69500 66200	64500	- -	SS/FP SS/FP

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

*No failure; load reached maximum capacity of jacks

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_s ksi
212	11-8-90-0-o-2.5-2-25	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.48	60
213	11-8-90-0-o-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.48	60
214	11-12-90-0-o-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	3.5	-	-	4.74	60
215	11-12-180-0-o-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	3.5	-	-	4.74	60
216	11-5-90-0-i-2.5-2-14	A B	60	-	-	-	-	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
217	11-5-90-0-i-2.5-2-26	A B	60	-	-	-	-	1.86	6	4.0	0.50	4.0	0.375	1	6.32	60
218	(2@5.35) 11-5-90-0-i-2.5-13-13	A B	60	-	-	-	-	-	-	-	0.50	7.0	-	-	7.90	60
219	11-8-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.48	60
220	11-8-90-0-i-2.5-2-21	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
221	11-8-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60
222	11-12-90-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
223	11-12-90-0-i-2.5-2-17.5	A B	60	-	-	-	-	2.4	12	4.0	0.50	4.0	-	-	4.74	60
224	11-12-90-0-i-2.5-2-25	A B	60	-	-	-	-	3.6	18	4.0	0.50	4.0	0.5	1	6.32	60
225	11-15-90-0-i-2.5-2-24	A B	60	-	-	-	-	-	-	-	0.50	3.5	-	-	6.32	60
226	11-15-90-0-i-2.5-2-11	A B	60	-	-	-	-	-	-	-	0.50	3.0	-	-	3.16	60
227	11-15-90-0-i-2.5-2-10‡	A B	60	-	-	-	-	-	-	-	0.50	4.5	-	-	6.94	120
228	11-15-90-0-i-2.5-2-15‡	A B	60	-	-	-	-	-	-	-	0.50	4.5	-	-	6.94	120
229	11-5-90-0-i-3.5-2-17	A B	60	-	-	-	-	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
230	11-5-90-0-i-3.5-2-14	A B	60	-	-	-	-	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
231	11-5-90-0-i-3.5-2-26	A B	60	-	-	-	-	1.86	6	4.0	0.50	4.0	0.375	1	6.32	60
232	11-8-180-0-i-2.5-2-21	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
233	11-8-180-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	8.0	-	-	6.28	60
234	11-12-180-0-i-2.5-2-17	A B	60	-	-	-	-	-	-	-	0.50	6.0	-	-	9.40	60
235	11-5-90-1#4-i-2.5-2-17	A B	60	0.5	0.2	1	8.75	2.2	11	4.0	0.50	4.0	0.375	2	4.74	60
236	11-5-90-1#4-i-3.5-2-17	A B	60	0.5	0.2	1	8.75	2.2	11	4.0	0.50	4.0	0.375	2	4.74	60
237	11-5-90-2#3-i-2.5-2-17	A B	60	0.38	0.2	2	8.00	2	10	4.0	0.50	4.0	0.375	2	4.74	60

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

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
238	11-5-90-2#3-i-2.5-2-14	A B	90°	Horizontal	A615	13.5 13.8	13.6	4910	13	1.41	0.069	21.5	19.5	8.375
239	(2@5.35) 11-5-90-2#3-i-2.5-13-13	A B	90°	Horizontal	A615	13.9 13.8	13.8	5330	11	1.41	0.085	14	19.5	8.375
240	11-12-90-2#3-i-2.5-2-17.5	A B	90°	Horizontal	A1035	18.0 17.5	17.8	13710	30	1.41	0.085	21.5	19.5	8.375
241	11-12-90-2#3-i-2.5-2-25	A B	90°	Horizontal	A1035	25.0 24.5	24.8	13710	30	1.41	0.085	21.5	19.5	8.375
242	11-15-90-2#3-i-2.5-2-23	A B	90°	Horizontal	A1035	23.5 23.5	23.5	16180	62	1.41	0.085	21.5	19.5	8.375
243	11-15-90-2#3-i-2.5-2-10.5	A B	90°	Horizontal	A1035	11.8 10.5	11.1	16180	63	1.41	0.085	21.5	19.5	8.375
244	11-15-90-2#3-i-2.5-2-10‡	A B	90°	Horizontal	A615	10.0 10.0	10.0	14045	76	1.41	0.085	21.5	19.5	8.375
245	11-15-90-2#3-i-2.5-2-15‡	A B	90°	Horizontal	A1035	14.0 14.3	14.1	14045	80	1.41	0.085	21.5	19.5	8.375
246	11-5-90-2#3-i-3.5-2-17	A B	90°	Horizontal	A1035	17.5 17.8	17.6	7070	28	1.41	0.085	23.5	19.5	8.375
247	11-5-90-2#3-i-3.5-2-14	A B	90°	Horizontal	A615	14.5 13.4	13.9	4910	12	1.41	0.069	23.5	19.5	8.375
248	11-5-90-5#3-i-2.5-2-14	A B	90°	Horizontal	A615	14.3 13.5	13.9	4910	12	1.41	0.069	21.5	19.5	8.375
249	11-5-90-5#3-i-3.5-2-14	A B	90°	Horizontal	A615	14.6 14.5	14.6	4910	14	1.41	0.069	23.5	19.5	8.375
250	11-8-90-6#3-o-2.5-2-16	A B	90°	Horizontal	A1035	15.9 16.5	16.2	9420	8	1.41	0.085	21.5	19.5	8.375
251	11-8-90-6#3-o-2.5-2-22	A B	90°	Horizontal	A1035	21.5 22.3	21.9	9120	7	1.41	0.085	21.5	19.5	8.375
252	11-12-90-6#3-o-2.5-2-17	A B	90°	Horizontal	A1035	15.6 17.3	16.4	11800	36	1.41	0.085	21.5	19.5	8.375
253	11-12-180-6#3-o-2.5-2-17	A B	180°	Horizontal	A1035	16.6 16.4	16.5	11800	36	1.41	0.085	21.5	19.5	8.375
254	11-5-90-6#3-i-2.5-2-20	A B	90°	Horizontal	A1035	19.5 19.0	19.3	5420	7	1.41	0.085	21.5	19.5	8.375
255	(2@5.35) 11-5-90-6#3-i-2.5-13-13	A B	90°	Horizontal	A615	14.0 13.8	13.9	5280	12	1.41	0.085	14	19.5	8.375
256	(2@5.35) 11-5-90-6#3-i-2.5-18-18	A B	90°	Horizontal	A1035	19.3 19.5	19.4	5280	12	1.41	0.085	14	19.5	8.375
257	11-8-90-6#3-i-2.5-2-16	A B	90°	Horizontal	A1035	15.5 16.4	15.9	9120	7	1.41	0.085	21.5	19.5	8.375
258	11-8-90-6#3-i-2.5-2-22	A B	90°	Horizontal	A1035	21.3 21.5	21.4	9420	8	1.41	0.085	21.5	19.5	8.375
259	11-8-90-6#3-i-2.5-2-22	A B	90°	Horizontal	A1035	21.9 22.0	21.9	9420	8	1.41	0.085	21.5	19.5	8.375
260	11-8-90-6#3-i-2.5-2-15	A B	90°	Horizontal	A1035	15.8 15.3	15.5	7500	5	1.41	0.085	21.5	19.5	8.375
261	11-8-90-6#3-i-2.5-2-19	A B	90°	Horizontal	A1035	19.1 19.4	19.2	7500	5	1.41	0.085	21.5	19.5	8.375
262	11-12-90-6#3-i-2.5-2-17	A B	90°	Horizontal	A1035	17.1 16.5	16.8	12370	37	1.41	0.085	21.5	19.5	8.375
263	11-12-90-6#3-i-2.5-2-16	A B	90°	Horizontal	A1035	14.8 16.0	15.4	13710	31	1.41	0.085	21.5	19.5	8.375

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

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

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

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

*No failure; load reached maximum capacity of jacks

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_s ksi
238	11-5-90-2#3-i-2.5-2-14	A B	60	0.38	0.2	2	8.00	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
239	(2@5.35) 11-5-90-2#3-i-2.5-13-13	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	7.0	-	-	7.90	60
240	11-12-90-2#3-i-2.5-2-17.5	A B	60	0.38	0.2	2	12.00	2.4	12	4.0	0.50	4.0	-	-	4.74	60
241	11-12-90-2#3-i-2.5-2-25	A B	60	0.38	0.2	2	12.00	3.2	16	4.0	0.50	4.0	0.5	1	6.32	60
242	11-15-90-2#3-i-2.5-2-23	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	3.0	-	-	6.32	60
243	11-15-90-2#3-i-2.5-2-10.5	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	2.8	-	-	3.16	60
244	11-15-90-2#3-i-2.5-2-10‡	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	4.5	-	-	6.94	120
245	11-15-90-2#3-i-2.5-2-15‡	A B	60	0.38	0.2	2	8.00	-	-	-	0.50	4.5	-	-	6.94	120
246	11-5-90-2#3-i-3.5-2-17	A B	60	0.38	0.2	2	8.00	2	10	4.0	0.50	4.0	0.375	2	4.74	60
247	11-5-90-2#3-i-3.5-2-14	A B	60	0.38	0.2	2	8.00	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
248	11-5-90-5#3-i-2.5-2-14	A B	60	0.38	0.6	5	4.38	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
249	11-5-90-5#3-i-3.5-2-14	A B	60	0.38	0.6	5	4.38	2.4	12	4.0	0.50	4.0	0.375	2	4.74	60
250	11-8-90-6#3-o-2.5-2-16	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.48	60
251	11-8-90-6#3-o-2.5-2-22	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.48	60
252	11-12-90-6#3-o-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	3.5	-	-	4.74	60
253	11-12-180-6#3-o-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	3.5	-	-	4.74	60
254	11-5-90-6#3-i-2.5-2-20	A B	60	0.38	0.7	6	4.00	1.2	6	4.0	0.50	4.0	0.375	2	4.74	60
255	(2@5.35) 11-5-90-6#3-i-2.5-13-13	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	7.0	-	-	7.90	60
256	(2@5.35) 11-5-90-6#3-i-2.5-18-18	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	7.0	-	-	7.90	60
257	11-8-90-6#3-i-2.5-2-16	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.48	60
258	11-8-90-6#3-i-2.5-2-22	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	2.5	-	-	6.32	60
259	11-8-90-6#3-i-2.5-2-22	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.48	60
260	11-8-90-6#3-i-2.5-2-15	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60
261	11-8-90-6#3-i-2.5-2-19	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60
262	11-12-90-6#3-i-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60
263	11-12-90-6#3-i-2.5-2-16	A B	60	0.38	0.7	6	4.00	2.4	12	4.0	0.50	4.0	0.375	1	4.74	60

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

*No failure; load reached maximum capacity of jacks

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
264	11-12-90-6#3-i-2.5-2-22	A B	90°	Horizontal	A1035	21.9 21.5	21.7	13710	31	1.41	0.085	21.5	19.5	8.375
265	11-15-90-6#3-i-2.5-2-22	A B	90°	Horizontal	A1035	22.3 22.4	22.3	16180	62	1.41	0.085	21.5	19.5	8.375
266	11-15-90-6#3-i-2.5-2-9.5	A B	90°	Horizontal	A1035	9.0 10.3	9.6	16180	63	1.41	0.085	21.5	19.5	8.375
267	11-15-90-6#3-i-2.5-2-10a‡	A B	90°	Horizontal	A615	9.5 10.0	9.8	14045	76	1.41	0.085	21.5	19.5	8.375
268	11-15-90-6#3-i-2.5-2-10b‡	A B	90°	Horizontal	A615	9.5 9.8	9.6	14050	77	1.41	0.085	21.5	19.5	8.375
269	11-15-90-6#3-i-2.5-2-15‡	A B	90°	Horizontal	A1035	14.5 15.0	14.8	14045	80	1.41	0.085	21.5	19.5	8.375
270	11-5-90-6#3-i-3.5-2-20	A B	90°	Horizontal	A1035	20.5 20.3	20.4	5420	7	1.41	0.085	23.5	19.5	8.375
271	11-8-180-6#3-i-2.5-2-15	A B	180°	Horizontal	A1035	15.1 15.5	15.3	7500	5	1.41	0.085	21.5	19.5	8.375
272	11-8-180-6#3-i-2.5-2-19	A B	180°	Horizontal	A1035	19.6 19.9	19.8	7870	6	1.41	0.085	21.5	19.5	8.375
273	11-12-180-6#3-i-2.5-2-17	A B	180°	Horizontal	A1035	16.9 16.5	16.7	12370	37	1.41	0.085	21.5	19.5	8.375
274	11-12-180-6#3-i-2.5-2-17	A B	180°	Horizontal	A1035	16.8 16.8	16.8	12370	37	1.41	0.085	21.5	19.5	8.375
275	11-5-90-5#4s-i-2.5-2-20	A B	90°	Horizontal	A1035	20.0 20.3	20.1	5420	7	1.41	0.085	21.5	19.5	8.375
276	11-5-90-5#4s-i-3.5-2-20	A B	90°	Horizontal	A1035	19.8 19.3	19.5	5960	8	1.41	0.085	23.5	19.5	8.375

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

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

	Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T lb	T_{Total} lb	T_{avg} lb	f_{su} psi	$f_{su,avg}$ psi	Slip at Failure in.	Failure Type
264	11-12-90-6#3-i-2.5-2-22	A B	2.9 3.1	3.0	2.4 2.8	13.3	2	200100 199200	402380	201190	128300 127700	129000	- -	SS/FB FB
265	11-15-90-6#3-i-2.5-2-22	A B	3.0 2.5	2.8	1.8 1.6	13.5	2	227500 195700	395600	197800	145800 125400	126800	- -	FB/SS SB/FB
266	11-15-90-6#3-i-2.5-2-9.5	A B	2.5 3.0	2.8	2.5 1.3	13.3	2	58200 56600	114800	57400	37300 36300	36800	0.358 -	FP FP
267	11-15-90-6#3-i-2.5-2-10a[‡]	A B	2.6 2.8	2.7	2.5 2.0	13.4	2	83600 81800	165	82700	53590 52436	53013	- -	FP FP
268	11-15-90-6#3-i-2.5-2-10b[‡]	A B	2.8 2.8	2.8	2.5 2.3	13.0	2	76600 74600	151	75600	49103 47821	48462	 -	FP FP
269	11-15-90-6#3-i-2.5-2-15[‡]	A B	2.6 2.6	2.6	2.5 2.0	13.6	2	145700 144900	291	145300	93397 92885	93141	- -	FP FP
270	11-5-90-6#3-i-3.5-2-20	A B	3.8 3.9	3.8	1.8 2.0	13.1	2	150200 135300	271640	135820	96300 86700	87100	- -	SS/FP SS
271	11-8-180-6#3-i-2.5-2-15	A B	2.9 3.1	3.0	2.0 1.6	13.0	2	112400 111000	223400	111700	72100 71200	71600	- -	SS SS
272	11-8-180-6#3-i-2.5-2-19	A B	2.9 2.9	2.9	1.5 1.3	13.3	2	170000 149000	298000	149000	109000 95500	95500	- -	FB/SS FB/SS
273	11-12-180-6#3-i-2.5-2-17	A B	2.6 2.8	2.7	2.9 3.3	13.5	2	123100 117600	232700	116400	78900 75400	74600	- 0.379	FP FP/SB
274	11-12-180-6#3-i-2.5-2-17	A B	2.5 2.8	2.6	2.7 2.6	13.4	2	148900 173000	297400	148700	95400 110900	95300	- -	FP/SS SB/FB
275	11-5-90-5#4s-i-2.5-2-20	A B	2.5 2.8	2.6	2.3 2.0	13.4	2	141400 161600	282090	141045	90600 103600	90400	- -	FP/SS FP/SS
276	11-5-90-5#4s-i-3.5-2-20	A B	3.8 3.8	3.8	2.3 2.8	13.1	2	186700 153500	305930	152965	119700 98400	98100	- -	SS/FP FP/SS

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

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.^{2}	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_s ksi
264	11-12-90-6#3-i-2.5-2-22	A B	60	0.38	0.7	6	4.00	3.06	12	4.0	0.50	4.0	0.375	2	6.32	60
265	11-15-90-6#3-i-2.5-2-22	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	3.0	-	-	6.32	60
266	11-15-90-6#3-i-2.5-2-9.5	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	2.3	-	-	3.16	60
267	11-15-90-6#3-i-2.5-2-10a‡	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	4.5	-	-	6.94	120
268	11-15-90-6#3-i-2.5-2-10b‡	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	4.5	-	-	6.32	120
269	11-15-90-6#3-i-2.5-2-15‡	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	4.5	-	-	6.94	120
270	11-5-90-6#3-i-3.5-2-20	A B	60	0.38	0.7	6	4.00	1.2	6	4.0	0.50	4.0	0.375	2	4.74	60
271	11-8-180-6#3-i-2.5-2-15	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60
272	11-8-180-6#3-i-2.5-2-19	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60
273	11-12-180-6#3-i-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	3.0	-	-	4.74	60
274	11-12-180-6#3-i-2.5-2-17	A B	60	0.38	0.7	6	4.00	-	-	-	0.50	6.0	-	-	9.40	60
275	11-5-90-5#4s-i-2.5-2-20	A B	60	0.5	1	5	5.00	4	10	5.0	0.50	5.0	0.375	2	4.74	60
276	11-5-90-5#4s-i-3.5-2-20	A B	60	0.5	1	5	5.00	4	10	5.0	0.50	5.0	0.375	2	4.74	60

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

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
277	(4@4) 5-5-90-0-i-2.5-2-6	A B C D	90°	Horizontal	A1035	5.4 5.3 4.8 5.3	5.2	6430	11	0.625	0.073	13	5.3	8.375
278	(4@4) 5-5-90-0-i-2.5-2-10	A B C D	90°	Horizontal	A1035	9.0 8.0 9.3 9.9	9.0	6470	12	0.625	0.073	13	5.3	8.375
279	(4@4) 5-8-90-0-i-2.5-2-6	A B C D	90°	Horizontal	A1035	6.3 5.8 5.8 6.0	5.9	6950	18	0.625	0.073	13	5.3	8.375
280	(4@6) 5-8-90-0-i-2.5-2-6	A B C D	90°	Horizontal	A1035	6.0 6.0 5.8 6.0	5.9	6693	21	0.625	0.073	17	5.3	8.375
281	(4@6) 5-8-90-0-i-2.5-6-6	A B C D	90°	Horizontal	A1035	6.3 6.3 6.3 6.3	6.3	6693	21	0.625	0.073	17	5.3	8.375
282	(3@4) 5-8-90-0-i-2.5-2-6	A B C	90°	Horizontal	A1035	6.0 5.6 6.0	5.9	6950	18	0.625	0.073	11	5.3	8.375
283	(3@6) 5-8-90-0-i-2.5-2-6	A B C	90°	Horizontal	A1035	6.4 5.9 5.8	6.0	6950	18	0.625	0.073	13	5.3	8.375
284	(4@4) 5-5-90-2#3-i-2.5-2-6	A B C D	90°	Horizontal	A1035	6.3 6.1 6.3 6.4	6.3	6430	11	0.625	0.073	13	5.3	8.375
285	(4@4) 5-5-90-2#3-i-2.5-2-8	A B C D	90°	Horizontal	A1035	8.4 7.8 8.0 7.8	8.0	6430	11	0.625	0.073	13	5.3	8.375
286	(3@6) 5-8-90-5#3-i-2.5-2-6.25	A B C	90°	Horizontal	A1035	5.0 6.3 5.3	5.5	10110	196	0.625	0.073	13	5.3	8.375
287	(3@4) 5-8-90-5#3-i-2.5-2-6‡	A B C	90°	Horizontal	A1035	6.0 6.3 6.0	6.1	6703	22	0.625	0.073	11	5.3	8.375
288	(3@6) 5-8-90-5#3-i-2.5-2-6‡	A B C	90°	Horizontal	A1035	6.0 6.0 6.0	6.0	6703	22	0.625	0.073	13	5.3	8.375
289	(4@4) 5-5-90-5#3-i-2.5-2-7	A B C D	90°	Horizontal	A1035	6.6 7.9 7.5 6.5	7.1	6430	11	0.625	0.073	13	5.3	8.375
290	(4@4) 5-5-90-5#3-i-2.5-2-6	A B C D	90°	Horizontal	A1035	6.0 6.5 6.6 6.3	6.3	6430	11	0.625	0.073	13	5.3	8.375

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

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

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
277	(4@4) 5-5-90-0-i-2.5-2-6	A B C D	60	-	0	-	-	1.10	10	2.0	0.375	2.5	0.375	1	1.27	60
278	(4@4) 5-5-90-0-i-2.5-2-10	A B C D	60	-	0	-	-	1.10	10	2.0	0.375	3.0	0.500	1	1.27	60
279	(4@4) 5-8-90-0-i-2.5-2-6	A B C D	60	0	NA	0	0.0	-	-	-	0.375	3.0	-	-	3.16	60
280	(4@6) 5-8-90-0-i-2.5-2-6	A B C D	60	0	NA	0	0.0	-	-	-	0.375	3.0	-	-	3.16	60
281	(4@6) 5-8-90-0-i-2.5-6-6	A B C D	60	0	NA	0	0.0	-	-	-	0.375	3.0	-	-	4.74	60
282	(3@4) 5-8-90-0-i-2.5-2-6	A B C	60	0	NA	0	0	-	-	-	0.375	3.0	-	-	3.16	60
283	(3@6) 5-8-90-0-i-2.5-2-6	A B C	60	0	NA	0	0	-	-	-	0.375	3.0	-	-	3.16	60
284	(4@4) 5-5-90-2#3-i-2.5-2-6	A B C D	60	0.4	0.2	2	4.0	0.66	6	4.0	0.375	3.0	0.375	2	1.27	60
285	(4@4) 5-5-90-2#3-i-2.5-2-8	A B C D	60	0.4	0.2	2	5.0	1.20	6	2.5	0.375	3.0	0.500	2	1.27	60
286	(3@6) 5-8-90-5#3-i-2.5-2-6.25	A B C	60	0.4	0.6	5	2	-	-	-	0.50	3.0	0.375	1	1.27	60
287	(3@4) 5-8-90-5#3-i-2.5-2-6‡	A B C	60	0.4	0.6	5	2	-	-	-	0.38	3.0	-	-	3.16	120
288	(3@6) 5-8-90-5#3-i-2.5-2-6‡	A B C	60	0.4	0.6	5	2	-	-	-	0.38	3.0	-	-	3.16	120
289	(4@4) 5-5-90-5#3-i-2.5-2-7	A B C D	60	0.4	0.6	5	1.8	0.55	5	1.8	0.375	2.8	0.500	2	1.27	60
290	(4@4) 5-5-90-5#3-i-2.5-2-6	A B C D	60	0.4	0.6	5	2.0	0.55	5	2.0	0.375	3.0	0.375	2	1.27	60

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
291	(4@6) 5-8-90-5#3-i-2.5-2-6‡	A	90°	Horizontal	A1035	6.0	6.0	6693	21	0.625	0.073	17	5.3	8.375
		B				6.0								
		C				6.0								
		D				6.0								
292	(4@6) 5-8-90-5#3-i-2.5-6-6‡	A	90°	Horizontal	A1035	6.8	6.4	6693	21	0.625	0.073	17	5.3	8.375
		B				6.0								
		C				6.5								
		D				6.3								
293	(4@4) 5-8-90-5#3-i-2.5-2-6‡	A	90°	Horizontal	A1035	5.8	6.0	6703	22	0.625	0.073	17	5.3	8.375
		B				5.5								
		C				6.3								
		D				6.5								
294	(3@6) 5-8-90-5#3-i-3.5-2-6.25	A	90°	Horizontal	A1035	6.3	6.3	10110	196	0.625	0.073	15	5.3	8.375
		B				6.3								
		C				6.3								

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

Specimen	Hook	c_{so} in.	$c_{so,avg}$ in.	c_{th} in.	c_h in.	N_h	T_{ind} lb	T_{total} lb	T lb	$f_{su,\text{ ind}}$ psi	f_{su} psi	Slip at Failure in.	Failure Type
(4@5) 5-8-90-5#3-i-2.5sc-6tc-6‡	A	2.5	2.6	1.3	3.1	4	32100	124600	31200	103548	100645	-	FP
	B	6.5		2.0	3.1		29900			96452		-	FP
	C	6.5		1.5	2.9		30800			99355		-	FP
	D	2.7		1.8	-		31800			102581		-	FP
(4@3) 5-8-90-5#3-i-2.5sc-2tc-6‡	A	2.5	2.5	2.3	1.9	4	28000	110000	27500	90323	88710	-	FP
	B	5.0		2.5	1.9		27300			88065		-	FP
	C	5.0		1.8	1.9		28600			92258		-	FP
	D	2.5		1.5	-		26200			84516		-	FP
(3@6) 5-8-90-5#3-i-3.5-2-6.25	A	3.5	3.6	2.1	2.6	3	36100	105900	35300	116500	113900	-	FP
	B	6.6		2.1	3.3		33800			109000		-	FP
	C	3.8		2.1	-		40800			131600		0.454	FP

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.	N_{cti}	s_{cti} in.	d_{s} in.	s_{s} in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{vs} ksi
291	(4@6) 5-8-90-5#3-i-2.5-2-6‡	A B C D	60	0.4	0.6	5	1.7	-	-	-	0.375	3.0	-	-	3.16	120
292	(4@6) 5-8-90-5#3-i-2.5-6-6‡	A B C D	60	0.4	0.6	5	1.7	-	-	-	0.375	3.0	-	-	4.74	120
293	(4@4) 5-8-90-5#3-i-2.5-2-6‡	A B C D	60	0.4	0.6	5	1.7	-	-	-	0.375	3.0	-	-	3.16	120
294	(3@6) 5-8-90-5#3-i-3.5-2-6.25	A B C	60	0.4	0.6	5	2	-	-	-	0.50	3.0	0.375	1	1.27	60

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
295	(3@5.5) 8-5-90-0-i-2.5-2-16	A B C	90°	Horizontal	A1035[b]	16.5 15.8 16.0	16.1	6255	13	1	0.078	17	10.5	8.375
296	(3@5.5) 8-5-90-0-i-2.5-2-10	A B C	90°	Horizontal	A1035[b]	9.0 9.4 9.8	9.4	6461	14	1	0.078	17	10.5	8.375
297	(3@5.5) 8-5-90-0-i-2.5-2-8‡	A B C	90°	Horizontal	A615	7.5 8.0 8.0	7.8	5730	18	1	0.073	17	10.5	8.375
298	(3@3) 8-5-90-0-i-2.5-2-10‡	A B C	90°	Horizontal	A615	10.0 10.3 10.0	10.1	4490	10	1	0.073	12	10.5	8.375
299	(3@5) 8-5-90-0-i-2.5-2-10‡	A B C	90°	Horizontal	A615	10.3 10.1 10.0	10.1	4490	10	1	0.073	16	10.5	8.375
300	(3@5.5) 8-8-90-0-i-2.5-2-8	A B C	90°	Horizontal	A1035[b]	7.8 8.8 7.3	7.9	8700	24	1	0.078	17	10.5	8.375
301	(3@3) 8-8-90-0-i-2.5-9-9	A B C	90°	Horizontal	A615	9.5 9.5 9.3	9.4	7510	21	1	0.073	12	10.5	8.375
302	(3@4) 8-8-90-0-i-2.5-9-9	A B C	90°	Horizontal	A615	9.3 9.3 9.3	9.3	7510	21	1	0.073	14	10.5	8.375
303	(3@3) 8-12-90-0-i-2.5-2-12‡	A B C	90°	Horizontal	A1035[c]	12.1 12.1 12.2	12.1	11040	31	1	0.073	12	10.5	8.375
304	(3@4) 8-12-90-0-i-2.5-2-12‡	A B C	90°	Horizontal	A1035[c]	12.9 12.5 12.5	12.6	11440	32	1	0.073	14	10.5	8.375
305	(3@5) 8-12-90-0-i-2.5-2-12‡	A B C	90°	Horizontal	A1035[c]	12.3 12.0 12.3	12.2	11460	33	1	0.073	16	10.5	8.375
306	(4@3) 8-8-90-0-i-2.5-9-9	A B C D	90°	Horizontal	A615	9.4 9.3 9.3 9.6	9.4	7510	21	1	0.073	15	10.5	8.375
307	(4@4) 8-8-90-0-i-2.5-9-9	A B C D	90°	Horizontal	A615	9.4 9.1 9.0 9.1	9.2	7510	21	1	0.073	18	10.5	8.375
308	(3@3) 8-5-180-0-i-2.5-2-10‡	A B C	180°	Horizontal	A615	9.8 10.0 9.8	9.8	5260	15	1	0.073	12	10.5	8.375
309	(3@5) 8-5-180-0-i-2.5-2-10‡	A B C	180°	Horizontal	A615	10.0 10.0 10.0	10.0	5260	15	1	0.073	16	10.5	8.375
310	(3@5.5) 8-5-90-2#3-i-2.5-2-14	A B C	90°	Horizontal	A1035[b]	14.6 13.9 14.8	14.4	6460	14	1	0.078	17	10.5	8.375
311	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5	A B C	90°	Horizontal	A1035[b]	9.8 8.8 8.9	9.1	6460	14	1	0.078	17	10.5	8.375

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

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

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

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
295	(3@5.5) 8-5-90-0-i-2.5-2-16	A B C	60	-	-	-	-	2.0	10	3	0.50	3.0	0.375	1	3.16	60
296	(3@5.5) 8-5-90-0-i-2.5-2-10	A B C	60	-	-	-	-	2.0	10	3	0.50	3.0	0.500	1	3.16	60
297	(3@5.5) 8-5-90-0-i-2.5-2-8‡	A B C	60	-	-	-	-	-	-	-	0.50	4.0	-	-	6.32	120
298	(3@3) 8-5-90-0-i-2.5-2-10‡	A B C	60	-	-	-	-	-	-	-	0.38	3.0	-	-	3.16	120
299	(3@5) 8-5-90-0-i-2.5-2-10‡	A B C	60	-	-	-	-	-	-	-	0.38	4.0	-	-	3.16	120
300	(3@5.5) 8-8-90-0-i-2.5-2-8	A B C	60	-	-	0	-	2.2	20	3	0.50	1.8	-	-	3.16	60
301	(3@3) 8-8-90-0-i-2.5-9-9	A B C	60	-	-	-	-	-	-	-	0.38	4.0	-	-	4.74	60
302	(3@4) 8-8-90-0-i-2.5-9-9	A B C	60	-	-	-	-	-	-	-	0.38	4.0	-	-	4.74	60
303	(3@3) 8-12-90-0-i-2.5-2-12‡	A B C	60	0.375	-	0	-	-	-	-	0.38	3.0	-	-	3.16	120
304	(3@4) 8-12-90-0-i-2.5-2-12‡	A B C	60	0.375	-	0	-	-	-	-	0.38	3.0	-	-	3.16	120
305	(3@5) 8-12-90-0-i-2.5-2-12‡	A B C	60	0.375	-	0	-	-	-	-	0.38	3.0	-	-	3.16	120
306	(4@3) 8-8-90-0-i-2.5-9-9	A B C D	60	0.375	-	0	3.0	-	-	-	0.375	4.0	-	-	6.32	60
307	(4@4) 8-8-90-0-i-2.5-9-9	A B C D	60	0.375	-	0	0.0	-	-	-	0.375	4.0	-	-	6.32	60
308	(3@3) 8-5-180-0-i-2.5-2-10‡	A B C	60	-	-	-	-	-	-	-	0.50	4.0	-	-	6.32	120
309	(3@5) 8-5-180-0-i-2.5-2-10‡	A B C	60	-	-	-	-	-	-	-	0.50	3.0	-	-	6.32	120
310	(3@5.5) 8-5-90-2#3-i-2.5-2-14	A B C	60	0.375	0.2	2	8	2.0	10	2.5	0.38	3.0	0.500	2	3.16	60
311	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5	A B C	60	0.375	0.2	2	8	2.0	10	2.5	0.38	2.5	0.500	2	1.89	60

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
312	(3@5.5) 8-5-90-2#3-i-2.5-2-14(1)	A B C	90°	Horizontal	A1035[c]	14.7 15.2 14.8	14.9	5450	7	1	0.073	17	10.5	8.375
313	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5(1)	A B C	90°	Horizontal	A1035[c]	7.3 8.9 8.4	8.2	5450	7	1	0.073	17	10.5	8.375
314	(3@3) 8-5-90-2#3-i-2.5-2-10[‡]	A B C	90°	Horizontal	A615	9.9 10.1 10.0	10.0	4760	11	1	0.073	12	10.5	8.375
315	(3@5) 8-5-90-2#3-i-2.5-2-10[‡]	A B C	90°	Horizontal	A615	10.5 10.6 10.4	10.5	4760	11	1	0.073	16	10.5	8.375
316	(3@3) 8-5-180-2#3-i-2.5-2-10[‡]	A B C	180°	Horizontal	A615	10.5 10.3 10.0	9.4	5400	16	1	0.073	12	10.5	8.375
317	(3@5) 8-5-180-2#3-i-2.5-2-10[‡]	A B C	180°	Horizontal	A615	9.6 9.8 9.8	9.4	5400	16	1	0.073	16	10.5	8.375
318	(3@5.5) 8-5-90-5#3-i-2.5-2-8	A B C	90°	Horizontal	A1035[b]	8.0 8.1 7.8	8.0	6620	15	1	0.078	17	10.5	8.375
319	(3@5.5) 8-5-90-5#3-i-2.5-2-12	A B C	90°	Horizontal	A1035[b]	12.4 12.1 12.1	12.2	6620	15	1	0.078	17	10.5	8.375
320	(3@5.5) 8-5-90-5#3-i-2.5-2-8(1)	A B C	90°	Horizontal	A1035[c]	7.3 8.4 7.3	7.6	5660	8	1	0.073	17	10.5	8.375
321	(3@5.5) 8-5-90-5#3-i-2.5-2-12(1)	A B C	90°	Horizontal	A1035[c]	11.4 12.5 12.0	12.0	5660	8	1	0.073	17	10.5	8.375
322	(3@5.5) 8-5-90-5#3-i-2.5-2-8(2)[‡]	A B C	90°	Horizontal	A615	8.0 8.0 8.5	8.2	5730	18	1	0.073	17	10.5	8.375
323	(3@3) 8-5-90-5#3-i-2.5-2-10[‡]	A B C	90°	Horizontal	A615	10.0 9.8 9.9	9.9	4810	12	1	0.073	12	10.5	8.375
324	(3@5) 8-5-90-5#3-i-2.5-2-10[‡]	A B C	90°	Horizontal	A615	10.0 10.0 9.8	9.9	4850	13	1	0.073	16	10.5	8.375
325	(3@3) 8-8-90-5#3-i-2.5-9-9	A B C	90°	Horizontal	A615	9.5 9.0 9.5	9.3	7440	22	1	0.073	12	10.5	8.375
326	(3@4) 8-8-90-5#3-i-2.5-9-9	A B C	90°	Horizontal	A615	8.9 9.1 9.3	9.1	7440	22	1	0.073	14	10.5	8.375
327	(3@3) 8-12-90-5#3-i-2.5-2-12[‡]	A B C	90°	Horizontal	A1035[c]	11.9 11.9 11.6	11.8	11040	31	1	0.073	12	10.5	8.375
328	(3@4) 8-12-90-5#3-i-2.5-2-12[‡]	A B C	90°	Horizontal	A1035[c]	12.5 12.0 12.5	12.3	11440	32	1	0.073	14	10.5	8.375

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

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

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

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

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

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
312	(3@5.5) 8-5-90-2#3-i-2.5-2-14(1)	A B C	60	0.375	0.2	2	6	1.6	8	3	0.38	2.5	0.375	2	3.16	60
313	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5(1)	A B C	60	0.375	0.2	2	6	2.0	10	3	0.50	2.5	0.375	1	3.16	60
314	(3@3) 8-5-90-2#3-i-2.5-2-10‡	A B C	60	0.375	0.2	2	3	-	-	-	0.50	5.0	-	-	4.74	120
315	(3@5) 8-5-90-2#3-i-2.5-2-10‡	A B C	60	0.375	0.2	2	3	-	-	-	0.38	3.0	-	-	3.16	120
316	(3@3) 8-5-180-2#3-i-2.5-2-10‡	A B C	60	0.375	0.2	2	3	-	-	-	0.50	4.0	-	-	6.32	120
317	(3@5) 8-5-180-2#3-i-2.5-2-10‡	A B C	60	0.375	0.2	2	3	-	-	-	0.50	3.0	-	-	6.32	120
318	(3@5.5) 8-5-90-5#3-i-2.5-2-8	A B C	60	0.375	0.6	5	3	2.0	10	3.3	0.38	2.5	0.500	2	1.89	60
319	(3@5.5) 8-5-90-5#3-i-2.5-2-12	A B C	60	0.375	0.6	5	3	2.0	10	3.2	0.38	2.5	0.500	2	1.27	60
320	(3@5.5) 8-5-90-5#3-i-2.5-2-8(1)	A B C	60	0.375	0.6	5	3	2.0	10	3	0.50	2.5	0.375	1	3.16	60
321	(3@5.5) 8-5-90-5#3-i-2.5-2-12(1)	A B C	60	0.375	0.6	5	3	1.0	5	2.8	0.50	3.5	0.500	1	3.16	60
322	(3@5.5) 8-5-90-5#3-i-2.5-2-8(2)‡	A B C	60	0.375	0.6	5	3	-	-	-	0.50	4.0	-	-	6.32	120
323	(3@3) 8-5-90-5#3-i-2.5-2-10‡	A B C	60	0.375	0.6	5	3	-	-	-	0.50	4.0	-	-	4.74	120
324	(3@5) 8-5-90-5#3-i-2.5-2-10‡	A B C	60	0.375	0.6	5	3	-	-	-	0.38	3.0	-	-	3.95	120
325	(3@3) 8-8-90-5#3-i-2.5-9-9	A B C	60	0.375	0.6	5	3	-	-	-	0.38	4.0	-	-	4.74	60
326	(3@4) 8-8-90-5#3-i-2.5-9-9	A B C	60	0.375	0.6	5	3	-	-	-	0.38	4.0	-	-	4.74	60
327	(3@3) 8-12-90-5#3-i-2.5-2-12‡	A B C	60	0.375	0.6	5	3	-	-	-	0.38	3.0	-	-	3.16	120
328	(3@4) 8-12-90-5#3-i-2.5-2-12‡	A B C	60	0.375	0.6	5	3	-	-	-	0.38	3.0	-	-	3.16	120

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

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
329	(3@5) 8-12-90-5#3-i-2.5-2-12‡	A	90°	Horizontal	A1035[c]	11.9	12.2	11460	33	1	0.073	16	10.5	8.375
		B				12.4								
		C				12.3								
330	(4@3)8-8-90-5#3-i-2.5-9-9	A	90°	Horizontal	A615	9.3	9.3	7440	22	1	0.073	15	10.5	8.375
		B				9.3								
		C				9.3								
		D				9.3								
331	(4@4) 8-8-90-5#3-i-2.5-9-9	A	90°	Horizontal	A615	9.5	9.5	7440	22	1	0.073	18	10.5	8.375
		B				9.5								
		C				9.3								
		D				9.6								
332	(3@3) 8-5-180-5#3-i-2.5-2-10‡	A	180°	Horizontal	A615	10.1	9.9	5540	17	1	0.073	12	10.5	8.375
		B				9.9								
		C				9.8								
333	(3@5) 8-5-180-5#3-i-2.5-2-10‡	A	180°	Horizontal	A615	9.9	9.7	5540	17	1	0.073	16	10.5	8.375
		B				9.8								
		C				9.5								

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

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

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

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

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
329	(3@5) 8-12-90-5#3-i-2.5-2-12‡	A B C	60	0.375	0.6	5	3	-	-	-	0.38	3.0	-	-	3.16	120
330	(4@3)8-8-90-5#3-i-2.5-9-9	A B C D	60	0.375	0.6	5	3.0	-	-	-	0.375	4.0	-	-	4.74	60
331	(4@4) 8-8-90-5#3-i-2.5-9-9	A B C D	60	0.375	0.6	5	3.0	-	-	-	0.375	4.0	-	-	4.74	60
332	(3@3) 8-5-180-5#3-i-2.5-2-10‡	A B C	60	0.375	0.6	5	3	-	-	-	0.50	4.0	-	-	6.32	120
333	(3@5) 8-5-180-5#3-i-2.5-2-10‡	A B C	60	0.375	0.6	5	3	-	-	-	0.50	3.0	-	-	6.32	120

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

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

	Specimen	Hook	Bend Angle	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	$\ell_{eh,avg}$ in.	f_{cm} psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
		A				13.8								
334	(3@5.35) 11-5-90-0-i-2.5-13-13	B	90°	Horizontal	A615	14.3	13.8	5330	11	1.41	0.085	21.5	19.5	8.375
		C				13.5								
		A				14.0								
335	(3@5.35) 11-5-90-2#3-i-2.5-13-13	B	90°	Horizontal	A615	14.0	13.9	5330	11	1.41	0.085	21.5	19.5	8.375
		C				13.8								
		A				13.5								
336	(3@5.35) 11-5-90-6#3-i-2.5-13-13	B	90°	Horizontal	A615	13.5	13.6	5280	12	1.41	0.085	21.5	19.5	8.375
		C				13.8								
		A				18.6								
337	(3@5.35) 11-5-90-6#3-i-2.5-18-18	B	90°	Horizontal	A1035	18.6	18.6	5280	12	1.41	0.085	21.5	19.5	8.375
		C				18.6								

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

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

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

	Specimen	Hook	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	A_{cti} in.	N_{cti}	s_{cti} in.	d_s in.	s_s in.	d_{cto} in.	N_{cto}	A_s in.^{2}	f_{ys} ksi
		A														
334	(3@5.35) 11-5-90-0-i-2.5-13-13	B	60	-	-	-	-	-	-	-	0.50	7.0	-	-	7.90	60
		C														
		A														
335	(3@5.35) 11-5-90-2#3-i-2.5-13-13	B	60	0.375	0.22	2	8	-	-	-	0.50	7.0	-	-	7.90	60
		C														
		A														
336	(3@5.35) 11-5-90-6#3-i-2.5-13-13	B	60	0.375	0.66	6	4	-	-	-	0.50	7.0	-	-	7.90	60
		C														
		A														
337	(3@5.35) 11-5-90-6#3-i-2.5-18-18	B	60	0.375	0.66	6	4	-	-	-	0.50	7.0	-	-	7.90	60
		C														

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

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

†60,000 psi nominal yield strength for all transverse reinforcement
*Information not provided
^{a} Nominal value

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

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

†60,000 psi nominal yield strength for all transverse reinforcement

*Information not provided

[a] Nominal value

APPENDIX C: TEST-TO-CALCULATED RATIOS

Table C.1 Test-to-calculated ratios for specimens with two hooked bars and no transverse reinforcement

Specimen		T	Descriptive Equation[a]		Design Equation[b]	
		lb	T_h lb	T/T_h	T_h lb	T/T_h
1	5-5-90-0-o-1.5-2-5†	14070	16600	0.85	10400	1.35
2	5-5-90-0-o-1.5-2-6.5†	17815	21900	0.81	13300	1.34
3	5-5-90-0-o-1.5-2-8†	23500	28500	0.82	17000	1.38
4	5-5-90-0-o-2.5-2-5	19285	15700	1.23	9900	1.95
5	5-5-180-0-o-1.5-2-9.5†	29485	32400	0.91	19100	1.54
6	5-5-180-0-o-1.5-2-11.25†	32400	39500	0.82	22900	1.41
7	5-5-180-0-o-2.5-2-9.5†	30130	32800	0.92	19400	1.55
8	5-5-90-0-i-2.5-2-10	33585	33800	0.99	24800	1.35
9	5-5-90-0-i-2.5-2-7	26265	24200	1.09	18300	1.44
10	5-8-90-0-i-2.5-2-6†	29570	27000	1.10	20100	1.47
11	5-8-90-0-i-2.5-2-6(1)	22425	25600	0.88	19100	1.17
12	5-8-90-0-i-2.5-2-8†	31675	31600	1.00	23200	1.37
13	(2@4) 5-8-90-0-i-2.5-2-6	18000	21900	1.02	12500	1.79
14	(2@6) 5-8-90-0-i-2.5-2-6	21100	22400	1.07	15700	1.53
15	5-12-90-0-i-2.5-2-10	41655	46500	0.90	32900	1.27
16	5-12-90-0-i-2.5-2-5	19220	21000	0.92	15900	1.21
17	5-15-90-0-i-2.5-2-5.5	32500	28100	1.16	20700	1.57
18	5-15-90-0-i-2.5-2-7.5	42200	35100	1.20	25300	1.67
19	5-5-90-0-i-3.5-2-10	41925	37900	1.11	27500	1.52
20	5-5-90-0-i-3.5-2-7	26515	26600	1.00	19900	1.33
21	5-8-90-0-i-3.5-2-6†	25475	25200	1.01	18900	1.35
22	5-8-90-0-i-3.5-2-6(1)	24540	26900	0.91	20000	1.23
23	5-8-90-0-i-3.5-2-8†	32745	35000	0.94	25500	1.28
24	5-12-90-0-i-3.5-2-5	22120	22600	0.98	17100	1.29
25	5-12-90-0-i-3.5-2-10	46000	46000	1.00	32400	1.42
26	5-8-180-0-i-2.5-2-7	27110	29900	0.91	22000	1.23
27	5-8-180-0-i-3.5-2-7	30755	30100	1.02	22200	1.39
79	8-5-90-0-o-2.5-2-10a†	42315	47800	0.89	27800	1.52
80	8-5-90-0-o-2.5-2-10b†	33650	45100	0.75	26300	1.28
81	8-5-90-0-o-2.5-2-10c†	55975	50100	1.12	29000	1.93
82	8-8-90-0-o-2.5-2-8	33015	44100	0.75	25600	1.29
83	8-8-90-0-o-3.5-2-8	35870	40600	0.88	23800	1.51
84	8-8-90-0-o-4-2-8	37510	42500	0.88	24800	1.51
85	8-5-90-0-i-2.5-2-16†	83240	77700	1.07	54100	1.54
86	8-5-90-0-i-2.5-2-9.5†	44485	43700	1.02	32000	1.39
87	8-5-90-0-i-2.5-2-12.5†	65820	62500	1.05	44300	1.49
88	8-5-90-0-i-2.5-2-18	80880	91900	0.88	62900	1.29
89	8-5-90-0-i-2.5-2-13	65540	64200	1.02	45400	1.44
90	8-5-90-0-i-2.5-2-15(1)	63765	73500	0.87	51300	1.24
91	8-5-90-0-i-2.5-2-15	75480	74200	1.02	51700	1.46
92	(2@3) 8-5-90-0-i-2.5-2-10‡	40300	46300	0.87	22500	1.79
93	(2@5) 8-5-90-0-i-2.5-2-10‡	40100	44100	0.91	27400	1.46
94	8-8-90-0-i-2.5-2-8	45245	42900	1.05	31300	1.45
95	8-8-90-0-i-2.5-2-10	51455	49200	1.05	35400	1.45
96	8-8-90-0-i-2.5-2-8(1)	36820	41700	0.88	30400	1.21

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] T_h calculated using Eq. (4.7) for specimens without transverse reinforcement and Eq. (4.12) for specimens with transverse reinforcement
[b] T_h calculated using Eq. (5.7)

Table C.1 Cont Test-to-calculated ratios for specimens with two hooked bars and no transverse reinforcement

Specimen		*T*	Descriptive Equation[a]		Design Equation[b]	
		lb	T_h lb	T/T_h	T_h lb	T/T_h
97	8-8-90-0-i-2.5sc-2tc-9‡	35100	48500	0.72	35000	1.00
98	8-8-90-0-i-2.5sc-9tc-9	37700	46400	0.81	33600	1.12
99	(2@3) 8-8-90-0-i-2.5-9-9	30700	46000	0.67	22300	1.38
100	(2@4) 8-8-90-0-i-2.5-9-9	34200	50600	0.68	27700	1.23
101	8-12-90-0-i-2.5-2-9	49925	50900	0.98	36400	1.37
102	8-12-90-0-i-2.5-2-12.5	66950	76300	0.88	52500	1.28
103	8-12-90-0-i-2.5-2-12	65900	71700	0.92	49600	1.33
104	8-15-90-0-i-2.5-2-8.5	43600	55000	0.79	38800	1.12
105	8-15-90-0-i-2.5-2-13	78100	82700	0.94	56300	1.39
106	8-5-90-0-i-3.5-2-18	95370	90900	1.05	62300	1.53
107	8-5-90-0-i-3.5-2-13	68100	64200	1.06	45400	1.50
108	8-5-90-0-i-3.5-2-15(2)	87710	72700	1.21	50800	1.73
109	8-5-90-0-i-3.5-2-15(1)	70650	77500	0.91	53700	1.32
110	8-8-90-0-i-3.5-2-8(1)	43845	39000	1.12	28700	1.53
111	8-8-90-0-i-3.5-2-10	55565	49900	1.11	35900	1.55
112	8-8-90-0-i-3.5-2-8(2)	42035	43100	0.98	31400	1.34
113	8-12-90-0-i-3.5-2-9	60240	50900	1.18	36400	1.65
114	8-8-90-0-i-4-2-8	37430	40500	0.92	29700	1.26
115	8-5-180-0-i-2.5-2-11†	46145	48900	0.94	35500	1.30
116	8-5-180-0-i-2.5-2-14†	49150	64900	0.76	45900	1.07
117	(2@3) 8-5-180-0-i-2.5-2-10‡	51800	46700	1.11	22700	2.28
118	(2@5)8-5-180-0-i-2.5-2-10‡	53200	45900	1.16	28300	1.88
119	8-8-180-0-i-2.5-2-11.5	62800	48600	1.29	35000	1.79
120	8-12-180-0-i-2.5-2-12.5	75200	75100	1.00	51800	1.45
121	8-5-180-0-i-3.5-2-11†	59290	52000	1.14	37500	1.58
122	8-5-180-0-i-3.5-2-14†	63505	65500	0.97	46300	1.37
123	8-15-180-0-i-2.5-2-13.5	89900	89900	1.00	60700	1.48
212	11-8-90-0-o-2.5-2-25	174700	178600	0.98	92700	1.88
213	11-8-90-0-o-2.5-2-17	107200	112600	0.95	61000	1.76
214	11-12-90-0-o-2.5-2-17	105400	122500	0.86	65700	1.60
215	11-12-180-0-o-2.5-2-17	83500	124000	0.67	66400	1.26
216	11-5-90-0-i-2.5-2-14	66590	79700	0.84	56200	1.18
217	11-5-90-0-i-2.5-2-26	148725	156800	0.95	103800	1.43
218	(2@5.35) 11-5-90-0-i-2.5-13-13	60600	78900	0.77	48300	1.25
219	11-8-90-0-i-2.5-2-17	132100	120600	1.10	81100	1.63
220	11-8-90-0-i-2.5-2-21	125120	135400	0.92	90400	1.38
221	11-8-90-0-i-2.5-2-17	104780	113800	0.92	77100	1.36
222	11-12-90-0-i-2.5-2-17	119700	119800	1.00	80400	1.49
223	11-12-90-0-i-2.5-2-17.5	124620	133700	0.93	88700	1.40
224	11-12-90-0-i-2.5-2-25	199745	192400	1.04	123500	1.62
225	11-15-90-0-i-2.5-2-24	213300	201200	1.06	128300	1.66
226	11-15-90-0-i-2.5-2-11	48100	90700	0.53	62200	0.77
227	11-15-90-0-i-2.5-2-10‡	51500	68500	0.75	48300	1.07
228	11-15-90-0-i-2.5-2-15‡	92200	105000	0.88	71100	1.30
229	11-5-90-0-i-3.5-2-17	108120	105200	1.03	72200	1.50
230	11-5-90-0-i-3.5-2-14	69515	83500	0.83	58600	1.19
231	11-5-90-0-i-3.5-2-26	182255	161700	1.13	106600	1.71

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

[a] T_h calculated using Eq. (4.7) for specimens without transverse reinforcement and Eq. (4.12) for specimens with transverse reinforcement

[b] T_h calculated using Eq. (5.7)

Table C.1 Cont Test-to-calculated ratios for specimens with two hooked bars and no transverse reinforcement

Specimen		T lb	Descriptive Equation[a]		Design Equation[b]	
			T_h lb	T/T_h	T_h lb	T/T_h
232	11-8-180-0-i-2.5-2-21	128125	139100	0.92	92600	1.38
233	11-8-180-0-i-2.5-2-17	100450	118800	0.85	80100	1.25
234	11-12-180-0-i-2.5-2-17	107500	120800	0.89	81000	1.33

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] T_h calculated using Eq. (4.7) for specimens without transverse reinforcement and Eq. (4.12) for specimens with transverse reinforcement
[b] T_h calculated using Eq. (5.7)

Table C.2 Test-to-calculated ratios for specimens with two hooked bars with transverse reinforcement

Specimen		T lb	Descriptive Equation[a]		Design Equation[b]	
			T_h lb	T/T_h	T_h lb	T/T_h
28	5-5-90-1#3-i-2.5-2-8†	33135	30600	1.08	22400	1.48
29	5-5-90-1#3-i-2.5-2-6†	19915	20500	0.97	15600	1.28
30	5-8-90-1#3-i-2.5-2-6†	26575	26600	1.00	20000	1.33
31	5-8-90-1#3-i-2.5-2-6(1)	25400	26000	0.98	19600	1.30
32	5-8-90-1#3-i-3.5-2-6†	30085	26200	1.15	19700	1.53
33	5-8-90-1#3-i-3.5-2-6(1)	25905	27600	0.94	20700	1.25
34	5-5-180-1#3-i-2.5-2-8†	36450	31300	1.16	22900	1.59
35	5-5-180-1#3-i-2.5-2-6†	23915	24000	1.00	18000	1.33
36	5-8-180-1#3-i-2.5-2-7	32910	31900	1.03	23600	1.39
37	5-8-180-1#3-i-3.5-2-7	30500	30700	0.99	22800	1.34
38	5-5-90-1#4-i-2.5-2-8†	27535	31700	0.87	23200	1.19
39	5-5-90-1#4-i-2.5-2-6†	21455	24100	0.89	18100	1.19
40	5-8-90-1#4-i-2.5-2-6	24290	28500	0.85	21300	1.14
41	5-8-90-1#4-i-3.5-2-6	25240	30800	0.82	22900	1.10
42	5-5-180-1#4-i-2.5-2-8†	38420	33400	1.15	24300	1.58
43	5-5-180-1#4-i-2.5-2-6†	22975	26900	0.85	20000	1.15
44	5-5-180-2#3-o-1.5-2-11.25†	43050	46400	0.93	26800	1.61
45	5-5-180-2#3-o-1.5-2-9.5†	20300	35700	0.57	21200	0.96
46	5-5-180-2#3-o-2.5-2-9.5†	43900	37200	1.18	22000	2.00
47	5-5-180-2#3-o-2.5-2-11.25†	42325	45400	0.93	26300	1.61
48	5-5-90-2#3-i-2.5-2-8†	37155	33600	1.11	24500	1.52
49	5-5-90-2#3-i-2.5-2-6†	29445	26000	1.13	19300	1.53
50	5-8-90-2#3-i-2.5-2-6†	30640	28700	1.07	21400	1.43
51	5-8-90-2#3-i-2.5-2-8†	40170	38900	1.03	28300	1.42
52	5-12-90-2#3-i-2.5-2-5	24350	29000	0.84	21700	1.12
53	5-15-90-2#3-i-2.5-2-6	42600	34300	1.24	25600	1.66
54	5-15-90-2#3-i-2.5-2-4	18700	21300	0.88	16500	1.13
55	5-5-90-2#3-i-3.5-2-6	21095	25500	0.83	18900	1.12
56	5-5-90-2#3-i-3.5-2-8	22830	32600	0.70	23800	0.96
57	5-8-90-2#3-i-3.5-2-6†	30035	29700	1.01	22100	1.36
58	5-8-90-2#3-i-3.5-2-8†	28655	33400	0.86	24600	1.16
59	5-12-90-2#3-i-3.5-2-5	28365	27200	1.04	20500	1.38
60	5-12-90-2#3-i-3.5-2-10	46000	52500	0.88	37500	1.23

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] T_h calculated using Eq. (4.7) for specimens without transverse reinforcement and Eq. (4.12) for specimens with transverse reinforcement
[b] T_h calculated using Eq. (5.7)

Table C.2 Cont Test-to-calculated ratios for specimens with two hooked bars with transverse reinforcement

Specimen		T lb	Descriptive Equation[a]		Design Equation[b]	
			T_h lb	T/T_h	T_h lb	T/T_h
61	5-5-180-2#3-i-2.5-2-8†	34080	34400	0.99	25000	1.36
62	5-5-180-2#3-i-2.5-2-6†	26730	25100	1.06	18700	1.43
63	5-8-180-2#3-i-2.5-2-7	29230	34000	0.86	25000	1.17
64	5-8-180-2#3-i-3.5-2-7	30930	32600	0.95	24100	1.28
65	5-8-90-4#3-i-2.5-2-8†	26410	41400	0.64	29700	0.89
66	5-8-90-4#3-i-3.5-2-8†	38480	44700	0.86	31900	1.21
67	5-5-90-5#3-o-1.5-2-5†	22000	30500	0.72	19100	1.15
68	5-5-90-5#3-o-1.5-2-8†	25110	42200	0.60	25500	0.98
69	5-5-90-5#3-o-1.5-2-6.5†	21710	36800	0.59	22600	0.96
70	5-5-90-5#3-o-2.5-2-5†	22530	30800	0.73	19300	1.17
71	5-5-90-5#3-o-2.5-2-8†	28400	40700	0.70	24700	1.15
72	5-5-90-5#3-i-2.5-2-7	31695	35500	0.89	25200	1.26
73	5-12-90-5#3-i-2.5-2-5	34420	35600	0.97	25600	1.34
74	5-15-90-5#3-i-2.5-2-4	31360	30700	1.02	22400	1.40
75	5-15-90-5#3-i-2.5-2-5	39200	36100	1.09	26200	1.50
76	5-5-90-5#3-i-3.5-2-7	36025	38600	0.93	27300	1.32
77	5-12-90-5#3-i-3.5-2-5	30440	33900	0.90	24500	1.24
78	5-12-90-5#3-i-3.5-2-10	46000	62900	0.73	44000	1.05
124	8-5-90-1#3-i-2.5-2-16†	74810	77100	0.97	53300	1.40
125	8-5-90-1#3-i-2.5-2-12.5†	64835	62000	1.05	43800	1.48
126	8-5-90-1#3-i-2.5-2-9.5†	49035	44300	1.11	32300	1.52
127	8-5-180-1#3-i-2.5-2-11†	49730	54600	0.91	38800	1.28
128	8-5-180-1#3-i-2.5-2-14†	69020	73400	0.94	51000	1.35
129	8-5-180-1#3-i-3.5-2-11†	55390	53400	1.04	38100	1.45
130	8-5-180-1#3-i-3.5-2-14†	75995	74300	1.02	51500	1.48
131	8-8-180-1#4-i-2.5-2-11.5	72230	70400	1.03	50000	1.44
132	8-5-90-2#3-i-2.5-2-16†	79630	78900	1.01	54600	1.46
133	8-5-90-2#3-i-2.5-2-9.5†	53620	47900	1.12	34700	1.55
134	8-5-90-2#3-i-2.5-2-12.5†	72065	62800	1.15	44400	1.62
135	8-5-90-2#3-i-2.5-2-8.5	50550	48700	1.04	35200	1.44
136	8-5-90-2#3-i-2.5-2-14	76965	72500	1.06	50700	1.52
137	(2@3) 8-5-90-2#3-i-2.5-2-10‡	46800	52700	0.89	27300	1.71
138	(2@5) 8-5-90-2#3-i-2.5-2-10‡	48500	50500	0.96	30900	1.57
139	8-8-90-2#3-i-2.5-2-8	47875	47400	1.01	34700	1.38
140	8-8-90-2#3-i-2.5-2-10	61025	57200	1.07	41400	1.47
141	8-12-90-2#3-i-2.5-2-9	61015	55800	1.09	40700	1.50
142	8-12-90-2#3-i-2.5-2-11	68700	68300	1.01	49100	1.40
143	8-12-90-2#3vr-i-2.5-2-11	52650	66700	0.79	48000	1.10
144	8-15-90-2#3-i-2.5-2-6	37600	41300	0.91	31200	1.21
145	8-15-90-2#3-i-2.5-2-11	83300	73400	1.13	52800	1.58
146	8-5-90-2#3-i-3.5-2-17	89915	91700	0.98	62900	1.43
147	8-5-90-2#3-i-3.5-2-13	80360	72200	1.11	50600	1.59
148	8-8-90-2#3-i-3.5-2-8	48775	47100	1.04	34600	1.41
149	8-8-90-2#3-i-3.5-2-10	53885	51800	1.04	37800	1.43
150	8-12-90-2#3-i-3.5-2-9	49775	55800	0.89	40700	1.22
151	8-5-180-2#3-i-2.5-2-11†	60235	54100	1.11	38600	1.56
152	8-5-180-2#3-i-2.5-2-14†	76280	70800	1.08	49500	1.54

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

[a] T_h calculated using Eq. (4.7) for specimens without transverse reinforcement and Eq. (4.12) for specimens with transverse reinforcement

[b] T_h calculated using Eq. (5.7)

Table C.2 Cont Test-to-calculated ratios for specimens with two hooked bars with transverse reinforcement

Specimen		T lb	Descriptive Equation[a]		Design Equation[b]	
			T_h lb	T/T_h	T_h lb	T/T_h
151	8-5-180-2#3-i-2.5-2-11†	60235	54100	1.11	38600	1.56
152	8-5-180-2#3-i-2.5-2-14†	76280	70800	1.08	49500	1.54
153	(2@3) 8-5-180-2#3-i-2.5-2-10‡	57700	54200	1.06	27300	2.11
154	(2@5) 8-5-180-2#3-i-2.5-2-10‡	61900	52900	1.17	32500	1.90
155	8-8-180-2#3-i-2.5-2-11.5	58170	60900	0.96	43800	1.33
156	8-12-180-2#3-i-2.5-2-11	64650	67500	0.96	48500	1.33
157	8-12-180-2#3vr-i-2.5-2-11	65800	68300	0.96	49100	1.34
158	8-5-180-2#3-i-3.5-2-11†	55870	52200	1.07	37300	1.50
159	8-5-180-2#3-i-3.5-2-14†	63465	69800	0.91	48800	1.30
160	8-15-180-2#3-i-2.5-2-11	78900	73700	1.07	53000	1.49
161	8-8-90-2#4-i-2.5-2-10	61360	57100	1.07	41100	1.49
162	8-8-90-2#4-i-3.5-2-10	69465	59900	1.16	43000	1.62
163	8-5-90-4#3-i-2.5-2-16†	90430	89600	1.01	61400	1.47
164	8-5-90-4#3-i-2.5-2-12.5†	68585	68300	1.00	47900	1.43
165	8-5-90-4#3-i-2.5-2-9.5†	54915	56600	0.97	40300	1.36
166	8-5-90-5#3-o-2.5-2-10a†	54255	64800	0.84	38600	1.41
167	8-5-90-5#3-o-2.5-2-10b†	65590	65800	1.00	39200	1.67
168	8-5-90-5#3-o-2.5-2-10c†	57700	68200	0.85	40400	1.43
169	8-8-90-5#3-o-2.5-2-8	57980	60200	0.96	36600	1.58
170	8-8-90-5#3-o-3.5-2-8	54955	56900	0.97	34800	1.58
171	8-8-90-5#3-o-4-2-8	39070	59000	0.66	35900	1.09
172	8-5-90-5#3-i-2.5-2-10b†	69715	65200	1.07	45800	1.52
173	8-5-90-5#3-i-2.5-2-10c†	68835	66300	1.04	46600	1.48
174	8-5-90-5#3-i-2.5-2-15	73375	90200	0.81	61700	1.19
175	8-5-90-5#3-i-2.5-2-13	82375	82500	1.00	57000	1.45
176	8-5-90-5#3-i-2.5-2-12(1)	66365	69200	0.96	48400	1.37
177	8-5-90-5#3-i-2.5-2-12	84900	73600	1.15	51400	1.65
178	8-5-90-5#3-i-2.5-2-12(2)	71470	74100	0.96	51600	1.39
179	8-5-90-5#3-i-2.5-2-8	47480	50600	0.94	36100	1.32
180	8-5-90-5#3-i-2.5-2-10a†	82800	65500	1.26	46000	1.80
181	(2@3) 8-5-90-5#3-i-2.5-2-10‡	57900	63100	0.92	33200	1.74
182	(2@5) 8-5-90-5#3-i-2.5-2-10‡	56000	60300	0.93	37900	1.48
183	8-8-90-5#3-i-2.5-2-8	50265	52900	0.95	38000	1.32
184	8-8-90-5#3-i-2.5-2-9‡	64390	60800	1.06	43300	1.49
185	8-8-90-5#3-i-2.5-9-9‡	63290	62500	1.01	44400	1.43
186	(2@3) 8-8-90-5#3-i-2.5-9-9	58790	63500	0.93	33600	1.75
187	(2@4) 8-8-90-5#3-i-2.5-9-9	57450	61400	0.94	36200	1.59
188	8-12-90-5#3-i-2.5-2-9	64755	66100	0.98	47200	1.37
189	8-12-90-5#3-i-2.5-2-10	64550	69400	0.93	49500	1.30
190	8-12-90-5#3-i-2.5-2-12‡	87700	86700	1.01	60800	1.44
191	8-12-90-5#3vr-i-2.5-2-10	60200	74200	0.81	52700	1.14
192	8-12-90-4#3vr-i-2.5-2-10	59250	72100	0.82	51400	1.15
193	8-15-90-5#3-i-2.5-2-6	48500	53000	0.92	38600	1.26
194	8-15-90-5#3-i-2.5-2-10	90000	77800	1.16	55400	1.62
195	8-5-90-5#3-i-3.5-2-15	80340	91400	0.88	62500	1.29
196	8-5-90-5#3-i-3.5-2-13	77070	79900	0.96	55400	1.39
197	8-5-90-5#3-i-3.5-2-12(1)	76430	75300	1.02	52300	1.46
198	8-5-90-5#3-i-3.5-2-12	79150	76700	1.03	53500	1.48

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] T_h calculated using Eq. (4.7) for specimens without transverse reinforcement and Eq. (4.12) for specimens with transverse reinforcement
[b] T_h calculated using Eq. (5.7)

Table C.2 Cont Test-to-calculated ratios for specimens with two hooked bars with transverse reinforcement

Specimen		T lb	Descriptive Equation[a] T_h lb	Descriptive Equation[a] T/T_h	Design Equation[b] T_h lb	Design Equation[b] T/T_h
199	8-8-90-5#3-i-3.5-2-8	55810	56600	0.99	40400	1.38
200	8-12-90-5#3-i-3.5-2-9*	67830	66100	1.03	47200	1.44
201	(2@5) 8-5-180-5#3-i-2.5-2-10‡	66640	64100	1.04	39500	1.69
202	8-12-180-5#3-i-2.5-2-10	64100	71300	0.90	50700	1.26
203	8-12-180-5#3vr-i-2.5-2-10	67800	77900	0.87	55100	1.23
204	8-12-180-4#3vr-i-2.5-2-10	69200	70900	0.98	50700	1.36
205	8-15-180-5#3-i-2.5-2-9.5	86000	74500	1.15	53200	1.62
206	8-5-90-4#4s-i-2.5-2-15	93655	98900	0.95	66800	1.40
207	8-5-90-4#4s-i-2.5-2-12(1)	90815	83200	1.09	57000	1.59
208	8-5-90-4#4s-i-2.5-2-12	99755	85500	1.17	58700	1.70
209	8-5-90-4#4s-i-3.5-2-15	90865	97300	0.93	65800	1.38
210	8-5-90-4#4s-i-3.5-2-12(1)	95455	82800	1.15	56800	1.68
211	8-5-90-4#4s-i-3.5-2-12	98155	84600	1.16	58000	1.69
235	11-5-90-1#4-i-2.5-2-17	101500	111500	0.91	76700	1.32
236	11-5-90-1#4-i-3.5-2-17	106270	111900	0.95	76900	1.38
237	11-5-90-2#3-i-2.5-2-17	100695	110500	0.91	76000	1.32
238	11-5-90-2#3-i-2.5-2-14	77420	83000	0.93	58400	1.33
239	(2@5.35) 11-5-90-2#3-i-2.5-13-13	69100	85700	0.81	53000	1.30
240	11-12-90-2#3-i-2.5-2-17.5	130390	136900	0.95	94800	1.38
241	11-12-90-2#3-i-2.5-2-25	211000	193700	1.09	130100	1.62
242	11-15-90-2#3-i-2.5-2-23	209600	190600	1.10	128800	1.63
243	11-15-90-2#3-i-2.5-2-10.5	50100	88200	0.57	63700	0.79
244	11-15-90-2#3-i-2.5-2-10‡	63900	76800	0.83	55900	1.14
245	11-15-90-2#3-i-2.5-2-15‡	115200	108800	1.06	76900	1.50
246	11-5-90-2#3-i-3.5-2-17	109645	116900	0.94	80500	1.36
247	11-5-90-2#3-i-3.5-2-14	82275	84900	0.97	59600	1.38
248	11-5-90-5#3-i-2.5-2-14	95170	96600	0.99	67000	1.42
249	11-5-90-5#3-i-3.5-2-14	97990	100800	0.97	69700	1.41
250	11-8-90-6#3-o-2.5-2-16	136800	130600	1.05	74900	1.83
251	11-8-90-6#3-o-2.5-2-22	170200	171200	0.99	95200	1.79
252	11-12-90-6#3-o-2.5-2-17	115900	138500	0.84	79300	1.46
253	11-12-180-6#3-o-2.5-2-17	113100	139000	0.81	79600	1.42
254	11-5-90-6#3-i-2.5-2-20	136270	136800	1.00	92500	1.47
255	(2@5.35) 11-5-90-6#3-i-2.5-13-13	89700	102200	0.88	63400	1.41
256	(2@5.35) 11-5-90-6#3-i-2.5-18-18	121600	136900	0.89	82400	1.48
257	11-8-90-6#3-i-2.5-2-16	133000	128000	1.04	88100	1.51
258	11-8-90-6#3-i-2.5-2-22	184600	168700	1.09	113700	1.62
259	11-8-90-6#3-i-2.5-2-22	191000	172800	1.11	116200	1.64
260	11-8-90-6#3-i-2.5-2-15	108300	120200	0.90	82700	1.31
261	11-8-90-6#3-i-2.5-2-19	145400	145800	1.00	98900	1.47
262	11-12-90-6#3-i-2.5-2-17	161600	142700	1.13	98100	1.65
263	11-12-90-6#3-i-2.5-2-16	115195	134300	0.86	93000	1.24
264	11-12-90-6#3-i-2.5-2-22	201190	184900	1.09	124900	1.61
265	11-15-90-6#3-i-2.5-2-22	197800	196800	1.01	132800	1.49
266	11-15-90-6#3-i-2.5-2-9.5	57400	92500	0.62	66000	0.87
267	11-15-90-6#3-i-2.5-2-10a‡	82700	91200	0.91	64900	1.27
268	11-15-90-6#3-i-2.5-2-10b‡	75600	90200	0.84	64300	1.18
269	11-15-90-6#3-i-2.5-2-15‡	145300	130000	1.12	90300	1.61

† Specimens had constant 80 kip axial load

‡ Specimen contained A1035 Grade 120 for column longitudinal steel

[a] T_h calculated using Eq. (4.7) for specimens without transverse reinforcement and Eq. (4.12) for specimens with transverse reinforcement

[b] T_h calculated using Eq. (5.7)

Table C.2 Cont Test-to-calculated ratios for specimens with two hooked bars with transverse reinforcement

Specimen		T lb	Descriptive Equation[a]		Design Equation[b]	
			T_h lb	T/T_h	T_h lb	T/T_h
270	11-5-90-6#3-i-3.5-2-20	135820	144100	0.94	97000	1.40
271	11-8-180-6#3-i-2.5-2-15	111700	118900	0.94	81900	1.36
272	11-8-180-6#3-i-2.5-2-19	149000	151000	0.99	102200	1.46
273	11-12-180-6#3-i-2.5-2-17	116400	141700	0.82	97500	1.19
274	11-12-180-6#3-i-2.5-2-17	148700	142500	1.04	98000	1.52
275	11-5-90-5#4s-i-2.5-2-20	141045	156000	0.90	103900	1.36
276	11-5-90-5#4s-i-3.5-2-20	152965	154600	0.99	103300	1.48

† Specimens had constant 80 kip axial load
‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] T_h calculated using Eq. (4.7) for specimens without transverse reinforcement and Eq. (4.12) for specimens with transverse reinforcement
[b] T_h calculated using Eq. (5.7)

Table C.3 Test-to-calculated ratios for specimens with multiple hooked bars without transverse reinforcement

Specimen		T lb	Descriptive Equation[a]		Design Equation[b]	
			T_h lb	T/T_h	T_h lb	T/T_h
277	(4@4) 5-5-90-0-i-2.5-2-6	14500	18600	0.78	10800	1.34
278	(4@4) 5-5-90-0-i-2.5-2-10	28400	34500	0.82	18500	1.54
279	(4@4) 5-8-90-0-i-2.5-2-6	15500	22200	0.70	12600	1.23
280	(4@6) 5-8-90-0-i-2.5-2-6	19300	21900	0.88	15300	1.26
281	(4@6) 5-8-90-0-i-2.5-6-6	16100	23200	0.69	16200	0.99
282	(3@4) 5-8-90-0-i-2.5-2-6	16800	23200	0.72	12200	1.38
283	(3@6) 5-8-90-0-i-2.5-2-6	24900	23200	1.07	15400	1.62
295	(3@5.5) 8-5-90-0-i-2.5-2-16	62800	81400	0.77	48700	1.29
296	(3@5.5) 8-5-90-0-i-2.5-2-10	36100	45400	0.80	28600	1.26
297	(3@5.5) 8-5-90-0-i-2.5-2-8‡	24400	36000	0.68	23500	1.04
298	(3@3) 8-5-90-0-i-2.5-2-10‡	28500	44300	0.64	22600	1.26
299	(3@5) 8-5-90-0-i-2.5-2-10‡	32200	44400	0.73	27100	1.19
300	(3@5.5) 8-8-90-0-i-2.5-2-8	41000	41100	1.00	25700	1.60
301	(3@3) 8-8-90-0-i-2.5-9-9	47200	47700	0.99	23300	2.03
302	(3@4) 8-8-90-0-i-2.5-9-9	26400	46700	0.57	25400	1.04
303	(3@3) 8-12-90-0-i-2.5-2-12‡	48000	70400	0.68	33100	1.45
304	(3@4) 8-12-90-0-i-2.5-2-12‡	55800	74300	0.75	38000	1.47
305	(3@5) 8-12-90-0-i-2.5-2-12‡	52400	71400	0.73	41300	1.27
306	(4@3) 8-8-90-0-i-2.5-9-9	18700	47400	0.39	22900	0.82
307	(4@4) 8-8-90-0-i-2.5-9-9	18000	46200	0.39	25500	0.71
308	(3@3) 8-5-180-0-i-2.5-2-10‡	47200	45100	1.05	21900	2.16
309	(3@5) 8-5-180-0-i-2.5-2-10‡	45900	45900	1.00	28700	1.60
334	(3@5.35) 11-5-90-0-i-2.5-13-13	51500	78200	0.66	49200	1.05

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] T_h calculated using Eq. (4.7) for specimens without transverse reinforcement and Eq. (4.12) for specimens with transverse reinforcement
[b] T_h calculated using Eq. (5.7)

Table C.4 Test-to-calculated ratios for specimens with multiple hooked bars with transverse reinforcement

Specimen		T lb	Descriptive Equation[a]		Design Equation[b]	
			T_h lb	T/T_h	T_h lb	T/T_h
284	(4@4) 5-5-90-2#3-i-2.5-2-6	21400	25500	0.84	14800	1.45
285	(4@4) 5-5-90-2#3-i-2.5-2-8	26000	32600	0.80	18400	1.41
286	(3@6) 5-8-90-5#3-i-2.5-2-6.25	25800	31000	0.83	20900	1.23
287	(3@4) 5-8-90-5#3-i-2.5-2-6‡	34900	31200	1.12	19100	1.83
288	(3@6) 5-8-90-5#3-i-2.5-2-6‡	36300	30900	1.17	21800	1.67
289	(4@4) 5-5-90-5#3-i-2.5-2-7	27100	33000	0.82	18200	1.49
290	(4@4) 5-5-90-5#3-i-2.5-2-6	25900	29800	0.87	17800	1.46
291	(4@6) 5-8-90-5#3-i-2.5-2-6‡	28300	28600	0.99	20300	1.39
292	(4@6) 5-8-90-5#3-i-2.5-6-6‡	31200	30100	1.04	20700	1.51
293	(4@4) 5-8-90-5#3-i-2.5-2-6‡	27500	28600	0.96	16900	1.63
294	(3@6) 5-8-90-5#3-i-3.5-2-6.25	35300	34300	1.03	22300	1.58
310	(3@5.5) 8-5-90-2#3-i-2.5-2-14	57300	76900	0.75	46900	1.22
311	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5	40900	48200	0.85	30400	1.35
312	(3@5.5) 8-5-90-2#3-i-2.5-2-14(1)	65300	76400	0.85	45600	1.43
313	(3@5.5) 8-5-90-2#3-i-2.5-2-8.5(1)	32400	41700	0.78	27200	1.19
314	(3@3) 8-5-90-2#3-i-2.5-2-10‡	40700	49200	0.83	24600	1.65
315	(3@5) 8-5-90-2#3-i-2.5-2-10‡	44700	51800	0.86	33000	1.35
316	(3@3) 8-5-180-2#3-i-2.5-2-10‡	54600	47600	1.15	23900	2.28
317	(3@5) 8-5-180-2#3-i-2.5-2-10‡	51500	47600	1.08	29700	1.73
318	(3@5.5) 8-5-90-5#3-i-2.5-2-8	37100	48800	0.76	31100	1.19
319	(3@5.5) 8-5-90-5#3-i-2.5-2-12	66100	71700	0.92	44300	1.49
320	(3@5.5) 8-5-90-5#3-i-2.5-2-8(1)	31400	45700	0.69	28400	1.11
321	(3@5.5) 8-5-90-5#3-i-2.5-2-12(1)	47900	68100	0.70	42100	1.14
322	(3@5.5) 8-5-90-5#3-i-2.5-2-8(2)‡	48000	48600	0.99	31700	1.51
323	(3@3) 8-5-90-5#3-i-2.5-2-10‡	47300	55400	0.85	29100	1.63
324	(3@5) 8-5-90-5#3-i-2.5-2-10‡	61300	55700	1.10	34400	1.78
325	(3@3) 8-8-90-5#3-i-2.5-9-9	39800	57400	0.69	29900	1.33
326	(3@4) 8-8-90-5#3-i-2.5-9-9	36600	56100	0.65	32200	1.14
327	(3@3) 8-12-90-5#3-i-2.5-2-12‡	62200	77100	0.81	38900	1.60
328	(3@4) 8-12-90-5#3-i-2.5-2-12‡	64900	81100	0.80	43800	1.48
329	(3@5) 8-12-90-5#3-i-2.5-2-12‡	64800	80300	0.81	48700	1.33
330	(4@3)8-8-90-5#3-i-2.5-9-9	31400	54100	0.58	27900	1.13
331	(4@4) 8-8-90-5#3-i-2.5-9-9	29500	55300	0.53	31400	0.94
332	(3@3) 8-5-180-5#3-i-2.5-2-10‡	58900	57200	1.03	29600	1.99
333	(3@5) 8-5-180-5#3-i-2.5-2-10‡	58700	56100	1.05	34000	1.73
335	(3@5.35) 11-5-90-2#3-i-2.5-13-13	57900	83900	0.69	51300	1.13
336	(3@5.35) 11-5-90-6#3-i-2.5-13-13	66200	92000	0.72	56400	1.17
337	(3@5.35) 11-5-90-6#3-i-2.5-18-18	111900	123800	0.90	74100	1.51

‡ Specimen contained A1035 Grade 120 for column longitudinal steel
[a] T_h calculated using Eq. (4.7) for specimens without transverse reinforcement and Eq. (4.12) for specimens with transverse reinforcement
[b] T_h calculated using Eq. (5.7)

Table C.5 Test-to-calculated ratios for specimens from other researchers

		Specimen	T (lb)	Descriptive Equation[a] T_h (lb)	Descriptive Equation[a] T/T_h	Design Equation[b] T_h (lb)	Design Equation[b] T/T_h
Marques and Jirsa (1975)	338	J7-180-12-1-H	36600	40600	0.90	21900	1.67
	339	J7-180-15-1-H	52200	52900	0.99	27900	1.87
	340	J 7- 90 -12 -1 - H	37200	40100	0.93	21600	1.72
	341	J 7- 90 -15 -1 - H	54600	55100	0.99	28800	1.90
	342	J 7- 90 -15 -1 - L	58200	55800	1.04	29200	1.99
	343	J 7- 90 -15 -1 - M	60000	56600	1.06	29500	2.03
	344	J 11 - 180 -15 -1 - H	70200	69400	1.01	31100	2.26
	345	J 11- 90 -12 -1 - H	65520	52700	1.24	24200	2.71
	346	J 11- 90 -15 -1 - H	74880	71600	1.05	32000	2.34
	347	J 11- 90 -15 -1 - L	81120	70900	1.14	31700	2.56
Pinc et al. (1977)	348	9-12	47000	47300	0.99	23200	2.03
	349	9-18	74000	79200	0.93	37100	1.99
	350	11-24	120120	121900	0.99	52000	2.31
	351	11-15	78000	73600	1.06	32800	2.38
	352	11-18	90480	88800	1.02	38900	2.33
	353	11-21	113880	110400	1.03	47400	2.40
Johnson & Jirsa (1981)	354	4-3.5-8-M	4400	5300	0.83	4600	0.96
	355	4-5-11-M	12000	9800	1.22	8000	1.50
	356	4-5-14-M	9800	9800	1.00	8000	1.23
	357	7-5-8-L	13000	10900	1.19	9100	1.43
	358	7-5-8-M	16500	13000	1.27	10600	1.56
	359	7-5-8-H	19500	13700	1.42	11100	1.76
	360	7-5-14-L	8500	10900	0.78	9100	0.93
	361	7-5-14-M	11200	12600	0.89	10300	1.09
	362	7-5-14-H	11900	13700	0.87	11100	1.07
	363	7-7-8-M	32000	21200	1.51	16500	1.94
	364	7-7-11-M	27000	21200	1.27	16500	1.64
	365	7-7-14-M	22000	22500	0.98	17400	1.26
	366	9-7-11-M	30800	24200	1.27	18800	1.64
	367	9-7-14-M	24800	25500	0.97	19700	1.26
	368	9-7-18-M	22300	24300	0.92	18900	1.18
	369	7-8-11-M	34800	26900	1.29	20500	1.70
	370	7-8-14-M	26500	24900	1.06	19100	1.39
	371	9-8-14-M	30700	30600	1.00	23300	1.32
	372	11-8.5-11-L	37000	29300	1.26	22900	1.62
	373	11-8.5-11-M	51500	35900	1.43	27200	1.89
	374	11-8.5-11-H	54800	37200	1.47	28100	1.95
	375	11-8.5-14-L	31000	29300	1.06	22900	1.35
	376	11-8.5-14-M	39000	35800	1.09	27100	1.44
	377	11-8.5-14-H	45500	37200	1.22	28100	1.62
	378	7-7-11-M	24000	20200	1.19	15900	1.51
	379	7-7-11-L	22700	18900	1.20	15000	1.51
	380	11-8.5-11-M	38000	33500	1.13	25600	1.48
	381	11-8.5-11-L	40000	31300	1.28	24200	1.65
	382	7-5-8-M	38002	20100	0.73	47200	0.31
	383	7-5-14-M	38003	20100	0.56	15700	0.72

[a] T_h calculated using Eq. (4.7) for specimens without transverse reinforcement and Eq. (4.12) for specimens with transverse reinforcement
[b] T_h calculated using Eq. (5.7)

Table C.5 Cont. Test-to-calculated ratios for specimens from other researchers

		Specimen	T (lb)	Descriptive Equation[a] T_h (lb)	Descriptive Equation[a] T/T_h	Design Equation[b] T_h (lb)	Design Equation[b] T/T_h
Hamad et al. (1993)	384	7-90-U	25998	34900	0.74	19500	1.33
	385	7-90-U'	36732	43300	0.85	23500	1.56
	386	11-90-U	48048	59100	0.81	27400	1.75
	387	11-90-U'	75005	73300	1.02	33000	2.27
	388	11-180-U-HS	58843	79700	0.74	35500	1.66
	389	11-90-U-HS	73788	79700	0.93	35500	2.08
	390	11-90-U-T6	71807	65700	1.09	50600	1.42
Ramirez & Russel (2008)	391	I-1	30000	28800	1.04	15800	1.90
	392	I-3	30000	31800	0.94	17200	1.74
	393	I-5	30500	32100	0.95	17400	1.75
	394	I-2	88000	81200	1.08	34300	2.57
	395	I-2'	105000	104900	1.00	43300	2.42
	396	I-4	99100	89500	1.11	37300	2.66
	397	I-6	114000	90300	1.26	37600	3.03
	398	III-13	41300	32900	1.26	25200	1.64
	399	III-15	38500	34400	1.12	25900	1.49
	400	III-14	105000	92500	1.14	53800	1.95
	401	III-16	120000	97100	1.24	55400	2.17
Lee & Park (2010)	402	H1	86345	81600	1.06	41900	2.06
	403	H2	76992	59000	1.30	30900	2.49
	404	H3	53761	63900	0.84	43600	1.23

[a] T_h calculated using Eq. (4.7) for specimens without transverse reinforcement and Eq. (4.12) for specimens with transverse reinforcement
[b] T_h calculated using Eq. (5.7)

APPENDIX D: SPECIMEN IDENTIFICATION FOR DATA POINTS PRESENTED IN FIGURES

Table D.1 Specimen identification for data points presented in figures

Figure	Specimen Numbers
Figure 4.1	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 338-353, 384-389, 391-397, 402-403
Figure 4.2	48-59, 61-64, 132-143, 145-152, 155-160, 237-238, 240, 242, 244-247
Figure 4.3	72-77, 172-184, 188-192, 194-200, 202-205, 254, 257-265, 267-274, 390, 398-401, 404
Figure 4.4	9-11, 18, 20-23, 26-27, 86-87, 89, 95, 101-103, 105, 107, 111, 113, 115-116, 119-123, 216, 219-223, 229-230, 232-234, 338-347, 351-353, 384-389, 395, 403
Figure 4.5	28-37, 124-125, 127-130
Figure 4.6	48-53, 55-58, 61-64, 134, 136, 142-143, 145, 147, 151-152, 155-160
Figure 4.7	172-173, 180,189, 191, 194, 202-203, 205, 254, 257, 260-263, 270-274
Figure 4.8	8-12, 15-18, 20-27, 48-59, 61-64, 72-77
Figure 4.9	85-91, 94-96, 101-116, 119-123, 132-136, 139-152, 155-160, 172-180, 183, 188-200, 202-205
Figure 4.10	216-217, 219-225, 229-234, 237-238, 240, 242, 246-247, 254, 257-265, 270-274
Figure 4.11	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 338-353, 384-389, 391-397, 402-403
Figure 4.12	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 338-353, 384-389, 391-397, 402-403
Figure 4.13	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 338-353, 384-389, 391-397, 402-403
Figure 4.14	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 338-353, 384-389, 391-397, 402-403
Figure 4.15	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 338-353, 384-389, 391-397, 402-403
Figure 4.16	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 338-353, 384-389, 391-397, 402-403
Figure 4.17	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 338-353, 384-389, 391-397, 402-403
Figure 4.21	142-143, 156-157, 189, 191-192, 202-204
Figure 4.22	142-143, 156-157, 189, 191-192, 202-204
Figure 4.23	142-143, 156-157, 189, 191-192, 202-204
Figure 4.25a	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 4.25b	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 4.26	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 4.27	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 4.28	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 4.29	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276

Table D.1 Cont. Specimen identification for data points presented in figures

Figure	Specimen Numbers
Figure 4.30	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 4.31	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 4.32	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 4.33	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 4.34	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 4.35	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 277-280, 282-296, 298-300, 303-305, 309, 338-353, 384-389, 391-397, 402-403
Figure 4.36	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 277-280, 282-296, 298-300, 303-305, 309, 338-353, 384-389, 391-397, 402-403
Figure 4.37	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276, 284-291, 293-315, 318-321, 323-324, 327-329
Figure 4.38	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276, 284-291, 293-315, 318-321, 323-324, 327-329
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Figure 4.40	82-84, 96, 112, 114
Figure 4.41	214-215, 222, 234, 252-253, 262, 273-274
Figure 4.42	212-213, 219, 250-251, 257-259
Figure 4.43	1-12, 15-27, 44-53, 55-59, 61-64, 67-73, 76-77
Figure 4.44	79-97, 101-116, 119-123, 166-184, 188-192, 194-200, 202-205
Figure 4.45	212-217, 219-225, 227-234, 250-254, 257-265, 267-274
Figure 4.46	13-14, 117-118, 144, 153-154, 193, 201
Figure 4.47	354-383
Figure 4.48	354-383
Figure 5.1	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 338-353, 384-389, 391-397, 402-403
Figure 5.2	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 5.3	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 338-353, 384-389, 391-397, 402-403
Figure 5.4	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 5.5	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 338-353, 384-389, 391-397, 402-403
Figure 5.6	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276
Figure 5.7	8-12, 15-27, 85-97, 101-116, 119-122, 216-217, 219-225, 227-234, 338-353, 384-389, 391-397, 402-403
Figure 5.8	28-43, 48-59, 61-66, 72-77, 124-143, 145-152, 155-165, 172-184, 188-192, 194-200, 202-238, 240, 242, 244-249, 254, 257-265, 267-276

Table D.1 Cont. Specimen identification for data points presented in figures

Figure	Specimen Numbers
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