ANCHORAGE OF HIGH-STRENGTH REINFORCING BARS WITH STANDARD HOOKS – INITIAL TESTS

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ABSTRACT

The effects of embedment length, side cover, quantity of confining transverse reinforcement, location of hook (inside or outside the column core), concrete compressive strength, hooked bar size, and hook bend angle on anchorage capacity are investigated using the results of 329 tests of standard hooks loaded in tension. No. 5, 8, and 11 hooks were tested in beam-column joints with concrete compressive strengths ranging from 4,300 to 13,700 psi. The results of the tests are compared with the provisions in ACI 318-11, and equations to describe the anchorage strength of 90° hooks for hooks not confined by transverse reinforcement, hooks confined by two No. 3 ties, and hooks confined by No. 3 ties spaced at $3d_b$ are developed. Hooks cast inside the column core have greater ultimate anchorage force than those cast outside the column core, hook bend angle has a negligible effect on ultimate anchorage force, and ultimate anchorage force increases as the quantity of confining transverse reinforcement increases. For hooks not confined by transverse reinforcement, the anchorage capacity increases more rapidly than embedment length. For hooks confined by transverse reinforcement, small embedment lengths develop significant anchorage forces; increases in embedment length result in additional capacity, but anchorage capacity is less than proportional to embedment length. Comparisons to the provisions in ACI 318-11 show that the ultimate anchorage force of larger hooked bars and the effect of concrete compressive strength are overpredicted by the current design requirements. Analysis of 90° hooks cast inside the column core show that there is an increase in ultimate anchorage force with an increase in bar diameter; this effect increases as the quantity of confining transverse reinforcement increases within the range of values evaluated in this study. Ultimate anchorage force also increases with an increase in cover to the center of the bar for bars not confined by transverse reinforcement; this effect decreases as the quantity of transverse reinforcement increases and has no effect for bars confined by No. 3 ties spaced at $3d_b$.

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

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CHAPTER 1 INTRODUCTION

1.1 GENERAL

For a reinforced concrete member to attain its capacity, the reinforcement must be bonded or anchored to the concrete so that the reinforcement can develop its yield strength at sections subjected to maximum forces. This is often accomplished by embedding the reinforcement deep enough into the concrete 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, another form of anchorage is needed, often through the use of hooks. Hooked bars are standard in reinforced concrete construction, but the anchorage strength of hooked bars has not been studied as extensively as some other aspects that affect concrete design. Furthermore, very little research has been done to determine the capacity of hooked high-strength bars or hooked bars in high-strength concrete. The purpose of this report is to describe an ongoing investigation into the effects of embedment length, quantity of confining transverse reinforcement, location of hook (inside or outside the column core), concrete compressive strength, hooked bar size, side cover, and hook bend angle on the anchorage capacity of standard hooks, as defined in Section 7.1 of ACI 318-11, for bar stresses ranging from 60,000 to 120,000 psi and for concrete with compressive strengths ranging from 5,000 to over 13,000 psi.

1.2 PREVIOUS WORK

The current versions of the ACI 318 Building Code Requirements for Structural Concrete (2011), ACI 349 Code Requirements for Nuclear Safety-Related Concrete Structures (2006), and the AASHTO Bridge Specifications (2012) have provisions for the development of bars with standard hooks that are based on a tests conducted by Minor and Jirsa (1972) and Marquez and Jirsa (1975). Overall, however, these tests included only a relatively small number of specimens that contained standard hooks; in addition, the tests used neither high-strength steels nor high-strength concrete. The results of the prior studies are, however, highly instructive. In addition to the work done by Minor and Jirsa (1972) and Marquez and Jirsa (1975), work by Pinc, Watkins, & Jirsa (1977), Soroushian, Obaseki, Nagi, & Rojas (1988), Hamad, Jirsa, and D'Abreu de Paulo (1993), and Ramirez and Russell (2008) is summarized next.

Minor and Jirsa (1972)

Minor and Jirsa (1972) 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 confining transverse reinforcement. Bond was prevented 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) ranged from 1.6 to 6 in., the No. 7 bars had a range of bonded lengths from 4.3 to 8.5 in., and the specimens with No. 9 bars specimens had a bonded length of 8.3 in. Concrete compressive strengths ranged from 2,400 to 6,600 psi.

Minor and Jirsa found that both larger bend angles and smaller bend radii resulted in larger bar slip for a given stress. They concluded that it is preferable to use 90° rather than 180° hooks to reduce slip of the hook and maintain joint stiffness.

Marques and Jirsa (1975)

Marques and Jirsa (1975) tested 22 beam-column joint specimens containing No. 7 and No. 11 bar 90° and 180° standard hooks. They investigated the effects of axial loading, longitudinal reinforcement ratio, side concrete cover, and lateral confining reinforcement (ties) in the joint on the anchorage capacity of standard hooked bars. The specimens were cast with two hooks in concrete and had nominal axial loads of 135, 270, 420, or 540 kips. Compressive strengths ranged from 4,000 to 5,050 psi. No. 3 ties were spaced at either 2.5 or 5 in. throughout the joint in the specimens in which confining transverse reinforcement was provided. The hooks had side covers ranging from 1.5 to 2.875 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 hooks. 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 loads have a negligible effect on the anchorage strength of hooked bars and that there are 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:

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

where f_h is the tensile stress developed in a standard hook 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 confinement provided. When additional development length is needed to achieve f_y in the hooked bar, the straight lead embedment ℓ_l between the bend in the hook and critical section can be calculated using. Eq. (2), where ℓ' is the greater of $4d_b$ or 4 in.

$$\ell_l = \frac{0.04A_b\left(f_y - f_h\right)}{\sqrt{f_c'}} + \ell' \tag{2}$$

Pinc, Watkins, and Jirsa (1977)

Pinc et al. (1977) tested eight beam-column joint specimens with 90° hooks, four with No. 9 bars, and four with No. 11 bars. The dimensions of the columns ranged from 12×12 in. to 12×21 in. for the specimens with No. 9 bars and from 12×15 in. to 12×24 in. for the specimens with No. 11 bars. Column dimensions were increased in 3 in. increments. Confining transverse reinforcement was not provided in the joint, and specimens were cast with two hooks in concrete, the compressive strengths ranged from 3,600 to 5,400 psi. Side cover of 2.875 in. was used for all specimens. Axial loads varied from 108 to 230 kips depending on the specimen. Visual damage at specimen failure included severe cracking and spalling on the sides of the column. Pinc et al. (1977) concluded that failure of hooked bars is not governed by pullout, but rather by loss of side cover. The principal factor affecting anchorage capacity is embedment length.

Soroushian, Obaseki, Nagi, and Rojas (1988)

Soroushian et al. (1988) tested seven specimens with 90° standard hooks. One specimen had two No. 6 bar hooks, five specimens had two No. 8 bar hooks, and one specimen had two No. 10 bar hooks. The hooks were cast inside of the column core in specimens with dimensions of 14×12 in., side cover of 3.5 in., and tail cover of 2 in. Concrete compressive strengths ranged from 3,780 to 6,050 psi, and plastic tubes were placed on the straight embedment lengths of the hooks to eliminate bond along the straight bar lengths. Confining transverse reinforcement in the joint region consisted of No. 3 or No. 4 bars spaced at 3 or 4 in. in accordance with the requirements for reinforced concrete frames in high-seismic risk zones in ACI 318-83.

Reactions were centered 5.5 in. above and below the hooked bar. During loading, crack behavior included cracks in the plane of the hooks that 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 was determined to be the cause of failure. Soroushian et al. (1988) concluded that for the same embedment length, the capacity of hooked bar anchorages increases for larger bar sizes and with confinement of the concrete surrounding the hooks. Concrete compressive strength did not influence hook pullout behavior.

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

Hamad et al. (1993) conducted 24 beam-column joint tests comparing the hook capacity of epoxy-coated and conventional steel reinforcement. The specimens were similar to those of Marques and Jirsa (1975), with two hooks cast 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 block 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. and tail cover of 2 in. Concrete compressive strengths ranged from 3,700 to

7,200 psi. Three values of confining transverse reinforcement were provided: no reinforcement, No. 3 bars at 6 in. on center, and No. 3 bars at 4 in. on center. Columns were either 12×12 in. with four No. 8 longitudinal bars or 12×15 in. with six No. 8 longitudinal bars. Hamad et. al (1993) observed an increase in anchorage strength with increasing concrete compressive strength, side cover, and quantity of confining transverse reinforcement.

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 as cantilevers without axial load. Concrete compressive strengths ranged from 8,910 to 16,500 psi. Specimens contained either no confinement or 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 in.

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 compressive concrete strengths up to 15,000 psi as long as confining transverse reinforcement spaced no greater than three bar diameters was provided. 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.

1.3 SCOPE OF WORK

A total of 329 standard hooks have been tested to investigate the effects of embedment length, side cover, quantity of confining transverse reinforcement, location of hook (inside or outside the column core), concrete compressive strength, hooked bar size, and hook bend angle on anchorage capacity. No. 5, 8, and 11 hooks were tested in concrete with compressive strengths ranging from 4,300 to 13,700 psi. Nominal clear covers from the outside of the bar to the outside of the column (side covers) range from 1.5 to 4 in. The results of the tests are reported and used to develop descriptive equations relating the key parameters to anchorage strength.

CHAPTER 2 EXPERIMENTAL WORK

2.1 SPECIMEN DESIGN

Specimens are designed to determine the effects of embedment length, side cover, quantity of confining transverse reinforcement, location of hook (inside or outside the column core), concrete compressive strength, hooked bar size, and hook bend angle. Table 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 concrete with nominal compressive strengths ranging from 5,000 to 12,000 psi (actual strengths ranged from 4,300 to 13,700 psi). Each specimen had two hooks cast either inside or outside the column core (the column core is defined as the area of concrete contained within the longitudinal column reinforcement). Hooks were placed with an outside to outside spacing of 8 in. for No. 5 hooks, 12 in. for No. 8 hooks, and 16.5 in. for No. 11 hooks. Tail cover was 2 in. for all specimens, and nominal side covers varied from 1.5 to 4 in.

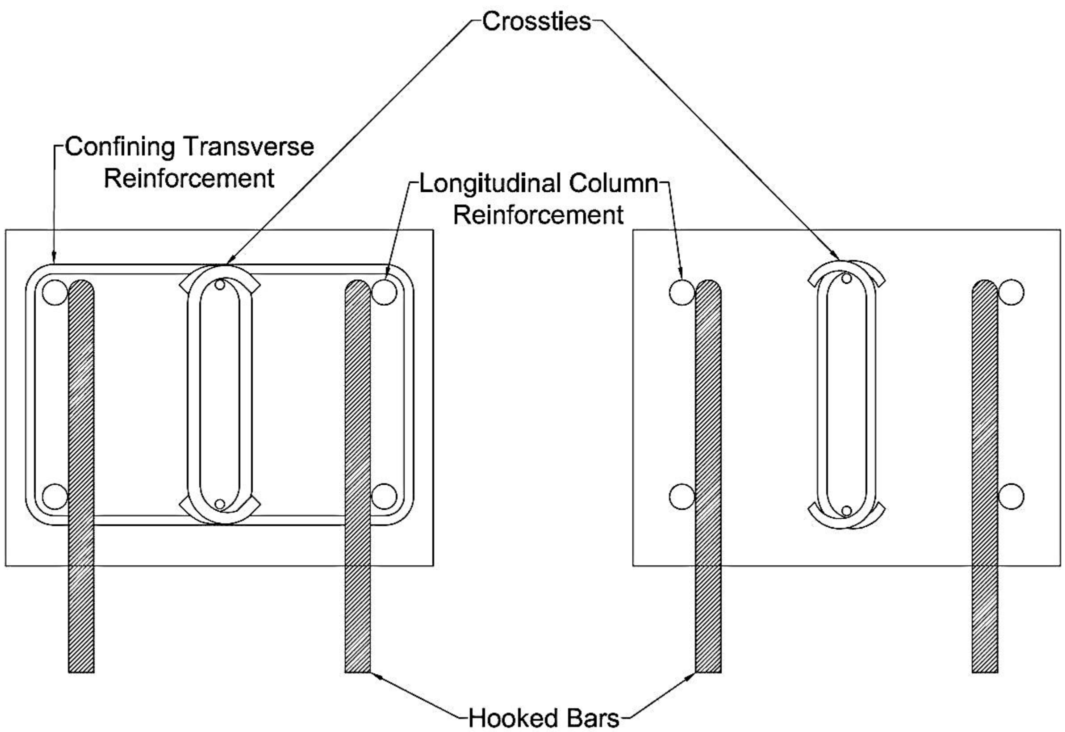
Table 1 Range of variables tested

Parameters	**Range**
Bar Size of Hooks	5, 8, 11
Hook Bend Angle	90°, 180°
Nominal Concrete Compressive Strength, f_c' (psi)	5000, 8000, 12000
Placement of Hooks: Inside or Outside Column Core	i/o
Amount of Confining Transverse Reinforcement (Number and Bar Size)	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.)	2
Nominal Embedment Length, ℓ_{eh} (in.)	5 to 26

Each of the variables described above is denoted in the specimen title. Consider the following title 11-12-90-2#3-i-2-2.5-17b(1); the first number (11) represents the bar size of the hook, the second number (12) is the nominal concrete compressive strength in ksi, the third number (90) is the bend angle of the hook in degrees, the fourth and fifth numbers (2#3) indicates the number and bar size, respectively, of the transverse reinforcement confining the hook (0 denotes no confining transverse reinforcement), the sixth symbol (i) indicates the location of the hooks (i for inside and o for outside the column core as defined by the longitudinal reinforcement), the seventh number (2) is the tail cover in in., the eighth number (2.5) is the side 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 is part of a series, which occurs when multiple specimens of the same dimensions and amounts of reinforcement are cast at the same time with the same concrete (the absence of a letter indicates the specimen is not part of a series), and the last number in parentheses (1) indicates that the specimen or series is a replication (the first replication in this case) of an earlier specimen or series concrete (the absence of a number indicates the specimen or series does not replicate an earlier specimen or series).

Specimens are designed to represent exterior beam-column joints and are cast without the beam. The width of the column is determined by adding the side cover to the outside-outside hook spacing. For a series of specimens where side cover is the only variable being investigated, identical column reinforcement is used; only the side cover and width of the specimen changes. The depth is found by adding the tail cover to the embedment length. For this report, embedment length ℓ_{eh} is the distance measured from the front of the column face to the back of the tail of the hook. Unlike the development length ℓ_{dh} defined in Section 12.5.2 of the ACI 318-11, which is chosen to ensure a bar can develop its yield strength, embedment length is a measured value and does not depend on the yield strength of the hook. During specimen design, an embedment length is chosen to ensure a bond failure, rather than a bar failure. This was initially accomplished by using an embedment length equal to 80% of the development length as defined in ACI 318-11 and later by extrapolating trends from test results.

After the dimensions of the specimen are selected, the maximum shear and moment in the specimen are determined assuming both hooks reach their maximum failure load simultaneously. These loads are used to design the column reinforcement. For specimens where the shear demand is greater than the combined shear capacity of the concrete and the confining transverse reinforcement in the joint (or the concrete alone when there is no confining transverse reinforcement), crossties are placed in the center of the column oriented in the direction of the beam longitudinal reinforcement, as shown in Figure 1. No. 3 longitudinal reinforcing bars are added to the column to hold the crossties in place if the moment demand on the specimen is not large enough to require more than four longitudinal column reinforcement bars. The majority of



(a) (b)

Figure 1 Cross section detail of specimens with (a) confining transverse reinforcement and (b) without confining transverse reinforcement. Shown with No. 3 longitudinal bars supporting the crossties the tests were conducted with three levels of confining transverse reinforcement, (1) no confining transverse reinforcement, (2) two No. 3 ties, which were spaced at $8d_b$ for No. 5 and 8 hook and $8.5d_b$ for No. 11 hook, 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 confinement required to qualify for the 0.8 reduction in development length specified in Section 12.5.3 of ACI 318-11, shown in Figure 2. 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 hooks, 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. Additional specimens were designed with other combinations of confining transverse reinforcement 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 318-11 Section 21.7.3 for joints in special moment frames.

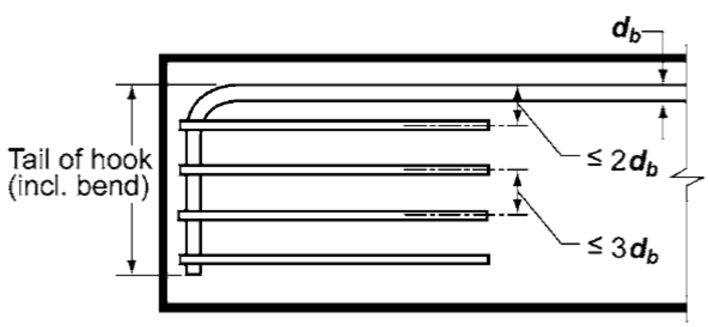
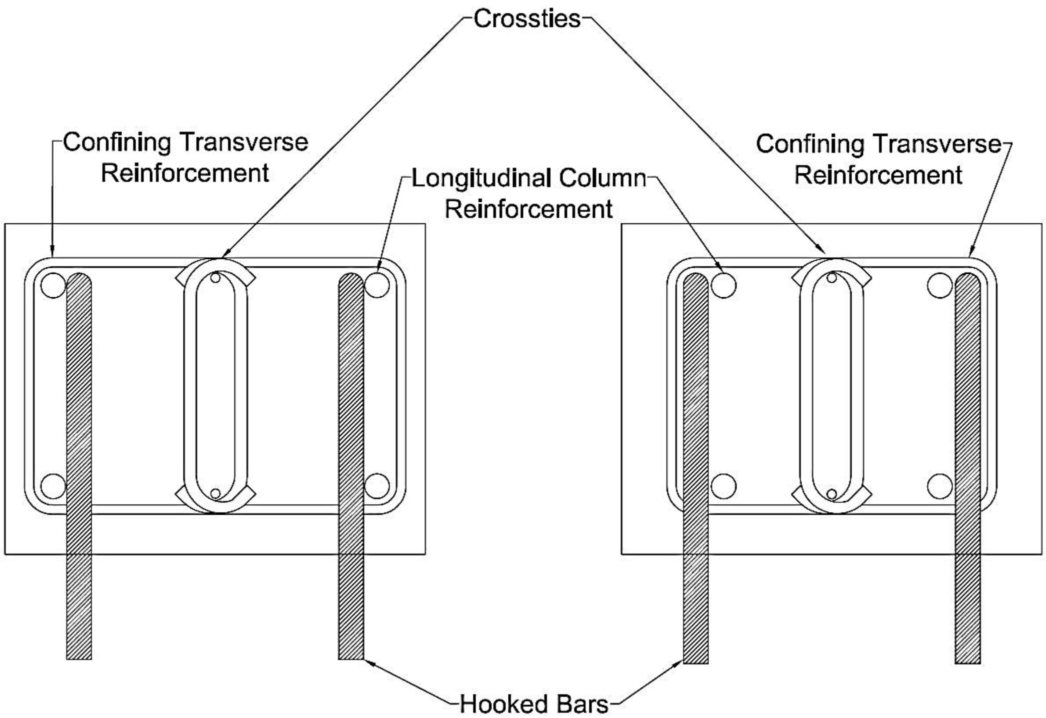


Figure 2 Ties placed along tail of hook as per Section 12.5
R12.5.3(b) ACI 318-11

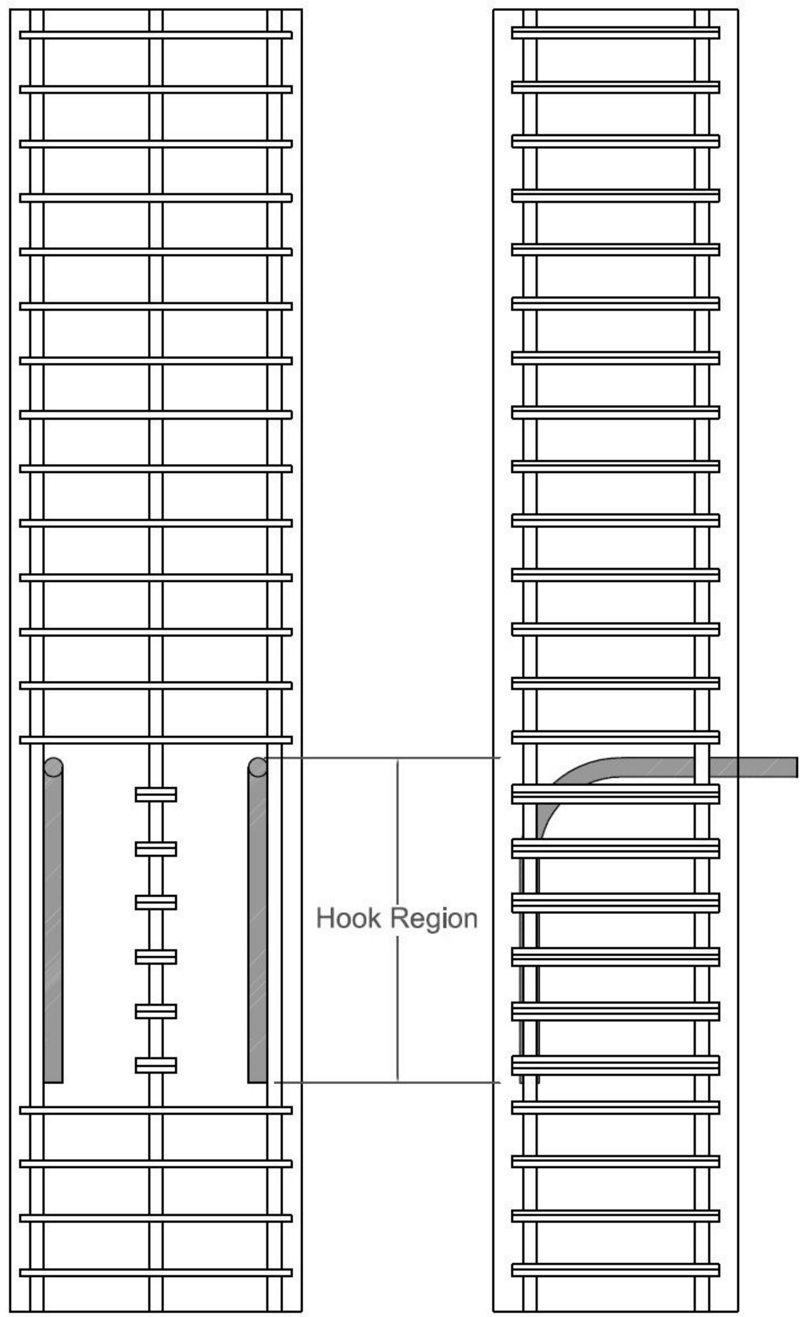
For the majority of the specimens tested, hooks were cast inside the column longitudinal reinforcement; some specimens were cast with hooks outside of the column longitudinal reinforcement. Figure 3 shows the differences between the two cases. The width of the specimen, side cover, and hook spacing were kept the same; only the location of the column longitudinal reinforcement changed between the specimens.



(a) (b)

Figure 3 Cross section detail of specimens with hooks placed (a) inside column core and (b) outside column core

Typical specimens are shown in Figure 4. Figure 4a shows the front view of a specimen with hooks inside the core and no confining transverse reinforcement; Figure 4b shows the side view of a specimen with hooks cast inside the core and No. 3 ties spaced at $3d_b$ as confining transverse reinforcement. The heights of specimens were chosen so that the support reactions from the test frame did not interfere with the joint region during testing, as shown in Figure 5. The height of specimens with No. 5 or No. 8 hooked bars was 52.75 in., and the height of the specimens with No. 11 hooked bars was 96 in.



(a) (b)

Figure 4 Details of typical 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

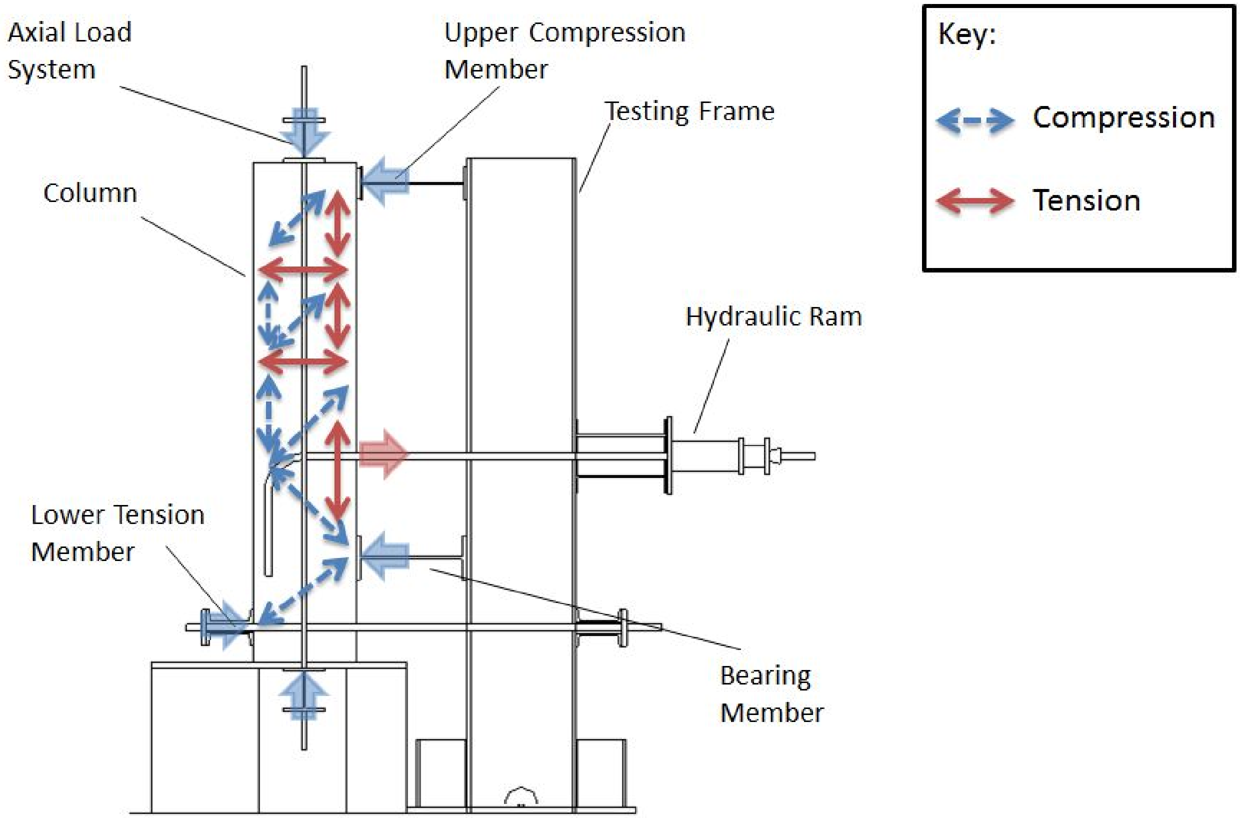


Figure 5 Test setup with force diagram

2.2 MATERIAL PROPERTIES

Specimens were cast using non-air-entrained ready-mix concrete with nominal compressive strengths of 5,000, 8,000, and 12,000 psi. Actual strengths ranged from 4,300 to 13,700 psi. The concrete contained Type I/II portland cement, 0.75-in. maximum size crushed limestone, 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 psi concrete; both products are from W.R. Grace. Mix proportions are listed in Table 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 were used for the study. To provide maximum flexibility in the tests, the majority of specimens were cast with hooks made of A1035 steel. The ancillary steel for column and transverse reinforcement consisted of ASTM A615 Grade 60 reinforcing bars. Yield strength, nominal diameter, rib spacing, rib height, gap width, and relative rib area for the steel used as hooked bars in presented in Table 3.

Table 2 Concrete mix proportions

Material	Quantity (SSD)		
Design Compressive Strength	**5000 psi**	**8000 psi**	**12000 psi**
Type I/II Cement, lb/yd^3	600	700	750
Water, lb/yd^3	263	225	217
Crushed Limestone, lb/yd^3	1734	1683	1796
Pea Gravel, lb/yd^3	-	-	316
Kansas River Sand, lb/yd^3	1396	1375	1050
Estimated Air Content, %	1	1	1
High-Range Water-Reducer, oz (US)	24 [1]	140 [1]	68 [2]
w/c ratio	0.44	0.32	0.29

[1] ADVA 140. [2] ADVA 575

Table 3 Hooked bar properties

Bar Size	ASTM Designation	Yield Strength (ksi)	Nominal Diameter (in.)	Average Rib Spacing (in.)	Average Rib Height		Gap Width		Relative Rib Area[2]
					A[1] (in.)	B[2] (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	122	1	0.574	0.057	0.052	0.16	0.157	0.078
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] Per ASTM A615, A706. [2] Per ACI 408R-3

2.3 TEST PROCEDURE

Specimens are tested using a self-reacting system designed to simulate the axial, tensile, and compressive forces in a beam-column joint (Figure 6). The test frame is a modified version of the apparatus used by Marques and Jirsa (1975). The locations of reactions on the testing apparatus can be altered to accommodate different sized specimens as shown in Table 4. The flange width of the upper compression member and the bearing member are $6^{5}/_{8}$ -in. and $8^{3}/_{8}$ -in., respectively.

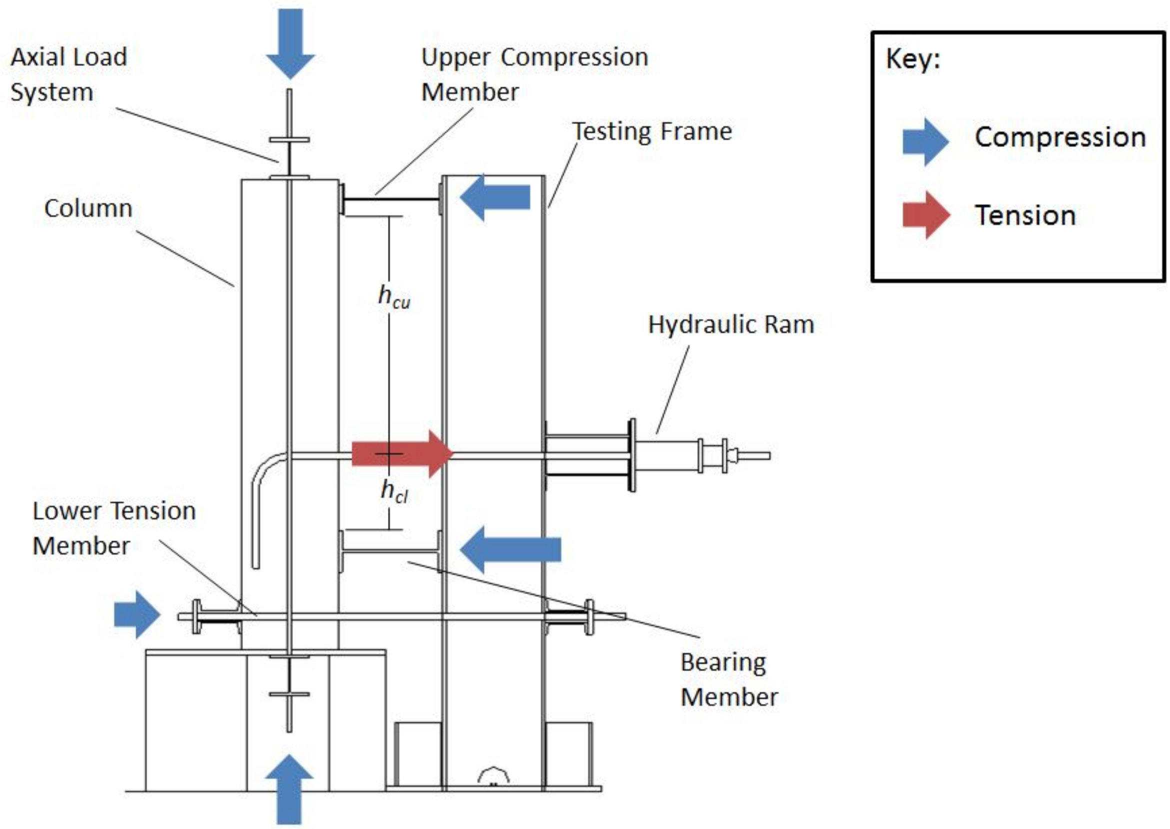


Figure 6 Forces applied to specimen during testing

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). The axial load was kept constant based on findings by Marques and Jirsa (1975) that changes in axial load result in negligible changes in the anchorage strength of the hooks.

Tensile forces are 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 hook simulates the compression zone of the beam and the horizontal reactions at the top and bottom of the specimen are used to prevent overturning. A detailed description of the test frame and testing procedure is provided by Peckover and Darwin (2013).

Table 4 Location of reaction forces

	No. 5 Hook	No. 8 Hook	No. 11 Hook
Height of Specimen, (in.)	52.75	52.75	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 6

2.4 TEST PROGRAM

Tables 5 and 6 summarize the tests covered in this report for 264 90° and 65 180° hooks, respectively, including bar size, side cover, and confining transverse reinforcement. Of the 264 90° hooks, 94 had no confining transverse reinforcement. Of the 170 hooks with confining transverse reinforcement, 18 had one No. 3 tie, 12 had one No. 4 tie, 56 had two No. 3 ties, 4 had two No. 4 ties, 10 had four No. 3 ties, 8 had confinement in accordance with ACI 318-11 Section 21.7.3 for joints in special moment frames, 58 had No. 3 ties spaced at $3d_b$, and 4 had five No. 3 ties not spaced at $3d_b$. Of the 65 180° hooks, 19 had no confining transverse reinforcement, 16 had one No. 3 tie, 6 had one No. 4 tie, and 24 had two No. 3 ties as confining transverse reinforcement. The ties confining the 180° hooks were horizontal, that is, parallel to the straight portion of the hook.

Table 5 90° hook test program

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	14	8	6	10	-	2	-	4	-
		3.5	14	4	2	14	-	2	-	6	-
		4	-	-	-	-	-	-	-	-	-
	Outside Core										
	Side Cover (in.)	1.5	5	-	-	-	-	-	-	4	-
		2.5	3	-	-	-	-	-	-	3	-
	Inside Core										
No. 8 Hooks	Side Cover (in.)	2.5	18	6	-	12	2	6	2	13	-
		3.5	12	-	-	10	2	-	2	8	-
		4	2	-	-	-	-	-	-	-	-
	Outside Core										
	Side Cover (in.)	2.5	8	-	-	-	-	-	-	8	-
		3.5	2	-	-	-	-	-	-	2	-
		4	2	-	-	-	-	-	-	2	-
No. 11 Hooks	Inside Core										
	Side Cover (in.)	2.5	8	-	2	6	-	-	2	6	2
		3.5	6	-	2	4	-	-	2	2	2

Table 6 180° hook test program

180° 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.)	1.5	-	-	-	-	-	-	-	-	-
		2.5	2	6	4	6	-	-	-	-	-
		3.5	2	2	-	2	-	-	-	-	-
	Outside Core										
	Side Cover (in.)	1.5	3	-	-	2	-	-	-	-	-
		2.5	2	-	-	4	-	-	-	-	-
No. 8 Hooks	Inside Core										
	Side Cover (in.)	2.5	6	4	2	6	-	-	-	-	-
		3.5	4	4	-	4	-	-	-	-	-

CHAPTER 3 EXPERIMENTAL RESULTS

3.1 GENERAL

This chapter describes the general cracking patterns observed during the tests of 329 standard hooks for concrete beam-column joints and summarizes the test results. During the tests, five failure modes were observed. These failure modes include front pullout, front blowout, side splitting, side blowout, and tail kickout. The summary of the tests include those presented in Chapter 4 and covers hooks not confined by transverse reinforcement, hooks confined by two No. 3 ties, and hooks confined by ties spaced at $3d_b$, the last of which qualifies for a 0.8 reduction in development length in accordance with ACI 318-11. Hooks confined by other quantities of transverse reinforcement have been tested, but are not included in the analysis in this report. They are, however, included in Appendix B and will be addressed in later reports.

3.2 CRACKING PATTERNS

Figure 7 shows the typical crack progression observed in the specimens. Cracking in the specimens almost always begins with a horizontal crack on the front face of the column at the level of the hooked bars, extending around the side of the column (Figure 7a). This cracking pattern is similar to cracking observed with bond failures for straight bar reinforcement in reinforced concrete beams. As the load increases, the horizontal crack continues to grow along the side face of the column until it reaches a depth about equal to the location of the bend of the hooked bar (Figure 7b), at which point radial cracks form on the front of the column from the hooked reinforcement. Vertical and diagonal cracks also form along the length of the horizontal crack on the side of the column. These cracks continue to grow towards the front of the column (Figure 7c). Cracks below the level of the hooked bar reinforcement extend to the compression reaction (Figure 7d), which represents the compression zone of the beam in a beam-column joint. Cracks above the level of the hooked bar reinforcement extend to just below the top reaction on the column. At failure, the diagonal cracks on the side of the column extend across the front of the column and widen as concrete is pulled out of the front of the column (Figure 7e). Some specimens exhibit more cracking and spalling at failure depending on the failure type, as described next.

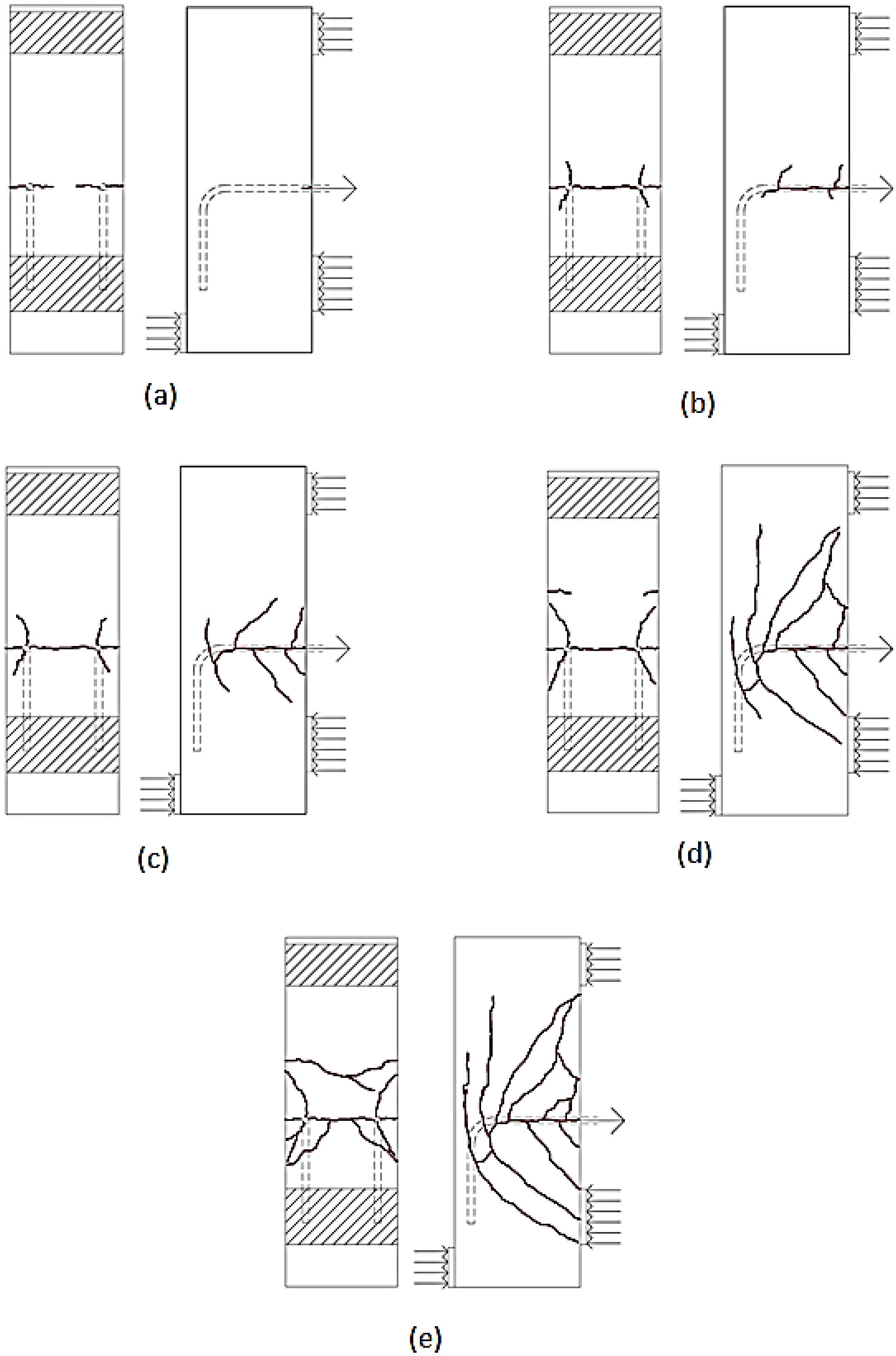


Figure 7 Typical crack progression

3.3 FAILURE TYPES

3.3.1 Front Pullout

A front pullout failure (Figure 8) is characterized by a mass of concrete being pulled forward with the hook from the front face of the column. This failure mode is often coupled with side splitting or side blowout.

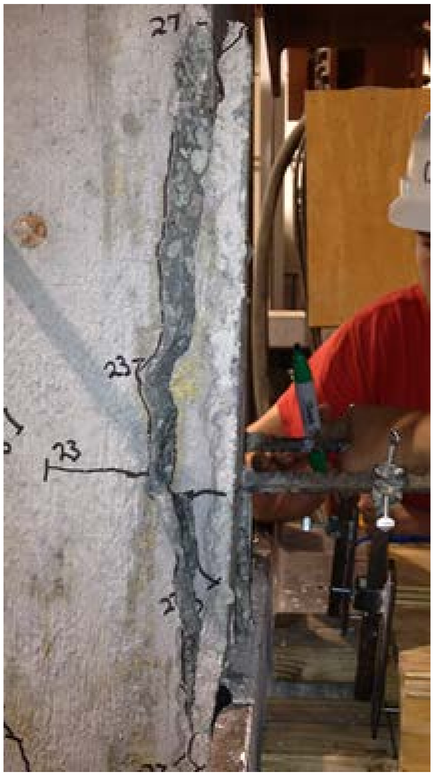


Figure 8 Front pullout failure

3.3.2 Front Blowout

A front blowout failure (Figure 9) is similar to a front pullout failure; however, a front blowout failure is a more sudden, higher energy failure than a front pullout failure. Likewise, the front blowout failure is associated with spalling of the concrete on the front face of the column at failure. This failure mode is often coupled with side blowout or side splitting.

Figure 9 Front blowout failure

3.3.3 Side Splitting

A side splitting failure (Figure 10) occurs when the concrete cover on the side of the hooked bar cracks and separates from the column as the hooked anchorage loses strength. The splitting plane for this failure mode is in line with the vertical plane passing through the hooked bar. Often a long vertical crack on the back face of the column can be observed at failure due to side splitting, as shown in Figure 10. This failure type is often coupled with front pullout or front blowout.

Figure 10 Side splitting failure

3.3.4 Side Blowout

Side blowout (Figure 11) is associated with side splitting in the same way that front blowout is associated with front pullout. A side blowout failure is a higher energy failure and more sudden than side splitting. Also, during a side blowout failure, there will often be a loss of concrete side cover to the outside reinforcement on the column (i.e., if there is confining transverse reinforcement present, the ties will be exposed after failure; otherwise, the hooked bar will be exposed after failure). This failure type is often coupled with front blowout or front pullout.

Figure 11 Side blowout failure

3.3.5 Tail Kickout

Tail kickout (Figure 12) has been observed in a few specimens. This failure occurs when the tail extension of No. 8 or No. 11 90° hooked bars pushes the concrete cover off of the back of the column, often exposing the tail of the hooked bar. It commonly occurs for hooks with no confining transverse reinforcement. Tail kickout is often sudden. Tail kickout is observed in conjunction with other failure types and does not appear to be the main cause of failure.

Figure 12 Tail kickout failure

3.4 TEST DATA

The results of the tests used for analysis in this report are presented in this section. All test results are presented in Appendix B. The data includes tests on concrete beam-column joints containing No. 5, No. 8, and No. 11 hooked bars with 90° and 180° bends, placed both inside and outside the longitudinal column reinforcement. Three levels of confinement by transverse reinforcement are investigated for each bar size: (1) No transverse reinforcement confining the hooked bar – involves a beam column joint where column ties are not placed in the joint region. This is considered the base case for the hooked anchorage. (2) Hooked bars confined by two No. 3 ties represent an intermediate amount of confining transverse reinforcement. (3) The quantity of reinforcement required to use the 0.8 reduction factor to calculate development length in accordance with ACI 318-11 Section 12.5.3(b). For 90° No. 5 and No. 8 bar standard hooks, this is provided by five No. 3 ties confining the hooked bar. For No. 11 bar 90° standard hooks, this is provided by six No. 3 ties confining the hooked bar. Other amounts of transverse reinforcement have also been tested, 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. The results of those tests can be found in Appendix B and will be addressed later reports.

3.4.1 No. 5 Hooked Bars

No. 5 Hooks with No Confining Transverse Reinforcement

Table 7 shows the results for 45 No. 5 hooked bars with no confining 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 11,600 psi, and embedment lengths ranged from 4.8 to 11.3 in. Nominal side covers were 1.5, 2.5, and 3.5 in. Ultimate bar forces at failure ranged from 14,100 to 43,200 lb, corresponding to bar stresses at failure of 45,500 and 139,400 psi, respectively. Only hook B of specimen 5-12-90-0-i-2.5-2-10 exhibited a tail kickout at failure.

Table 7 No. 5 hooks with no confining transverse reinforcement

Specimen	Hook	Bend Angle	ℓ_{eh} in.	f_c' psi	Hook Bar Type	b in.	c_{so} in.	c_{th} in.	c_h in.	T lb	Failure Type
5-5-90-0-o-1.5-2-5	A	90°	5.0	4930	A615	11	1.5	2.0	6.8	14100	FP/SB
	B	90°	5.0	4930	A615	11	1.8	2.0	6.8	19600	FP/SB
5-5-90-0-o-1.5-2-6.5	A	90°	6.5	5650	A615	11	1.5	2.0	6.6	20800	FP
	B	90°	5.9	5650	A615	11	1.6	2.8	6.6	18200	FP/SB
5-5-90-0-o-1.5-2-8	B	90°	7.9	5650	A1035	11	1.5	2.1	6.6	23500	SB
5-5-90-0-o-2.5-2-5	A	90°	4.8	4930	A1035	13	2.5	2.1	6.4	19500	FP/SB
	B	90°	4.8	4930	A1035	13	2.5	2.1	6.4	23500	FP/SB
5-5-90-0-o-2.5-2-8	A	90°	9.0	5780	A1035	13	2.6	1.5	6.6	30300	SB
5-5-180-0-o-1.5-2-11	A	180°	11.3	4520	A1035	11	1.8	2.3	6.6	32400	FP/SB
5-5-180-0-o-1.5-2-9	A	180°	9.6	4420	A1035	11	1.6	2.1	6.4	35200	FP
	B	180°	9.3	4420	A1035	11	1.6	2.1	6.4	30400	FP/SB
5-5-180-0-o-2.5-2-9	A	180°	9.5	4520	A1035	13	2.5	1.9	6.6	40400	FP
	B	180°	9.5	4520	A1035	13	2.5	1.8	6.6	34000	FP
5-5-90-0-i-2.5-2-10	A	90°	9.4	5230	A1035	13	2.8	2.9	6.4	37400	FP/SS
	B	90°	9.4	5230	A1035	13	2.6	2.9	6.4	32900	FP/SS
5-5-90-0-i-2.5-2-7	A	90°	6.9	5190	A1035	13	2.5	2.8	6.8	26600	FP/SS
	B	90°	7.0	5190	A1035	13	2.5	2.6	6.8	26100	FP/SS
5-8-90-0-i-2.5-2-6	A	90°	6.1	9080	A1035	13	2.5	2.6	7.0	21700	FP
	B	90°	6.5	9080	A1035	13	2.5	2.3	7.0	25000	FP
5-8-90-0-i-2.5-2-6(1)	A	90°	6.8	8450	A1035	13	2.8	2.0	6.4	27600	FB/SB
	B	90°	6.8	8450	A1035	13	2.6	2.0	6.4	32100	SB/FB
5-8-90-0-i-2.5-2-8	A	90°	8.0	8580	A1035	13	2.5	2.0	6.6	31900	SS/FP
	B	90°	7.5	8580	A1035	13	2.8	2.0	6.6	35900	SS/FP
5-12-90-0-i-2.5-2-10	A	90°	10.0	10290	A1035	13	2.4	2.5	6.6	40800	SB
	B	90°	11.0	10290	A1035	13	2.5	1.5	6.6	42500	FB/SB/K
5-12-90-0-i-2.5-2-5	A	90°	5.1	11600	A1035	13	2.6	2.1	6.5	19400	FP/SS
	B	90°	4.8	11600	A1035	13	2.6	2.5	6.5	18000	FP
5-5-90-0-i-3.5-2-10	A	90°	10.5	5190	A1035	15	3.5	1.8	6.5	43200	SB/FP
	B	90°	10.4	5190	A1035	15	3.5	1.9	6.5	41100	SB/FP
5-5-90-0-i-3.5-2-7	A	90°	7.5	5190	A1035	15	3.4	1.3	7.0	27200	SS
	B	90°	7.6	5190	A1035	15	3.5	1.1	7.0	25900	FP/SS
5-8-90-0-i-3.5-2-6	A	90°	6.5	9300	A1035	15	3.8	2.1	6.9	24400	FP/SS
	B	90°	6.6	9300	A1035	15	3.8	1.9	6.9	27500	FP/SS
5-8-90-0-i-3.5-2-6(1)	A	90°	6.3	8580	A1035	15	3.6	2.0	6.6	25100	FP/SS
	B	90°	6.4	8580	A1035	15	3.5	2.0	6.6	29100	FP/SS
5-8-90-0-i-3.5-2-8	A	90°	8.6	8380	A1035	15	3.6	2.0	7.1	39100	FB/SS
	B	90°	8.5	8380	A1035	15	3.5	2.0	7.1	34300	SS
5-12-90-0-i-3.5-2-5	A	90°	5.5	10410	A1035	15	3.6	1.7	7.0	22000	FP
	B	90°	5.4	10410	A1035	15	3.6	1.8	7.0	23200	FP
5-12-90-0-i-3.5-2-10	A	90°	10.1	11600	A1035	15	3.5	2.0	6.8	46000	*
	B	90°	10.0	11600	A1035	15	3.5	2.0	6.8	46000	*
5-8-180-0-i-2.5-2-7	A	180°	7.4	9080	A1035	13	2.5	2.1	6.3	26700	FP/SS
	B	180°	7.1	9080	A1035	13	2.6	2.4	6.3	35200	SB/FP
5-8-180-0-i-3.5-2-7	A	180°	7.4	9080	A1035	15	3.6	1.9	7.1	34100	SS/FP
	B	180°	7.3	9080	A1035	15	3.4	2.0	7.1	31400	FP/SS

Notation described in Appendix A
*Test stopped prior to failure

No. 5 Hooks with Two No. 3 Ties Confining the Hooked Bar

Table 8 shows the results for 38 No. 5 hooked bars with two No. 3 ties confining the hooked bar. 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 11,090 psi, and embedment lengths ranged from 4.8 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). Ultimate bar forces at failure ranged from 21,500 to 48,300 lb, corresponding to bar stresses at failure from 69,400 to 155,800 psi. Testing was stopped on specimen 5-10-90-2#3-i-3.5-2-10 prior to concrete failure to prevent fracturing of the hook.

Table 8 No. 5 hooks with 2 No. 3 ties as confining transverse reinforcement

Specimen	Hook	Bend Angle	ℓ_{eh} in.	f'_c psi	Hook Bar Type	b in.	c_{so} in.	c_{th} in.	c_h in.	T lb	Failure Type
5-5-180-2#3-o-2.5-2-11	A	180°	11.1	4520	A1035	13	2.5	2.5	6.6	43600	FP
	B	180°	11.4	4520	A1035	13	2.8	2.1	6.6	42500	FP/SB
5-5-180-2#3-o-1.5-2-11	A	180°	11.6	4420	A1035	11	1.6	1.9	6.6	48300	FP/SB
	B	180°	11.5	4420	A1035	11	1.5	1.9	6.6	43000	FP/SB
5-5-180-2#3-o-2.5-2-9	A	180°	9.1	4420	A1035	13	2.5	2.1	6.6	35500	FP/SB
	B	180°	9.3	4420	A1035	13	2.5	2.0	6.6	43900	FP
5-5-90-2#3-i-2.5-2-6	A	90°	6.0	5800	A1035	13	2.6	2.5	6.6	31800	FP/SS
	B	90°	5.8	5800	A1035	13	2.6	2.8	6.6	29200	FP/SS
5-5-90-2#3-i-2.5-2-8	A	90°	8.0	5860	A1035	13	2.5	2.0	6.6	27900	SS/FP
	B	90°	7.5	5860	A1035	13	2.5	2.5	6.6	38900	SS/FP
5-8-90-2#3-i-2.5-2-6	A	90°	6.0	8580	A1035	13	2.8	2.0	6.1	33500	FP/SS
	B	90°	6.0	8580	A1035	13	2.9	2.0	6.1	30900	FP/SS
5-8-90-2#3-i-2.5-2-8	A	90°	8.3	8380	A1035	13	2.6	2.0	6.5	39800	FP/SS
	B	90°	8.5	8380	A1035	13	2.5	2.0	6.5	40500	FP/SS
5-12-90-2#3-i-2.5-2-5	A	90°	5.3	11090	A1035	13	2.4	2.5	6.6	25200	FP/SS
	B	90°	4.8	11090	A1035	13	2.5	1.5	6.6	29400	FP
5-5-90-2#3-i-3.5-2-6	A	90°	6.0	5230	A1035	15	3.4	2.3	6.5	21500	SS/FP
	B	90°	5.8	5230	A1035	15	3.4	2.5	6.5	22400	SS/FP
5-5-90-2#3-i-3.5-2-8	A	90°	7.9	5190	A1035	15	3.4	2.3	6.8	43700	FP
	B	90°	7.5	5190	A1035	15	3.5	2.8	6.8	45700	FP
5-8-90-2#3-i-3.5-2-6	A	90°	6.5	8580	A1035	15	3.5	2.0	6.4	29900	FP
	B	90°	6.0	8580	A1035	15	3.8	2.0	6.4	30100	FP/SS
5-8-90-2#3-i-3.5-2-8	A	90°	7.1	8710	A1035	15	3.5	2.0	6.6	38000	FP
	B	90°	7.0	8710	A1035	15	3.5	2.0	6.6	28600	FP

Table 8 cont. No. 5 hooks with 2 No. 3 ties as confining transverse reinforcement

Specimen	Hook	Bend Angle	ℓ_{eh} in.	f'_c psi	Hook Bar Type	b in.	c_{so} in.	c_{th} in.	c_h in.	T lb	Failure Type
5-10-90-2#3-i-3.5-2-10	A	90°	10.8	11090	A1035	15	3.5	2.0	6.8	46000	*
	B	90°	10.6	11090	A1035	15	3.6	2.1	6.8	46000	*
5-12-90-2#3-i-3.5-2-5	A	90°	5.6	10410	A1035	15	3.8	1.8	6.6	27900	FP
	B	90°	5.3	10410	A1035	15	3.5	2.2	6.6	28900	FP
5-5-180-2#3-i-2.5-2-6	A	180°	5.8	5860	A1035	13	2.6	2.0	6.6	26900	FP/SS
	B	180°	5.5	5860	A1035	13	2.6	2.3	6.6	26900	FP
5-5-180-2#3-i-2.5-2-8	A	180°	8.0	5670	A1035	13	2.5	2.0	6.9	34000	FP/SS
	B	180°	8.0	5670	A1035	13	2.5	2.0	6.9	34500	FP/SS
5-8-180-2#3-i-2.5-2-7	A	180°	7.0	9080	A1035	13	2.5	2.3	6.4	34600	FP/SS
	B	180°	7.3	9080	A1035	13	2.5	2.1	6.4	28700	FP/SS
5-8-180-2#3-i-3.5-2-7	A	180°	6.8	9080	A1035	15	3.4	2.4	7.0	29300	FP/SS
	B	180°	6.9	9080	A1035	15	3.5	2.3	7.0	32600	FP

Notation described in Appendix A
*Test stopped prior to failure

No. 5 Hooks with Five No. 3 Ties Confining the Hooked Bar

Table 9 shows the results for 17 No. 5 hooked bars with five No. 3 ties confining the hooked bar. The ties in these specimens are spaced at $3d_b$, which qualifies these specimens for the 0.8 reduction factor in accordance with ACI 318-11 Section 12.5.3(b). This group of specimens includes 90° hooked bars placed inside and outside the longitudinal column reinforcement. Concrete compressive strengths ranged from 4,930 to 11,090 psi, and embedment lengths ranged from 4.8 to 11.3 in. Nominal side covers were 1.5, 2.5, and 3.5 in. Ultimate bar forces at failure ranged from 20,900 to 46,000 lb, corresponding to bar stresses at failure of 67,400 to 148,400 psi. Some tests were stopped at a load of 46,000 lb to prevent fracturing of the hook.

Table 9 No. 5 hooks with 5 No. 3 ties as confining transverse reinforcement

Specimen	Hook	Bend Angle	ℓ_{eh} in.	f_c' psi	Hook Bar Type	b in.	c_{so} in.	c_{th} in.	c_h in.	T lb	Failure Type
5-5-90-5#3-o-1.5-2-6	A	90°	6.5	5780	A1035	11	1.6	2.0	6.5	26200	FP/SB
	B	90°	6.5	5780	A1035	11	1.6	2.0	6.5	20900	FP/SB
5-5-90-5#3-o-1.5-2-8	A	90°	8.0	5650	A1035	11	1.6	2.3	6.4	25200	FP/SB
	B	90°	7.8	5650	A1035	11	1.5	2.6	6.4	30400	FP/SB
5-5-90-5#3-o-2.5-2-5	A	90°	5.2	4930	A1035	13	2.6	1.9	6.6	22000	FP/SB
	B	90°	5.1	4930	A1035	13	2.6	1.9	6.6	29000	FP/SB
5-5-90-5#3-o-2.5-2-8	A	90°	7.5	5650	A1035	13	2.6	2.1	6.5	28400	FP
5-5-90-5#3-i-2.5-2-7	A	90°	5.6	5230	A1035	13	2.8	3.6	6.5	32100	FP
	B	90°	7.0	5230	A1035	13	2.8	2.3	6.5	31300	FP/SS
5-12-90-5#3-i-2.5-2-5	A	90°	5.1	10410	A1035	13	2.6	2.1	6.5	33900	FP/SS
	B	90°	5.8	10410	A1035	13	2.6	1.5	6.5	34900	SS/FP
5-5-90-5#3-i-3.5-2-7	A	90°	7.5	5190	A1035	15	3.4	2.0	7.0	44300	FP
	B	90°	6.8	5190	A1035	15	3.5	2.8	7.0	35200	FP
5-12-90-5#3-i-3.5-2-10	A	90°	11.0	11090	A1035	15	3.5	2.0	6.9	46000	*
	B	90°	11.3	11090	A1035	15	3.5	1.8	6.9	46000	*
5-12-90-5#3-i-3.5-2-5	A	90°	5.3	11090	A1035	15	3.3	2.3	6.9	31500	FP
	B	90°	4.8	11090	A1035	15	3.3	2.8	6.9	31300	FP

Notation described in Appendix A
*Test stopped prior to failure

3.4.2 No. 8 Hooked Bars

No. 8 Hooks with No Confining Transverse Reinforcement

Table 10 shows the results for 54 No. 8 hooked bars with no confining transverse reinforcement. The specimens contain 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 4,550 to 11,160 psi, and embedment lengths ranged from 7.6 to 19.5 in. Nominal side covers were 2.5, 3.5, and 4 in. The ultimate bar forces in the hooked bars at failure ranged from 30,600 to 105,100 lb, corresponding to bar stresses of 38,700 to 133,000 psi. Eight hooks exhibited tail kickout at failure.

Table 10 No. 8 hooks with no confining transverse reinforcement

Specimen	Hook	Bend Angle	ℓ_{eh} in.	f'_c psi	Hook Bar Type	b in.	c_{so} in.	c_{th} in.	c_h in.	T lb	Failure Type
8-5-90-0-o-2.5-2-10a	A	90°	10.3	5270	A1035	17	2.5	2.0	10	40600	FP/SS
	B	90°	10.5	5270	A1035	17	2.6	1.8	10.0	46600	SS/FP
8-5-90-0-o-2.5-2-10b	A	90°	9.3	5440	A1035	17	2.5	3.3	10.0	47900	FP/SS
	B	90°	10.3	5440	A1035	17	2.5	2.3	10.0	30600	SS/FP
8-5-90-0-o-2.5-2-10c	A	90°	10.8	5650	A1035	17	2.5	1.5	10.0	62700	FP/SS
	B	90°	10.5	5650	A1035	17	2.5	1.8	10.0	54600	SS/FP/K
8-8-90-0-o-2.5-2-8	A	90°	8.6	8740	A1035	17	2.8	1.8	9.0	44400	SB/K
	B	90°	8.3	8740	A1035	17	2.5	2.1	9.0	33200	SB/K
8-8-90-0-o-3.5-2-8	A	90°	7.6	8810	A1035	19	3.5	2.4	9.8	35600	FP/SS
	B	90°	8.0	8810	A1035	19	3.6	2.0	9.8	44500	SS/FP
8-8-90-0-o-4-2-8	A	90°	8.1	8630	A1035	20	4.5	2.5	9.8	37100	SS/FP
	B	90°	8.3	8630	A1035	20	3.8	2.4	9.8	39200	SS
8-5-90-0-i-2.5-2-12.5	A	90°	13.3	5240	A1035	17	2.8	1.3	9.8	65300	SS/FP
	B	90°	13.3	5240	A1035	17	2.8	1.3	9.8	69900	SS
8-5-90-0-i-2.5-2-13	A	90°	13.3	5560	A1035	17	2.5	2.0	9.8	73100	SS
	B	90°	13.5	5560	A1035	17	2.5	1.8	9.8	65200	FP/SS
8-5-90-0-i-2.5-2-16	A	90°	16.0	4980	A1035	17	2.8	1.8	9.5	83300	FP/SB
	B	90°	16.8	4980	A1035	17	2.8	1.4	9.5	86100	FB/K
8-5-90-0-i-2.5-2-18	A	90°	19.5	5380	A1035	17	2.5	0.8	10.5	100200	FB/SS/K
	B	90°	17.9	5380	A1035	17	2.5	2.4	10.5	79800	FB/SS/K
8-5-90-0-i-2.5-2-9.5	A	90°	9.0	5140	A615	17	2.8	3.0	9.5	44600	FP
	B	90°	10.3	5140	A615	17	2.5	1.8	9.5	65800	SS
8-8-90-0-i-2.5-2-10	A	90°	9.8	7700	A1035	17	2.8	2.0	9.0	50000	FP
	B	90°	9.5	7700	A1035	17	2.9	2.0	9.0	52900	FP
8-8-90-0-i-2.5-2-8	A	90°	8.0	8780	A1035	17	2.8	2.8	9.5	38000	FP/SS
	B	90°	8.0	8780	A1035	17	2.8	2.8	9.5	37700	FP/SS
8-8-90-0-i-2.5-2-8(1)	A	90°	8.9	7910	A1035	17	2.8	2.0	8.6	54700	FP/K
	B	90°	8.0	7910	A1035	17	2.9	2.0	8.6	45200	FP/SS
8-12-90-0-i-2.5-2-9	A	90°	9.0	11160	A1035	17	2.8	2.4	9.6	50800	FP/SS
	B	90°	9.0	11160	A1035	17	2.6	2.4	9.6	54800	SS/FP
8-5-90-0-i-3.5-2-13	A	90°	13.4	5560	A1035	19	3.6	1.9	9.4	69400	FP/SS
	B	90°	13.4	5560	A1035	19	3.4	1.9	9.4	68300	SS/FP
8-5-90-0-i-3.5-2-18	A	90°	19.0	5380	A1035	19	3.8	1.4	9.4	96000	FP/SS/K
	B	90°	18.0	5380	A1035	19	3.4	2.4	9.4	105100	FB/SS
8-8-90-0-i-3.5-2-10	A	90°	8.8	7700	A1035	19	3.8	2.0	9.0	55200	FP/SS
	B	90°	10.8	7700	A1035	19	3.8	2.0	9.0	71900	SS/FP
8-8-90-0-i-3.5-2-8	A	90°	8.5	8780	A1035	19	3.6	2.1	10.0	41200	FP
	B	90°	8.0	8780	A1035	19	3.8	2.6	10.0	42900	FP
8-8-90-0-i-3.5-2-8(1)	A	90°	7.8	7910	A1035	19	3.5	2.0	9.0	43700	SS/FP
	B	90°	7.8	7910	A1035	19	3.8	2.0	9.0	44000	SS/FP
8-12-90-0-i-3.5-2-9	A	90°	9.0	11160	A1035	19	3.5	2.4	9.8	61400	FP
	B	90°	9.0	11160	A1035	19	3.8	2.1	9.8	68500	FP/SS

Table 10 cont. No. 8 hooks with no confining transverse reinforcement

Specimen	Hook	Bend Angle	ℓ_{eh} in.	f_c' psi	Hook Bar Type	b in.	c_{so} in.	c_{th} in.	c_h in.	T lb	Failure Type
8-8-90-0-i-4-2-8	A	90°	7.6	8740	A1035	20	4.5	2.9	9.5	37600	FP/SS
	B	90°	8.0	8740	A1035	20	3.9	2.5	9.5	48700	FP
8-5-180-0-i-2.5-2-11	A	180°	11.0	4550	A615	15	3.0	2.0	9.8	45600	SS/FP
	B	180°	11.0	4550	A615	15	2.8	2.0	9.8	50500	SS
8-5-180-0-i-2.5-2-14	A	180°	14.0	4840	A1035	15	2.8	2.0	9.8	49400	SS
	B	180°	14.0	4840	A1035	15	2.6	2.0	9.8	69400	SS
8-8-180-0-i-2.5-2-11.5	A	180°	9.3	8630	A1035	17	3.0	4.5	9.5	62800	FP/SB
	B	180°	9.3	8630	A1035	17	3.0	4.5	9.5	80200	FP/SS
8-5-180-0-i-3.5-2-11	A	180°	11.6	4550	A615	17	3.8	2.0	10.0	58600	FP/SS
	B	180°	11.6	4550	A615	17	3.8	2.0	10.0	60500	SS
8-5-180-0-i-3.5-2-14	A	180°	14.4	4840	A1035	17	3.9	2.0	9.8	63700	SS
	B	180°	13.9	4840	A1035	17	3.8	2.0	9.8	78000	FB/SS

Notation described in Appendix A

No. 8 Hooks with Two No. 3 Ties Confining the Hooked Bar

Table 11 shows the results for 32 No. 8 hooked bars with two No. 3 ties confining the hook. Specimens in this group consisted of 90° and 180° hooked bars placed inside the longitudinal column reinforcement. Concrete compressive strength ranged from 4,300 to 11,160 psi, and embedment lengths ranged from 8.0 to 17.5 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). Bar forces at failure ranged from 46,200 to 102,600 lb, corresponding to bar stresses of 58,500 to 129,900 psi.

Table 11 No. 8 hooks with 2 No. 3 ties as confining transverse reinforcement

Specimen	Hook	Bend Angle	ℓ_{eh} in.	f'_c psi	Hook Bar Type	b in.	c_{so} in.	c_{th} in.	c_h in.	T lb	Failure Type
8-5-90-2#3-i-2.5-2-12.5	A	90°	12	5240	A1035	17	2.8	2.6	9.5	74100	FP
	B	90°	12.0	5240	A1035	17	2.8	2.6	9.5	76300	FP/SS
8-5-90-2#3-i-2.5-2-16	A	90°	15.0	4810	A1035	17	2.8	2.9	9.5	80000	SS/FP
	B	90°	15.8	4810	A1035	17	2.9	2.1	9.5	92800	FP
8-5-90-2#3-i-2.5-2-9.5	A	90°	9.0	5140	A615	17	2.5	2.6	10.0	54900	FP
	B	90°	9.3	5140	A615	17	2.5	2.3	10.0	53600	FP
8-8-90-2#3-i-2.5-2-10	A	90°	9.9	8990	A1035	17	2.8	2.0	8.5	60700	FP
	B	90°	9.5	8990	A1035	17	2.8	2.0	8.5	67000	FB
8-8-90-2#3-i-2.5-2-8	A	90°	8.0	7700	A1035	17	3.0	2.0	9.0	46200	FP/SS
	B	90°	8.5	7700	A1035	17	2.9	2.0	9.0	55400	FP/SS
8-12-90-2#3-i-2.5-2-9	A	90°	9.0	11160	A1035	17	2.9	2.3	9.5	61800	FP/SS
	B	90°	9.0	11160	A1035	17	2.6	2.3	9.5	60300	SS/FP
8-5-90-2#3-i-3.5-2-13	A	90°	17.5	5570	A1035	19	3.3	1.8	10.1	102600	SS
	B	90°	17.0	5570	A1035	19	3.5	2.3	10.1	88600	SS/FP
8-5-90-2#3-i-3.5-2-17	A	90°	13.8	5560	A1035	19	3.1	1.5	10.3	81200	SS/FP
	B	90°	13.5	5560	A1035	19	3.6	1.8	10.3	86900	SS/FP
8-8-90-2#3-i-3.5-2-10	A	90°	8.8	8990	A1035	19	3.6	2.0	8.5	54000	SS
	B	90°	8.8	8990	A1035	19	3.8	2.0	8.5	53800	FP
8-8-90-2#3-i-3.5-2-8	A	90°	8.0	8290	A1035	19	3.6	2.0	8.5	48300	FP
	B	90°	8.1	8290	A1035	19	3.8	2.0	8.5	49300	FP
8-12-90-2#3-i-3.5-2-9	A	90°	9.0	11160	A1035	19	3.6	2.3	9.6	50300	FP/SS
	B	90°	9.0	11160	A1035	19	4.0	2.4	9.6	49300	FP/SS
8-5-180-2#3-i-2.5-2-11	A	180°	10.8	4550	A615	15	2.8	2.0	9.5	64200	SS/FP
	B	180°	10.5	4550	A615	15	2.5	2.0	9.5	61900	SS/FP
8-5-180-2#3-i-2.5-2-14	A	180°	13.5	4870	A1035	15	2.8	2.0	9.8	87100	FP
	B	180°	14.0	4870	A1035	15	2.8	2.0	9.8	76900	FP/SS
8-8-180-2#3-i-2.5-2-11.5	A	180°	10.5	8810	A1035	17	2.8	2.3	10.0	70100	FB/SS
	B	180°	10.3	8810	A1035	17	2.8	2.5	10.0	59500	FP/SS
8-5-180-2#3-i-3.5-2-11	A	180°	10.1	4300	A615	17	3.4	2.0	9.8	57200	SS/FP
	B	180°	10.6	4300	A615	17	3.5	2.0	9.8	54900	SS/FP
8-5-180-2#3-i-3.5-2-14	A	180°	13.5	4870	A1035	17	3.6	2.0	9.8	68300	FP/SS
	B	180°	13.6	4870	A1035	17	3.8	2.0	9.8	73000	FP/SS

Notation described in Appendix A

No. 8 Hooks with Five No. 3 Ties Confining the Hooked Bar

Table 12 shows the results of 33 No. 8 hooked bars with five No. 3 ties confining the hooks. Specimens in this group contain 90° hooked bars placed inside and outside the longitudinal column reinforcement. The ties in these specimens were spaced at $3d_b$, which permits the use of the 0.8 reduction factor in accordance with ACI 318-11 Section 12.5.3(b). Concrete compressive strengths ranged from 4,850 to 11,160 psi, and embedment lengths ranged from 7.3 to 15.8 in. Nominal side covers were 2.5 and 3.5 in. Bar forces at failure ranged from 39,600 to 93,100 lb, corresponding to ultimate bar stresses from 50,100 to 117,800 psi.

Table 12 No. 8 hooks with 5 No. 3 ties as confining transverse reinforcement

Specimen	Hook	Bend Angle	ℓ_{eh} in.	f_c' psi	Hook Bar Type	b in.	c_{so} in.	c_{th} in.	c_h in.	T lb	Failure Type
8-5-90-5#3-o-2.5-2-10a	A	90°	10.3	5270	A1035	17	2.6	1.8	9.9	55700	SS
	B	90°	10.5	5270	A1035	17	2.6	2.0	9.9	55800	SB
8-5-90-5#3-o-2.5-2-10b	A	90°	10.5	5440	A1035	17	2.5	2.0	9.9	66400	FP/SB
	B	90°	10.5	5440	A1035	17	2.6	2.0	9.9	69500	SB/FP
8-5-90-5#3-o-2.5-2-10c	A	90°	11.3	5650	A1035	17	2.6	1.3	9.9	80600	SS/FP
	B	90°	10.5	5650	A1035	17	2.5	2.0	9.9	57700	SS/FP
8-8-90-5#3-o-2.5-2-8	A	90°	8.3	8630	A1035	17	2.8	1.8	9.3	56100	FP/SS
	B	90°	8.8	8630	A1035	17	2.8	1.3	9.3	66800	FB/SS
8-8-90-5#3-o-3.5-2-8	A	90°	7.8	8810	A1035	19	3.5	2.3	9.5	53900	FP
	B	90°	8.0	8810	A1035	19	3.5	2.0	9.5	56100	FP/SS
8-8-90-5#3-o-4-2-8	A	90°	8.5	8740	A1035	20	3.9	1.5	10.0	39600	SS/FP
	B	90°	8.0	8740	A1035	20	4.5	2.0	10.0	41500	FP
8-5-90-5#3-i-2.5-2-10a	B	90°	10.5	5270	A1035	17	2.5	1.8	9.8	82800	FP/SS
8-5-90-5#3-i-2.5-2-10b	A	90°	10.3	5440	A1035	17	2.8	2.0	9.9	78800	FP/SS
	B	90°	10.5	5440	A1035	17	2.6	1.8	9.9	66700	FP
8-5-90-5#3-i-2.5-2-10c	A	90°	10.5	5650	A1035	17	2.5	2.0	10.0	68900	FP/SS
	B	90°	10.5	5650	A1035	17	2.5	2.0	10.0	69600	FP/SS
8-5-90-5#3-i-2.5-2-13	A	90°	13.8	5560	A1035	17	2.5	1.5	10.3	93100	SS/FP
	B	90°	13.5	5560	A1035	17	2.4	1.8	10.3	81300	FP/SS
8-5-90-5#3-i-2.5-2-15	A	90°	15.3	4850	A1035	17	2.8	1.9	9.9	77100	FP/SS
	B	90°	15.8	4850	A1035	17	2.5	1.4	9.9	72600	FP/SS
8-8-90-5#3-i-2.5-2-8	A	90°	7.3	8290	A1035	17	2.9	2.0	8.5	56000	FP
	B	90°	7.3	8290	A1035	17	2.8	2.0	8.5	51200	FP
8-12-90-5#3-i-2.5-2-9	A	90°	9.0	11160	A1035	17	2.5	2.5	9.5	66500	FP/SS
	B	90°	9.0	11160	A1035	17	2.6	2.5	9.5	63100	FP/SS
8-5-90-5#3-i-3.5-2-13	A	90°	13.3	5570	A1035	19	3.4	2.1	10.4	89600	SS
	B	90°	13.0	5570	A1035	19	3.5	2.4	10.4	76000	SS/FP
8-5-90-5#3-i-3.5-2-15	A	90°	15.8	4850	A1035	19	3.6	1.3	10.3	81200	SS/FP
	B	90°	15.8	4850	A1035	19	3.5	1.3	10.3	87100	SS/FP
8-8-90-5#3-i-3.5-2-8	A	90°	8.0	7910	A1035	19	3.5	2.0	8.9	55400	FP
	B	90°	8.0	7910	A1035	19	3.6	2.0	8.9	56200	FP
8-12-90-5#3-i-3.5-2-9	A	90°	9.0	11160	A1035	19	3.3	2.5	9.5	68800	FP/SS
	B	90°	9.0	11160	A1035	19	3.4	2.5	9.5	82200	FP/SS

Notation described in Appendix A

3.4.3 No. 11 Hooked Bars

No. 11 Hooks with No Confining Transverse Reinforcement

Table 13 shows the results for 14 No. 11 hooked bars with no confining transverse reinforcement. The specimens had 90° hooked bars placed inside the longitudinal column reinforcement. Concrete compressive strengths ranged from 4,910 to 13,330 psi, and embedment lengths ranged from 14.8 to 26.0 in. Nominal side covers were 2.5 and 3.5 in. Bar forces at failure ranged from 69,000 to 205,100 lb, corresponding to ultimate bar stresses of 48,900 to 145,500 psi. Four of the 14 hooks in this group, 11-5-90-0-i-2.5-2-26 hook B, 11-12-90-0-i-2.5-2-17 hook A, 11-5-90-0-i-3.5-2-14 hook B, and 11-5-90-0-i-3.5-2-17 hook A, exhibited tail kickout at failure.

Table 13 No. 11 hooks with no confining transverse reinforcement

Specimen	Hook	Bend Angle	ℓ_{eh} in.	f'_c psi	Hook Bar Type	b in.	c_{so} in.	c_{th} in.	c_h in.	T lb	Failure Type
11-5-90-0-i-2.5-2-14	A	90°	13.5	4910	A615	21.5	2.8	2.5	13.3	67200	FP/SS
	B	90°	15.3	4910	A615	21.5	2.8	0.8	13.3	81400	SS
11-5-90-0-i-2.5-2-26	A	90°	26.0	5360	A1035	21.5	2.5	2.1	13.3	165700	FB/SS
	B	90°	26.0	5360	A1035	21.5	2.9	2.1	13.3	146800	FB/SS/K
11-12-90-0-i-2.5-2-17	A	90°	17.6	13330	A1035	21.5	2.8	2.1	13.8	123600	SS/K
	B	90°	17.8	13330	A1035	21.5	2.5	2.0	13.8	125600	SS
11-12-90-0-i-2.5-2-25	A	90°	24.9	13330	A1035	21.5	2.5	2.4	13.1	205100	SB
	B	90°	24.4	13330	A1035	21.5	2.5	2.9	13.1	198100	SB
11-5-90-0-i-3.5-2-14	A	90°	14.8	4910	A615	23.5	3.8	1.5	13.3	82600	FP/SS
	B	90°	15.3	4910	A615	23.5	3.9	1.0	13.3	69000	FP/SS/K
11-5-90-0-i-3.5-2-17	A	90°	18.1	5600	A1035	23.5	4.0	1.8	13.1	105000	SS/K
	B	90°	17.6	5600	A1035	23.5	3.9	2.5	13.1	117600	SS
11-5-90-0-i-3.5-2-26	A	90°	26.0	5960	A1035	23.5	3.8	2.4	13.5	198300	SB/FB
	B	90°	26.0	5960	A1035	23.5	3.8	2.4	13.5	181700	FB/SB

Notation described in Appendix A

No. 11 Hooks with Two No. 3 Ties Confining the Hooked Bar

Table 14 shows the results for 10 No. 11 hooked bars with two No. 3 ties as confining transverse reinforcement. These specimens contain 90° hooked bars placed inside the longitudinal column reinforcement. Concrete compressive strengths ranged from 4,910 to 13,710 psi, and embedment lengths ranged from 13.4 to 18.0 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 or 1.5d_b from the center of the hooked bar. Bar forces at failure ranged from 77,200 to 133,200 lb, corresponding to bar stresses of 54,800 to 94,500 psi. Two of the 10 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.

Table 14 No. 11 hooks with 2 No. 3 ties confining transverse reinforcement

Specimen	Hook	Bend Angle	ℓ_{eh} in.	f_c' psi	Hook Bar Type	b in.	c_{so} in.	c_{th} in.	c_h in.	T lb	Failure Type
11-5-90-2#3-i-2.5-2-14	A	90°	13.5	4910	A615	21.5	2.8	2.5	13.3	77700	FP/SS
	B	90°	13.8	4910	A615	21.5	2.9	2.3	13.3	77200	SS
11-5-90-2#3-i-2.5-2-17	A	90°	17.4	5600	A1035	21.5	2.5	2.3	13.4	108400	SS/FP
	B	90°	17.8	5600	A1035	21.5	2.6	1.8	13.4	103200	SS/FP
11-12-90-2#3-i-2.5-2-17	A	90°	18.0	13710	A1035	21.5	2.5	1.5	13.3	133200	SS
	B	90°	17.5	13710	A1035	21.5	2.5	2.0	13.3	129900	SS
11-5-90-2#3-i-3.5-2-14	A	90°	14.5	4910	A615	23.5	3.8	1.6	13.3	92700	FP/SS
	B	90°	13.4	4910	A615	23.5	3.9	2.8	13.3	81800	SS/FP/K
11-5-90-2#3-i-3.5-2-17	A	90°	17.5	7070	A1035	23.5	3.6	2.1	13.4	107800	SS/FP/K
	B	90°	17.8	7070	A1035	23.5	3.6	2.0	13.4	111500	SS

Notation described in Appendix A

No. 11 Hooks with Six No. 3 Ties Confining the Hooked Bar

The results for eight No. 11 hooked bars with six No. 3 ties confining the hooks are shown in Table 15. The specimens contain 90° hooked bars placed inside the longitudinal column reinforcement. The ties in these specimens were spaced at $3d_b$, qualifying for the 0.8 reduction factor in accordance with ACI 318-11 Section 12.5.3(b). Concrete compressive strengths ranged from 5,420 to 13,710 psi, and embedment lengths ranged from 14.8 to 21.9 in. Nominal side covers were 2.5 and 3.5 in. Bar forces at failure ranged from 115,100 to 200,100 lb, corresponding to stresses of 81,600 to 141,900 psi.

Table 15 No. 11 hooks with 6 No. 3 ties confining transverse reinforcement

Specimen	Hook	Bend Angle	ℓ_{eh} in.	f'_c psi	Hook Bar Type	b in.	c_{so} in.	c_{th} in.	c_h in.	T lb	Failure Type
11-5-90-6#3-i-2.5-2-20	A	90°	19.5	5420	A1035	21.5	2.6	2.8	12.9	153100	FP/SS
	B	90°	19.0	5420	A1035	21.5	2.6	3.3	12.9	135000	FP/SS
11-12-90-6#3-i-2.5-2-16	A	90°	14.8	13710	A1035	21.5	2.5	3.3	13.0	115100	SS/FP
	B	90°	16.0	13710	A1035	21.5	2.5	2.0	13.0	127500	SB/FB
11-12-90-6#3-i-2.5-2-22	A	90°	21.9	13710	A1035	21.5	2.9	2.4	13.3	200100	SS/FB
	B	90°	21.5	13710	A1035	21.5	3.1	2.8	13.3	199200	FB
11-5-90-6#3-i-3.5-2-20	A	90°	20.0	5420	A1035	23.5	3.8	2.3	13.1	150200	SS/FP
	B	90°	20.0	5420	A1035	23.5	3.9	2.3	13.1	135300	SS

Notation described in Appendix A

CHAPTER 4 ANALYSIS AND DISCUSSION

4.1 GENERAL

The purpose of this chapter is to analyze the test results for hooks in three categories: Hooks not confined by transverse reinforcement, hooks confined by two No. 3 ties, and hooks confined by No. 3 ties spaced at $3d_b$.

As a first step, the test data are compared with the provisions for the development length of hooked bars in ACI 318-11. Next, the data for 90° hooks cast inside the column core are used to develop equations that characterize the relationship between ultimate bar force and key parameters (embedment length, concrete compressive strength, bar diameter, and cover to the center of the bar). In the final sections, the test data are analyzed to determine the effect of quantity of transverse reinforcement, side cover, hook bend angle, and hook placement (inside or outside the column longitudinal reinforcement) on the anchorage strength of hooked bars in concrete beam-column joints.

In much that follows, to see trends in the data, dummy variables regression analysis (Draper and Smith 1981) is used. Dummy variables analysis is a least squares regression analysis that allows differences in populations to be taken into account when formulating relationships between principal variables. For instance, the effect of embedment length ℓ_{eh} on ultimate bar force T can be found for three different bar sizes based on the assumption that the effect of *changes* in ℓ_{eh} on *changes* in T is the same for the three bar sizes, but that the absolute value of T for a given ℓ_{eh} will differ for each bar size.

Consider the following equation:

$$Y = \gamma X + \beta_1 Z_1 + \beta_2 Z_2 + \beta_n Z_n \tag{3}$$

In this case, if Y is the ultimate bar force T (dependent variable) and X is the embedment length ℓ_{eh} (independent variable), then γ would be the slope of the regression lines. The factors β_n increase or decrease the intercept for each population, that is, No. 5, 8, and 11 bars would all have different intercepts on the T axis. The variables Z_n are the dummy variables, which can have a value of either 1 or 0 and act as on/off switches for the intercept factors β_n. This method will show 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 use of dummy variables analyses to determine trends amongst test data, Student's t-test is used to determine the statistical significance of differences between test parameters (such as the effect hook bend angle has on anchorage capacity). Based on the null hypothesis that the means of the two samples being investigated are equal, 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% chance that there is no actual difference between the populations (or a 95% chance there is an actual difference) when the data indicates that there is a statistically significant difference in the sample means. A two-tailed test with unequal variances is used throughout this report. This indicates that there is a probability $\alpha/2$ that $\mu_1 > \mu_2$ and a probability $\alpha/2$ that $\mu_1 < \mu_2$. Differences are considered statistically significant for values of α less than or equal to 0.05 and not statistically significant for values of α greater than or equal to 0.20. If α is between 0.05 and 0.20, the value of α will be stated.

As will be shown in the following sections, comparisons between the test data and the provisions in ACI 318-11 for the development length of hooks indicate that the provisions do not accurately predict the effects of concrete compressive strength and bar size on the anchorage strength of hooks. Also, when the reduction factors allowed by ACI 318-11 Section 12.5.3 are used, hooks with ties placed at $3d_b$ in concrete with compressive strength greater than 11,000 psi for No. 8 bars and 6,000 psi for No. 11 bars fail at forces lower than predicted by the ACI 318-11 demonstrating that the current code provisions for hooks can produce unsafe designs for hooks with larger bar sizes cast in higher-strength concrete.

The following sections also show that anchorage strength increases with an increase in amount of confining transverse reinforcement. The presence of confining transverse reinforcement increases anchorage capacity by confining the concrete and helping to carry the tensile forces after cracking. Increasing side cover increases anchorage capacity for hooks with no confining transverse reinforcement. This effect, however, becomes less significant as the amount of confining transverse reinforcement increases. The current test data show no statistically significant differences in capacity of hooked bars with 90° and 180° bends. A direct comparison between hooks in the same group of specimens placed inside and outside the longitudinal column reinforcement indicates that hooks placed inside the column core have greater capacity than hooks placed outside. However, a Student's t-test performed on data for 90° and 180° hooks placed in different groups indicates that the difference is not statistically significant; therefore, additional tests are recommended where direct comparison is possible.

4.2 COMPARISON WITH ACI 318-11

Figures 13 through 15 compare the ratio of measured ultimate bar stress f_{su} to the bar stress calculated in accordance with Section 12.5.2 of ACI 318-11 $f_{s,ACI}$ as a function of concrete compressive strength. Figure 13 shows the results for No. 5, No. 8, and No. 11 bars with 2.5-in. and 3.5-in side cover without confining transverse reinforcement. Figures 14 and 15 show the results, respectively, 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.

Section 12.5.2 of ACI 318-11 expresses the development length of a hook ℓ_{dh} 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), the expression for ℓ_{dh} also includes factors for the effects of epoxy coating ψ_e and lightweight concrete λ. Because all the tests conducted in this study are on uncoated bars in normalweight concrete, the values of ψ_e and λ are taken as 1.0. To obtain $f_{s,ACI}$, the development length ℓ_{dh} in Eq. (4) is replaced by embedment length ℓ_{eh}, yield strength f_y is replaced by bar stress $f_{s,ACI}$, and the equation is solved for $f_{s,ACI}$, as shown in Eq. (5). The values for ℓ_{eh} and f_c' used in Eq. (5) are the measured rather than the nominal values.

$$\ell_{dh} = \left(\frac{0.02\psi_e f_y}{\lambda\sqrt{f_c'}}\right)d_b \tag{4}$$

$$f_{s,\mathrm{ACI}} = \frac{50\ell_{eh}\sqrt{f_c'}}{d_b} \tag{5}$$

As permitted by Section 12.5.3 of ACI 318-11, the comparisons include the 0.7 reduction factor in ℓ_{dh} permitted for No. 11 bars and smaller with at least 2.5 in. of clear cover the side of the hook and 2 in. of clear cover to the tail of the hook and, for 90° hooks, the 0.8 reduction factor permitted for No. 11 bars and smaller confined by stirrups or ties parallel to the bar being developed spaced no more than three bar diameters $3d_b$ apart.

Figure 13 includes results for 72 90° hooks with no confining transverse reinforcement, 14 of which are No. 5 hooks with 2.5-in. side cover, 14 are No. 5 hooks with 3.5-in. side cover, 18 are No. 8 hooks with 2.5-in. side cover, 12 are No. 8 hooks with 3.5-in. side cover, 8 are No. 11 hooks with 2.5-in. side cover, and 6 are No. 11 hooks with 3.5-in. side cover. As shown in the figure, the ratio of $f_{su}/f_{s,ACI}$ decreases as bar size and concrete compressive strength increase.

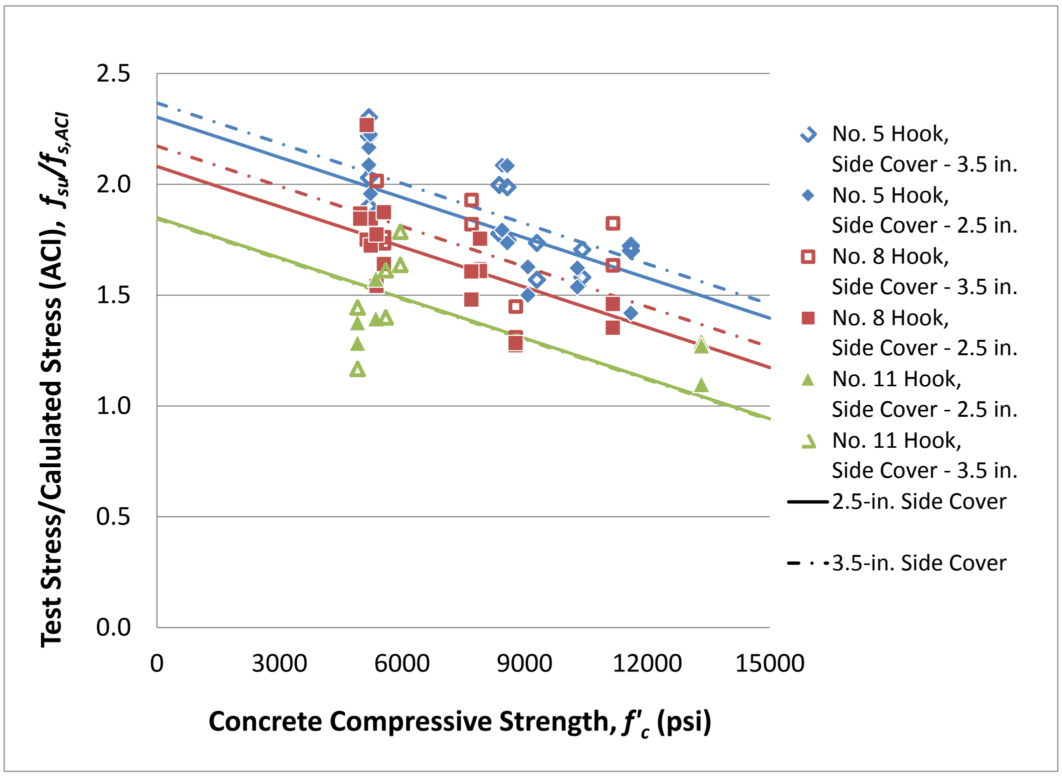


Figure 13 Ratio of test stress to calculated stress $f_{su}/f_{s,ACI}$ versus f_c' for 90° hooks with no confining transverse reinforcement

These comparisons show that the current provisions for the development length of hooked bars overestimate the contributions of both bar size and compressive strength on the stress developed in a hooked bar. There is an increase in the ratio of $f_{su}/f_{s,ACI}$ as side cover increases for the No. 5

and No. 8 hooks, but not for No. 11 hooks. Although the difference is most significant for No. 8 bars, there is still an effect for No. 5 bars. The apparent lack of increase in anchorage strength for an increase in side cover for No. 11 bars may be due to the low number of No. 11 hooked bars tested. There are just 16 No. 11 hooks included in Figure 13, only 4 of which – all with 2.5-in. side cover – were cast in concrete with compressive strengths greater than 6,000 psi.

Figure 14 includes results for 54 hooks confined by two No. 3 column ties, 10 are No. 5 hooks with 2.5-in. side cover, 12 are No. 5 hooks with 3.5-in. side cover, 12 are No. 8 hooks with 2.5-in. side cover, 10 are No. 8 hooks with 3.5-in. side cover, 6 are No. 11 hooks with 2.5-in. side cover, and 4 are No. 11 hooks with 3.5-in. side cover. As for the hooks without confining

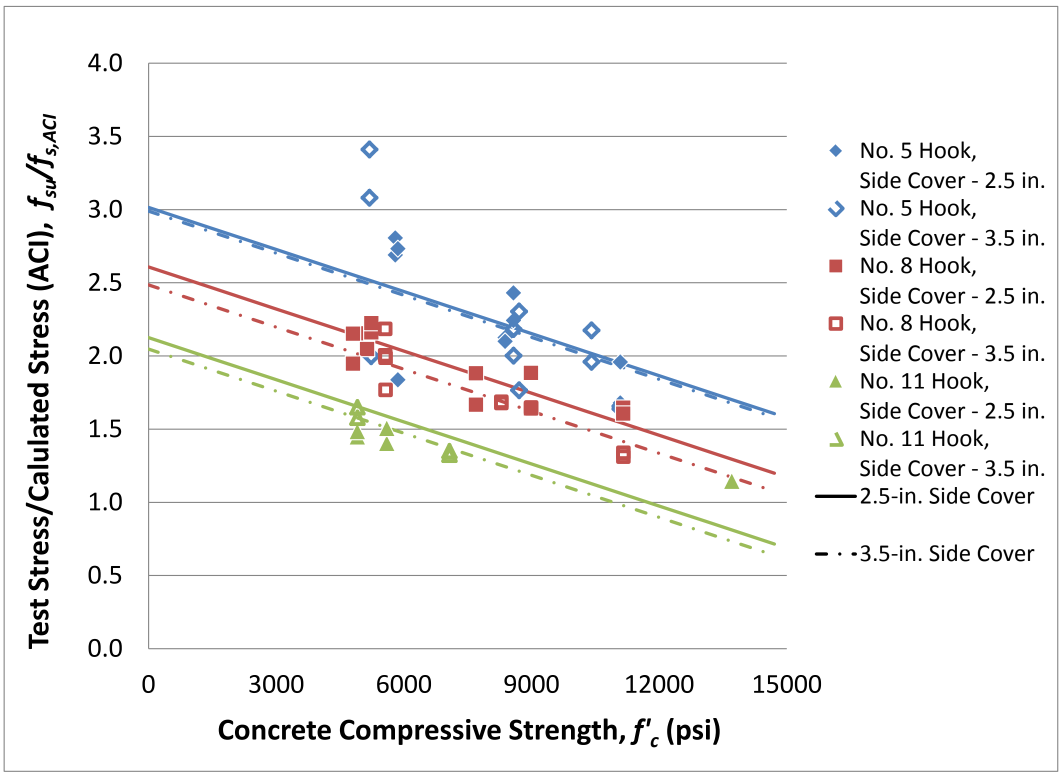


Figure 14 Ratio of test stress to calculated stress $f_{su}/f_{s,ACI}$ versus f_c' for 90° hooks with two No. 3 ties as confining transverse reinforcement

transverse reinforcement, there is a decrease in the ratio $f_{su}/f_{s,ACI}$ as bar size and concrete compressive strength increase. The figure exhibits essentially no change in anchorage strength for an increase in side cover for the No. 5 hooks and a slight decrease in anchorage strength with an increase in side cover for No. 8 and No. 11 hooks, albeit, the decreases are not statistically significant.

Figure 15 includes results for 37 hooks confined by No. 3 ties spaced at $3d_b$. Of the 37, 4 are No. 5 hooks with 2.5-in. side cover, 6 are No. 5 hooks with 3.5-in. side cover, 13 are No. 8 hooks with 2.5-in. side cover, 8 are No. 8 hooks with 3.5-in. side cover, 6 are No. 11 hooks with 2.5-in. side cover, and 2 are No. 11 hooks with 3.5 in. side cover. The No. 5 and No. 8 hooks were confined by five No. 3 ties, and the No. 11 hooks were confined by six No. 3 ties. The $3d_b$ spacing of the confining reinforcement permits the 0.8 factor in Section 12.5.3(b) of ACI 318-11 to be applied.

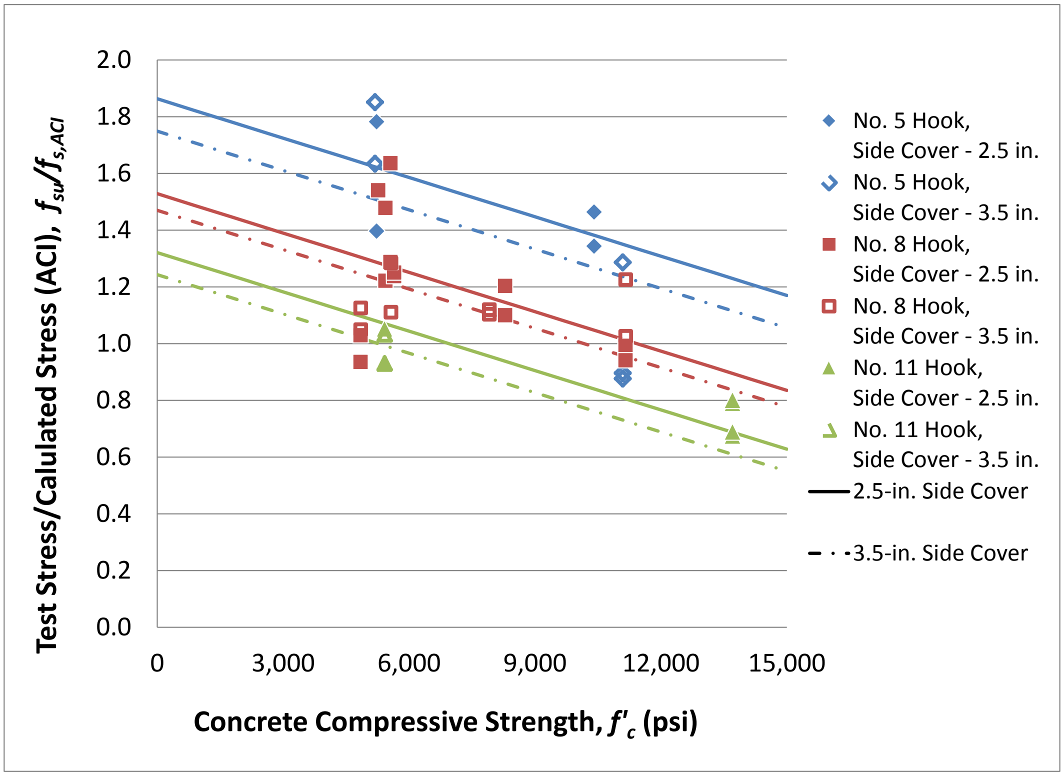


Figure 15 Ratio of test stress to calculated stress $f_{su}/f_{s,ACI}$ versus f_c' for 90° hooks with No. 3 ties at $3d_b$ as confining transverse reinforcement

The parallel lines formed from the dummy variables analysis have a negative slope and a decreasing intercept as bar size increases. Thus, as for the bars without confining transverse reinforcement, the ratio $f_{su}/f_{s,ACI}$ decreases with increasing bar size and concrete compressive strength. Perhaps because of the small amount of data, the hooks with the greater side cover actually exhibit a lower value of $f_{su}/f_{s,ACI}$. These differences, however, are not statistically significant. The ratio $f_{su}/f_{s,ACI}$ drops below 1.0 for No. 8 bars at concrete compressive strengths of about 11,000 psi and for No. 11 bars at concrete compressive strengths of about 6,000 psi. The ratio $f_{su}/f_{s,\mathrm{ACI}}$ drops below 1.0 in these cases because of the 0.7 and 0.8 factors that are allowed in accordance with ACI 318-11 Section 12.5.3. Currently, ACI 318-11 only allows concrete strengths up to 10,000 psi to be used in the design of hooked bars; however, using higher strengths for concrete in design with the reduction factors allowed by ACI 318-11 Section 12.5.3, as recommended by Ramirez and Russell (2008), would produce unsafe designs for No. 8 hooked bars. No. 11 bars, on the other hand, exhibit unsafe anchorage strengths for concrete compressive strengths as low as 6,000 psi, which are currently allowed for use in design by ACI 318-11 Section 12.5.3, when the 0.7 and 0.8 reduction factors are included. Ramirez and Russell (2008) also found these reduction factors to produce unsafe designs and recommended that the 0.7 reduction factor permitted for hooked bars with at least 2.5 in. side cover be increased from 0.7 to 0.8.

The observations presented in this section indicate that the provisions in ACI 318-11 for the design of hooked bars should be adjusted to more accurately account for the effects of concrete compressive strength and bar diameter on anchorage strength, and that the 0.8 factor in Section 12.5.3(b) be removed.

4.3 ANALYSIS OF HOOK BEHAVIOR

As demonstrated in Section 4.2, ACI 318-11 does not accurately predict the behavior and capacity of standard hooks in tension. In this section, equations are developed to express the anchorage strength of 90° standard hooks placed inside the longitudinal column reinforcement based on the test results in this study as a function of what appear to be the principal controlling parameters. Three cases are addressed: hooks not confined by transverse reinforcement, hooks confined by two No. 3 column ties, and hooks confined by column ties spaced at $3d_b$, the quantity of confining transverse reinforcement that is required by ACI 318-11 Section 12.5.3(b) that permits hook development length ℓ_{dh} to be multiplied by the 0.8 reduction factor.

A similar approach is taken to develop the equations for all three cases. First, a dummy variables analysis, as described in Section 4.1, is performed that expresses ultimate bar force T as a function of embedment length ℓ_{eh} for the three bar sizes (No. 5, 8, and 11) and the two principal side covers (2.5 and 3.5 in.) used in this study, to obtain a general understanding of the effect of embedment length, bar size, and side cover on T. Next, the ultimate bar force T normalized to the concrete compressive strength f_c' to a power p_1, is expressed as a function of the embedment length ℓ_{eh} multiplied by bar diameter d_b to a power p_2 and concrete side cover to the center of the bar c_b to a power p_3. The powers p_1, p_2, and p_3 are modified to minimize the spread in the parallel lines obtained in the dummy variables analysis. The average intercept on the $T/f_c'^{\,p_1}$ axis is then used to obtain a single expression that expresses T as a function of embedment length ℓ_{eh}, bar diameter d_b, side cover center of the bar c_b, and concrete compressive strength f_c'. The resulting equation is then checked by plotting the ratio of the measured values to the values calculated by the equation T/T_{calc} versus concrete compressive strength f_c', again using a dummy variables analysis with the data separated based on bar size. If the slope of the lines from this dummy variables analysis is positive, the effect of concrete compressive strength f_c' is under-predicted; if the slope of the lines from the dummy variables analysis is negative, the effect of concrete compressive strength f_c' is over-predicted. The power p_1 for concrete compressive strength f_c' is then adjusted and the process repeated until the slope is equal to zero. This power is used in the final equation. While hooks with transverse reinforcement other than the three cases considered here have been tested, the number of tests is too small to perform similar analyses.

4.3.1 90° Hooks with No Confining Transverse Reinforcement

Figure 16 shows ultimate bar force at failure T as a function of embedment length ℓ_{eh}. This and other figures in this section show the results for 72 hooked bars, 14 for No. 5 bars with 2.5-in. side cover, 14 for No. 5 bars with 3.5-in. side cover, 18 for No. 8 bar with 2.5-in. side cover, 12 for No. 8 bar with 3.5-in. side cover, 8 for No. 11 bars with 2.5-in. side cover, and 6 for No. 11 bars with 3.5-in. side cover. Embedment lengths range from 4.75 to 26 in. and ultimate bar force T ranges from 18,000 to 205,000 lb, which, as will be demonstrated, increases with increases in embedment length and bar size. The dummy variables analysis, without normalizing for concrete compressive strength, shows no difference in T as a function of side cover for No. 5 hooks, a higher T for increased side cover for No. 8 hooks, and a lower T for increased side cover for No. 11 hooks.

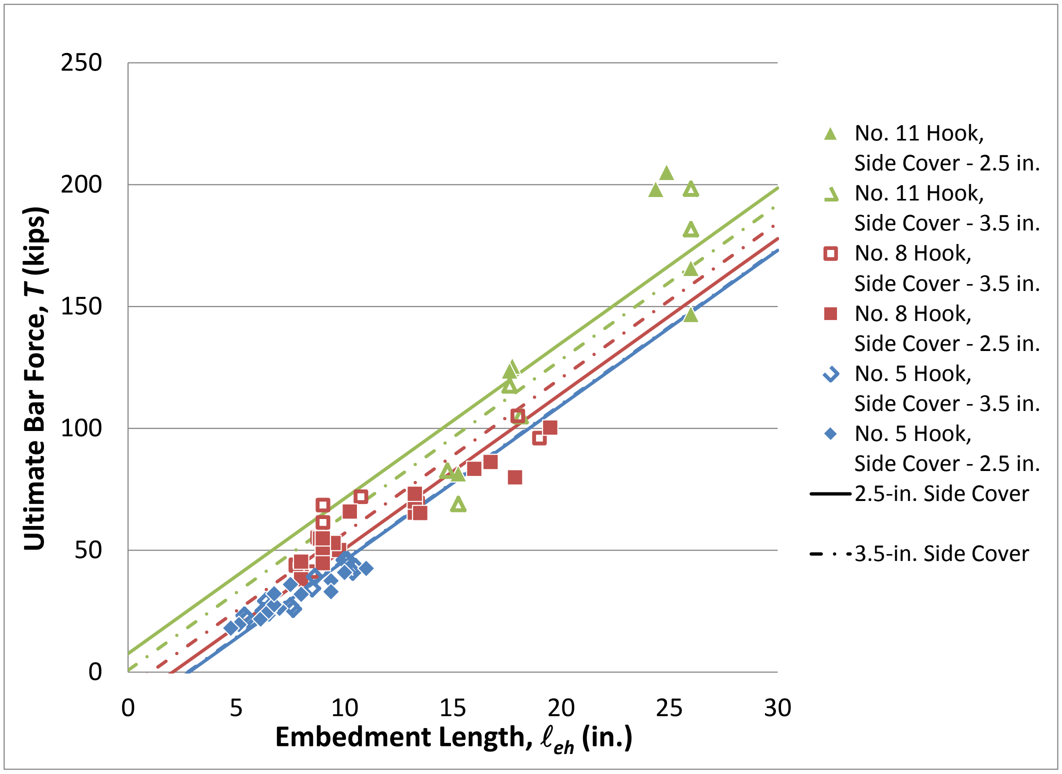


Figure 16 Ultimate bar force versus embedment length for 90° hooks with no confining transverse reinforcement

Using the process described in the beginning of this section, a linear equation is developed that minimizes the scatter in $T/f_c'^{\,p_1}$ as a function of $d_b^{p_2}$ and $c_b^{p_3}$. The result of the analysis is represented by the closely spaced lines in Figure 17. Using the average intercept of the lines, the linear expression for the best fit with the data is

$$\frac{T}{f_c'^{\,0.29}} = 362\ell_{eh}d_b^{0.1}c_b^{0.3} - 1227 \tag{6}$$

where,

T = ultimate bar force, lb

f'_c = concrete compressive strength, psi

ℓ_{eh} = embedment length, in.

c_b = side cover to the center of the bar, in.

d_b = bar diameter, in.

The intercept for No. 5 hooks with 2.5-in. side cover -1,315, for No. 5 hooks with 3.5-in. side cover is -1,295, for No.8 hooks with 2.5-in. side cover is -1,116, for No. 8 hooks with 3.5-in. side cover is -1,252, for No. 11 hooks with 2.5-in. side cover is -1,114, and for No. 11 hooks with 3.5-in. side cover is -1,291. The negative intercept in Eq. (6), as well as the spread in the data points, suggests a nonlinear relationship between T and ℓ_{eh}. This nonlinear relationship can be tied to the observed failure mode of the hooks, as described in Section 3.3. An increase in the embedment length of the hook increases, mobilizes a progressively greater volume of concrete, which, in turn, mobilizes a greater force prior to failure. As will be demonstrated in Sections 4.3.2 and 4.3.3, this relationship appears to be quite different for hooks confined by transverse reinforcement. The nonlinear relationship is shown in Eq. (7) and also shown in Figure 17.

$$\frac{T}{f_c'^{\,0.29}} = 137\left(\ell_{eh} d_b^{0.1} c_b^{0.3}\right)^{1.25} \tag{7}$$

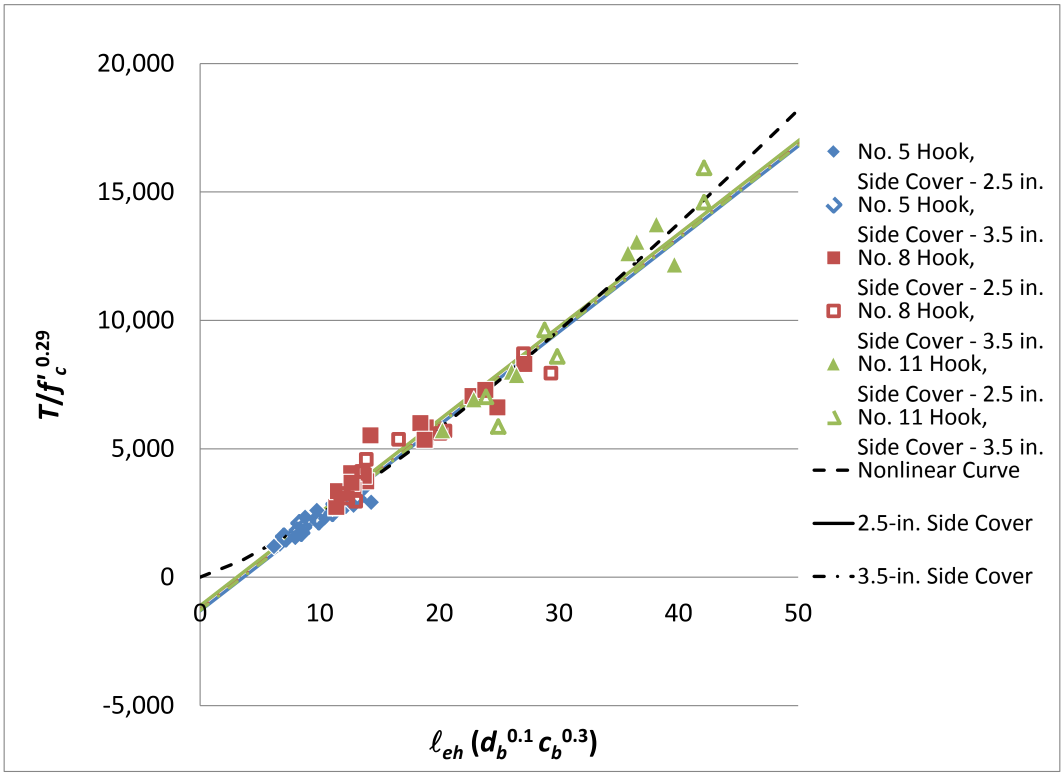


Figure 17 Development of an equation for 90° hooks with no confining transverse reinforcement

The ratios of the measured ultimate bar forces to those calculated using Eq. (7) T/T_{calc} are plotted in Figure 18 versus f_c'. The mean ratio is 1.002, standard deviation is 0.115, and the ratio ranges from 0.765 to 1.456. The zero slope of the dummy variables lines based on bar size and side cover indicates that the 0.29 power captures the average effect of concrete compressive strength on bar force T. The intercept for No. 5 hooks with 2.5-in. side cover is 0.936, for No. 5 hooks with 3.5-in. side cover is 0.953, for No.8 hooks with 2.5-in. side cover is 1.068, for No. 8 hooks with 3.5-in. side cover is 1.041, for No. 11 hooks with 2.5-in. side cover is 0.996, and for No. 11 hooks with 3.5-in. side cover is 0.961. The measured and calculated ultimate bar forces are presented in Table C.1 of Appendix C.

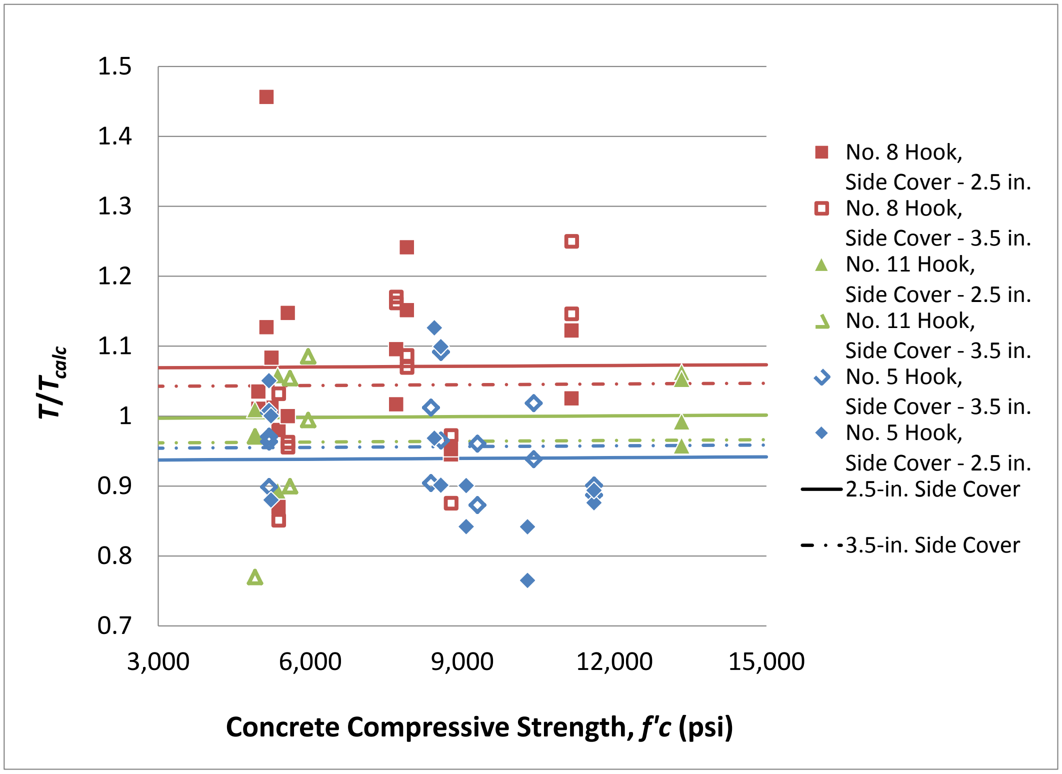


Figure 18 Ratio of test ultimate bar force to calculated ultimate bar force T/T_{calc} versus concrete compressive strength for 90° hooks with no confining transverse reinforcement

Because $f_c'^{\,0.29}$ is neither especially elegant nor likely to be adopted for design, the process described to obtain a best fit with the data is repeated to find a more attractive equation. Figure 19 shows the results of this process. In this case, the $1/4$ power of f_c' and the $1/5$ power of both c_b and d_b provide a suitable fit. The expression for the linear equation with the average intercept of the lines shown in Figure 19 is

$$\frac{T}{f_c'^{\,1/4}} = 574\ell_{eh}(c_b d_b)^{1/5} - 1626 \tag{8}$$

In Figure 19, the intercept for No. 5 hooks with 2.5-in. side cover is -1,651, for No. 5 hooks with 3.5-in. side cover is -1,608, for No.8 hooks with 2.5-in. side cover is -1,558, for No. 8 hooks with

3.5-in. side cover is -1,490, for No. 11 hooks with 2.5-in. side cover is -1,810, and for No. 11 hooks with 3.5-in. side cover is -1,813. The expression for the nonlinear fit to the data is

$$\frac{T}{f_c'^{\,1/4}} = 224(\ell_{eh}(d_b c_b)^{1/5})^{5/4} \tag{9}$$

where,

T = ultimate bar force, lb

f_c' = concrete compressive strength, psi

ℓ_{eh} = embedment length, in.

c_b = side cover to the center of the bar, in.

d_b = bar diameter, in.

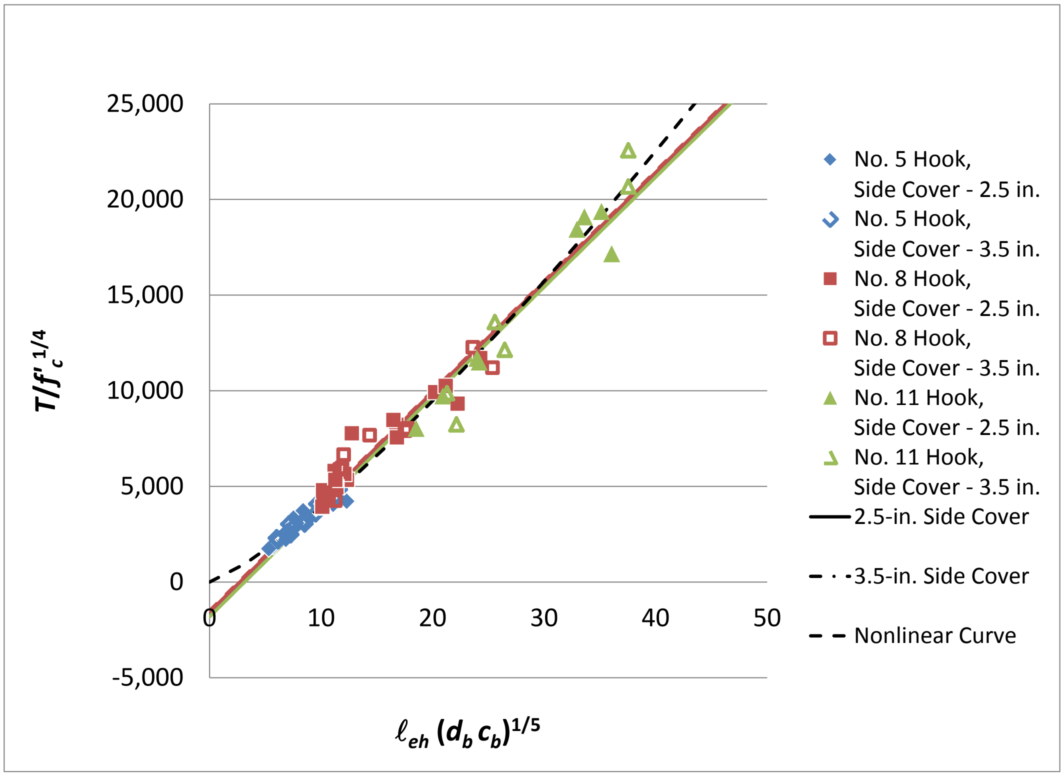


Figure 19 Development of a "design style" equation for 90° hooks with no confining transverse reinforcement

Equations (8) and (9) can be converted to "design style" equations by substituting development length ℓ_{dh} for embedment length ℓ_{eh} and the product $A_b f_y$ for T, and solving for ℓ_{dh}. The resulting equations are

$$\ell_{dh} = \frac{\dfrac{A_b f_y}{f_c'^{\,1/4}} + 1626}{574(d_b c_b)^{1/5}} \tag{10}$$

$$\ell_{dh} = \left(\frac{A_b f_y}{224\left(f_c' d_b c_b \right)^{1/4}} \right)^{4/5} \tag{11}$$

where,

A_b = ultimate bar force, lb

f_y = yield strength of the bar, psi

f_c' = concrete compressive strength, psi

ℓ_{dh} = development length, in.

c_b = side cover to the center of the bar, in.

d_b = bar diameter, in.

Substituting $\dfrac{\pi d_b^2}{4}$ for A_b in Eq. (10) and (11) gives, respectively,

$$\ell_{dh} = \frac{\dfrac{f_y}{f_c'^{\,1/4}} + \dfrac{2070}{d_b^2}}{731\left(\dfrac{c_b}{d_b^4} \right)^{1/5}} d_b \tag{12}$$

$$\ell_{dh} = \frac{1}{92}\left(\frac{f_y^4}{f_c'} \frac{d_b^2}{c_b} \right)^{1/5} d_b \tag{13}$$

Although expressed in a "design style," Eq. (10) through Eq. (13) are *not* recommended for design. More data will be available as this study proceeds and simplifications will be investigated.

The ratio of measured to calculated ultimate bar forces based on Eq. (9) are shown in Figure 20. The mean of this ratio for the data is 1.029, the standard deviation is 0.116, the maximum is 1.43, and the minimum is 0.77. The dummy variables best fit lines in Figure 20 have a positive slope of 5.33 x 10^{-6} psi^{-1}, indicating that Eq. (11) under predicts the effect of

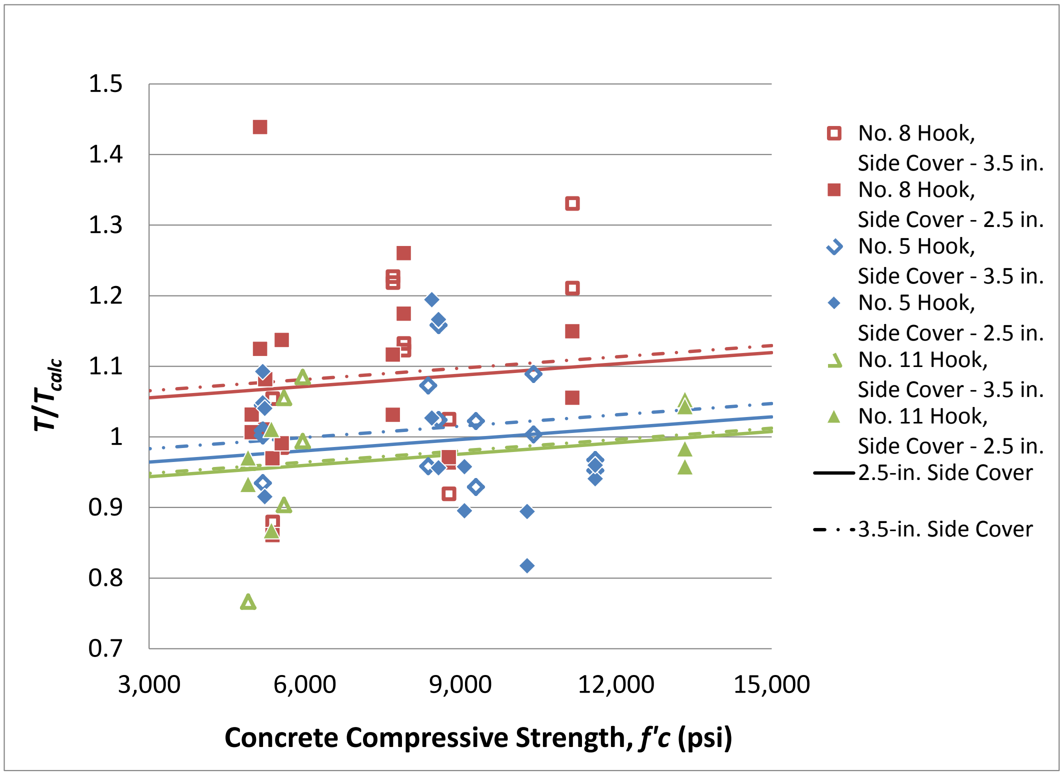


Figure 20 Ratio of test ultimate bar force to calculated ultimate bar force T/T_{calc} versus concrete compressive strength for 90° hooks with no confining transverse reinforcement

concrete compressive strength on anchorage strength of hooked bars, clearly expected with the lower power of f_c'. The intercept for No. 5 hooks with 2.5-in. side cover is 0.948, for No. 5 hooks with 3.5-in. side cover is 0.967, for No. 8 hooks with 2.5-in. side cover is 1.039, for No. 8 hooks with 3.5-in. side cover is 1.049, for No. 11 hooks with 2.5-in. side cover is 0.928, and for No. 11 hooks with 3.5-in. side cover is 0.932.

4.3.2 90° Hooks with Two No. 3 Ties as Confining Transverse Reinforcement

The figures in this section show the results from 56 hooked bars, 10 of which are No. 5 bars with 2.5-in. side cover, 14 are No. 5 bars with 3.5-in. side cover, 12 are No. 8 bars with 2.5-in. side cover, 10 are No. 8 bars with 3.5-in. side cover, 6 are No. 11 bars with 2.5-in. side cover, and 4 are No. 11 bars with 3.5-in. side cover. Figure 21 shows embedment length ℓ_{eh} as a function of ultimate bar force at failure T. Embedment lengths range from 4.75 to 18 in. and ultimate bar forces range from 21,500 to 133,200 lb. Ultimate bar force at failure increases with increases in embedment length and bar size.

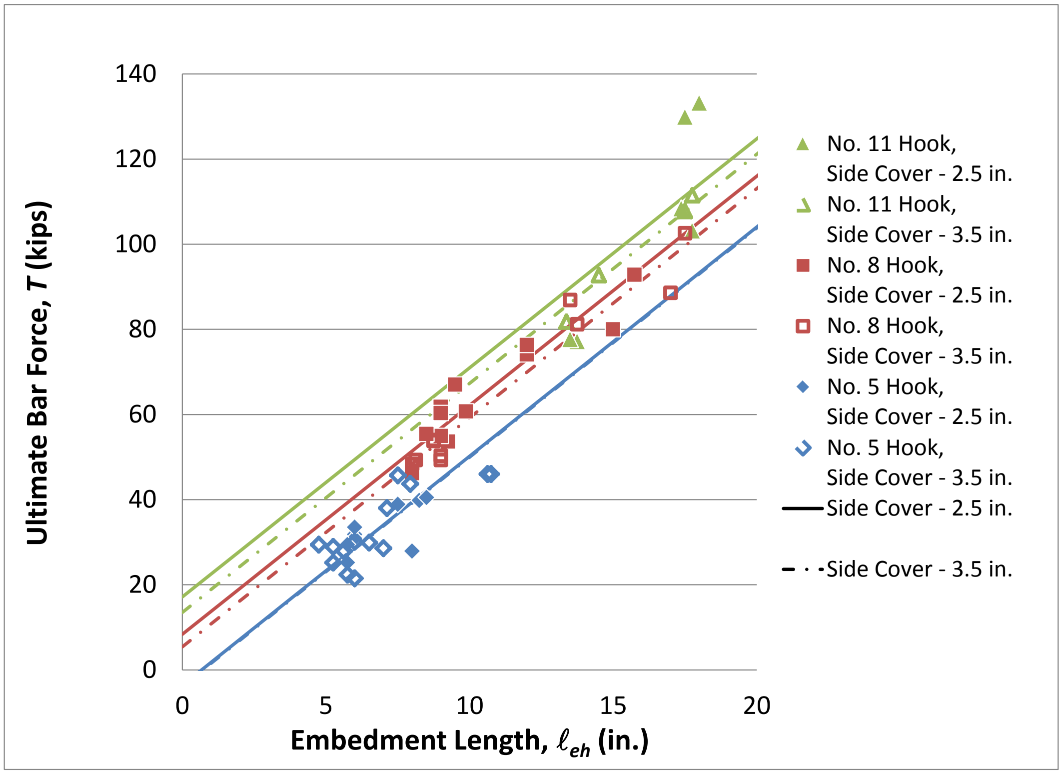


Figure 21 Ultimate bar force versus embedment length for 90° hooks with two No. 3 ties as confining transverse reinforcement

Using the process described in Section 5.6, the dummy variables lines are condensed as shown in Figure 22. The intercept for No. 5 hooks with 2.5-in. side cover is -293, for No. 5 hooks with 3.5-in. side cover is -456, for No. 8 hooks with 2.5-in. side cover is 2,011, for No. 8

hooks with 3.5-in. side cover is 384, for No. 11 hooks with 2.5-in. side cover is 181, and for No. 11 hooks with 3.5-in. side cover is -418. Because the intercepts are close to zero and the data show a linear trend, only a linear expression is developed relating ultimate bar force to embedment length, bar diameter, concrete compressive strength, and cover to the center of the bar. This equation is

$$\frac{T}{f_c'^{\,0.112}} = 1994\ell_{eh}\left(d_b^{0.3}c_b^{0.05}\right) + 235 \qquad (14)$$

where,

T = ultimate bar force, lb

f_c' = concrete compressive strength, psi

ℓ_{eh} = embedment length, in.

c_b = side cover to the center of the bar, in.

d_b = bar diameter, in.

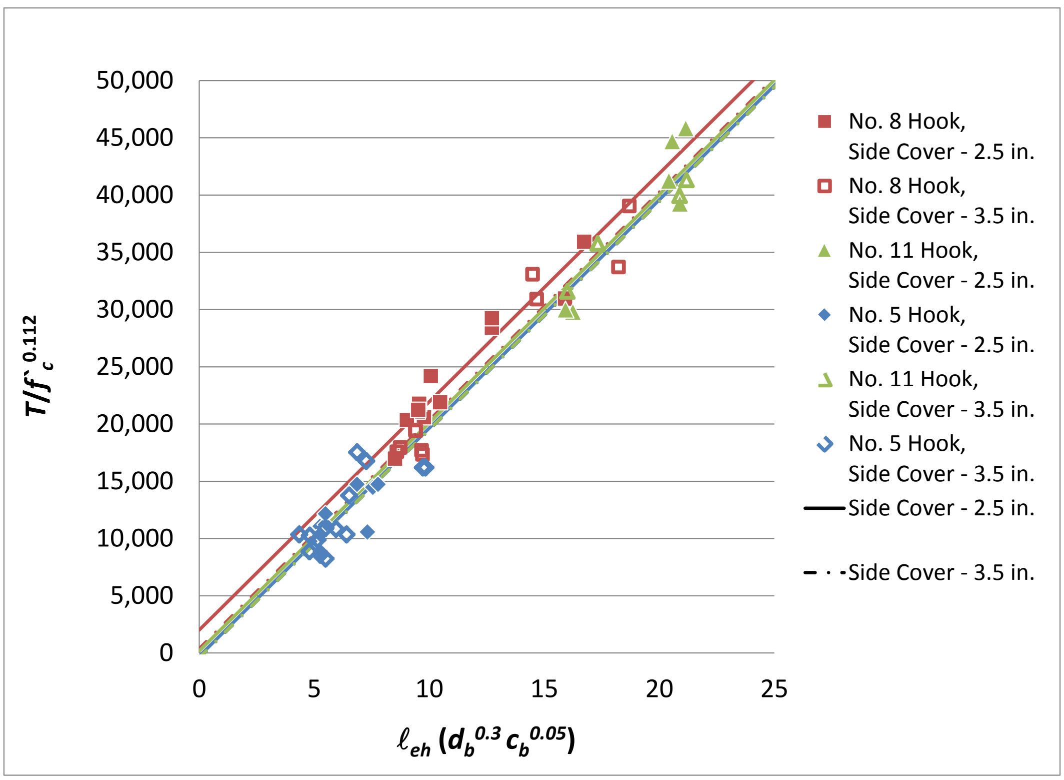


Figure 22 Development of an equation for 90° hooks with two No. 3 ties as confining transverse reinforcement

It can be seen that with the addition of confining transverse reinforcement the effects of concrete compressive strength and cover to the center of the bar are significantly lower (p_1 and p_2 drop, respectively, from 0.29 to 0.112 and from 0.3 to 0.05) and the effect of bar diameter is significantly higher (p_3 increases from 0.1 to 0.3) than for bars not confined by transverse reinforcement. Replacing embedment length ℓ_{eh} with development length ℓ_{dh} and T with the product $A_b f_y$ in Eq. (14) and solving for ℓ_{dh} gives

$$\ell_{dh} = \frac{\dfrac{A_b f_y}{f_c'^{\,0.112}} - 235}{1994 d_b^{0.3} c_b^{0.05}} \tag{15}$$

The ratios of the measured failure loads to those calculated using Eq. (14) are plotted as a function of f_c' in Figure 23. The mean ratio is 0.998, the standard deviation is 0.113, and the ratio T/T_{calc} ranges from 0.712 to 1.260 with the No. 5, especially those with 3.5-in. side cover,

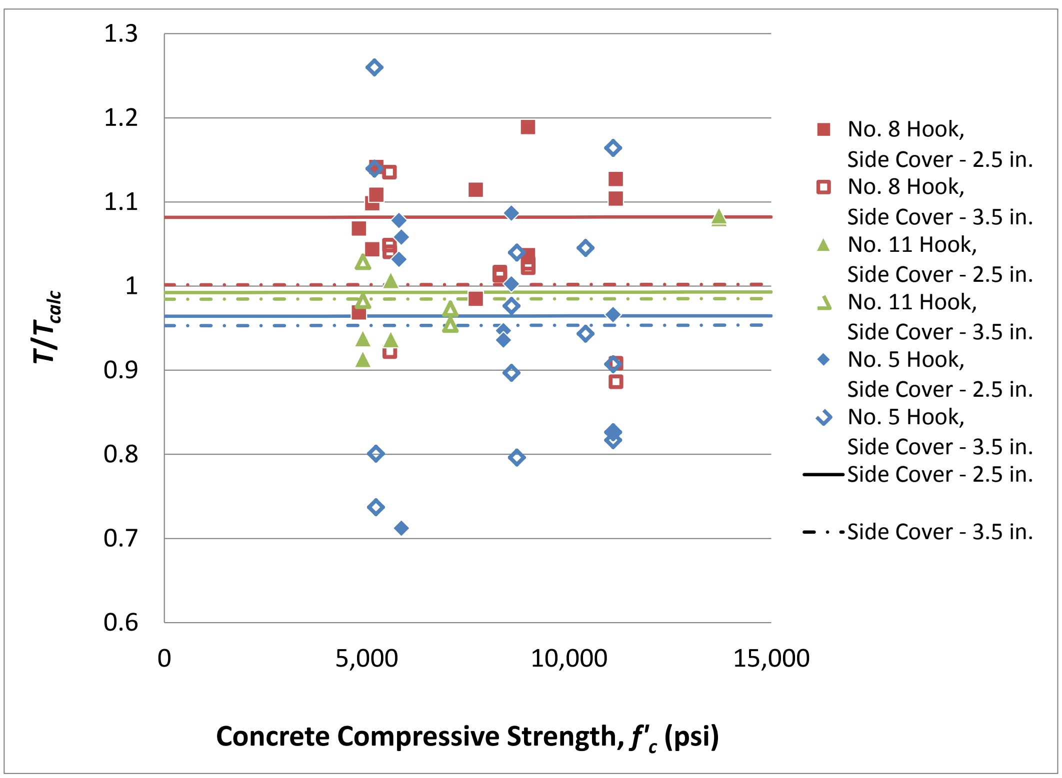


Figure 23 Ratio of test ultimate bar force to calculated ultimate bar force T/T_{calc} versus concrete compressive strength for 90° hooks with two No. 3 ties as confining transverse reinforcement

producing, by far, the greatest scatter. The zero slope in Figure 23 indicates that the 0.112 power captures the average effect of concrete compressive strength on bar force T. The average intercepts are 0.946 for No. 5 bars with 2.5-in. side cover, 0.953 for No. 5 bars with 3.5-in. side cover, 1.082 for No. 8 bars with 2.5-in. side cover, 1.001 for No. 8 bars with 3.5-in. side cover, 0.992 for No. 11 bars with 2.5-in. side cover, and 0.984 for No. 11 bars with 3.5-in. side cover. A table of the measured and calculated ultimate bar forces is presented in Table C1 in Appendix C.

4.3.3 90° Hooks with No. 3 Ties at $3d_b$ as Confining Transverse Reinforcement

This section describes the derivation of an equation describing the relationship between embedment length, concrete compressive strength, bar diameter, and ultimate bar force for hooks confined by No. 3 ties spaced at $3d_b$. Figure 24 shows ultimate bar force as a function of embedment length for No. 5, 8, and 11 hooks with 2.5-in. and 3.5-in. side cover. The figure includes the results for 8 No. 5 hooks, 21 No. 8 hooks, and 8 No. 11 hooks, for a total of 37 hooks, with embedment lengths ranging from 5.13 to 21.88 in. and bar forces ranging from 31,300 to 200,100 lb.

Figure 24 demonstrates that for a given embedment length, larger bars have higher ultimate bar forces than smaller bars when confined with No. 3 ties spaced at $3d_b$. The effect of bar size is more striking than that observed for bars without confining transverse reinforcement and bars confined by two No. 3 ties (Figures 17 and 22). The figure also shows that all the best fit lines have a positive intercept with the vertical axis, suggesting that even hooks with short confined embedment length and small bar sizes can develop significant bar force. The *increase* in anchorage capacity T, as demonstrated here and in Figure 25, is approximately proportional to the increase in embedment length ℓ_{eh}, but the value of T is less than proportional to ℓ_{eh} with increasing values of ℓ_{eh}. Finally, the figure demonstrates that increasing side cover has little if any effect on the anchorage capacity of hooks. The No. 5 hooks with 3.5-in. side cover have a best-fit line that is slightly lower than that for No. 5 hooks with 2.5-in. side cover, while the opposite is true for the No. 8 hooks. The No. 11 hooks show a decrease in ultimate bar force with an increase in side cover, but this could be due to the low number of tests.

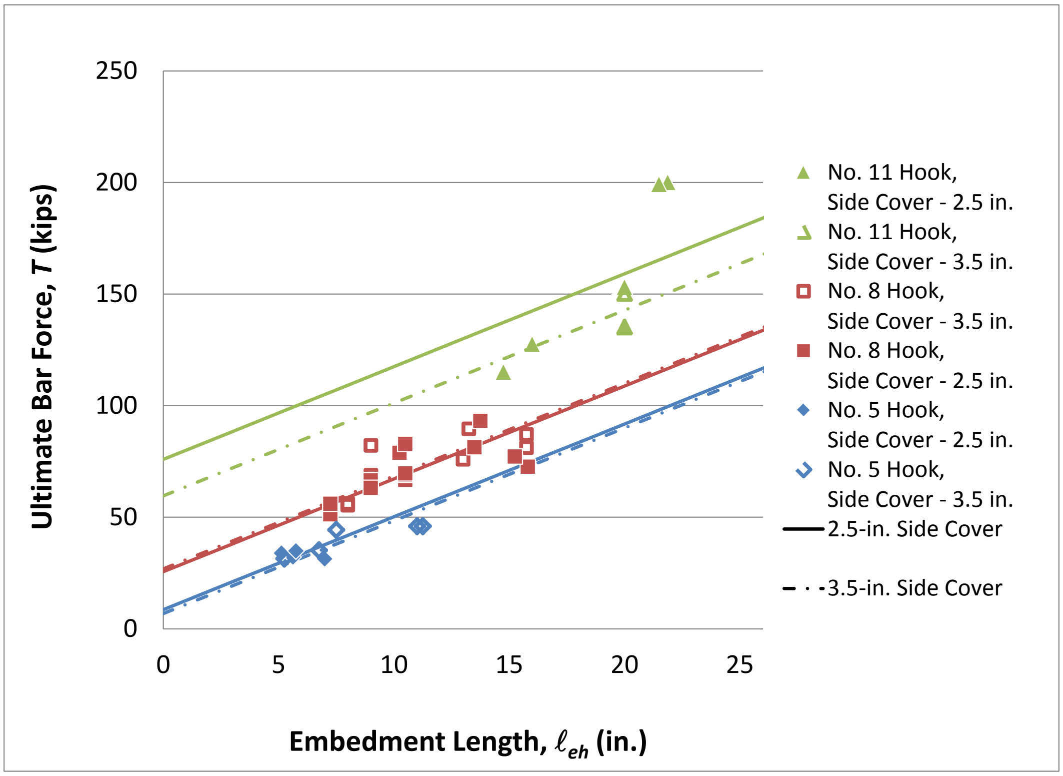


Figure 24 Ultimate bar force versus embedment length for 90° hooks with No. 3 ties at $3d_b$ as confining transverse reinforcement

Using the process described, a best-fit is obtained between $T/f_c'^{1/10}$ and the product $\ell_{eh}d_b$. In this analysis, the effect of cover to the center of the bar c_b was found to be negligible but the effect of bar size was found to be much greater than for the two other cases analyzed. The one-tenth power of f_c' is much less than for hooks without confining transverse reinforcement but very similar to that for hooks confined by two No. 3 ties.

Figure 25 presents the results of the analysis with the ultimate bar force normalized with respect to the concrete compressive strength to the $1/10$ power plotted as a function of the product of embedment length ℓ_{eh} and hook bar diameter d_b. The equation for the best fit line with the average intercept shown in Figure 25 is

$$\frac{T}{f_c'^{1/10}} = 1984\ell_{eh}d_b - 7493 \qquad (16)$$

In Figure 25, the intercepts for No. 5 hooks with 2.5-in. side cover is 6,266, for No. 5 hooks with 3.5-in. side cover is 6,194, for No.8 hooks with 2.5-in. side cover is 7,955, for No. 8 hooks with 3.5-in. side cover is 8,101, for No. 11 hooks with 2.5-in. side cover is 8,374, and for No. 11 hooks with 3.5-in. side cover is 4,462.

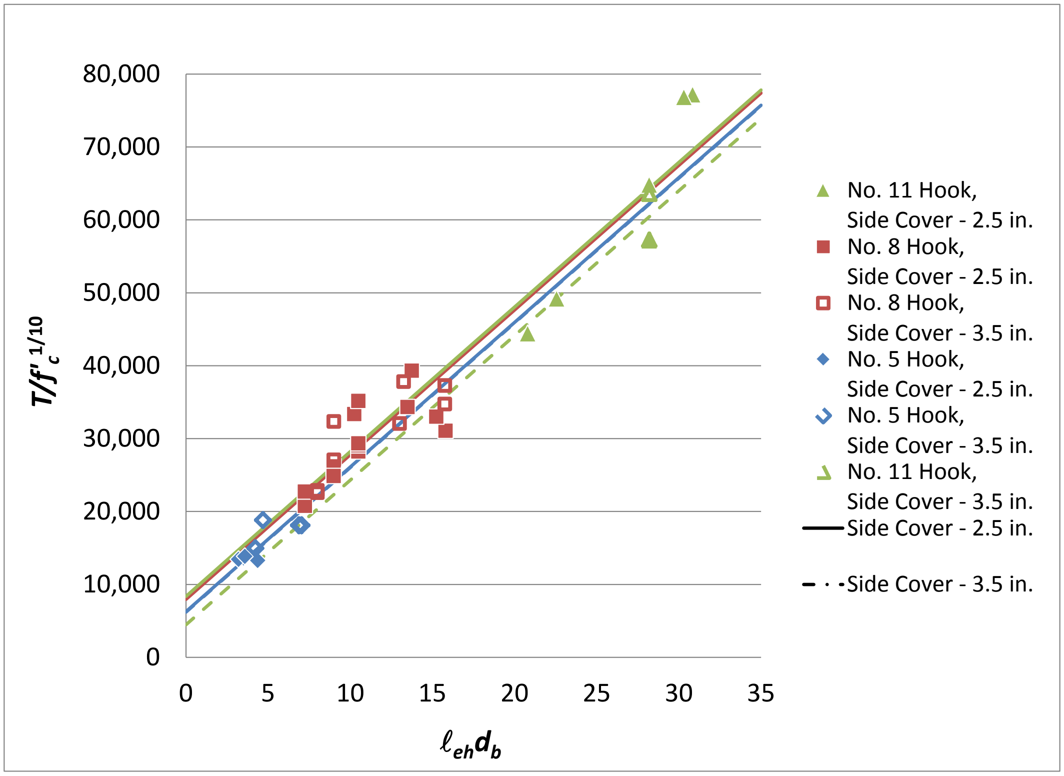


Figure 25 Development of an equation for 90° hooks with No. 3 ties at 3db as confining transverse reinforcement

As shown in Figure 25, the product $\ell_{eh} d_b$ helps capture the ability of larger hooked bars to mobilize greater force prior to failure. Substituting ℓ_{dh} for ℓ_{eh} and the product $A_b f_y$ for T in Eq. (16) and solving for ℓ_{dh} gives

$$\ell_{dh} = \frac{\dfrac{A_b f_y}{f_c'^{\,1/10}} - 7493}{1984 d_b} \tag{17}$$

To check the objectivity of the $1/10$ power to represent the effect of concrete compressive strength on anchorage strength, the ratio of test to calculated strength T/T_{calc} was plotted against concrete compressive strength in Figure 26. The ratios in Figure 26 have a mean of 0.99, a standard deviation of 0.112, and range from 0.799 to 1.277. The parallel dummy variables analysis lines have the following intercepts, 0.931 for No. 5 bars with 2.5-in. side cover, 0.931 for No. 5 bars with 3.5-in. side cover, 1.025 for No. 8 bars with 2.5-in. side cover, 1.029 for No. 8 bars with 3.5-in. side cover, 1.024 for No 11 bars with 2.5-in side cover and 0.960 for No. 11 bars with 3.5-in. side cover.

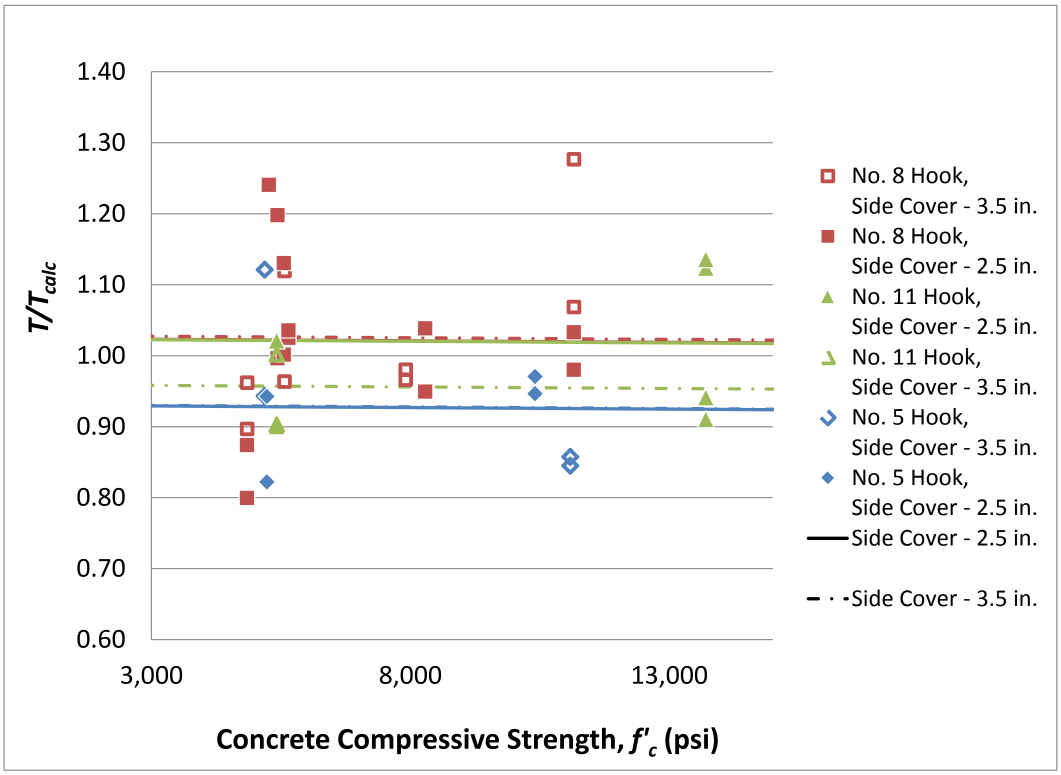


Figure 26 Ratio of test ultimate bar force to calculated ultimate bar force T/T_{calc} versus concrete compressive strength for 90° hooks with No. 3 ties at $3d_b$ as confining transverse reinforcement

4.4 EFFECT OF CONFINING TRANSVERSE REINFORCEMENT AND SIDE COVER

The effects of confining transverse reinforcement on the anchorage capacity of hooked bars are illustrated in Figures 27, 29, and 31 for No. 5, No. 8 and No. 11 bars, respectively, which compare ultimate bar force T with embedment length ℓ_{eh}. As shown in the three figures, increasing amounts of confining transverse reinforcement provide increased anchorage capacity. To account for the effect of concrete compressive strength on ultimate bar force T, analyses described in Section 4.3 established that compressive strength f_c' has less of an effect than the value $\sqrt{f_c'}$ used in ACI 318-11. The current tests indicate $f_c'^{\,0.29}$, $f_c'^{\,0.112}$, and $f_c'^{\,0.10}$ are appropriate, respectively, for hooks with no confining transverse reinforcement, hooks confined by two No. 3 ties, and hooks confined by No. 3 ties spaced at $3d_b$. To help eliminate the effect of differences in f_c', T is multiplied by the ratio of 5,000 psi to actual concrete compressive strength to the power p_1, with p_1 equal to 0.29 for hooks with no confining transverse reinforcement, 0.112 for hooks with two No. 3 ties as confining transverse reinforcement, and 0.10 for hooks with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement, to obtain the normalized ultimate bar force T_n. Similar comparisons to that shown in Figures 27, 29, and 31 are shown, respectively, in Figures 28, 30, and 32 based on normalized ultimate bar force T_n.

Figure 27 presents the results for No. 5 90° and 180° hooked bars, 32 hooks with no confining transverse reinforcement, 32 hooks with two No. 3 ties as confining transverse reinforcement, and 10 hooks with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement. The hooks have side covers of 2.5 and 3.5 in., and concrete compressive strengths range from

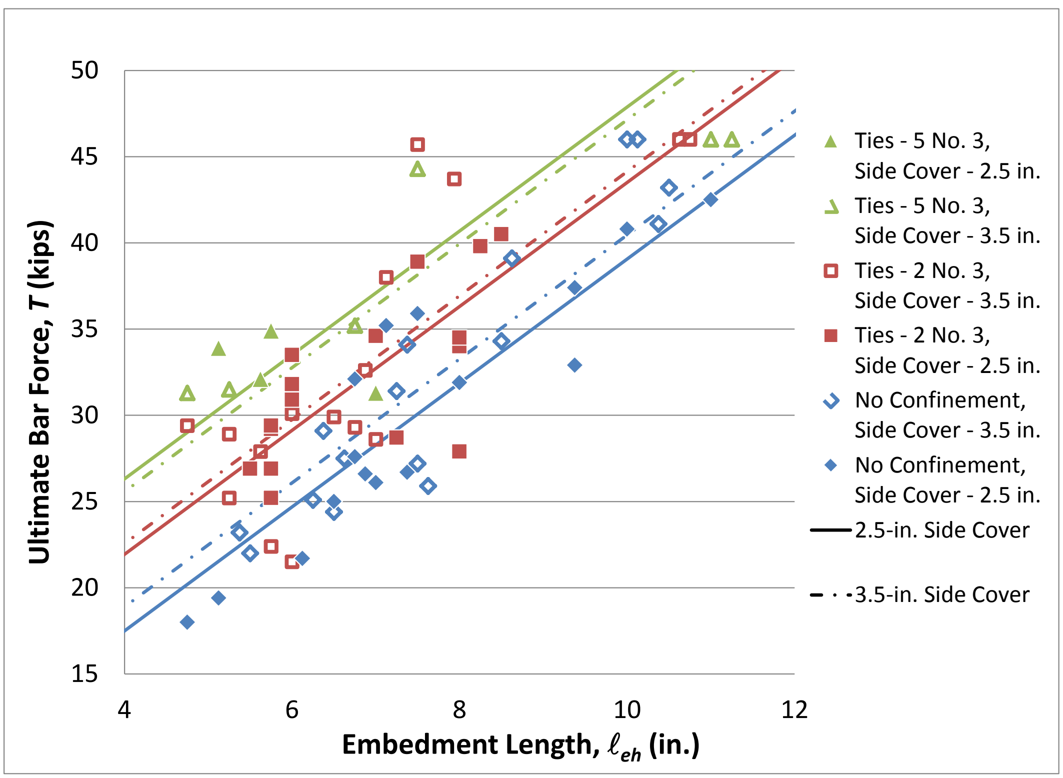


Figure 27 Ultimate bar force versus embedment length for 90° and 180° No. 5 hooks with varying quantities of transverse reinforcement and side covers

5,190 to 11,600 psi. Ultimate bar forces range from 18,000 to 46,000 lb. While there are a smaller number of hooked bars with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement than for the other two cases, a clear trend is apparent that shows an increase in anchorage capacity with an increase in the quantity of confining transverse reinforcement. Additionally, as the amount of confining transverse reinforcement increases, the effect that side cover has on anchorage capacity decreases. For the hooks with no confining transverse reinforcement, those with 3.5-in. side cover have, on average, a slightly higher ultimate bar force than corresponding hooks with 2.5-in. side cover. Hooks with two No. 3 ties as confining transverse reinforcement show, on average, no difference in strength as a function of side cover and hooks with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement exhibit a small decrease in capacity with a larger side cover.

To limit the influence of concrete compressive strength on the analysis, the same data is plotted in terms of normalized ultimate bar force T_n in Figure 28. As the quantity of confining transverse reinforcement increases, the effect side cover has on ultimate bar force again decreases. The equations characterizing hook behavior presented in Section 4.3 echo this trend represented by the decreasing power p_3 of the cover term c_b and eventual elimination of the term for moving from hooks without confining transverse reinforcement to hooks with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement. Results of Student's t-test indicate that the difference in anchorage capacity between No. 5 hooks with 2.5-in. and 3.5-in. side covers for all three levels of confinement is not statistically significant; however, this contradiction could be due to small sample sizes. For this and other evaluations of the results of dummy variable analyses, Student's t-test is performed on the intercepts with the vertical axis of lines drawn from each data point parallel to the best-fit line obtained in the dummy variables analysis. Additional testing is being conducted to confirm that increases in confinement decrease the effects of side cover.

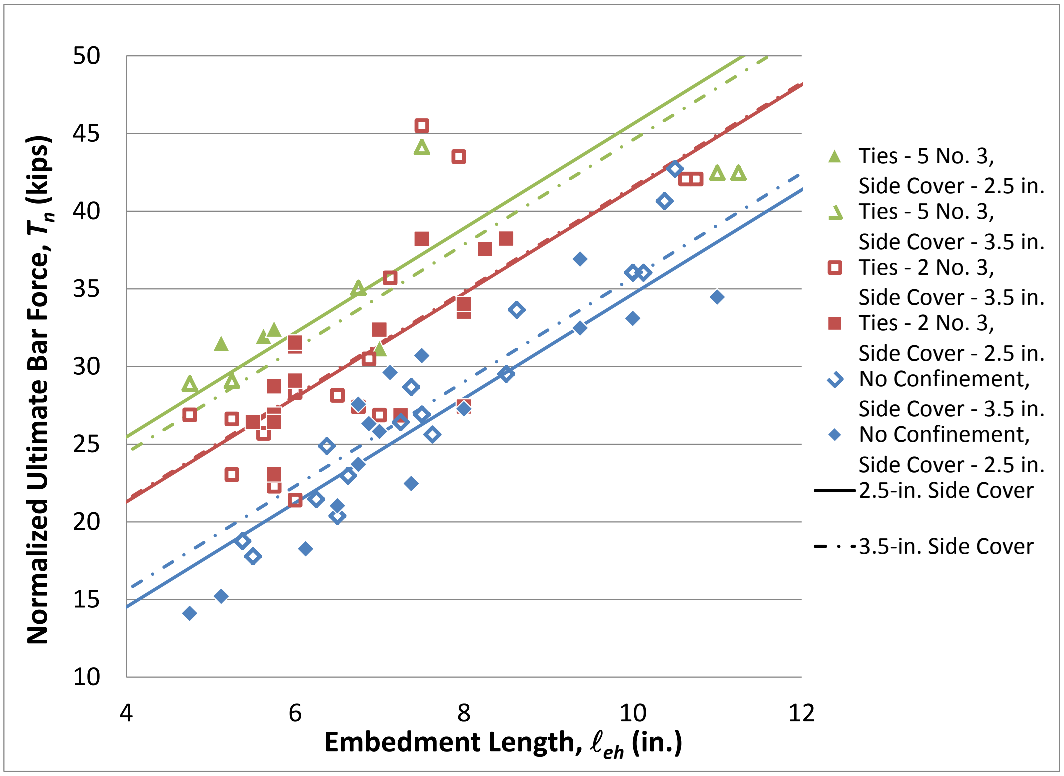


Figure 28 Normalized ultimate bar force versus embedment length for 90° and 180° No. 5 hooks with varying quantities of transverse reinforcement and side covers

Figures 29 and 30 present the results for 93 90° and 180° No. 8 hooks with 2.5-in and 3.5-in side covers and concrete compressive strengths that range from 4,300 to 11,160 psi. Justification for considering both 90° and 180° hooks is presented in Section 4.5. Of the 93 hooks, 40 hooks have no confining transverse reinforcement, 32 hooks have two No. 3 ties as confining transverse reinforcement, and 21 hooks have No. 3 ties spaced at $3d_b$ as confining transverse reinforcement, the later representing only 90° hooks. Similar to the results for the No. 5 bars, the dummy variables analysis lines in Figure 29 show that increases in the quantity of confining transverse reinforcement result in increased anchorage capacity, and as the amount of confinement increases, side cover has less of an effect on ultimate bar force. This is also seen in Section 4.3, where the effective power for cover to the center of the bar p_3 decreases with the addition of confining transverse reinforcement.

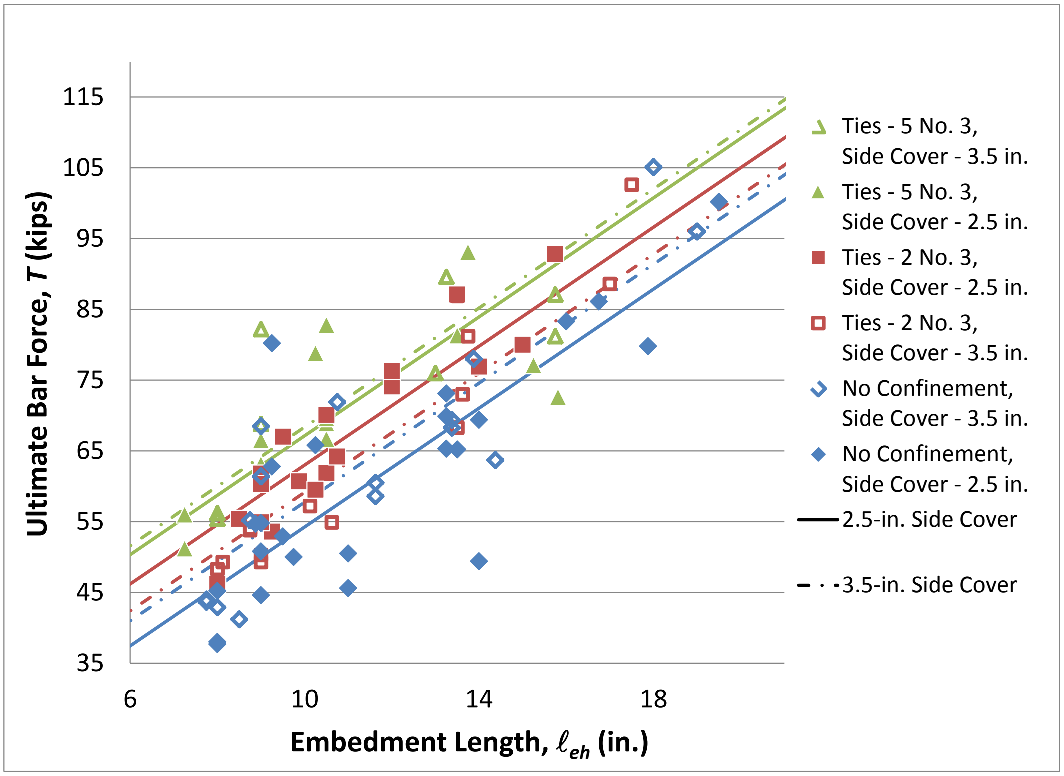


Figure 29 Ultimate bar force versus embedment length for 90° and 180° No. 8 hooks with varying quantities of transverse reinforcement and side covers

When the same data are compared in terms of anchorage strength normalized with concrete compressive strength in Figure 30, additional side cover increases anchorage capacity for bars without confining transverse reinforcement, decreases capacity for bars confined by two No. 3 ties, and has no effect on bars confined by No. 3 ties spaced at $3d_b$. The results of Student's t-test indicate that the difference in anchorage capacity between No. 8 hooks with 2.5-in. and 3.5-in. side covers when there is no confining transverse reinforcement or No. 3 ties spaced at $3d_b$ as confining transverse reinforcement is not statistically significant, but that the difference in anchorage capacity for No. 8 hooks with two No. 3 ties and 2.5-in. and 3.5-in. side covers is significant. Further testing is being conducted to determine if the results for hooks confined by two No. 3 ties are skewed due to small sample sizes and that increases in confinement decrease the effects of side cover on T_n.

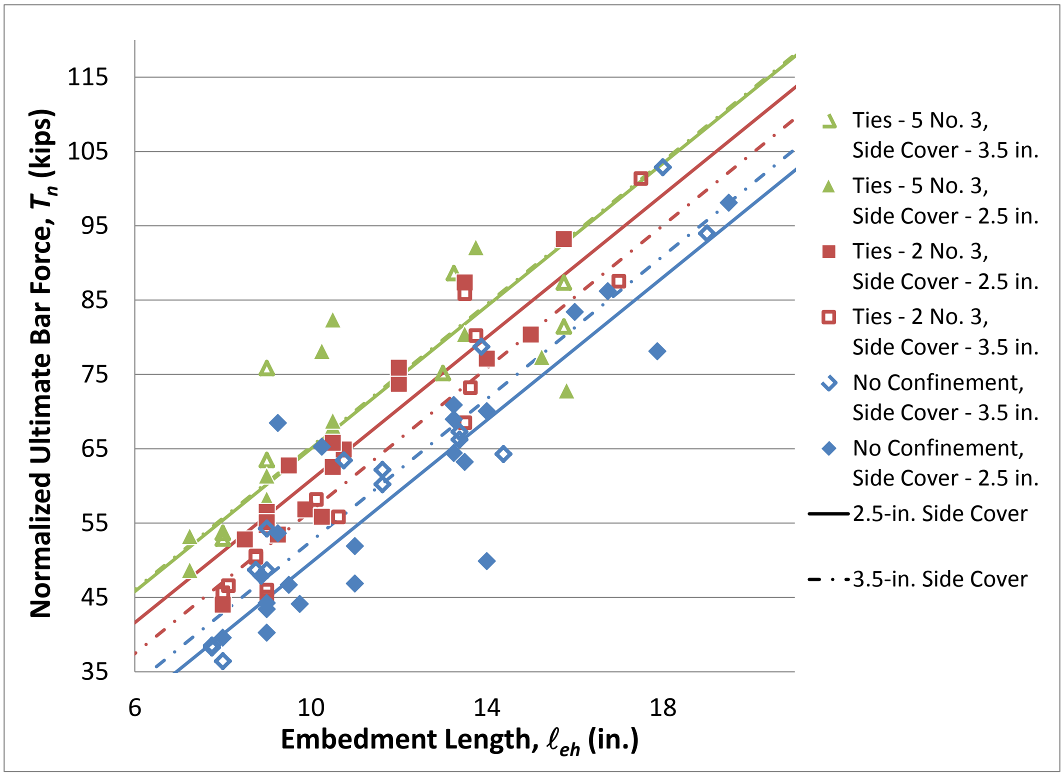


Figure 30 Normalized ultimate bar force versus embedment length for 90° and 180° No. 8 hooks with varying quantities of transverse reinforcement and side covers

Figure 31 shows the results for 90° No. 11 hooked bars with different levels of confining transverse reinforcement; to date, no 180° No 11 hooks have been tested. In accordance with Section 7.2 of ACI 318-11, No. 11 hooks are required to have a larger bend radius with respect to bar diameter than No. 5 and No. 8 hooked bars. To meet the $3d_b$ spacing requirement, six No. 3 ties must be used for No. 11 hooked bars instead of the five needed for No. 5 and No. 8 hooked bars. The results include 14 hooks with no confining transverse reinforcement, 10 hooks with two No. 3 ties as confining transverse reinforcement, and 8 hooks with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement. Concrete compressive strengths range from 4,910 to 13,710 psi and ultimate bar forces range from 13,380 to 205,100 lb. The dummy variables analyses lines in Figure 31 indicate that an increase in side cover slightly decreases the anchorage capacity for bars with no confining transverse reinforcement and hooks confined by two No. 3 ties, and greatly decreases the anchorage capacity for bars confined by No. 3 ties spaced at $3d_b$. These trends, however, ignore the effect of concrete compressive strength.

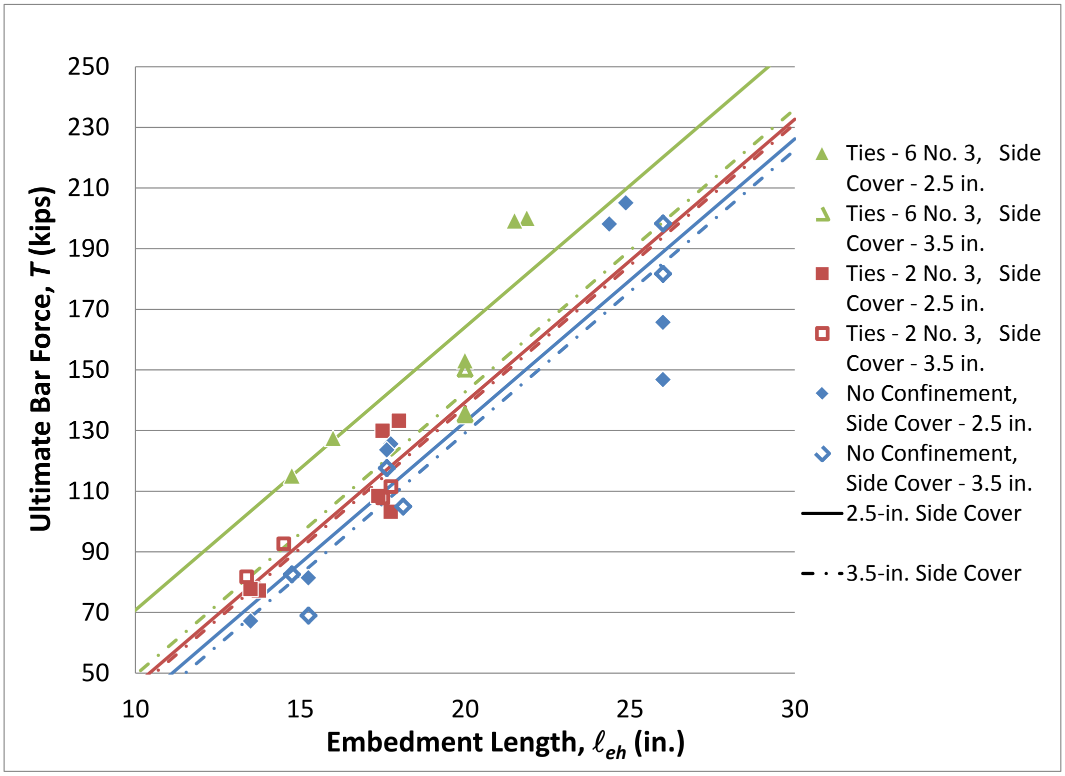


Figure 31 Ultimate bar force versus embedment length for 90° No. 11 hooks with varying quantities of transverse reinforcement and side covers

Normalizing ultimate bar force to limit the effect of differences in concrete compressive strength, as shown in Figure 32, indicates that as the quantity of confining transverse reinforcement increases, the effect of side cover on ultimate bar force decreases. The data for hooks without confining transverse reinforcement shows an increase in anchorage capacity as side cover increases, the data for hooks confined by two No. 3 ties shows no effect on anchorage strength as side cover increases, and the data for hooks confined by No. 3 ties spaced at $3d_b$ shows a decrease in anchorage capacity as side cover increases. The latter observation is likely a function of the low quantity of data. Results from the t-test analyses indicate that the difference in anchorage capacity between No. 11 hooks with 2.5-in. and 3.5-in. side covers when confined by two No. 3 ties or No. 3 ties spaced at $3d_b$ as confining transverse reinforcement is not statistically significant and that the difference in capacity between hooks with 2.5-in and 3.5-in.

side covers for No. 11 bars with no confining transverse reinforcement has a significance level of $\alpha = 0.06$. Additional tests are being conducted to solidify these results and determine if the same trends apply to 180° No. 11 hooks.

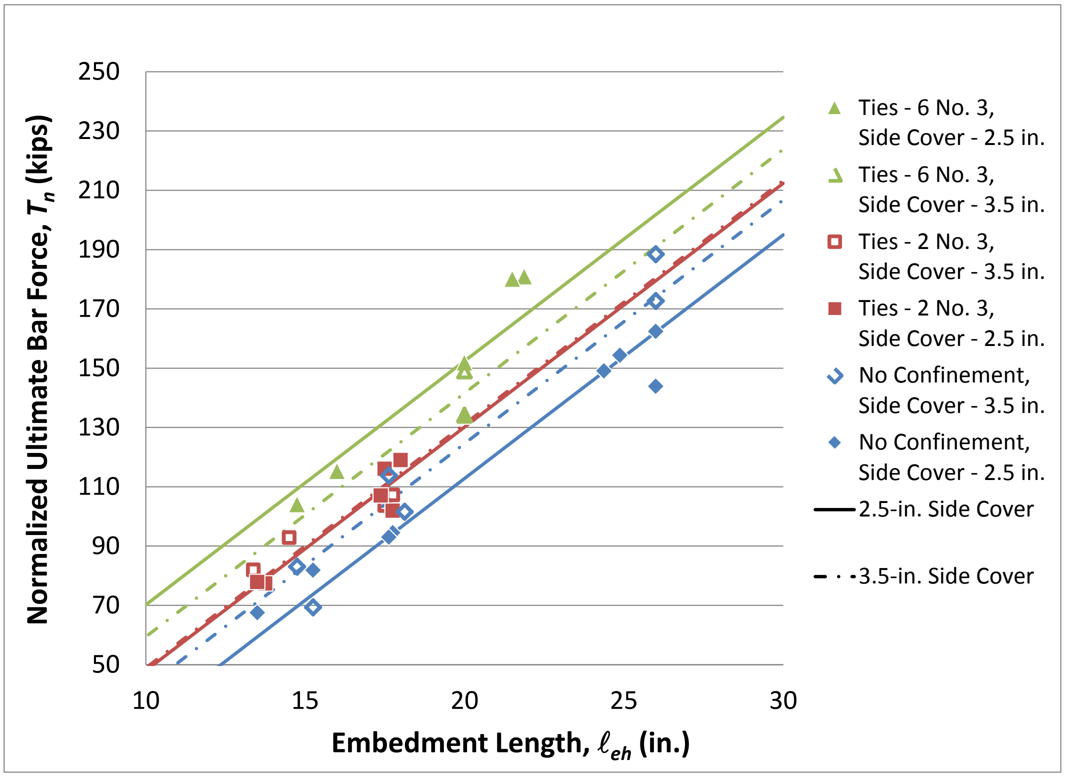


Figure 32 Normalized ultimate bar force versus embedment length for 90° No. 11 hooks with varying quantities of transverse reinforcement and side covers

4.5 EFFECT OF HOOK BEND ANGLE

Figures 33 through 36 compare the anchorage capacities of 90° and 180° hooks of No. 5 and No. 8 hooks with no confining transverse reinforcement placed inside the column core and 2.5-in. and 3.5-in. side cover. Figure 33 shows the results for 40 hooks with 2.5-in. side cover. Of the 40, 14 are 90° No. 5 hooks, 2 are 180° No. 5 hooks, 18 are 90° No. 8 hooks, and 6 are 180° No. 8 hooks. Embedment lengths ℓ_{eh} range from 4.75 to 19.5 in. and ultimate bar forces T range from 18,000 to 100,000 lb. The general trend shows an increase in ultimate bar force as embedment length increases. For a given value of ℓ_{eh}, T is about 11,000 lb higher for No. 8 bars than for No. 5 bars. There appears, however, to be no correlation between anchorage strength and bend angle. The No. 5 hooks show a slight increase in ultimate bar force when 180° hooks are used while the No. 8 hooks show a minimal decrease when 180° hooks are used. To limit the effects of concrete compressive strength, the results are compared, as described in the previous section, based on the normalized ultimate bar force T_n. As shown in Figure 34, the results are even less dependent on bend angle than indicated in Figure 33. This is supported by Student's t-test that indicate that the differences in anchorage capacity between 90° and 180° hooks for No. 5 and No. 8 bars are not statistically significant.

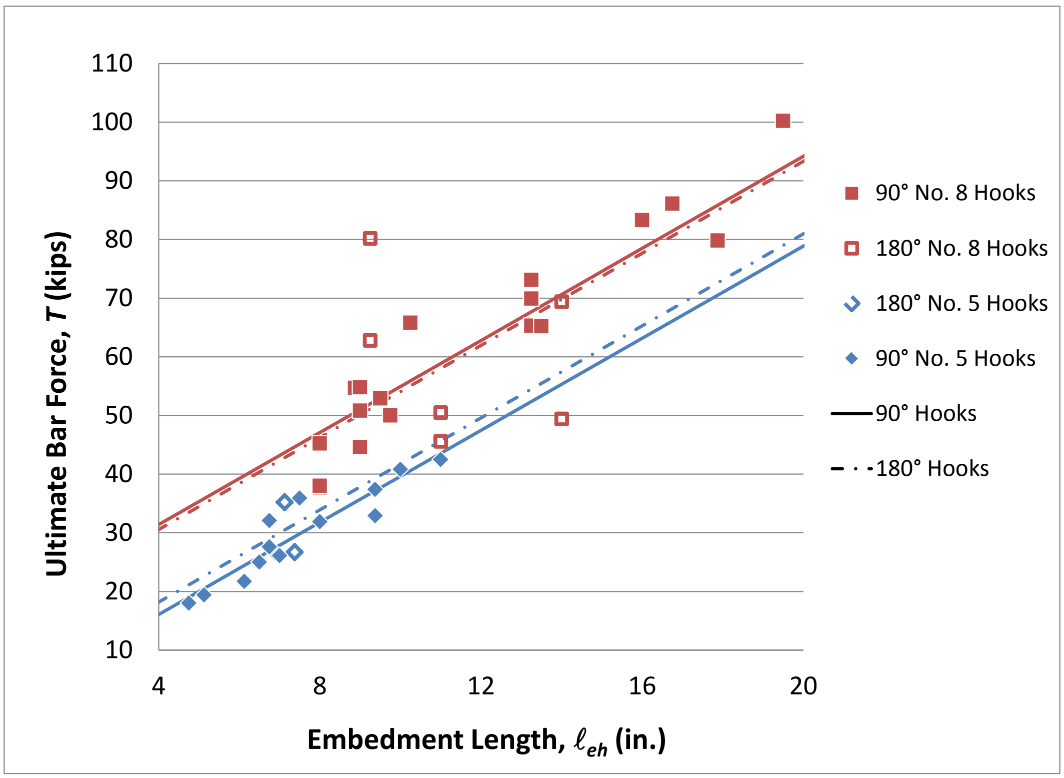


Figure 33 Comparison of No. 5 and No. 8, 90° and 180° hooks cast inside the column core with 2.5-in. side cover and no confining transverse reinforcement

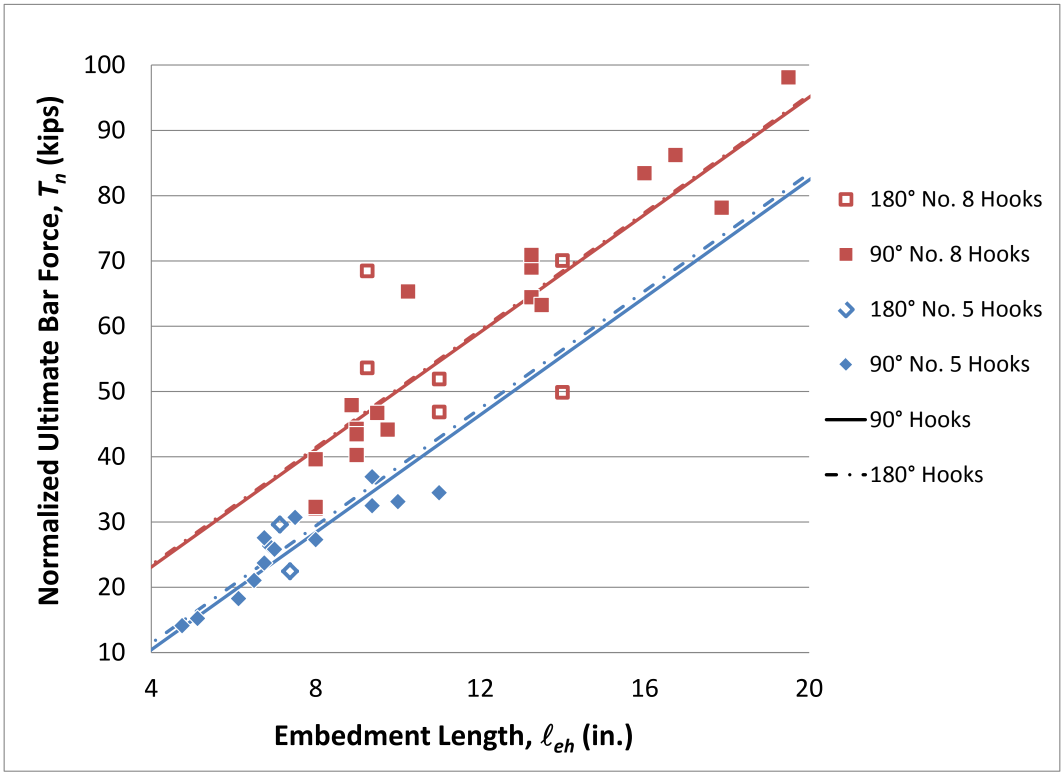


Figure 34 Comparison of normalized No. 5 and No. 8, 90° and 180° hooks cast inside the column core with 2.5-in. side cover and no confining transverse reinforcement

Figure 35 compares the anchorage strength of 90° and 180°, No. 5 and No. 8 hooks with no confining transverse reinforcement and 3.5-in. side cover. Of the 32 hooks, 14 are No. 5 bar hooks with 90° bends, 2 are No. 5 bar hooks with 180° bends, 12 are No. 8 bar hooks with 90° bends, and 4 are No. 8 bar hooks with 180° bends. Embedment lengths ℓ_{eh} range from 5.5 to 19 in. and ultimate bar forces T range from 22,000 to 105,000 lb. For a given value of ℓ_{eh}, T is about 13,000 lb higher for No. 8 bars than for No. 5 bars. The No. 5 bar tests show an increase in ultimate bar force at failure of about 2,000 lb for 180° hooks compared to 90° hooks, while the No. 8 bar tests show a decrease in ultimate bar force at failure of about 6,000 lb for 180° hooks.

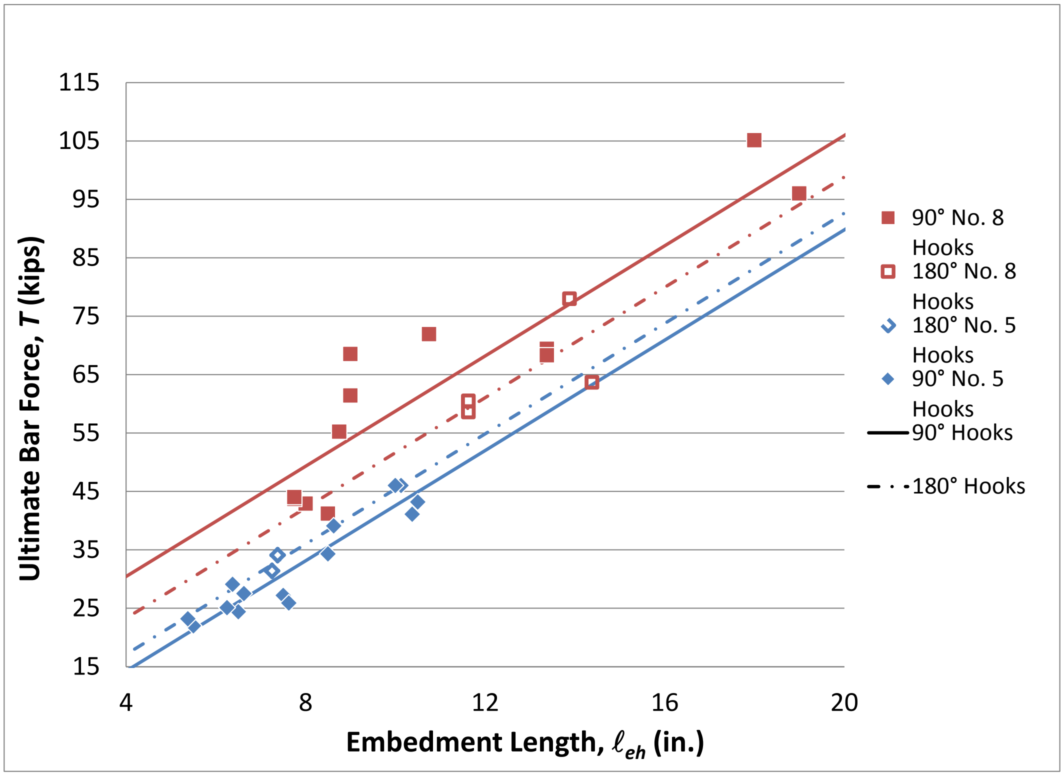


Figure 35 Comparison of No. 5 and No. 8, 90° and 180° hooks cast inside the column core with 3.5-in. side cover and no confining transverse reinforcement

When the same data are compared in Figure 36 in terms of the normalized ultimate bar force T_n, there is no difference in anchorage capacity for No. 5 and No. 8 hooks as a function of bend angle. This is supported by the results of Student's t-test that indicate that the differences in anchorage capacity between 90° and 180° hooks for No. 5 and No. 8 bars are not statistically significant. Similar comparisons are needed to confirm this trend for No. 11 bars.

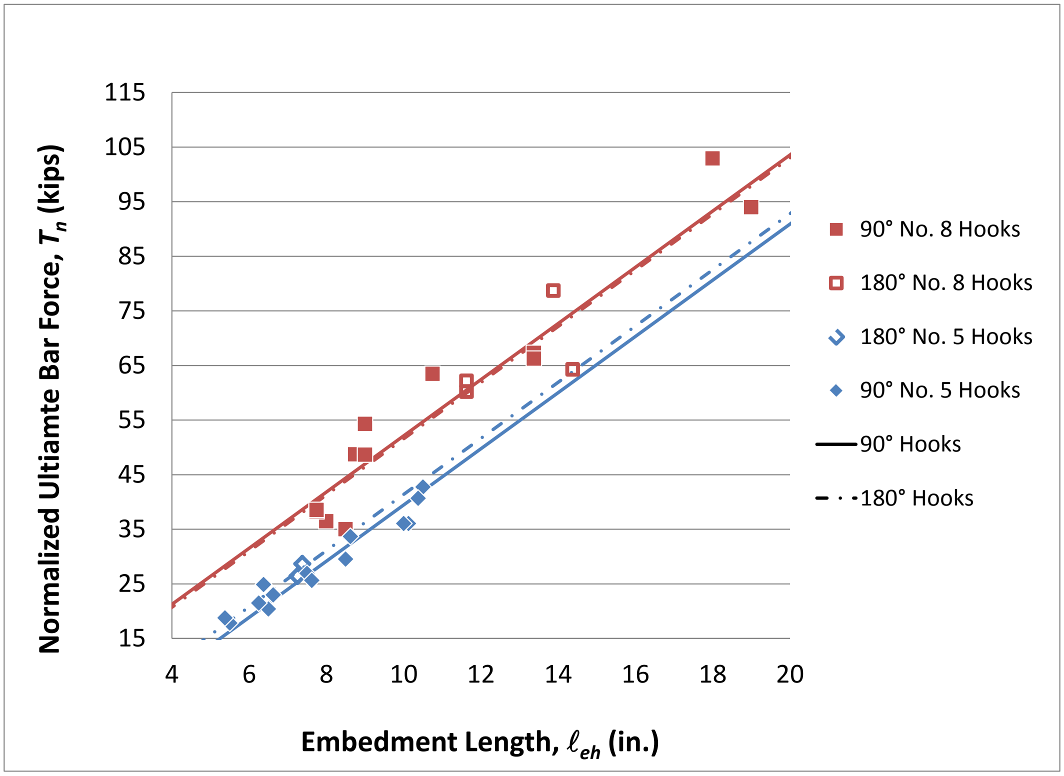


Figure 36 Comparison of normalized No. 5 and No. 8, 90° and 180° hooks cast inside the column core with 3.5-in. side cover and no confining transverse reinforcement

Figures 37 through 40 compare the anchorage strength of 90° and 180° hooks for No. 5 and No. 8 bars with two No. 3 ties as confining transverse reinforcement and 2.5-in. and 3.5-in. side cover. The ties were parallel to the straight portion of the hooked bars for both 90° and 180° hooks. Figure 37 shows the results for 34 hooks with 2.5-in. side cover. Of the 34, 10 are 90° No. 5 hooks, 6 are 180° No. 5 hooks, 12 are 90° No. 8 hooks, and 4 are 180° No. 8 hooks. Embedment lengths ℓ_{eh} range from 5.5 to 15.75 in. and ultimate bar forces T range from 25,200 to 92,800 lb. Concrete compressive strengths range from 4,550 to 11,160 psi. Similar to Figures 33 through 36, the general trend in Figure 37 shows an increase in ultimate bar force as embedment length increases and there appears to be little or no difference in anchorage strength as a function of bend angle. To limit the effects of concrete compressive strength, the comparisons are repeated based on the normalized ultimate bar force T_n. As shown in Figure 38, the space between the dummy variables analyses lines for No. 5 hooks decreases slightly while the lines remain close for No. 8 bars. A t-test analysis confirms there are no statistically significant differences between the anchorage capacities of 90° and 180° hooks for No. 5 and No. 8 bars with 2.5-in side cover. Additional testing is needed to confirm this trend for No. 11 sized bars.

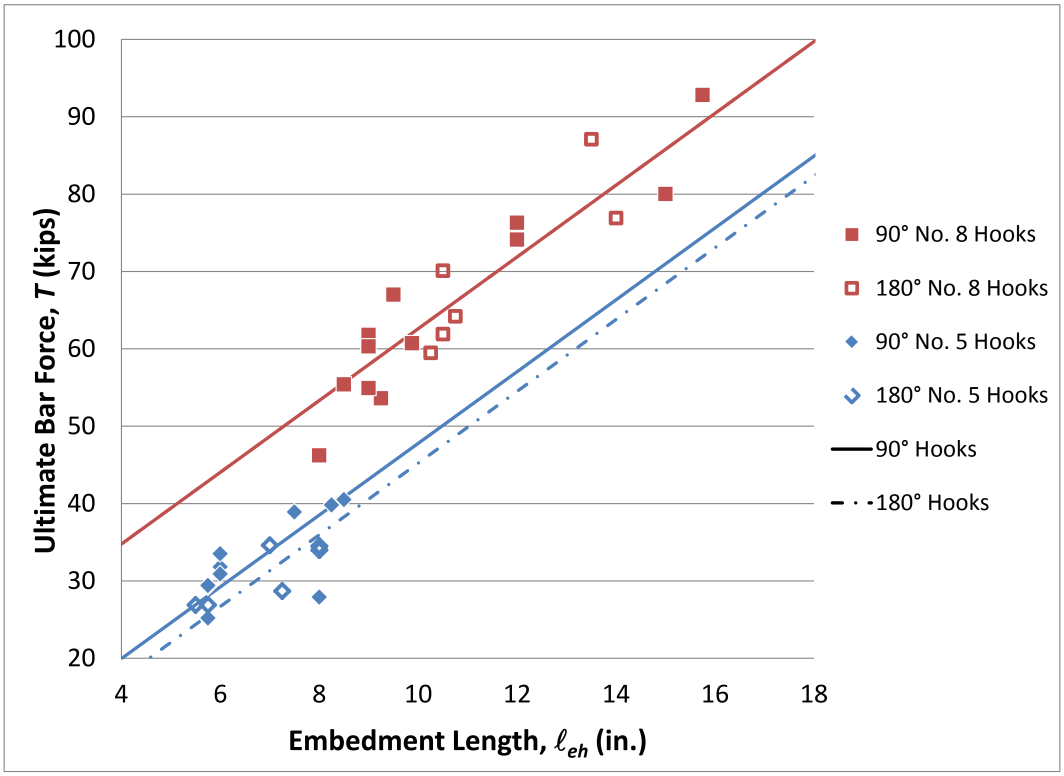


Figure 37 Comparison of No. 5 and No. 8, 90° and 180° hooks cast inside the column core with 2.5-in. side cover and two No. 3 ties as confining transverse reinforcement

Figure 39 compares the anchorage strength of 90° and 180°, No. 5 and No. 8 hooks with two No. 3 ties as confining transverse reinforcement and 3.5-in. side cover. Of the 32 hooks, 12 are 90° No. 5 hooks, 2 are 180° No. 5 hooks, 10 are 90° No. 8 hooks, and 4 are 180° No. 8 hooks. Embedment lengths ℓ_{eh} range from 5.75 to 17.50 in. and ultimate bar forces T range from 21,500 to 102,600 lb. Concrete compressive strengths range from 4,300 to 11,160 psi. There appears to be no difference in anchorage capacity between 90° and 180° No. 5 hooks; however, there is a decrease in capacity for 180° No. 8 hooks compared to 90° No. 8 hooks. When the same data are normalized to eliminate the effects of concrete compressive strength, the difference in the No. 8 dummy variable analyses lines decreases; however, the 180° No. 8 hooks still have lower anchorage strengths than 90° No. 8 hooks, as shown in Figure 40. The results of Student's t-test show that the difference in anchorage strength in 90° and 180° No. 5 bars is not statistically significant and the difference in strength between 90° and 180° No. 8 hooks has a significance level of $\alpha = 0.19$. This significance level, albeit below 0.20, is still well above 0.05, indicating the apparent lower strength of 180° No. 8 hooks compared to 90° hooks in this comparison is not strongly supported by these results. Further tests are being conducted to confirm these observations for all bar sizes.

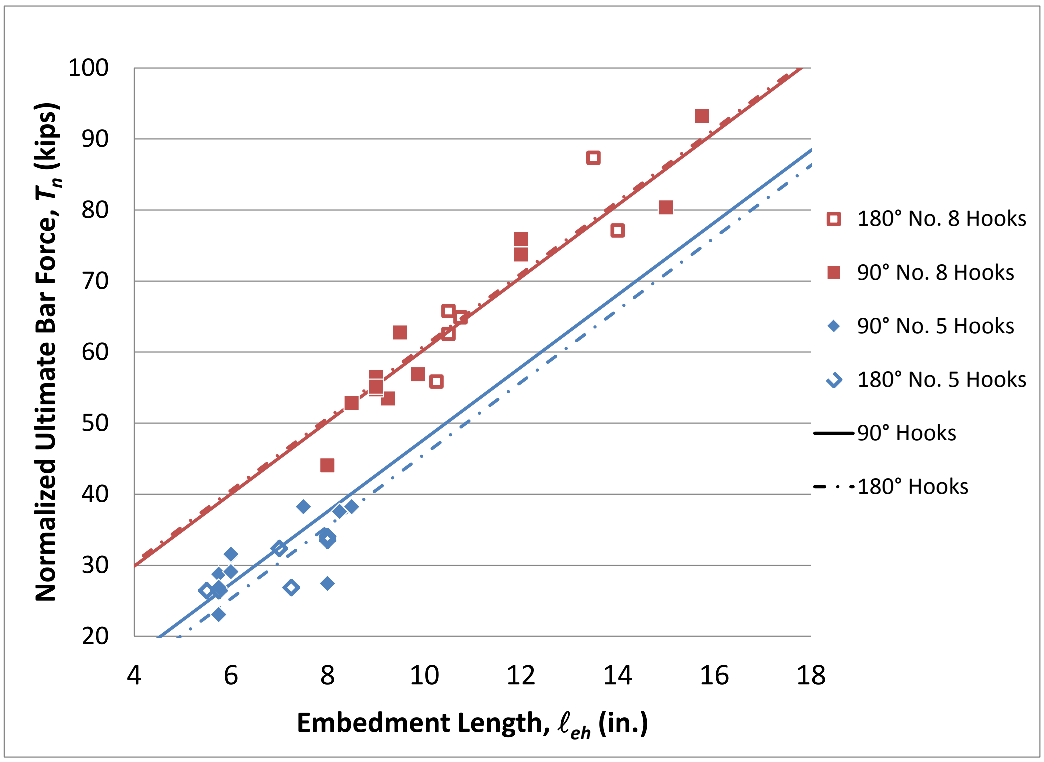


Figure 38 Comparison of normalized No. 5 and No. 8, 90° and 180° hooks cast inside the column core with 2.5-in. side cover and two No. 3 ties as confining transverse reinforcement

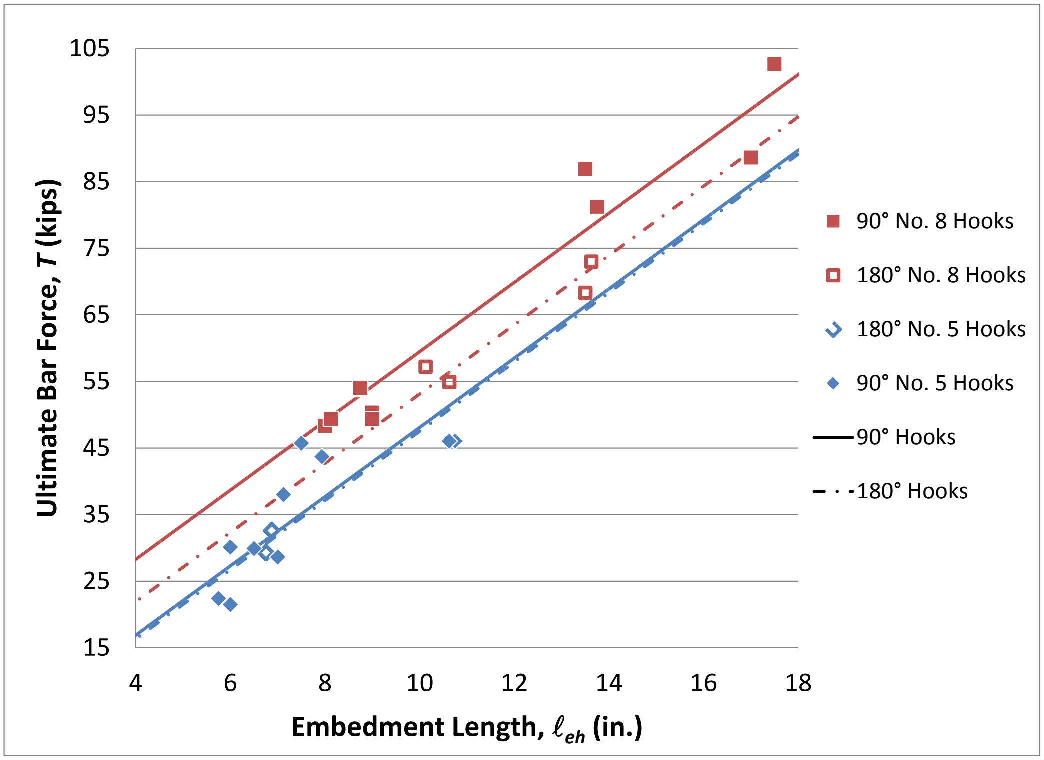


Figure 39 Comparison of No. 5 and No. 8, 90° and 180° hooks cast inside the column core with 3.5-in side cover and two No. 3 ties as confining transverse reinforcement

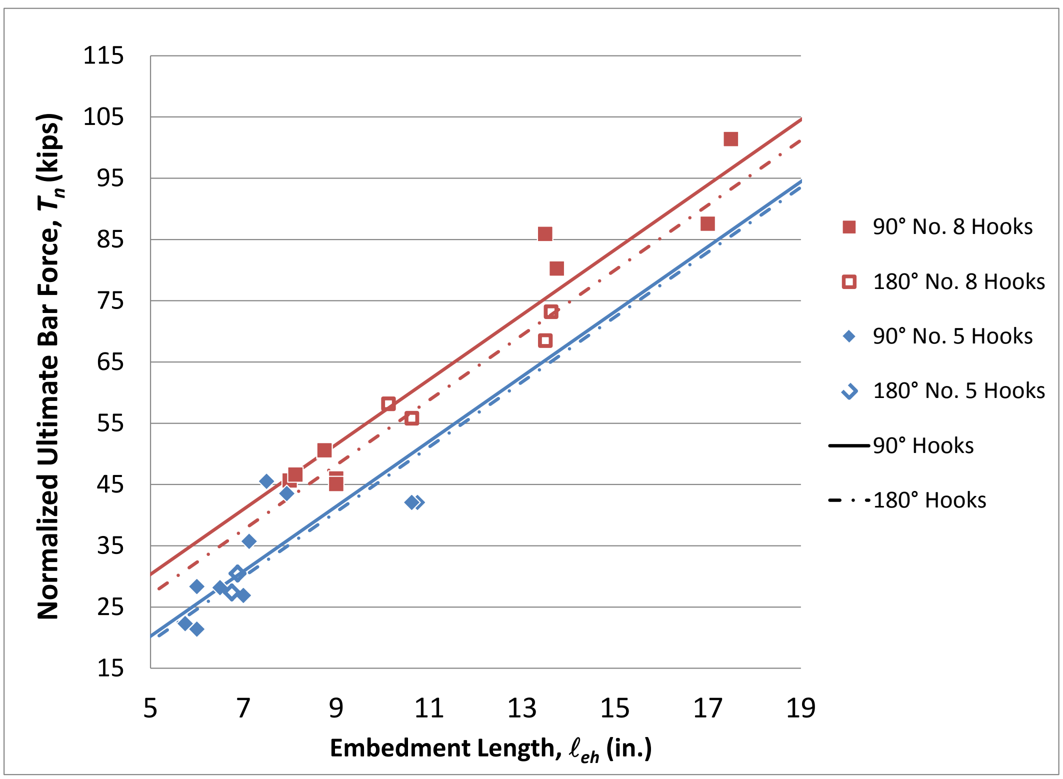


Figure 40 Comparison of normalized No. 5 and No. 8, 90° and 180° hooks cast inside the column core with 3.5-in. side cover and two No. 3 ties as confining transverse reinforcement

The spacing of two No. 3 ties used as confinement for 180° hooks is $3d_b$; however, the 0.8 reduction in development length as specified in Section 12.5.3(b) of ACI 318-11 does not apply because the ties are placed parallel to the bar being developed instead of perpendicular. For this reason, no comparison was done between 90° and 180° hooks with No. 3 ties spaced at $3d_b$, as confining transverse reinforcement. The similarity in strengths of 90° and 180° hooks confined by two No. 3 ties shown in Figures 37 through 40 strongly suggests that current ACI provisions are correct in omitting the allowance of the 0.8 reduction factor for 180° hooks with ties spaced at $3d_b$ parallel to the bar being developed. ACI 318-11 does allow the 0.8 reduction factor to be applied to 180° hooks with ties spaced at $3d_b$ perpendicular to the bar being developed; more tests, however, appear to be warranted to verify if this placement of confinement is sufficient to develop anchorage strengths high enough to justify the reduction factor to be applied.

The similarities seen in anchorage capacity between 90° and 180° hooks indicate that the two bend angles could be combined in the analysis that is used to form the characterizing equations in Section 4.3. The results of the analysis from the combined data is presented in Appendix D. The resulting equations for hooks without confining transverse reinforcement are

$$\ell_{dh} = \frac{\dfrac{A_b f_y}{f_c'^{\,1/3}} + 749}{241 d_b^{0.15} c_b^{0.3}} \tag{18}$$

$$\ell_{dh} = \frac{\left(\dfrac{A_b f_y}{109 f_c'^{\,1/3}}\right)^{\frac{5}{6}}}{d_b^{0.15} c_b^{0.3}} \tag{19}$$

The resulting equation for hooks confined by two No. 3 ties is

$$\ell_{dh} = \frac{\dfrac{A_b f_y}{f_c'^{\,0.114}} - 482}{2065 d_b^{0.3}} \tag{20}$$

4.6 EFFECT OF HOOK PLACEMENT INSIDE/OUTSIDE CORE

The effect that hook location (inside or outside the core) has on anchorage is shown in Figure 41. Hooks placed outside the core serve as a stand-in for hooks anchoring bars away from beam-column joints, such as in cantilevered beams. Figure 41 shows the results for six No. 8 hooked bars cast outside the column core without confining transverse reinforcement, six No. 8 hooked bars cast outside the column core with five No. 3 ties as confining transverse reinforcement, and five No. 8 hooked bars cast inside the column core with five No. 3 ties as confining transverse reinforcement. Five No. 3 ties in both cases meet the $3d_b$ spacing requirement for the 0.8 reduction factor in Section 12.5.3(b) of ACI 318-11. The specimens were

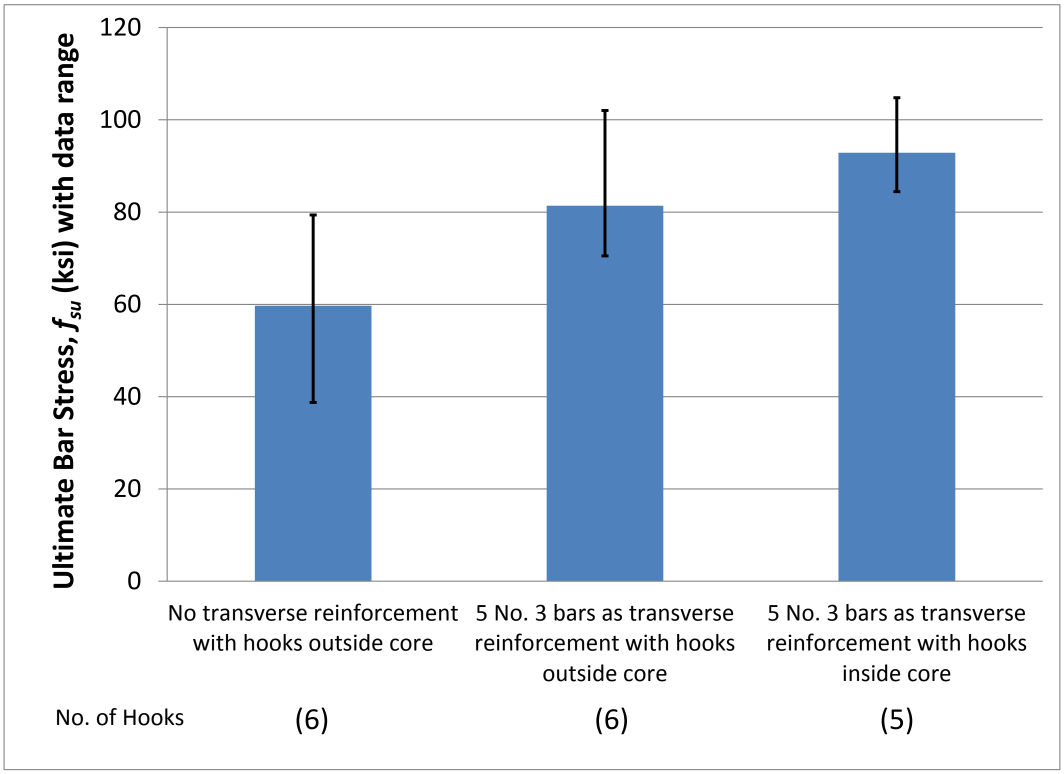


Figure 41 Comparison of inside versus outside the column core configurations for 90° No. 8 hooks with data range

cast at the same time in concrete with a nominal compressive strength of 5,000 psi and 2.5-in. side cover. The results of these tests are shown in Table 16. Figure 41 shows the average values and ranges of ultimate bar stress in ksi. The results demonstrate that hooks placed inside the column core have an increased anchorage capacity compared to hooks placed outside the column core. The results of Student's t-test indicate that the differences in anchorage capacity between No. 8 hooks cast outside the core with no confining transverse reinforcement versus those cast outside the core with No. 3 ties spaced at $3d_b$ are statistically significant. The differences in anchorage capacity between No. 8 hooks cast outside the column core with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement versus those cast with the same quantity of confining transverse reinforcement but inside the column core has a significance level of $\alpha = 0.11$.

Table 16 No. 8 hooked bars inside vs. outside column core configurations

Specimen	Hook	ℓ_{eh} in.	f'_c psi	Age days	c_{so} in.	c_{th} in.	c_h in.	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	T lbs	f_{su} psi	Failure Type
8-5-90-0-o-2.5-2-10a	A	10.25	5270	7	2.50	2.00	10.00	0.375	0	-	-	40600	51392	B/SS
	B	10.50	5270	7	2.63	1.75	10.00	0.375	0	-	-	46600	58987	SS/B
8-5-90-0-o-2.5-2-10b	A	9.25	5440	8	2.50	3.25	10.00	0.375	0	-	-	47900	60633	B/SS
	B	10.25	5440	8	2.50	2.25	10.00	0.375	0	-	-	30600	38734	SS/B
8-5-90-0-o-2.5-2-10c	A	10.75	5650	9	2.50	1.50	10.00	0.375	0	-	-	62700	79367	B/SS
	B	10.50	5650	9	2.50	1.75	10.00	0.375	0	-	-	54600	69114	SS/B/K
8-5-90-5#3-o-2.5-2-10a	A	10.25	5270	7	2.63	1.75	9.88	0.375	0.55	5	3	55700	70506	SS
	B	10.50	5270	7	2.63	2.00	9.875	0.375	0.55	5	3	55800	70633	SB
8-5-90-5#3-o-2.5-2-10b	A	10.50	5440	8	2.50	2.00	9.875	0.375	0.55	5	3	66400	84051	B/SB
	B	10.50	5440	8	2.63	2.00	9.875	0.375	0.55	5	3	69500	87975	SB/B
8-5-90-5#3-o-2.5-2-10c	A	11.25	5650	9	2.63	1.25	9.875	0.375	0.55	5	3	80600	102025	SS/B
	B	10.50	5650	9	2.50	2.00	9.875	0.375	0.55	5	3	57700	73038	SS/B
8-5-90-5#3-i-2.5-2-10a	B	10.50	5270	7	2.50	1.75	9.75	0.375	0.55	5	3	82800	104810	B/SS
8-5-90-5#3-i-2.5-2-10b	A	10.25	5440	8	2.75	2.00	9.875	0.375	0.55	5	3	78800	99747	B/SS
	B	10.50	5440	8	2.63	1.75	9.875	0.375	0.55	5	3	66700	84430	B
8-5-90-5#3-i-2.5-2-10c	A	10.50	5650	9	2.50	2.00	10.00	0.375	0.55	5	3	68900	87215	B/SS
	B	10.50	5650	9	2.50	2.00	10.00	0.375	0.55	5	3	69600	88101	B/SS

Figures 42 and 43 compare the ultimate bar force T to embedment length ℓ_{eh} for the No. 5 and No. 8 bars, respectfully, cast with no confining reinforcement and with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement placed inside and outside the column core with 2.5-in.

side cover. Figure 42 includes the results for 24 No. 5 hook tests. Of the 24, 17 hooks have no confining transverse reinforcement, including 14 hooks cast inside the column core and 3 hooks cast outside the column core. The remaining 7 data points represent hooks with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement, including 4 hooks cast inside the column core and 3 hooks cast outside the column core. Concrete compressive strengths ranged from 4,930 to 11,600 psi. Figure 43 includes the results of 47 No. 8 hook tests. Of the 47, 26 hooks have no confining transverse reinforcement, including 18 hooks cast inside the column core and 8 hooks cast outside the column core. The remaining 21 data points represent hooks with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement, including 13 hooks cast inside the column core and 8 hooks cast outside the column core. Concrete compressive strengths range from 4,850 to 11,160 psi. The parallel lines from the dummy variables analyses in both figures agree qualitatively with the results shown in Figure 41, indicating that hooks placed inside the column core have an increased anchorage capacity compared to hooks placed outside the column core.

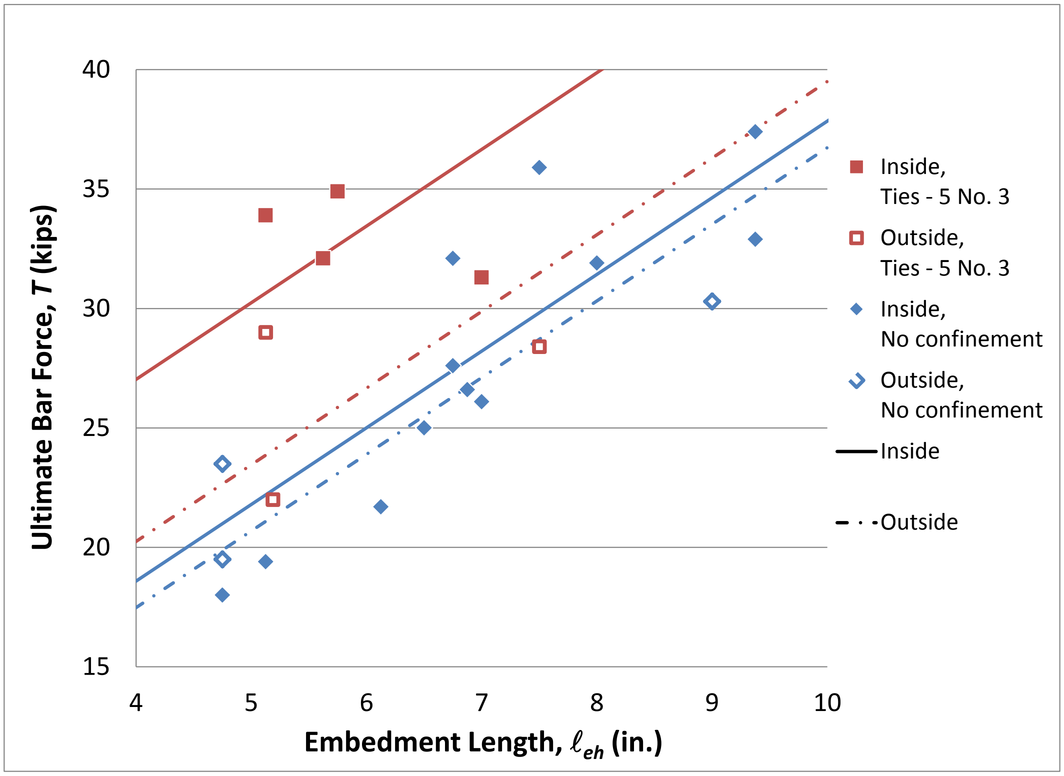


Figure 42 Comparison of inside versus outside the column core configurations for 90° No. 5 hooks with no confining transverse reinforcement and No. 3 ties spaced at $3d_b$ as confining transverse reinforcement

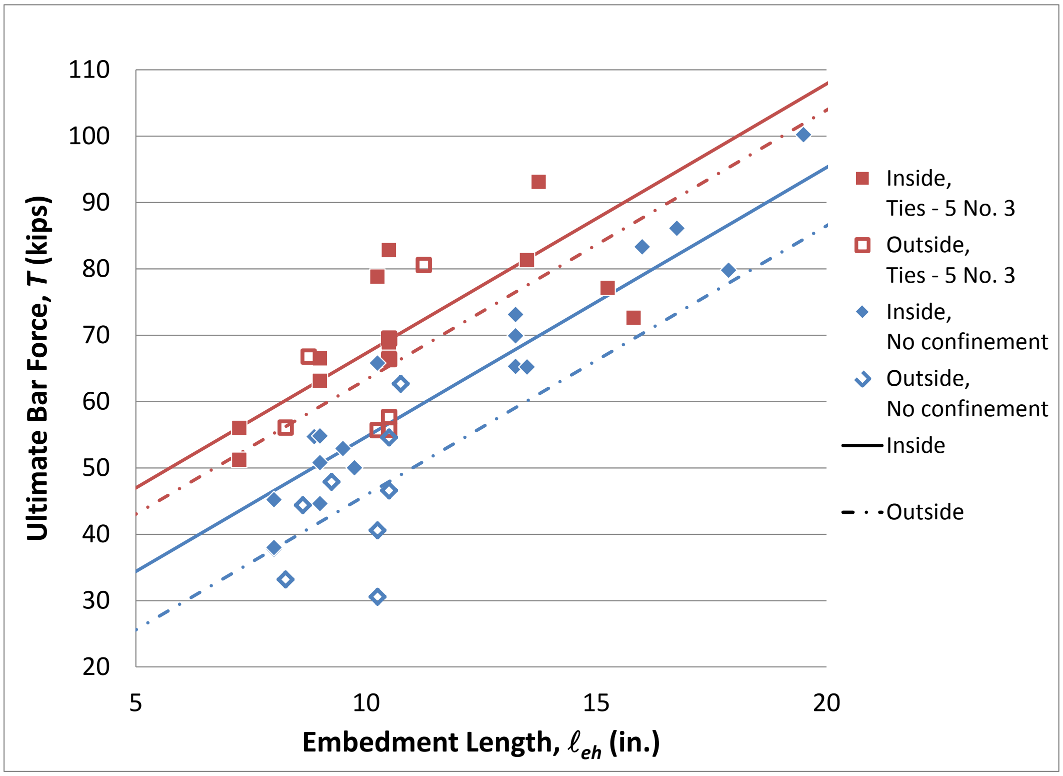


Figure 43 Comparison of inside versus outside the column core configurations for 90° No. 8 hooks with no confining transverse reinforcement and No. 3 ties spaced at $3d_b$ as confining transverse reinforcement

Figures 44 and 45 compare T_n with ℓ_{eh} for No. 5 and No. 8 bars, respectively. The trends are similar to those seen in Figures 41 through 43, with the exception of No. 5 hooks with no confining transverse reinforcement where the parallel dummy variables analysis lines indicate hooks placed outside the column core have a higher anchorage capacity than those placed inside the column core. The results from Student's t-test indicate that the differences in capacity of No. 5 hooks with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement and No. 8 hooks with no confining transverse reinforcement have a significance level of $\alpha = 0.10$. However, t-test results for No. 5 hooks with no confining transverse reinforcement and No. 8 hooks with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement indicate that the differences in anchorage capacity are not statistically significant. Because of the small number of tests of hooks cast outside of the core, especially for No. 5 hooks with no confining transverse reinforcement (three hooks, two of which came from the same specimen), further testing is being conducted to confirm the role of hook placement on anchorage capacity.

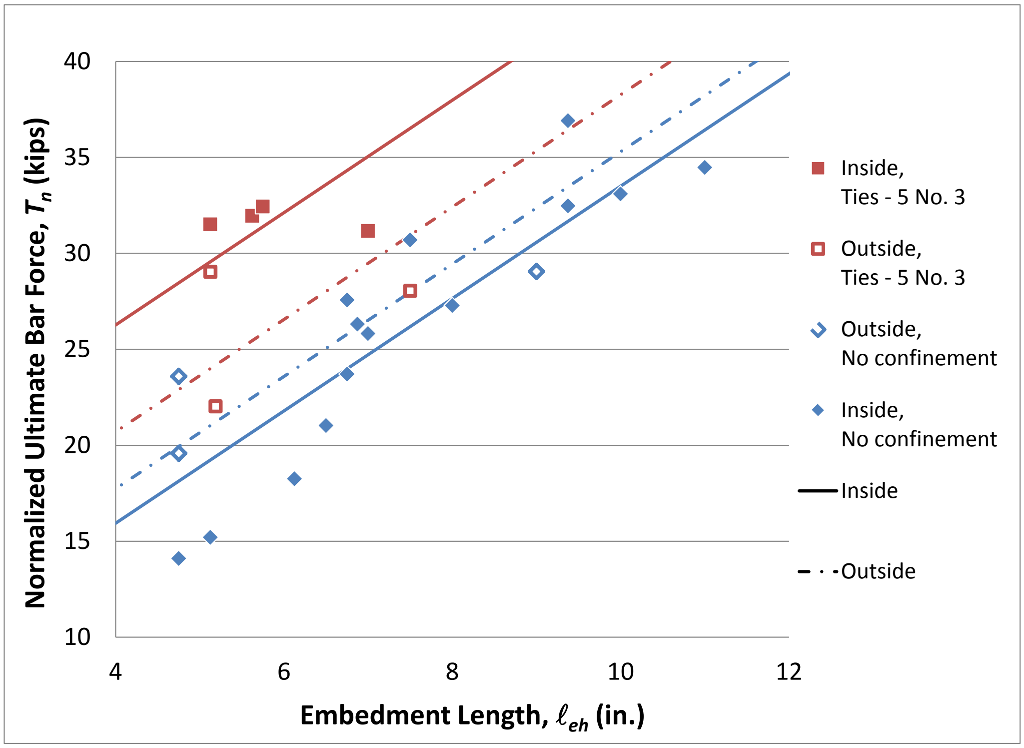


Figure 44 Comparison of inside versus outside the column core configurations for 90° No. 5 hooks with no confining transverse reinforcement and No. 3 ties spaced at $3d_b$ as confining transverse reinforcement with normalized concrete compressive strengths

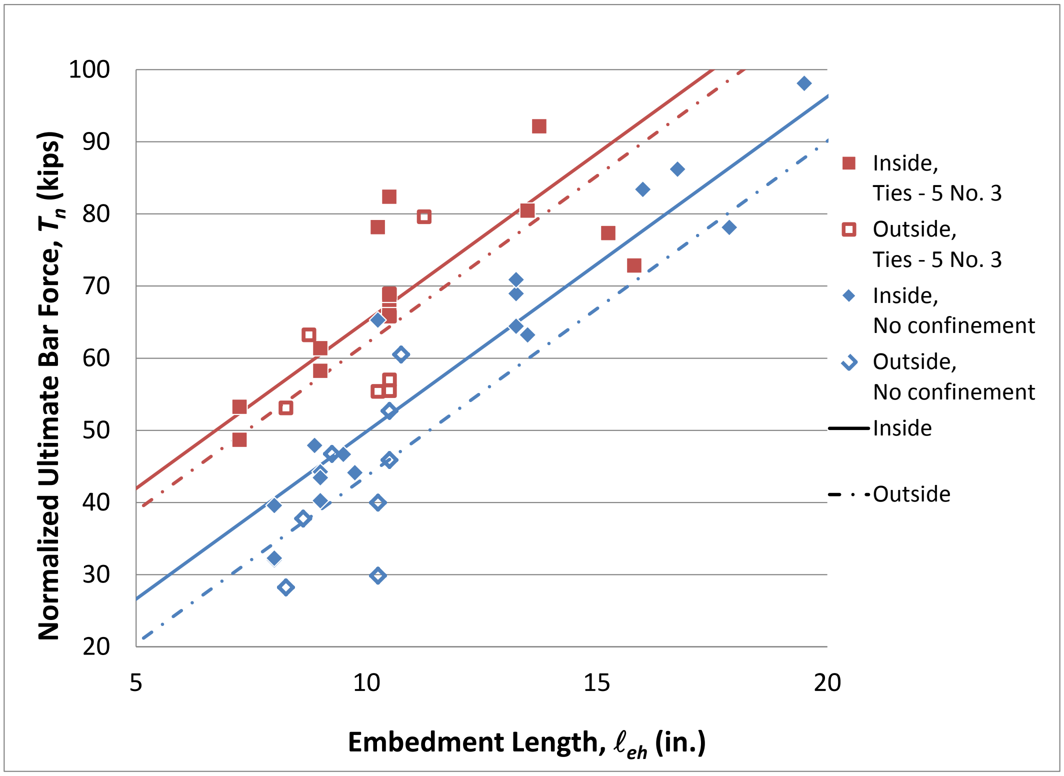


Figure 45 Comparison of inside versus outside the column core configurations for 90° No. 8 hooks with no confining transverse reinforcement and No. 3 ties spaced at $3d_b$ as confining transverse reinforcement with normalized concrete compressive strengths

CHAPTER 5 SUMMARY

5.1 SUMMARY

A total of 329 standard hooks have been tested to investigate the effects of embedment length, side cover, quantity of confining transverse reinforcement, location of hook (inside or outside the column core), concrete compressive strength, hooked bar size, and hook bend angle on anchorage capacity. No. 5, 8, and 11 hooks were tested in concrete with compressive strengths ranging from 4,300 to 13,700 psi. Equations based on the data collected in this study for hooks with no confining transverse reinforcement, hooks confined by two No. 3 ties, and hooks with No. 3 ties spaced at $3d_b$ as confining transverse reinforcement are presented.

5.2 CONCLUSIONS

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

1. Hooks cast inside the core exhibit greater ultimate anchorage force than those cast outside the core.
2. Hook bend angle appears to have no effect on ultimate anchorage force.
3. Ultimate anchorage force is increased with increased amounts of confining transverse reinforcement.
4. Side cover increases the ultimate anchorage force of hooks with no confining transverse reinforcement; however, the effect of side cover on anchorage capacity decreases as confining transverse reinforcement increases.
5. The provisions of ACI 318-11 overpredict the strength of larger hooked bars, the effect of concrete compressive strength, and the effect of transverse confining reinforcement on the ultimate anchorage force of hooked bars in tension.
6. The reduction factors in Section 12.5.3 of ACI 318-11 are unconservative.
7. Ultimate anchorage force increases with an increase in bar diameter; this effect is greater as the quantity of confining transverse reinforcement increases.

8. The ultimate anchorage force of hooked bars increases with an increase in embedment length. For bars not confined by transverse reinforcement, ultimate anchorage force increases more rapidly than increases in embedment length for the range of embedment lengths evaluated in this study. For bars confined by transverse reinforcement, ultimate anchorage force is significant even for short embedment lengths; ultimate anchorage force increases linearly with increases in embedment length, but ultimate anchorage force is less than proportional to embedment length.

5.3 FUTURE WORK

Ongoing research is being conducted to further explore the anchorage capacity of standard hooks in concrete. As well as conducting more tests on quantities of confining transverse reinforcement other than the cases emphasized in this report (none, two No. 3 ties, and No. 3 ties spaced at $3d_b$), future work will include specimens with more than two hooks, confining transverse reinforcement placed perpendicular rather than parallel to the bar being developed, concrete strengths as high as 15,000 psi, and specimens with varying depths for the simulated beam. Furthermore, another project testing the anchorage capacity of headed bars is being conducted side by side with the hook tests, giving a direct comparison between the two forms of mechanical anchorage for bars in tension.

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APPENDIX A NOTATION

A_h	Bar area of hook
A_{tr}	Area of transverse bars in 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_{th}	Clear cover measured from the tail of the hook to the back of the column
d_b	Nominal bar diameter of the hook
d_{tr}	Nominal bar diameter of transverse reinforcement
f_c'	Concrete compressive strength
f_{su}	Stress in hook at failure
f_{yt}	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_{eh}	Embedment length measured from the back of the hook to the front of the column
N_h	Number of hooks loaded simultaneously
N_{tr}	Number of stirrups/ties crossing the hook
T	Load on hook at failure
T_n	Load on hook at failure multiplied by concrete compressive strength normalized to 5,000 psi
T_{ACI}	Load on hook at failure as calculated by Section 12.5.3 of ACI 318-11
T_{calc}	Load on hook at failure as calculated by the equated derived in Sections 5.6.1 and 5.6.2
R_r	Relative rib area
s_{tr}	Center-to-center spacing of stirrups/ties around the hook

Failure types (described in Section 3.3)

FP	Front Pullout
FB	Front Blowout
SS	Side Splitting
SB	Side Blowout
K	Tail Kickout

Specimen identification

A-B-C-D#E-F-G-H-Ix(J)

A	ASTM in.-lb bar size
B	Nominal compressive strength of concrete
C	Angle of bend
D	Number of bars used as transverse reinforcement within the hook region
E	ASTM in.-lb bar size of transverse reinforcement (D#E = 0 = no transverse reinforcement)
F	Hooked bars placed inside (i) or outside (o) of longitudinal reinforcement
G	Nominal value of c_{so}
H	Nominal value of c_{th}
I	Nominal value of l_{eh}
x	Replication in a series, blank (or a), b, c, etc.
J	Replication not in a series

APPENDIX B TEST RESULTS

Table B1 Test results

Specimen	Hook	Bend Angle	Radius of Bend	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	f'_c psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
5-12-90-0-i-2.5-2-10	A	90°	1 7/8	Horizontal	A1035	10.00	10290	14	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	11.00	10290	14	0.625	0.073	13	5.25	8.38
5-12-90-0-i-2.5-2-5	A	90°	1 7/8	Horizontal	A1035	5.13	11600	84	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	4.75	11600	84	0.625	0.073	13	5.25	8.38
5-12-90-0-i-3.5-2-10	A	90°	1 7/8	Horizontal	A1035	10.13	11600	84	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	10.00	11600	84	0.625	0.073	15	5.25	8.38
5-12-90-0-i-3.5-2-5	A	90°	1 7/8	Horizontal	A1035	5.50	10410	15	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	5.38	10410	15	0.625	0.073	15	5.25	8.38
5-12-90-2#3-i-2.5-2-5	A	90°	1 7/8	Horizontal	A1035	5.75	11090	83	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	5.75	11090	83	0.625	0.073	13	5.25	8.38
5-12-90-2#3-i-3.5-2-10	A	90°	1 7/8	Horizontal	A1035	10.75	11090	83	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	10.63	11090	83	0.625	0.073	15	5.25	8.38
5-12-90-2#3-i-3.5-2-5	A	90°	1 7/8	Horizontal	A1035	5.63	10410	15	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	5.25	10410	15	0.625	0.073	15	5.25	8.38
5-12-90-5#3-i-2.5-2-5	A	90°	1 7/8	Horizontal	A1035	5.13	10410	15	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	5.75	10410	15	0.625	0.073	13	5.25	8.38
5-12-90-5#3-i-3.5-2-10	A	90°	1 7/8	Horizontal	A1035	11.00	11090	83	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	11.25	11090	83	0.625	0.073	15	5.25	8.38
5-12-90-5#3-i-3.5-2-5	A	90°	1 7/8	Horizontal	A1035	5.25	11090	83	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	4.75	11090	83	0.625	0.073	15	5.25	8.38
5-5-180-0-o-1.5-2-11.25	A	180°	2	Horizontal	A1035	11.25	4520	8	0.625	0.077	11	5.25	8.38
5-5-180-0-o-1.5-2-9.5	A	180°	2	Horizontal	A1035	9.63	4420	7	0.625	0.077	11	5.25	8.38
	B	180°	2	Horizontal	A1035	9.25	4420	7	0.625	0.077	11	5.25	8.38
5-5-180-0-o-2.5-2-9.5	A	180°	2	Horizontal	A1035	9.50	4520	8	0.625	0.077	13	5.25	8.38
	B	180°	2	Horizontal	A1035	9.50	4520	8	0.625	0.077	13	5.25	8.38
5-5-180-1#3-i-2.5-2-6	A	180°	2	Horizontal	A615	6.00	5800	9	0.625	0.060	13	5.25	8.38
	B	180°	2	Horizontal	A615	6.00	5800	9	0.625	0.060	13	5.25	8.38
5-5-180-1#3-i-2.5-2-8	A	180°	2	Horizontal	A1035	8.00	5670	7	0.625	0.073	13	5.25	8.38
	B	180°	2	Horizontal	A1035	7.75	5670	7	0.625	0.073	13	5.25	8.38
5-5-180-1#4-i-2.5-2-6	A	180°	2	Horizontal	A615	6.50	5670	7	0.625	0.060	13	5.25	8.38
	B	180°	2	Horizontal	A615	6.00	5670	7	0.625	0.060	13	5.25	8.38
5-5-180-1#4-i-2.5-2-8	A	180°	2	Horizontal	A1035	8.00	5310	6	0.625	0.073	13	5.25	8.38
	B	180°	2	Horizontal	A1035	8.00	5310	6	0.625	0.073	13	5.25	8.38
5-5-180-2#3-i-2.5-2-6	A	180°	2	Horizontal	A615	5.75	5860	8	0.625	0.060	13	5.25	8.38
	B	180°	2	Horizontal	A615	5.50	5860	8	0.625	0.060	13	5.25	8.38
5-5-180-2#3-i-2.5-2-8	A	180°	2	Horizontal	A1035	8.00	5670	7	0.625	0.073	13	5.25	8.38
	B	180°	2	Horizontal	A1035	8.00	5670	7	0.625	0.073	13	5.25	8.38
5-5-180-2#3-o-1.5-2-11.25	A	180°	2	Horizontal	A1035	11.63	4420	7	0.625	0.077	11	5.25	8.38
	B	180°	2	Horizontal	A1035	11.50	4420	7	0.625	0.077	11	5.25	8.38
5-5-180-2#3-o-1.5-2-9.5	B	180°	2	Horizontal	A1035	8.75	4520	8	0.625	0.077	11	5.25	8.38
5-5-180-2#3-o-2.5-2-11.25	A	180°	2	Horizontal	A1035	11.13	4520	8	0.625	0.077	13	5.25	8.38
	B	180°	2	Horizontal	A1035	11.38	4520	8	0.625	0.077	13	5.25	8.38
5-5-180-2#3-o-2.5-2-9.5	A	180°	2	Horizontal	A1035	9.13	4420	7	0.625	0.077	13	5.25	8.38
	B	180°	2	Horizontal	A1035	9.25	4420	7	0.625	0.077	13	5.25	8.38
5-5-90-0-i-2.5-2-10	A	90°	1 7/8	Horizontal	A1035	9.38	5230	6	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	9.38	5230	6	0.625	0.073	13	5.25	8.38
5-5-90-0-i-2.5-2-7	A	90°	1 7/8	Horizontal	A1035	6.88	5190	7	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	7.00	5190	7	0.625	0.073	13	5.25	8.38
5-5-90-0-i-3.5-2-10	A	90°	1 7/8	Horizontal	A1035	10.50	5190	7	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	10.38	5190	7	0.625	0.073	15	5.25	8.38
5-5-90-0-i-3.5-2-7	A	90°	1 7/8	Horizontal	A1035	7.50	5190	7	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	7.63	5190	7	0.625	0.073	15	5.25	8.38
5-5-90-0-o-1.5-2-5	A	90°	1 7/8	Horizontal	A615	5.00	4930	4	0.625	0.077	11	5.25	8.38
	B	90°	1 7/8	Horizontal	A615	5.00	4930	4	0.625	0.077	11	5.25	8.38
5-5-90-0-o-1.5-2-6.5	A	90°	1 7/8	Horizontal	A1035	6.50	5650	6	0.625	0.073	11	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	5.88	5650	6	0.625	0.073	11	5.25	8.38
5-5-90-0-o-1.5-2-8	B	90°	1 7/8	Horizontal	A1035	7.88	5650	6	0.625	0.073	11	5.25	8.38
5-5-90-0-o-2.5-2-5	A	90°	1 7/8	Horizontal	A615	4.75	4930	4	0.625	0.077	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A615	4.75	4930	4	0.625	0.077	13	5.25	8.38

Table B.1 cont. Test results

Specimen	Hook	c_{so} in.	c_{th} in.	c_h in.	N_h	A_h in.^{2}	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	T kip	f_{su} ksi	Failure Type
5-12-90-0-i-2.5-2-10	A	2.38	2.00	6.63	2	0.31	60	-	0	0	-	40.8	131.6	SB
	B	2.50	2.00	6.63	2	0.31	60	-	0	0	-	42.5	137.1	FB/SB/K
5-12-90-0-i-2.5-2-5	A	2.63	2.13	6.50	2	0.31	60	-	0	0	-	19.4	62.6	FP/SS
	B	2.63	2.50	6.50	2	0.31	60	-	0	0	-	18.0	58.1	FP
5-12-90-0-i-3.5-2-10	A	3.50	2.50	6.75	2	0.31	60	-	0	0	-	46.0	148.4	*
	B	3.50	1.50	6.75	2	0.31	60	-	0	0	-	46.0	148.4	*
5-12-90-0-i-3.5-2-5	A	3.63	1.69	7.00	2	0.31	60	-	0	0	-	22.0	71.0	FP
	B	3.63	1.81	7.00	2	0.31	60	-	0	0	-	23.2	74.8	FP
5-12-90-2#3-i-2.5-2-5	A	2.50	3.00	6.50	2	0.31	60	0.38	0.22	2	3.3	25.2	81.3	FP/SS
	B	2.75	3.00	6.50	2	0.31	60	0.38	0.22	2	3.3	29.4	94.8	FP
5-12-90-2#3-i-3.5-2-10	A	3.50	2.00	6.75	2	0.31	60	0.38	0.22	2	3.3	46.0	148.4	*
	B	3.63	2.13	6.75	2	0.31	60	0.38	0.22	2	3.3	46.0	148.4	*
5-12-90-2#3-i-3.5-2-5	A	3.75	1.81	6.63	2	0.31	60	0.38	0.22	2	3.3	27.9	90.0	FP
	B	3.50	2.19	6.63	2	0.31	60	0.38	0.22	2	3.3	28.9	93.2	FP
5-12-90-5#3-i-2.5-2-5	A	2.63	2.13	6.50	2	0.31	60	0.38	0.55	5	1.7	33.9	109.4	FP/SS
	B	2.63	1.50	6.50	2	0.31	60	0.38	0.55	5	1.7	34.9	112.6	SS/FP
5-12-90-5#3-i-3.5-2-10	A	3.50	2.00	6.88	2	0.31	60	0.38	0.55	5	1.7	46.0	148.4	*
	B	3.50	1.75	6.88	2	0.31	60	0.38	0.55	5	1.7	46.0	148.4	*
5-12-90-5#3-i-3.5-2-5	A	3.25	2.50	6.63	2	0.31	60	0.38	0.55	5	1.7	31.5	101.6	FP
	B	3.25	1.50	6.63	2	0.31	60	0.38	0.55	5	1.7	31.3	101.0	FP
5-5-180-0-o-1.5-2-11.25	A	1.75	2.25	6.63	2	0.31	60	-	0	0	-	32.4	104.5	FP/SB
5-5-180-0-o-1.5-2-9.5	A	1.63	2.13	6.38	2	0.31	60	-	0	0	-	35.2	113.5	FP
	B	1.63	2.13	6.38	2	0.31	60	-	0	0	-	30.4	98.1	FP/SB
5-5-180-0-o-2.5-2-9.5	A	2.50	1.88	6.63	2	0.31	60	-	0	0	-	40.4	130.3	FP
	B	2.50	1.75	6.63	2	0.31	60	-	0	0	-	34.0	109.7	FP
5-5-180-1#3-i-2.5-2-6	A	2.63	2.00	6.63	2	0.31	60	0.38	0.11	1	4.0	29.1	93.9	SS/FP
	B	2.63	2.00	6.63	2	0.31	60	0.38	0.11	1	4.0	24.3	78.4	FP/SS
5-5-180-1#3-i-2.5-2-8	A	2.63	2.25	6.63	2	0.31	60	0.38	0.11	1	4.0	36.6	118.1	SS
	B	2.50	2.50	6.63	2	0.31	60	0.38	0.11	1	4.0	39.9	128.7	SS/FP
5-5-180-1#4-i-2.5-2-6	A	2.50	2.00	6.63	2	0.31	60	0.50	0.20	1	4.0	25.3	81.6	FP/SS
	B	2.63	2.50	6.63	2	0.31	60	0.50	0.20	1	4.0	22.9	73.9	FP
5-5-180-1#4-i-2.5-2-8	A	2.50	2.00	6.63	2	0.31	60	0.50	0.20	1	4.0	43.1	139.0	FP/SS
	B	2.50	2.00	6.63	2	0.31	60	0.50	0.20	1	4.0	38.4	123.9	FP
5-5-180-2#3-i-2.5-2-6	A	2.63	2.00	6.63	2	0.31	60	0.38	0.22	2	2.5	26.9	86.8	FP/SS
	B	2.63	2.25	6.63	2	0.31	60	0.38	0.22	2	2.5	26.9	86.8	FP
5-5-180-2#3-i-2.5-2-8	A	2.50	2.00	6.88	2	0.31	60	0.38	0.22	2	2.5	34.0	109.7	FP/SS
	B	2.50	2.00	6.88	2	0.31	60	0.38	0.22	2	2.5	34.5	111.3	FP/SS
5-5-180-2#3-o-1.5-2-11.25	A	1.63	1.88	6.63	2	0.31	60	0.38	0.22	2	2.0	48.3	155.8	FP/SB
	B	1.50	1.88	6.63	2	0.31	60	0.38	0.22	2	2.0	43.0	138.7	FP/SB
5-5-180-2#3-o-1.5-2-9.5	B	1.63	2.38	6.63	2	0.31	60	0.38	0.22	2	2.0	20.3	65.5	FP/SB
5-5-180-2#3-o-2.5-2-11.25	A	2.50	2.50	6.63	2	0.31	60	0.38	0.22	2	2.0	43.6	140.6	FP
	B	2.75	2.13	6.63	2	0.31	60	0.38	0.22	2	2.0	42.5	137.1	FP/SB
5-5-180-2#3-o-2.5-2-9.5	A	2.50	2.13	6.63	2	0.31	60	0.38	0.22	2	2.0	35.5	114.5	FP/SB
	B	2.50	2.00	6.63	2	0.31	60	0.38	0.22	2	2.0	43.9	141.6	FP
5-5-90-0-i-2.5-2-10	A	2.75	2.88	6.44	2	0.31	60	-	0	0	-	37.4	120.6	FP/SS
	B	2.63	2.88	6.44	2	0.31	60	-	0	0	-	32.9	106.1	FP/SS
5-5-90-0-i-2.5-2-7	A	2.50	2.75	6.75	2	0.31	60	-	0	0	-	26.6	85.8	FP/SS
	B	2.50	2.63	6.75	2	0.31	60	-	0	0	-	26.1	84.2	FP/SS
5-5-90-0-i-3.5-2-10	A	3.50	1.75	6.50	2	0.31	60	-	0	0	-	43.2	139.4	SB/FP
	B	3.50	1.88	6.50	2	0.31	60	-	0	0	-	41.1	132.6	SB/FP
5-5-90-0-i-3.5-2-7	A	3.38	1.25	7.00	2	0.31	60	-	0	0	-	27.2	87.7	SS
	B	3.50	1.13	7.00	2	0.31	60	-	0	0	-	25.9	83.5	FP/SS
5-5-90-0-o-1.5-2-5	A	1.50	2.00	6.75	2	0.31	60	-	0	0	-	14.1	45.5	FP/SB
	B	1.75	2.00	6.75	2	0.31	60	-	0	0	-	19.6	63.2	FP/SB
5-5-90-0-o-1.5-2-6.5	A	1.53	2.00	6.63	2	0.31	60	-	0	0	-	20.8	67.1	FP
	B	1.63	2.75	6.63	2	0.31	60	-	0	0	-	18.2	58.7	FP/SB
5-5-90-0-o-1.5-2-8	B	1.50	2.13	6.63	2	0.31	60	-	0	0	-	23.5	75.8	SB
5-5-90-0-o-2.5-2-5	A	2.50	2.13	6.38	2	0.31	60	-	0	0	-	19.5	62.9	FP/SB
	B	2.50	2.13	6.38	2	0.31	60	-	0	0	-	23.5	75.8	FP/SB

*Test stopped prior to failure

Table B.1 cont. Test results

Specimen	Hook	Bend Angle	Radius of Bend	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	f'_c psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
5-5-90-1#3-i-2.5-2-6	A	90°	1 7/8	Horizontal	A615	4.75	5800	9	0.625	0.060	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A615	5.50	5800	9	0.625	0.060	13	5.25	8.38
5-5-90-1#3-i-2.5-2-8	A	90°	1 7/8	Horizontal	A1035	8.00	5310	6	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	7.63	5310	6	0.625	0.073	13	5.25	8.38
5-5-90-1#4-i-2.5-2-6	A	90°	1 7/8	Horizontal	A615	5.25	5860	8	0.625	0.060	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A615	5.75	5860	8	0.625	0.060	13	5.25	8.38
5-5-90-1#4-i-2.5-2-8	A	90°	1 7/8	Horizontal	A1035	7.38	5310	6	0.625	0.073	13	9.25	8.38
	B	90°	1 7/8	Horizontal	A1035	7.75	5310	6	0.625	0.073	13	9.25	8.38
5-5-90-2#3-i-2.5-2-6	A	90°	1 7/8	Horizontal	A615	6.00	5800	9	0.625	0.060	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A615	5.75	5800	9	0.625	0.060	13	5.25	8.38
5-5-90-2#3-i-2.5-2-8	A	90°	1 7/8	Horizontal	A1035	8.00	5860	8	0.625	0.073	13	5.38	8.38
	B	90°	1 7/8	Horizontal	A1035	7.50	5860	8	0.625	0.073	13	5.25	8.38
5-5-90-2#3-i-3.5-2-6	A	90°	1 7/8	Horizontal	A1035	6.00	5230	6	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	5.75	5230	6	0.625	0.073	15	5.25	8.38
5-5-90-2#3-i-3.5-2-8	A	90°	1 7/8	Horizontal	A1035	7.94	5190	7	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	7.50	5190	7	0.625	0.073	15	5.25	8.38
5-5-90-5#3-i-2.5-2-7	A	90°	1 7/8	Horizontal	A1035	5.63	5230	6	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	7.00	5230	6	0.625	0.073	13	5.25	8.38
5-5-90-5#3-i-3.5-2-7	A	90°	1 7/8	Horizontal	A1035	7.50	5190	7	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	6.75	5190	7	0.625	0.073	15	5.25	8.38
5-5-90-5#3-o-1.5-2-5	B	90°	1 7/8	Horizontal	A615	5.00	5205	5	0.625	0.077	11	5.25	8.38
5-5-90-5#3-o-1.5-2-6.5	A	90°	2	Horizontal	A1035	6.50	5780	7	0.625	0.073	11	5.25	8.38
	B	90°	2	Horizontal	A1035	6.50	5780	7	0.625	0.073	11	5.25	8.38
5-5-90-5#3-o-1.5-2-8	A	90°	1 7/8	Horizontal	A1035	8.00	5650	6	0.625	0.077	11	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	7.75	5650	6	0.625	0.077	11	5.25	8.38
5-5-90-5#3-o-2.5-2-5	A	90°	1 7/8	Horizontal	A615	5.19	4930	4	0.625	0.077	13	5.38	8.38
	B	90°	1 7/8	Horizontal	A615	5.13	4930	4	0.625	0.077	13	5.25	8.38
5-5-90-5#3-o-2.5-2-8	A	90°	1 7/8	Horizontal	A1035	7.50	5650	6	0.625	0.077	13	5.25	8.38
5-5-90-5#3-o-2.5-2-8(1)	A	90°	1 7/8	Horizontal	A1035	9.00	5780	7	0.625	0.073	13	5.25	8.38
5-8-180-0-i-2.5-2-7	A	180°	2	Horizontal	A1035	7.38	9080	11	0.625	0.073	13	5.25	8.38
	B	180°	2	Horizontal	A1035	7.13	9080	11	0.625	0.073	13	5.25	8.38
5-8-180-0-i-3.5-2-7	A	180°	2	Horizontal	A1035	7.38	9080	11	0.625	0.073	15	5.25	8.38
	B	180°	2	Horizontal	A1035	7.25	9080	11	0.625	0.073	15	5.25	8.38
5-8-180-1#3-i-2.5-2-7	A	180°	2	Horizontal	A1035	7.13	9300	13	0.625	0.073	13	5.25	8.38
	B	180°	2	Horizontal	A1035	7.25	9300	13	0.625	0.073	13	5.25	8.38
5-8-180-1#3-i-3.5-2-7	A	180°	2	Horizontal	A1035	7.13	9190	12	0.625	0.073	15	5.25	8.38
	B	180°	2	Horizontal	A1035	6.75	9190	12	0.625	0.073	15	5.25	8.38
5-8-180-2#3-i-2.5-2-7	A	180°	2	Horizontal	A1035	7.00	9080	11	0.625	0.073	13	5.25	8.38
	B	180°	2	Horizontal	A1035	7.25	9080	11	0.625	0.073	13	5.25	8.38
5-8-180-2#3-i-3.5-2-7	A	180°	2	Horizontal	A1035	6.75	9080	11	0.625	0.073	15	5.25	8.38
	B	180°	2	Horizontal	A1035	6.88	9080	11	0.625	0.073	15	5.25	8.38
5-8-90-0-i-2.5-2-6	A	90°	1 7/8	Horizontal	A615	6.75	8450	14	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A615	6.75	8450	14	0.625	0.073	13	5.25	8.38
5-8-90-0-i-2.5-2-6(1)	A	90°	1 7/8	Horizontal	A1035	6.13	9080	11	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	6.50	9080	11	0.625	0.073	13	5.25	8.38
5-8-90-0-i-2.5-2-8	A	90°	1 7/8	Horizontal	A1035	8.00	8580	15	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	7.50	8580	15	0.625	0.073	13	5.25	8.38
5-8-90-0-i-3.5-2-6	A	90°	1 7/8	Horizontal	A615	6.25	8580	15	0.625	0.073	15	5.38	8.38
	B	90°	1 7/8	Horizontal	A615	6.38	8580	15	0.625	0.073	15	5.25	8.38
5-8-90-0-i-3.5-2-6(1)	A	90°	1 7/8	Horizontal	A1035	6.50	9300	13	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	6.63	9300	13	0.625	0.073	15	5.25	8.38
5-8-90-0-i-3.5-2-8	A	90°	1 7/8	Horizontal	A1035	8.63	8380	13	0.625	0.060	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	8.50	8380	13	0.625	0.060	15	5.25	8.38
5-8-90-1#3-i-2.5-2-6	A	90°	1 7/8	Horizontal	A615	6.00	8450	14	0.625	0.060	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A615	6.25	8450	14	0.625	0.060	13	5.25	8.38
5-8-90-1#3-i-2.5-2-6(1)	A	90°	1 7/8	Horizontal	A1035	6.13	9300	13	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	5.63	9300	13	0.625	0.073	13	5.25	8.38
5-8-90-1#3-i-3.5-2-6	A	90°	1 7/8	Horizontal	A1035	6.00	8710	16	0.625	0.060	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	6.00	8710	16	0.625	0.060	15	5.25	8.38

Table B.1 cont. Test results

Specimen	Hook	c_{so} in.	c_{th} in.	c_h in.	N_h	A_h in.^{2}	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	T kip	f_{su} ksi	Failure Type
5-5-90-1#3-i-2.5-2-6	A	2.50	3.25	6.88	2	0.31	60	0.38	0.11	1	5.0	20.0	64.5	SS
	B	2.50	2.50	6.88	2	0.31	60	0.38	0.11	1	5.0	29.3	94.5	SS/FP
5-5-90-1#3-i-2.5-2-8	A	2.50	2.38	6.88	2	0.31	60	0.38	0.11	1	5.0	32.9	106.1	FP
	B	2.50	2.75	6.88	2	0.31	60	0.38	0.11	1	5.0	37.4	120.6	SB/FB
5-5-90-1#4-i-2.5-2-6	A	2.50	2.75	6.63	2	0.31	60	0.50	0.20	1	5.0	21.6	69.7	SS
	B	2.50	2.25	6.63	2	0.31	60	0.50	0.20	1	5.0	26.8	86.5	SS
5-5-90-1#4-i-2.5-2-8	A	2.50	2.75	6.88	2	0.31	60	0.50	0.20	1	5.0	35.7	115.2	FP/SS
	B	2.50	2.38	6.88	2	0.31	60	0.50	0.20	1	5.0	27.5	88.7	SB
5-5-90-2#3-i-2.5-2-6	A	2.63	2.50	6.63	2	0.31	60	0.38	0.22	2	4.0	31.8	102.6	FP/SS
	B	2.63	2.75	6.63	2	0.31	60	0.38	0.22	2	4.0	29.2	94.2	FP/SS
5-5-90-2#3-i-2.5-2-8	A	2.50	2.00	6.63	2	0.31	60	0.38	0.22	2	4.0	37.9	122.3	SS/FP
	B	2.50	2.50	6.63	2	0.31	60	0.38	0.22	2	4.0	38.9	125.5	SS/FP
5-5-90-2#3-i-3.5-2-6	A	3.38	2.25	6.50	2	0.31	60	0.38	0.22	2	3.5	21.5	69.4	SS/FP
	B	3.38	2.50	6.50	2	0.31	60	0.38	0.22	2	3.5	22.4	72.3	SS/FP
5-5-90-2#3-i-3.5-2-8	A	3.38	2.31	6.75	2	0.31	60	0.38	0.22	2	3.5	43.7	141.0	FP
	B	3.50	2.75	6.75	2	0.31	60	0.38	0.22	2	3.5	45.7	147.4	FP
5-5-90-5#3-i-2.5-2-7	A	2.75	3.63	6.50	2	0.31	60	0.38	0.55	5	1.8	32.1	103.5	FP
	B	2.75	2.25	6.50	2	0.31	60	0.38	0.55	5	1.8	31.3	101.0	FP/SS
5-5-90-5#3-i-3.5-2-7	A	3.38	2.00	7.00	2	0.31	60	0.38	0.55	5	1.8	44.3	142.9	FP
	B	3.50	2.75	7.00	2	0.31	60	0.38	0.55	5	1.8	35.2	113.5	FP
5-5-90-5#3-o-1.5-2-5	B	1.50	2.00	6.50	2	0.31	60	0.38	0.55	5	2.0	22.0	71.0	FP/SB
5-5-90-5#3-o-1.5-2-6.5	A	1.56	2.00	6.50	2	0.31	60	0.38	0.55	5	2.5	26.2	84.5	FP/SB
	B	1.56	2.00	6.50	2	0.31	60	0.38	0.55	5	2.5	20.9	67.4	FP/SB
5-5-90-5#3-o-1.5-2-8	A	1.56	2.25	6.38	2	0.31	60	0.38	0.55	5	2.5	25.2	81.3	FP/SB
	B	1.50	2.63	6.38	2	0.31	60	0.38	0.55	5	2.5	30.4	98.1	FP/SB
5-5-90-5#3-o-2.5-2-5	A	2.63	1.88	6.63	2	0.31	60	0.38	0.55	5	2.0	22.0	71.0	FP/SB
	B	2.63	1.88	6.63	2	0.31	60	0.38	0.55	5	2.0	29.0	93.5	FP/SB
5-5-90-5#3-o-2.5-2-8	A	2.56	2.13	6.50	2	0.31	60	0.38	0.55	5	2.5	28.4	91.6	FP
5-5-90-5#3-o-2.5-2-8(1)	A	2.56	1.50	6.63	2	0.31	60	0.38	0.55	5	2.5	30.3	97.7	SB
5-8-180-0-i-2.5-2-7	A	2.50	2.13	6.25	2	0.31	60	-	0	0	-	26.7	86.1	FP/SS
	B	2.63	2.38	6.25	2	0.31	60	-	0	0	-	35.2	113.5	SB/FP
5-8-180-0-i-3.5-2-7	A	3.63	1.88	7.13	2	0.31	60	-	0	0	-	34.1	110.0	SS/FP
	B	3.38	2.00	7.13	2	0.31	60	-	0	0	-	31.4	101.3	FP/SS
5-8-180-1#3-i-2.5-2-7	A	2.50	2.38	6.50	2	0.31	60	0.38	0.11	1	3.0	34.2	110.3	FP/SS
	B	2.50	2.25	6.50	2	0.31	60	0.38	0.11	1	3.0	35.4	114.2	FP/SS
5-8-180-1#3-i-3.5-2-7	A	3.50	2.13	7.00	2	0.31	60	0.38	0.11	1	3.0	35.8	115.5	FP
	B	3.50	2.50	7.00	2	0.31	60	0.38	0.11	1	3.0	28.9	93.2	FP
5-8-180-2#3-i-2.5-2-7	A	2.50	2.31	6.38	2	0.31	60	0.38	0.22	2	2.0	34.6	111.6	FP/SS
	B	2.50	2.06	6.38	2	0.31	60	0.38	0.22	2	2.0	28.7	92.6	FP/SS
5-8-180-2#3-i-3.5-2-7	A	3.38	2.44	7.00	2	0.31	60	0.38	0.22	2	2.0	29.3	94.5	FP/SS
	B	3.50	2.31	7.00	2	0.31	60	0.38	0.22	2	2.0	32.6	105.2	FP
5-8-90-0-i-2.5-2-6	A	2.75	1.25	6.38	2	0.31	60	-	0	0	-	27.6	89.0	FB/SB
	B	2.63	1.25	6.38	2	0.31	60	-	0	0	-	32.1	103.5	SB/FB
5-8-90-0-i-2.5-2-6(1)	A	2.50	2.63	7.00	2	0.31	60	-	0	0	-	21.7	70.0	FP
	B	2.50	2.25	7.00	2	0.31	60	-	0	0	-	25.0	80.6	FP
5-8-90-0-i-2.5-2-8	A	2.50	2.00	6.63	2	0.31	60	-	0	0	-	31.9	102.9	SS/FP
	B	2.75	2.50	6.63	2	0.31	60	-	0	0	-	35.9	115.8	SS/FP
5-8-90-0-i-3.5-2-6	A	3.63	1.75	6.63	2	0.31	60	-	0	0	-	25.1	81.0	FP/SS
	B	3.50	1.63	6.63	2	0.31	60	-	0	0	-	29.1	93.9	FP/SS
5-8-90-0-i-3.5-2-6	A	3.75	2.06	6.88	2	0.31	60	-	0	0	-	24.4	78.7	FP/SS
	B	3.75	1.94	6.88	2	0.31	60	-	0	0	-	27.5	88.7	FP/SS
5-8-90-0-i-3.5-2-8	A	3.63	1.38	7.13	2	0.31	60	-	0	0	-	39.1	126.1	FB/SS
	B	3.50	1.50	7.13	2	0.31	60	-	0	0	-	34.3	110.6	SS
5-8-90-1#3-i-2.5-2-6	A	2.50	2.00	6.63	2	0.31	60	0.38	0.11	1	6.0	26.2	84.5	FP
	B	2.50	1.75	6.63	2	0.31	60	0.38	0.11	1	6.0	27.9	90.0	SS
5-8-90-1#3-i-2.5-2-6(1)	A	2.63	2.13	6.50	2	0.31	60	0.38	0.11	1	6.0	29.3	94.5	FP/SS
	B	2.75	2.63	6.50	2	0.31	60	0.38	0.11	1	6.0	25.4	81.9	FP/SS
5-8-90-1#3-i-3.5-2-6	A	3.63	2.00	6.75	2	0.31	60	0.38	0.11	1	6.0	41.4	133.5	FP/SS
	B	3.63	2.00	6.75	2	0.31	60	0.38	0.11	1	6.0	31.2	100.6	FP/SS

Table B.1 cont. Test results

Specimen	Hook	Bend Angle	Radius of Bend	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	f'_c psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
5-8-90-1#3-i-3.5-2-6	A	90°	1 7/8	Horizontal	A1035	6.25	9190	12	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	6.25	9190	12	0.625	0.073	15	5.25	8.38
5-8-90-1#4-i-2.5-2-6	A	90°	1 7/8	Horizontal	A1035	5.94	9300	13	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	6.00	9300	13	0.625	0.073	13	5.25	8.38
5-8-90-1#4-i-3.5-2-6	A	90°	1 7/8	Horizontal	A1035	6.00	9190	12	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	7.00	9190	12	0.625	0.073	15	5.25	8.38
5-8-90-2#3-i-2.5-2-6	A	90°	1 7/8	Horizontal	A1035	6.00	8580	15	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	6.00	8580	15	0.625	0.073	13	5.25	8.38
5-8-90-2#3-i-2.5-2-8	A	90°	1 7/8	Horizontal	A1035	8.25	8380	13	0.625	0.073	13	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	8.50	8380	13	0.625	0.073	13	5.25	8.38
5-8-90-2#3-i-3.5-2-6	A	90°	1 7/8	Horizontal	A1035	6.50	8580	15	0.625	0.073	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	6.00	8580	15	0.625	0.073	15	5.25	8.38
5-8-90-2#3-i-3.5-2-8	A	90°	1 7/8	Horizontal	A1035	7.13	8710	16	0.625	0.060	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	7.00	8710	16	0.625	0.060	15	5.25	8.38
5-8-90-4#3-i-2.5-2-8	A	90°	1 7/8	Horizontal	A1035	7.88	8380	13	0.625	0.060	13	10.50	8.38
	B	90°	1 7/8	Horizontal	A1035	7.50	8380	13	0.625	0.060	13	10.50	8.38
5-8-90-4#3-i-3.5-2-8	A	90°	1 7/8	Horizontal	A1035	8.63	8380	13	0.625	0.060	15	5.25	8.38
	B	90°	1 7/8	Horizontal	A1035	8.25	8380	13	0.625	0.060	15	5.25	8.38
8-12-90-0-i-2.5-2-9	A	90°	3 1/16	Horizontal	A1035	9.00	11160	77	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	9.00	11160	77	1.000	0.078	17	10.50	8.38
8-12-90-0-i-3.5-2-9	A	90°	3 1/16	Horizontal	A1035	9.00	11160	77	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	9.00	11160	77	1.000	0.078	19	10.50	8.38
8-12-90-2#3-i-2.5-2-9	A	90°	3 1/16	Horizontal	A1035	9.00	11160	77	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	9.00	11160	77	1.000	0.078	17	10.50	8.38
8-12-90-2#3-i-3.5-2-9	A	90°	3 1/16	Horizontal	A1035	9.00	11160	77	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	9.00	11160	77	1.000	0.078	19	10.50	8.38
8-12-90-5#3-i-2.5-2-9	A	90°	3 1/16	Horizontal	A1035	9.00	11160	77	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	9.00	11160	77	1.000	0.078	17	10.50	8.38
8-12-90-5#3-i-3.5-2-9	A	90°	3 1/16	Horizontal	A1035	9.00	11160	77	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	9.00	11160	77	1.000	0.078	19	10.50	8.38
8-5-180-0-i-2.5-2-11	A	180°	3 1/4	Horizontal	A615	11.00	4550	7	1.000	0.078	15	10.50	8.38
	B	180°	3 1/4	Horizontal	A615	11.00	4550	7	1.000	0.078	15	10.50	8.38
8-5-180-0-i-2.5-2-14	A	180°	3 1/4	Horizontal	A1035	14.00	4840	8	1.000	0.078	15	10.50	8.38
	B	180°	3 1/4	Horizontal	A1035	14.00	4840	8	1.000	0.078	15	10.50	8.38
8-5-180-0-i-3.5-2-11	A	180°	3 1/4	Horizontal	A615	11.63	4550	7	1.000	0.078	17	10.50	8.38
	B	180°	3 1/4	Horizontal	A615	11.63	4550	7	1.000	0.078	17	10.50	8.38
8-5-180-0-i-3.5-2-14	A	180°	3 1/4	Horizontal	A1035	14.38	4840	8	1.000	0.078	17	10.50	8.38
	B	180°	3 1/4	Horizontal	A1035	13.88	4840	8	1.000	0.078	17	10.50	8.38
8-5-180-1#3-i-2.5-2-11	A	180°	3 1/4	Horizontal	A615	11.50	4300	6	1.000	0.078	15	10.50	8.38
	B	180°	3 1/4	Horizontal	A615	11.50	4300	6	1.000	0.078	15	10.50	8.38
8-5-180-1#3-i-2.5-2-14	A	180°	3 1/4	Horizontal	A1035	14.75	4870	9	1.000	0.078	15	10.50	8.38
	B	180°	3 1/4	Horizontal	A1035	15.00	4870	9	1.000	0.078	15	10.50	8.38
8-5-180-1#3-i-3.5-2-11	A	180°	3 1/4	Horizontal	A615	11.63	4550	7	1.000	0.078	17	10.50	8.38
	B	180°	3 1/4	Horizontal	A615	10.63	4550	7	1.000	0.078	17	10.50	8.38
8-5-180-1#3-i-3.5-2-14	A	180°	3 1/4	Horizontal	A1035	15.63	4840	8	1.000	0.078	17	10.50	8.38
	B	180°	3 1/4	Horizontal	A1035	14.50	4840	8	1.000	0.078	17	10.50	8.38
8-5-180-2#3-i-2.5-2-11	A	180°	3 1/4	Horizontal	A615	10.75	4550	7	1.000	0.078	15	10.50	8.38
	B	180°	3 1/4	Horizontal	A615	10.50	4550	7	1.000	0.078	15	10.50	8.38
8-5-180-2#3-i-2.5-2-14	A	180°	3 1/4	Horizontal	A1035	13.50	4870	9	1.000	0.078	15	10.50	8.38
	B	180°	3 1/4	Horizontal	A1035	14.00	4870	9	1.000	0.078	15	10.50	8.38
8-5-180-2#3-i-3.5-2-11	A	180°	3 1/4	Horizontal	A615	10.13	4300	6	1.000	0.078	17	10.50	8.38
	B	180°	3 1/4	Horizontal	A615	10.63	4300	6	1.000	0.078	17	10.50	8.38
8-5-180-2#3-i-3.5-2-14	A	180°	3 1/4	Horizontal	A1035	13.50	4870	9	1.000	0.078	17	10.50	8.38
	B	180°	3 1/4	Horizontal	A1035	13.63	4870	9	1.000	0.078	17	10.50	8.38
8-5-90-0-i-2.5-2-12.5	A	90°	3 1/16	Horizontal	A615	13.25	5240	9	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A615	13.25	5240	9	1.000	0.078	17	10.50	8.38
8-5-90-0-i-2.5-2-13	A	90°	3 1/16	Horizontal	A1035	13.25	5560	11	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	13.50	5560	11	1.000	0.078	17	10.50	8.38
8-5-90-0-i-2.5-2-16	A	90°	3 1/16	Horizontal	A1035	16.00	4980	7	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	16.75	4980	7	1.000	0.078	17	10.50	8.38

Table B.1 cont. Test results

Specimen	Hook	c_{so} in.	c_{th} in.	c_h in.	N_h	A_h in.^{2}	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	T kip	f_{su} ksi	Failure Type
5-8-90-1#3-i-3.5-2-6	A	3.75	2.38	6.75	2	0.31	60	0.38	0.11	1	6.0	29.0	93.5	FP/SS
	B	3.50	2.38	6.75	2	0.31	60	0.25	0.11	1	6.0	26.3	84.8	FP/SS
5-8-90-1#4-i-2.5-2-6	A	2.50	2.81	6.38	2	0.31	60	0.50	0.20	1	6.0	23.9	77.1	FP
	B	2.75	2.75	6.38	2	0.31	60	0.50	0.20	1	6.0	27.9	90.0	FP/SS
5-8-90-1#4-i-3.5-2-6	A	3.63	3.00	6.75	2	0.31	60	0.50	0.20	1	6.0	25.3	81.6	FP/SS
	B	3.50	2.00	6.75	2	0.31	60	0.50	0.20	1	6.0	25.2	81.3	FP/SS
5-8-90-2#3-i-2.5-2-6	A	2.75	2.00	6.13	2	0.31	60	0.38	0.22	2	5.0	33.5	108.1	FP/SS
	B	2.88	2.00	6.13	2	0.31	60	0.38	0.22	2	5.0	30.9	99.7	FP/SS
5-8-90-2#3-i-2.5-2-8	A	2.63	1.75	6.50	2	0.31	60	0.38	0.22	2	5.0	39.8	128.4	FP/SS
	B	2.50	1.50	6.50	2	0.31	60	0.38	0.22	2	5.0	40.5	130.6	FP/SS
5-8-90-2#3-i-3.5-2-6	A	3.50	1.50	6.38	2	0.31	60	0.38	0.22	2	5.0	29.9	96.5	FP
	B	3.75	2.00	6.38	2	0.31	60	0.38	0.22	2	5.0	30.1	97.1	FP/SS
5-8-90-2#3-i-3.5-2-8	A	3.50	2.88	6.63	2	0.31	60	0.38	0.22	2	5.0	38.0	122.6	FP
	B	3.50	3.00	6.63	2	0.31	60	0.38	0.22	2	5.0	28.6	92.3	FP
5-8-90-4#3-i-2.5-2-8	A	2.50	2.13	6.38	2	0.31	60	0.38	0.44	4	2.5	33.4	107.7	FP/SS
	B	2.50	2.50	6.38	2	0.31	60	0.38	0.44	4	2.5	27.0	87.1	FP/SS
5-8-90-4#3-i-3.5-2-8	A	3.50	1.38	6.88	2	0.31	60	0.38	0.44	4	2.5	42.5	137.1	FP
	B	3.50	1.75	6.88	2	0.31	60	0.38	0.44	4	2.5	39.3	126.8	SS/FP
8-12-90-0-i-2.5-2-9	A	2.75	2.38	9.63	2	0.79	60	-	0	0	-	50.8	64.3	FP/SS
	B	2.63	2.38	9.63	2	0.79	60	-	0	0	-	54.8	69.4	SS/FP
8-12-90-0-i-3.5-2-9	A	3.50	2.38	9.75	2	0.79	60	-	0	0	-	61.4	77.7	FP
	B	3.75	2.13	9.75	2	0.79	60	-	0	0	-	68.5	86.7	FP/SS
8-12-90-2#3-i-2.5-2-9	A	2.88	2.25	9.50	2	0.79	60	0.38	0.22	2	8.0	61.8	78.2	FP/SS
	B	2.63	2.25	9.50	2	0.79	60	0.38	0.22	2	8.0	60.3	76.3	SS/FP
8-12-90-2#3-i-3.5-2-9	A	3.63	2.31	9.63	2	0.79	60	0.38	0.22	2	8.0	50.3	63.7	FP/SS
	B	4.00	2.38	9.63	2	0.79	60	0.38	0.22	2	8.0	49.3	62.4	FP/SS
8-12-90-5#3-i-2.5-2-9	A	2.50	2.50	9.50	2	0.79	60	0.38	0.55	5	3.0	66.5	84.2	FP/SS
	B	2.63	2.50	9.50	2	0.79	60	0.38	0.55	5	3.0	63.1	79.9	FP/SS
8-12-90-5#3-i-3.5-2-9	A	3.25	2.50	9.50	2	0.79	60	0.38	0.55	5	3.0	68.8	87.1	FP/SS
	B	3.38	2.50	9.50	2	0.79	60	0.38	0.55	5	3.0	82.2	104.1	FP/SS
8-5-180-0-i-2.5-2-11	A	3.00	2.00	9.75	2	0.79	60	-	0	0	-	45.6	57.7	SS/FP
	B	2.75	2.00	9.75	2	0.79	60	-	0	0	-	50.5	63.9	SS
8-5-180-0-i-2.5-2-14	A	2.75	2.00	9.75	2	0.79	60	-	0	0	-	49.4	62.5	SS
	B	2.63	2.00	9.75	2	0.79	60	-	0	0	-	69.4	87.8	SS
8-5-180-0-i-3.5-2-11	A	3.75	1.38	10.00	2	0.79	60	-	0	0	-	58.6	74.2	FP/SS
	B	3.75	1.38	10.00	2	0.79	60	-	0	0	-	60.5	76.6	SS
8-5-180-0-i-3.5-2-14	A	3.88	1.63	9.75	2	0.79	60	-	0	0	-	63.7	80.6	SS
	B	3.75	2.13	9.75	2	0.79	60	-	0	0	-	78.0	98.7	FB/SS
8-5-180-1#3-i-2.5-2-11	A	2.50	1.50	10.00	2	0.79	60	0.38	0.11	1	3.5	57.3	72.5	SS/FP
	B	2.50	1.50	10.00	2	0.79	60	0.38	0.11	1	3.5	69.0	87.3	SS/FP
8-5-180-1#3-i-2.5-2-14	A	2.75	1.25	9.88	2	0.79	60	0.38	0.11	1	3.5	67.3	85.2	SS/FP
	B	2.88	1.00	9.88	2	0.79	60	0.38	0.11	1	3.5	70.9	89.7	FP/SS
8-5-180-1#3-i-3.5-2-11	A	3.75	1.38	10.00	2	0.79	60	0.38	0.11	1	3.5	62.9	79.6	SS
	B	3.50	2.38	10.00	2	0.79	60	0.38	0.11	1	3.5	56.2	71.1	SS
8-5-180-1#3-i-3.5-2-14	A	3.63	0.88	10.00	2	0.79	60	0.38	0.11	1	3.5	78.7	99.6	SS/FP
	B	3.63	2.00	10.00	2	0.79	60	0.38	0.11	1	3.5	76.9	97.3	SS/FP
8-5-180-2#3-i-2.5-2-11	A	2.75	2.25	9.50	2	0.79	60	0.38	0.22	2	3.5	64.2	81.3	SS/FP
	B	2.50	2.50	9.50	2	0.79	60	0.38	0.22	2	3.5	61.9	78.4	SS/FP
8-5-180-2#3-i-2.5-2-14	A	2.75	2.50	9.75	2	0.79	60	0.38	0.22	2	3.5	87.1	110.3	FP
	B	2.75	2.00	9.75	2	0.79	60	0.38	0.22	2	3.5	76.9	97.3	FP/SS
8-5-180-2#3-i-3.5-2-11	A	3.38	2.88	9.75	2	0.79	60	0.38	0.22	2	3.5	57.2	72.4	SS/FP
	B	3.50	2.38	9.75	2	0.79	60	0.38	0.22	2	3.5	54.9	69.5	SS/FP
8-5-180-2#3-i-3.5-2-14	A	3.63	2.50	9.75	2	0.79	60	0.38	0.22	2	3.5	68.3	86.5	FP/SS
	B	3.75	2.38	9.75	2	0.79	60	0.38	0.22	2	3.5	73.0	92.4	FP/SS
8-5-90-0-i-2.5-2-12.5	A	2.75	1.25	9.75	2	0.79	60	-	0	0	-	65.3	82.7	SS/FP
	B	2.75	1.25	9.75	2	0.79	60	-	0	0	-	69.9	88.5	SS
8-5-90-0-i-2.5-2-13	A	2.50	2.00	9.75	2	0.79	60	-	0	0	-	73.1	92.5	SS
	B	2.50	1.75	9.75	2	0.79	60	-	0	0	-	65.2	82.5	FP/SS
8-5-90-0-i-2.5-2-16	A	2.75	1.75	9.50	2	0.79	60	-	0	0	-	83.3	105.4	FP/SB
	B	2.75	1.38	9.50	2	0.79	60	-	0	0	-	86.1	109.0	FB/K

Table B.1 cont. Test results

Specimen	Hook	Bend Angle	Radius of Bend	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	f'_c psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
8-5-90-0-i-2.5-2-18	A	90°	3 1/16	Horizontal	A1035	19.50	5380	11	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	17.88	5380	11	1.000	0.078	17	10.50	8.38
8-5-90-0-i-2.5-2-9.5	A	90°	3 1/16	Horizontal	A615	9.00	5140	8	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A615	10.25	5140	8	1.000	0.078	17	10.50	8.38
8-5-90-0-i-3.5-2-13	A	90°	3 1/16	Horizontal	A1035	13.38	5560	11	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	13.38	5560	11	1.000	0.078	19	10.50	8.38
8-5-90-0-i-3.5-2-18	A	90°	3 1/16	Horizontal	A1035	19.00	5380	11	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	18.00	5380	11	1.000	0.078	19	10.50	8.38
8-5-90-0-o-2.5-2-10a	A	90°	3 1/16	Horizontal	A1035	10.25	5270	7	1.000	0.084	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	10.50	5270	7	1.000	0.084	17	10.50	8.38
8-5-90-0-o-2.5-2-10b	A	90°	3 1/16	Horizontal	A1035	9.25	5440	8	1.000	0.084	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	10.25	5440	8	1.000	0.084	17	10.50	8.38
8-5-90-0-o-2.5-2-10c	A	90°	3 1/16	Horizontal	A1035	10.75	5650	9	1.000	0.084	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	10.50	5650	9	1.000	0.084	17	10.50	8.38
8-5-90-1#3-i-2.5-2-12.5	A	90°	3 1/16	Horizontal	A1035	12.50	5140	8	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	12.50	5140	8	1.000	0.078	17	10.50	8.38
8-5-90-1#3-i-2.5-2-9.5	A	90°	3 1/16	Horizontal	A615	9.00	5240	9	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A615	9.00	5240	9	1.000	0.078	17	10.50	8.38
8-5-90-2#3-i-2.5-2-12.5	A	90°	3 1/16	Horizontal	A615	12.00	5240	9	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A615	12.00	5240	9	1.000	0.078	17	10.50	8.38
8-5-90-2#3-i-2.5-2-9.5	A	90°	3 1/16	Horizontal	A615	9.00	5140	8	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A615	9.25	5140	8	1.000	0.078	17	10.50	8.38
8-5-90-2#3-i-3.5-2-13	A	90°	3 1/16	Horizontal	A1035	17.50	5570	12	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	17.00	5570	12	1.000	0.078	19	10.50	8.38
8-5-90-2#3-i-3.5-2-17	A	90°	3 1/16	Horizontal	A1035	13.75	5560	11	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	13.50	5560	11	1.000	0.078	19	10.50	8.38
8-5-90-4#3-i-2.5-2-12.5	A	90°	3 1/16	Horizontal	A1035	11.88	4980	7	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	11.88	4980	7	1.000	0.078	17	10.50	8.38
8-5-90-4#3-i-2.5-2-9.5	A	90°	3 1/16	Horizontal	A615	9.50	5140	8	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A615	9.50	5140	8	1.000	0.078	17	10.50	8.38
8-5-90-4#4s-i-2.5-2-15	A	90°	3 1/16	Horizontal	A1035	15.63	4810	6	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	15.63	4810	6	1.000	0.078	17	10.50	8.38
8-5-90-4#4s-i-3.5-2-15	A	90°	3 1/16	Horizontal	A1035	15.50	4810	6	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	15.13	4810	6	1.000	0.078	19	10.50	8.38
8-5-90-5#3-i-2.5-2-10a	B	90°	3 1/16	Horizontal	A1035	10.50	5270	7	1.000	0.084	17	10.50	8.38
8-5-90-5#3-i-2.5-2-10b	A	90°	3 1/16	Horizontal	A1035	10.25	5440	8	1.000	0.084	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	10.50	5440	8	1.000	0.084	17	10.50	8.38
8-5-90-5#3-i-2.5-2-10c	A	90°	3 1/16	Horizontal	A1035	10.50	5650	9	1.000	0.084	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	10.50	5650	9	1.000	0.084	17	10.50	8.38
8-5-90-5#3-i-2.5-2-13	A	90°	3 1/16	Horizontal	A1035	13.75	5560	11	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	13.50	5560	11	1.000	0.078	17	10.50	8.38
8-5-90-5#3-i-2.5-2-15	A	90°	3 1/16	Horizontal	A1035	15.25	4850	7	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	15.81	4850	7	1.000	0.078	17	10.50	8.38
8-5-90-5#3-i-3.5-2-13	A	90°	3 1/16	Horizontal	A1035	13.25	5570	12	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	13.00	5570	12	1.000	0.078	19	10.50	8.38
8-5-90-5#3-i-3.5-2-15	A	90°	3 1/16	Horizontal	A1035	15.75	4850	7	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	15.75	4850	7	1.000	0.078	19	10.50	8.38
8-5-90-5#3-o-2.5-2-10a	A	90°	3 1/16	Horizontal	A1035	10.25	5270	7	1.000	0.084	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	10.50	5270	7	1.000	0.084	17	10.50	8.38
8-5-90-5#3-o-2.5-2-10b	A	90°	3 1/16	Horizontal	A1035	10.50	5440	8	1.000	0.084	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	10.50	5440	8	1.000	0.084	17	10.50	8.38
8-5-90-5#3-o-2.5-2-10c	A	90°	3 1/16	Horizontal	A1035	11.25	5650	9	1.000	0.084	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	10.50	5650	9	1.000	0.084	17	10.50	8.38
8-8-180-0-i-2.5-2-11.5	A	180°	3 1/4	Horizontal	A1035	9.25	8630	11	1.000	0.078	17	10.50	8.38
	B	180°	3 1/4	Horizontal	A1035	9.25	8630	11	1.000	0.078	17	10.50	8.38
8-8-180-1#4-i-2.5-2-11.5	A	180°	3 1/4	Horizontal	A1035	12.00	8740	12	1.000	0.078	17	10.50	8.38
	B	180°	3 1/4	Horizontal	A1035	12.25	8740	12	1.000	0.078	17	10.50	8.38
8-8-180-2#3-i-2.5-2-11.5	A	180°	3 1/4	Horizontal	A1035	10.50	8810	14	1.000	0.078	17	10.50	8.38
	B	180°	3 1/4	Horizontal	A1035	10.25	8810	14	1.000	0.078	17	10.50	8.38

Table B.1 cont. Test results

Specimen	Hook	c_{so} in.	c_{th} in.	c_h in.	N_h	A_h in.^{2}	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	T kip	f_{su} ksi	Failure Type
8-5-90-0-i-2.5-2-18	A	2.50	0.75	10.50	2	0.79	60	-	0	0	-	100.2	126.8	FB/SS/K
	B	2.50	2.38	10.50	2	0.79	60	-	0	0	-	79.8	101.0	FB/SS/K
8-5-90-0-i-2.5-2-9.5	A	2.75	3.00	9.50	2	0.79	60	-	0	0	-	44.6	56.5	FP
	B	2.50	1.75	9.50	2	0.79	60	-	0	0	-	65.8	83.3	SS
8-5-90-0-i-3.5-2-13	A	3.63	1.88	9.44	2	0.79	60	-	0	0	-	69.4	87.8	FP/SS
	B	3.38	1.88	9.44	2	0.79	60	-	0	0	-	68.3	86.5	SS/FP
8-5-90-0-i-3.5-2-18	A	3.75	1.38	9.38	2	0.79	60	-	0	0	-	96.0	121.5	FP/SS/K
	B	3.38	2.38	9.38	2	0.79	60	-	0	0	-	105.1	133.0	FB/SS
8-5-90-0-o-2.5-2-10a	A	2.50	2.00	10.00	2	0.79	60	-	0	0	-	40.6	51.4	FP/SS
	B	2.63	1.75	10.00	2	0.79	60	-	0	0	-	46.6	59.0	SS/FP
8-5-90-0-o-2.5-2-10b	A	2.50	3.25	10.00	2	0.79	60	-	0	0	-	47.9	60.6	FP/SS
	B	2.50	2.25	10.00	2	0.79	60	-	0	0	-	30.6	38.7	SS/FP
8-5-90-0-o-2.5-2-10c	A	2.50	1.50	10.00	2	0.79	60	-	0	0	-	62.7	79.4	FP/SS
	B	2.50	1.75	10.00	2	0.79	60	-	0	0	-	54.6	69.1	SS/FP/K
8-5-90-1#3-i-2.5-2-12.5	A	2.63	2.13	9.75	2	0.79	60	0.38	0.11	1	9.0	73.9	93.5	FP/SS
	B	2.75	2.13	9.75	2	0.79	60	0.38	0.11	1	9.0	64.8	82.0	SS/FP
8-5-90-1#3-i-2.5-2-9.5	A	2.63	2.50	9.75	2	0.79	60	0.38	0.11	1	9.0	62.0	78.5	SB
	B	2.75	2.50	9.75	2	0.79	60	0.38	0.11	1	9.0	55.0	69.6	FP/SS
8-5-90-2#3-i-2.5-2-12.5	A	2.75	2.63	9.50	2	0.79	60	0.38	0.22	2	3.0	74.1	93.8	FP
	B	2.75	2.63	9.50	2	0.79	60	0.38	0.22	2	3.0	76.3	96.6	FP/SS
8-5-90-2#3-i-2.5-2-9.5	A	2.50	2.56	10.00	2	0.79	60	0.38	0.22	2	3.0	54.9	69.5	FP
	B	2.50	2.31	10.00	2	0.79	60	0.38	0.22	2	3.0	53.6	67.8	FP
8-5-90-2#3-i-3.5-2-13	A	3.25	1.75	10.13	2	0.79	60	0.38	0.22	2	8.0	102.6	129.9	SS
	B	3.50	2.25	10.13	2	0.79	60	0.38	0.22	2	8.0	88.6	112.2	SS/FP
8-5-90-2#3-i-3.5-2-17	A	3.13	1.50	10.25	2	0.79	60	0.38	0.22	2	8.0	81.2	102.8	SS/FP
	B	3.63	1.75	10.25	2	0.79	60	0.38	0.22	2	8.0	86.9	110.0	SS/FP
8-5-90-4#3-i-2.5-2-12.5	A	2.50	2.00	10.00	2	0.79	60	0.38	0.44	4	4.0	83.1	105.2	FP
	B	2.50	2.00	10.00	2	0.79	60	0.38	0.44	4	4.0	68.6	86.8	FP
8-5-90-4#3-i-2.5-2-9.5	A	2.75	2.00	9.50	2	0.79	60	0.38	0.44	4	4.0	63.3	80.1	FP
	B	2.88	2.00	9.50	2	0.79	60	0.38	0.44	4	4.0	54.8	69.4	FP/SS
8-5-90-4#4s-i-2.5-2-15	A	3.00	1.63	9.13	2	0.79	60	0.50	0.80	4	4.0	93.3	118.1	SS/FP
	B	2.88	1.63	9.13	2	0.79	60	0.50	0.80	4	4.0	107.7	136.3	FP/SS
8-5-90-4#4s-i-3.5-2-15	A	4.13	1.75	9.50	2	0.79	60	0.50	0.80	4	4.0	106.0	134.2	FP/SS
	B	4.00	2.13	9.50	2	0.79	60	0.50	0.80	4	4.0	90.2	114.2	SS/FP
8-5-90-5#3-i-2.5-2-10a	B	2.50	1.75	9.75	2	0.79	60	0.38	0.55	5	3.0	82.8	104.8	FP/SS
8-5-90-5#3-i-2.5-2-10b	A	2.75	2.00	9.88	2	0.79	60	0.38	0.55	5	3.0	78.8	99.7	FP/SS
	B	2.63	1.75	9.88	2	0.79	60	0.38	0.55	5	3.0	66.7	84.4	FP
8-5-90-5#3-i-2.5-2-10c	A	2.50	2.00	10.00	2	0.79	60	0.38	0.55	5	3.0	68.9	87.2	FP/SS
	B	2.50	2.00	10.00	2	0.79	60	0.38	0.55	5	3.0	69.6	88.1	FP/SS
8-5-90-5#3-i-2.5-2-13	A	2.50	1.50	10.25	2	0.79	60	0.38	0.55	5	3.0	93.1	117.8	SS/FP
	B	2.38	1.75	10.25	2	0.79	60	0.38	0.55	5	3.0	81.3	102.9	FP/SS
8-5-90-5#3-i-2.5-2-15	A	2.75	1.94	9.88	2	0.79	60	0.38	0.55	5	3.0	77.1	97.6	FP/SS
	B	2.50	1.38	9.88	2	0.79	60	0.38	0.55	5	3.0	72.6	91.9	FP/SS
8-5-90-5#3-i-3.5-2-13	A	3.38	2.13	10.38	2	0.79	60	0.38	0.55	5	3.0	89.6	113.4	SS
	B	3.50	2.38	10.38	2	0.79	60	0.38	0.55	5	3.0	76.0	96.2	SS/FP
8-5-90-5#3-i-3.5-2-15	A	3.56	1.25	10.25	2	0.79	60	0.38	0.55	5	3.0	81.2	102.8	SS/FP
	B	3.50	1.25	10.25	2	0.79	60	0.38	0.55	5	3.0	87.1	110.3	SS/FP
8-5-90-5#3-o-2.5-2-10a	A	2.63	1.75	9.88	2	0.79	60	0.38	0.55	5	3.0	55.7	70.5	SS
	B	2.63	2.00	9.88	2	0.79	60	0.38	0.55	5	3.0	55.8	70.6	SB
8-5-90-5#3-o-2.5-2-10b	A	2.50	2.00	9.88	2	0.79	60	0.38	0.55	5	3.0	66.4	84.1	FP/SB
	B	2.63	2.00	9.88	2	0.79	60	0.38	0.55	5	3.0	69.5	88.0	SB/FP
8-5-90-5#3-o-2.5-2-10c	A	2.63	1.25	9.88	2	0.79	60	0.38	0.55	5	3.0	80.6	102.0	SS/FP
	B	2.50	2.00	9.88	2	0.79	60	0.38	0.55	5	3.0	57.7	73.0	SS/FP
8-8-180-0-i-2.5-2-11.5	A	3.00	4.50	9.50	2	0.79	60	-	0	0	-	62.8	79.5	FP/SB
	B	3.00	4.50	9.50	2	0.79	60	-	0	0	-	80.2	101.5	FP/SS
8-8-180-1#4-i-2.5-2-11.5	A	2.88	2.00	9.50	2	0.79	60	0.50	0.20	1	4.5	72.0	91.1	FP/SS
	B	2.75	1.75	9.50	2	0.79	60	0.50	0.20	1	4.5	72.5	91.8	FP/SS
8-8-180-2#3-i-2.5-2-11.5	A	2.75	2.25	10.00	2	0.79	60	0.38	0.22	2	3.5	70.1	88.7	FB/SS
	B	2.75	2.50	10.00	2	0.79	60	0.38	0.22	2	3.5	59.5	75.3	FP/SS

Table B.1 cont. Test results

Specimen	Hook	Bend Angle	Radius of Bend	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	f'_c psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
8-8-90-0-i-2.5-2-10	A	90°	3 1/16	Horizontal	A1035	9.75	7700	14	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	9.50	7700	14	1.000	0.078	17	10.50	8.38
8-8-90-0-i-2.5-2-8	A	90°	3 1/16	Horizontal	A1035	8.88	7910	15	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.00	7910	15	1.000	0.078	17	10.50	8.38
8-8-90-0-i-2.5-2-8(1)	A	90°	3 1/16	Horizontal	A1035	8.00	8780	13	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.00	8780	13	1.000	0.078	17	10.50	8.38
8-8-90-0-i-3.5-2-10	A	90°	3 1/16	Horizontal	A1035	8.75	7700	14	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	10.75	7700	14	1.000	0.078	19	10.50	8.38
8-8-90-0-i-3.5-2-8	A	90°	3 1/16	Horizontal	A1035	7.75	7910	15	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	7.75	7910	15	1.000	0.078	19	10.50	8.38
8-8-90-0-i-3.5-2-8(1)	A	90°	3 1/16	Horizontal	A1035	8.50	8780	13	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.00	8780	13	1.000	0.078	19	10.50	8.38
8-8-90-0-i-4-2-8	A	90°	3 1/16	Horizontal	A1035	7.63	8740	12	1.000	0.078	20	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.00	8740	12	1.000	0.078	20	10.50	8.38
8-8-90-0-o-2.5-2-8	A	90°	3 1/16	Horizontal	A1035	8.63	8740	12	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.25	8740	12	1.000	0.078	17	10.50	8.38
8-8-90-0-o-3.5-2-8	A	90°	3 1/16	Horizontal	A1035	7.63	8810	14	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.00	8810	14	1.000	0.078	19	10.50	8.38
8-8-90-0-o-4-2-8	A	90°	3 1/16	Horizontal	A1035	8.13	8630	11	1.000	0.078	20	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.25	8630	11	1.000	0.078	20	10.50	8.38
8-8-90-2#3-i-2.5-2-10	A	90°	3 1/16	Horizontal	A1035	9.88	8990	17	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	9.50	8990	17	1.000	0.078	17	10.50	8.38
8-8-90-2#3-i-2.5-2-8	A	90°	3 1/16	Horizontal	A1035	8.00	7700	14	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.50	7700	14	1.000	0.078	17	10.50	8.38
8-8-90-2#3-i-3.5-2-10	A	90°	3 1/16	Horizontal	A1035	8.75	8990	17	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.75	8990	17	1.000	0.078	19	10.50	8.38
8-8-90-2#3-i-3.5-2-8	A	90°	3 1/16	Horizontal	A1035	8.00	8290	16	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.13	8290	16	1.000	0.078	19	10.50	8.38
8-8-90-2#4-i-2.5-2-10	A	90°	3 1/16	Horizontal	A1035	8.50	8290	16	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	9.25	8290	16	1.000	0.078	17	10.50	8.38
8-8-90-2#4-i-3.5-2-10	A	90°	3 1/16	Horizontal	A1035	9.00	8290	16	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	9.75	8290	16	1.000	0.078	19	10.50	8.38
8-8-90-5#3-i-2.5-2-8	A	90°	3 1/16	Horizontal	A1035	7.25	8290	16	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	7.25	8290	16	1.000	0.078	17	10.50	8.38
8-8-90-5#3-i-3.5-2-8	A	90°	3 1/16	Horizontal	A1035	8.00	7910	15	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.00	7910	15	1.000	0.078	19	10.50	8.38
8-8-90-5#3-o-2.5-2-8	A	90°	3 1/16	Horizontal	A1035	8.25	8630	11	1.000	0.078	17	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.75	8630	11	1.000	0.078	17	10.50	8.38
8-8-90-5#3-o-3.5-2-8	A	90°	3 1/16	Horizontal	A1035	7.75	8810	14	1.000	0.078	19	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.00	8810	14	1.000	0.078	19	10.50	8.38
8-8-90-5#3-o-4-2-8	A	90°	3 1/16	Horizontal	A1035	8.50	8740	12	1.000	0.078	20	10.50	8.38
	B	90°	3 1/16	Horizontal	A1035	8.00	8740	12	1.000	0.078	20	10.50	8.38
11-12-90-0-i-2.5-2-17	A	90°	5 3/4	Horizontal	A1035	17.63	13330	31	1.410	0.085	22	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	17.75	13330	31	1.410	0.085	22	19.50	8.38
11-12-90-0-i-2.5-2-25	A	90°	5 3/4	Horizontal	A1035	24.88	13330	34	1.410	0.085	22	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	24.38	13330	34	1.410	0.085	22	19.50	8.38
11-12-90-2#3-i-2.5-2-17	A	90°	5 3/4	Horizontal	A1035	18.00	13710	30	1.410	0.085	22	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	17.50	13710	30	1.410	0.085	22	19.50	8.38
11-12-90-2#3-i-2.5-2-25	A	90°	5 3/4	Horizontal	A1035	25.00	13710	30	1.410	0.085	22	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	24.50	13710	30	1.410	0.085	22	19.50	8.38
11-12-90-6#3-i-2.5-2-16	A	90°	5 3/4	Horizontal	A1035	14.75	13710	31	1.410	0.085	22	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	16.00	13710	31	1.410	0.085	22	19.50	8.38
11-12-90-6#3-i-2.5-2-22	A	90°	5 3/4	Horizontal	A1035	21.88	13710	31	1.410	0.085	22	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	21.50	13710	31	1.410	0.085	22	19.50	8.38
11-5-90-0-i-2.5-2-14	A	90°	5 7/8	Horizontal	A615	13.50	4910	13	1.410	0.069	22	19.50	8.38
	B	90°	5 7/8	Horizontal	A615	15.25	4910	13	1.410	0.069	22	19.50	8.38
11-5-90-0-i-2.5-2-26	A	90°	5 3/4	Horizontal	A1035	26.00	5360	6	1.410	0.085	22	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	26.00	5360	6	1.410	0.085	22	19.50	8.38
11-5-90-0-i-3.5-2-14	A	90°	5 7/8	Horizontal	A615	14.75	4910	13	1.410	0.069	24	19.50	8.38
	B	90°	5 7/8	Horizontal	A615	15.25	4910	13	1.410	0.069	24	19.50	8.38

Table B.1 cont. Test results

Specimen	Hook	c_{so} in.	c_{th} in.	c_h in.	N_h	A_h in.^{2}	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	T kip	f_{su} ksi	Failure Type
8-8-90-0-i-2.5-2-10	A	2.75	2.25	9.00	2	0.79	60	-	0	0	-	50.0	63.3	FP
	B	2.88	2.50	9.00	2	0.79	60	-	0	0	-	52.9	67.0	FP
8-8-90-0-i-2.5-2-8	A	2.75	1.13	8.63	2	0.79	60	-	0	0	-	54.7	69.2	FP/K
	B	2.88	2.00	8.63	2	0.79	60	-	0	0	-	45.2	57.2	FP/SS
8-8-90-0-i-2.5-2-8(1)	A	2.75	2.75	9.50	2	0.79	60	-	0	0	-	38.0	48.1	FP/SS
	B	2.75	2.75	9.50	2	0.79	60	-	0	0	-	37.7	47.7	FP/SS
8-8-90-0-i-3.5-2-10	A	3.75	3.25	9.00	2	0.79	60	-	0	0	-	55.2	69.9	FP/SS
	B	3.75	1.25	9.00	2	0.79	60	-	0	0	-	71.9	91.0	SS/FP
8-8-90-0-i-3.5-2-8	A	3.50	2.25	9.00	2	0.79	60	-	0	0	-	43.7	55.3	SS/FP
	B	3.75	2.25	9.00	2	0.79	60	-	0	0	-	44.0	55.7	SS/FP
8-8-90-0-i-3.5-2-8(1)	A	3.63	2.13	10.00	2	0.79	60	-	0	0	-	41.2	52.2	FP
	B	3.75	2.63	10.00	2	0.79	60	-	0	0	-	42.9	54.3	FP
8-8-90-0-i-4-2-8	A	4.50	2.88	9.50	2	0.79	60	-	0	0	-	37.6	47.6	FP/SS
	B	3.88	2.50	9.50	2	0.79	60	-	0	0	-	48.7	61.6	FP
8-8-90-0-o-2.5-2-8	A	2.75	1.75	9.00	2	0.79	60	-	0	0	-	44.4	56.2	SB/K
	B	2.50	2.13	9.00	2	0.79	60	-	0	0	-	33.2	42.0	SB/K
8-8-90-0-o-3.5-2-8	A	3.50	2.38	9.75	2	0.79	60	-	0	0	-	35.6	45.1	FP/SS
	B	3.63	2.00	9.75	2	0.79	60	-	0	0	-	44.5	56.3	SS/FP
8-8-90-0-o-4-2-8	A	4.50	2.50	9.75	2	0.79	60	-	0	0	-	37.1	47.0	SS/FP
	B	3.75	2.38	9.75	2	0.79	60	-	0	0	-	39.2	49.6	SS
8-8-90-2#3-i-2.5-2-10	A	2.75	2.13	8.50	2	0.79	60	0.38	0.22	2	7.1	60.7	76.8	FP
	B	2.75	2.50	8.50	2	0.79	60	0.38	0.22	2	7.1	67.0	84.8	FB
8-8-90-2#3-i-2.5-2-8	A	3.00	2.00	9.00	2	0.79	60	0.38	0.22	2	7.1	46.2	58.5	FP/SS
	B	2.88	1.50	9.00	2	0.79	60	0.38	0.22	2	7.1	55.4	70.1	FP/SS
8-8-90-2#3-i-3.5-2-10	A	3.63	3.25	8.50	2	0.79	60	0.38	0.22	2	7.1	54.0	68.4	SS
	B	3.75	3.25	8.50	2	0.79	60	0.38	0.22	2	7.1	53.8	68.1	FP
8-8-90-2#3-i-3.5-2-8	A	3.63	2.00	8.50	2	0.79	60	0.38	0.22	2	7.1	48.3	61.1	FP
	B	3.75	1.88	8.50	2	0.79	60	0.38	0.22	2	7.1	49.3	62.4	FP
8-8-90-2#4-i-2.5-2-10	A	3.00	3.50	9.25	2	0.79	60	0.50	0.40	2	7.1	61.4	77.7	FP/SS
	B	3.00	2.75	9.25	2	0.79	60	0.50	0.40	2	7.1	71.3	90.3	FP/SS
8-8-90-2#4-i-3.5-2-10	A	3.75	3.00	9.13	2	0.79	60	0.50	0.40	2	7.1	69.5	88.0	SS/FP
	B	3.88	2.25	9.13	2	0.79	60	0.50	0.40	2	7.1	69.5	88.0	FP/SS
8-8-90-5#3-i-2.5-2-8	A	2.88	2.75	8.50	2	0.79	60	0.38	0.55	5	3.0	56.0	70.9	FP
	B	2.75	2.75	8.50	2	0.79	60	0.38	0.55	5	3.0	51.2	64.8	FP
8-8-90-5#3-i-3.5-2-8	A	3.50	2.00	8.88	2	0.79	60	0.38	0.55	5	3.0	55.4	70.1	FP
	B	3.63	2.00	8.88	2	0.79	60	0.38	0.55	5	3.0	56.2	71.1	FP
8-8-90-5#3-o-2.5-2-8	A	2.75	1.75	9.25	2	0.79	60	0.38	0.55	5	3.0	56.1	71.0	FP/SS
	B	2.75	1.25	9.25	2	0.79	60	0.38	0.55	5	3.0	66.8	84.6	FB/SS
8-8-90-5#3-o-3.5-2-8	A	3.50	2.25	9.50	2	0.79	60	0.38	0.55	5	3.0	53.9	68.2	FP
	B	3.50	2.00	9.50	2	0.79	60	0.38	0.55	5	3.0	56.1	71.0	FP/SS
8-8-90-5#3-o-4-2-8	A	3.88	1.50	10.00	2	0.79	60	0.38	0.55	5	3.0	39.6	50.1	SS/FP
	B	4.50	2.00	10.00	2	0.79	60	0.38	0.55	5	3.0	41.5	52.5	FP
11-12-90-0-i-2.5-2-17	A	3.75	2.13	13.75	2	1.56	60	-	0	0	-	123.6	79.2	SS/K
	B	2.50	2.00	13.75	2	1.56	60	-	0	0	-	125.6	80.5	SS
11-12-90-0-i-2.5-2-25	A	2.50	2.38	13.13	2	1.56	60	-	0	0	-	205.1	131.5	SB
	B	2.50	2.88	13.13	2	1.56	60	-	0	0	-	198.1	127.0	SB
11-12-90-2#3-i-2.5-2-17	A	2.50	1.50	13.25	2	1.56	60	0.38	0.22	2	12.0	133.2	85.4	SS
	B	2.50	2.00	13.25	2	1.56	60	0.38	0.22	2	12.0	129.9	83.3	SS
11-12-90-2#3-i-2.5-2-25	A	2.63	2.25	13.00	2	1.56	60	0.38	0.22	2	12.0	220.0	141.0	*
	B	3.00	2.75	13.00	2	1.56	60	0.38	0.22	2	12.0	220.0	141.0	*
11-12-90-6#3-i-2.5-2-16	A	2.50	3.25	13.00	2	1.56	60	0.38	0.66	6	4.0	115.1	73.8	SS/FP
	B	2.50	2.00	13.00	2	1.56	60	0.38	0.66	6	4.0	127.5	81.7	SB/FB
11-12-90-6#3-i-2.5-2-22	A	2.88	2.38	13.25	2	1.56	60	0.38	0.66	6	4.0	200.1	128.3	SS/FB
	B	3.13	2.75	13.25	2	1.56	60	0.38	0.66	6	4.0	199.2	127.7	FB
11-5-90-0-i-2.5-2-14	A	2.75	2.50	13.25	2	1.56	60	-	0	0	-	67.2	43.1	FP/SS
	B	2.75	0.75	13.25	2	1.56	60	-	0	0	-	81.4	52.2	SS
11-5-90-0-i-2.5-2-26	A	2.50	2.13	13.25	2	1.56	60	-	0	0	-	165.7	106.2	FB/SS
	B	2.94	2.13	13.25	2	1.56	60	-	0	0	-	146.8	94.1	FB/SS/K
11-5-90-0-i-3.5-2-14	A	3.75	1.50	13.25	2	1.56	60	-	0	0	-	82.6	52.9	FP/SS
	B	3.88	1.00	13.25	2	1.56	60	-	0	0	-	69.0	44.2	FP/SS/K

*Test stopped prior to failure

Table B.1 cont. Test results

Specimen	Hook	Bend Angle	Radius of Bend	Transverse Reinforcement Orientation	Hook Bar Type	ℓ_{eh} in.	f'_c psi	Age days	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
11-5-90-0-i-3.5-2-17	A	90°	5 3/4	Horizontal	A1035	18.13	5600	24	1.410	0.085	24	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	17.63	5600	24	1.410	0.085	24	19.50	8.38
11-5-90-0-i-3.5-2-26	A	90°	5 3/4	Horizontal	A1035	26.25	5960	8	1.410	0.085	24	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	25.75	5960	8	1.410	0.085	24	19.50	8.38
11-5-90-1#4-i-2.5-2-17	A	90°	5 3/4	Horizontal	A1035	17.75	5790	25	1.410	0.085	22	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	17.63	5790	25	1.410	0.085	22	19.50	8.38
11-5-90-1#4-i-3.5-2-17	A	90°	5 3/4	Horizontal	A1035	17.75	5790	25	1.410	0.085	24	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	17.75	5790	25	1.410	0.085	24	19.50	8.38
11-5-90-2#3-i-2.5-2-14	A	90°	5 7/8	Horizontal	A615	13.50	4910	13	1.410	0.069	22	19.50	8.38
	B	90°	5 7/8	Horizontal	A615	13.75	4910	13	1.410	0.069	22	19.50	8.38
11-5-90-2#3-i-2.5-2-17	A	90°	5 3/4	Horizontal	A1035	17.38	5600	24	1.410	0.085	22	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	17.75	5600	24	1.410	0.085	22	19.50	8.38
11-5-90-2#3-i-3.5-2-14	A	90°	5 7/8	Horizontal	A615	14.50	4910	12	1.410	0.069	24	19.50	8.38
	B	90°	5 7/8	Horizontal	A615	13.38	4910	12	1.410	0.069	24	19.50	8.38
11-5-90-2#3-i-3.5-2-17	A	90°	5 3/4	Horizontal	A1035	17.50	7070	28	1.410	0.085	24	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	17.75	7070	28	1.410	0.085	24	19.50	8.38
11-5-90-5#3-i-2.5-2-14	A	90°	5 7/8	Horizontal	A615	14.25	4910	12	1.410	0.069	22	19.50	8.38
	B	90°	5 7/8	Horizontal	A615	13.50	4910	12	1.410	0.069	22	19.50	8.38
11-5-90-5#3-i-3.5-2-14	A	90°	5 7/8	Horizontal	A615	14.63	4910	14	1.410	0.069	24	19.50	8.38
	B	90°	5 7/8	Horizontal	A615	14.50	4910	14	1.410	0.069	24	19.50	8.38
11-5-90-5#4s-i-2.5-2-20	A	90°	5 3/4	Horizontal	A1035	20.00	5420	7	1.410	0.085	22	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	20.25	5420	7	1.410	0.085	22	19.50	8.38
11-5-90-5#4s-i-3.5-2-20	A	90°	5 3/4	Horizontal	A1035	19.75	5960	8	1.410	0.085	24	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	19.25	5960	8	1.410	0.085	24	19.50	8.38
11-5-90-6#3-i-2.5-2-20	A	90°	5 3/4	Horizontal	A1035	19.50	5420	7	1.410	0.085	22	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	19.00	5420	7	1.410	0.085	22	19.50	8.38
11-5-90-6#3-i-3.5-2-20	A	90°	5 3/4	Horizontal	A1035	20.50	5420	7	1.410	0.085	24	19.50	8.38
	B	90°	5 3/4	Horizontal	A1035	20.25	5420	7	1.410	0.085	24	19.50	8.38

Table B.1 cont. Test results

Specimen	Hook	c_{so} in.	c_{th} in.	c_h in.	N_h	A_h in.^{2}	f_{yt} ksi	d_{tr} in.	A_{tr} in.^{2}	N_{tr}	s_{tr} in.	T kip	f_{su} ksi	Failure Type
11-5-90-0-i-3.5-2-17	A	4.00	1.75	13.13	2	1.56	60	-	0	0	-	105.0	67.3	SS/K
	B	3.88	2.50	13.13	2	1.56	60	-	0	0	-	117.6	75.4	SS
11-5-90-0-i-3.5-2-26	A	3.75	2.13	13.50	2	1.56	60	-	0	0	-	198.3	127.1	SB/FB
	B	3.75	2.63	13.50	2	1.56	60	-	0	0	-	181.7	116.5	FB/SB
11-5-90-1#4-i-2.5-2-17	A	2.75	1.75	13.13	2	1.56	60	0.50	0.20	1	8.8	99.4	63.7	SS/FP
	B	2.75	2.00	13.13	2	1.56	60	0.50	0.20	1	8.8	119.7	76.7	FP/SS
11-5-90-1#4-i-3.5-2-17	A	3.75	1.75	13.13	2	1.56	60	0.50	0.20	1	8.8	105.7	67.8	SS
	B	3.88	1.75	13.13	2	1.56	60	0.50	0.20	1	8.8	108.8	69.7	SS/FP/K
11-5-90-2#3-i-2.5-2-14	A	2.75	2.50	13.25	2	1.56	60	0.38	0.22	2	8.0	77.7	49.8	FP/SS
	B	2.88	2.25	13.25	2	1.56	60	0.38	0.22	2	8.0	77.2	49.5	SS
11-5-90-2#3-i-2.5-2-17	A	2.50	2.25	13.38	2	1.56	60	0.38	0.22	2	8.0	108.4	69.5	SS/FP
	B	2.63	1.75	13.38	2	1.56	60	0.38	0.22	2	8.0	103.2	66.2	SS/FP
11-5-90-2#3-i-3.5-2-14	A	3.75	1.63	13.25	2	1.56	60	0.38	0.22	2	8.0	92.7	59.4	FP/SS
	B	3.88	2.75	13.25	2	1.56	60	0.38	0.22	2	8.0	81.8	52.4	SS/FP/K
11-5-90-2#3-i-3.5-2-17	A	3.63	2.13	13.38	2	1.56	60	0.38	0.22	2	8.0	107.8	69.1	SS/FP/K
	B	3.63	2.00	13.38	2	1.56	60	0.38	0.22	2	8.0	111.5	71.5	SS
11-5-90-5#3-i-2.5-2-14	A	2.75	1.75	13.38	2	1.56	60	0.38	0.55	5	5.0	105.6	67.7	SS/FP
	B	2.88	2.50	13.38	2	1.56	60	0.38	0.55	5	5.0	94.1	60.3	SS/FP
11-5-90-5#3-i-3.5-2-14	A	3.88	1.38	13.13	2	1.56	60	0.38	0.55	5	5.0	101.3	64.9	FP/SS
	B	3.88	1.50	13.13	2	1.56	60	0.38	0.55	5	5.0	94.7	60.7	SS/FP
11-5-90-5#4s-i-2.5-2-20	A	2.50	2.25	13.38	2	1.56	60	0.50	1.00	5	5.0	141.4	90.6	FP/SS
	B	2.75	2.00	13.38	2	1.56	60	0.50	1.00	5	5.0	161.6	103.6	FP/SS
11-5-90-5#4s-i-3.5-2-20	A	3.75	2.25	13.13	2	1.56	60	0.50	1.00	5	5.0	186.7	119.7	SS/FP
	B	3.75	2.75	13.13	2	1.56	60	0.50	1.00	5	5.0	153.5	98.4	FP/SS
11-5-90-6#3-i-2.5-2-20	A	2.63	2.75	12.88	2	1.56	60	0.38	0.66	6	4.0	153.1	98.1	FP/SS
	B	2.63	3.25	12.88	2	1.56	60	0.38	0.66	6	4.0	135.0	86.5	FP/SS
11-5-90-6#3-i-3.5-2-20	A	3.75	1.75	13.13	2	1.56	60	0.38	0.66	6	4.0	150.2	96.3	SS/FP
	B	3.88	2.00	13.13	2	1.56	60	0.38	0.66	6	4.0	135.3	86.7	SS

APPENDIX C MEASURED AND CALCULATED FAILURE LOADS

Table C1 Ratios of measured and calculated ultimate bar forces

Specimen		d_b in.	c_b in.	f'_c psi	ℓ_{eh} in.	T lb	T_{ACI} lb	T_{calc} lb	T/T_{ACI}	T/T_{calc}
5-5-90-0-i-2.5-2-7	A	0.625	2.8125	5190	6.88	26600	24764	25328	1.07	1.05
	B	0.625	2.8125	5190	7.00	26100	25215	25905	1.04	1.01
5-5-90-0-i-2.5-2-10	A	0.625	3.0625	5230	9.38	37400	33899	38620	1.10	0.97
	B	0.625	2.9425	5230	9.38	32900	33899	38046	0.97	0.86
5-8-90-0-i-2.5-2-6	A	0.625	2.8125	9080	6.13	21700	29182	25784	0.74	0.84
	B	0.625	2.8125	9080	6.50	25000	30969	27772	0.81	0.90
5-8-90-0-i-2.5-2-6(1)	A	0.625	3.0625	8450	6.75	27600	31024	29438	0.89	0.94
	B	0.625	2.9425	8450	6.75	32100	31024	29000	1.03	1.11
5-8-90-0-i-2.5-2-8	A	0.625	2.8125	8580	8.00	31900	37051	35415	0.86	0.90
	B	0.625	3.0625	8580	7.50	35900	34736	33730	1.03	1.06
5-12-90-0-i-2.5-2-10	A	0.625	2.6925	10290	10.00	40800	35504	48542	1.15	0.84
	B	0.625	2.8125	10290	11.00	42500	55792	55585	0.76	0.76
5-12-90-0-i-2.5-2-5	A	0.625	2.9425	11600	5.13	19400	27599	22531	0.70	0.86
	B	0.625	2.9425	11600	4.75	18000	25580	20490	0.70	0.88
5-5-90-0-i-3.5-2-7	A	0.625	3.6925	5190	7.50	27200	27016	31273	1.01	0.87
	B	0.625	3.8125	5190	7.63	25900	27466	32312	0.94	0.80
5-5-90-0-i-3.5-2-10	A	0.625	3.8125	5190	10.50	43200	37822	48200	1.14	0.90
	B	0.625	3.8125	5190	10.38	41100	37372	47484	1.10	0.87
5-8-90-0-i-3.5-2-6	A	0.625	4.0625	9300	6.50	24400	31342	32100	0.78	0.76
	B	0.625	4.0625	9300	6.63	27500	31945	32873	0.86	0.84
5-8-90-0-i-3.5-2-6(1)	A	0.625	3.9425	8580	6.25	25100	28946	29524	0.87	0.85
	B	0.625	3.8125	8580	6.38	29100	29525	29886	0.99	0.97
5-8-90-0-i-3.5-2-8	A	0.625	3.9425	8380	8.63	39100	39478	43859	0.99	0.89
	B	0.625	3.8125	8380	8.50	34300	38905	42528	0.88	0.81
5-12-90-0-i-3.5-2-5	A	0.625	3.9425	10410	5.50	22000	28058	26615	0.78	0.83
	B	0.625	3.9425	10410	5.38	23200	27420	25862	0.85	0.90
5-12-90-0-i-3.5-2-10	A	0.625	3.8125	11600	10.13	46000	54525	58156	0.84	0.79
	B	0.625	3.8125	11600	10.00	46000	53852	57260	0.85	0.80
8-5-90-0-i-2.5-2-9.5	A	1	3.25	5140	9.00	44600	32262	39597	1.38	1.13
	B	1	3	5140	10.25	65800	36743	45209	1.79	1.46
8-5-90-0-i-2.5-2-12.5	A	1	3.25	5240	13.25	65300	47957	64573	1.36	1.01
	B	1	3.25	5240	13.25	69900	47957	64573	1.46	1.08
8-5-90-0-i-2.5-2-16	A	1	3.25	4980	16.00	83300	56455	80542	1.48	1.03
	B	1	3.25	4980	16.75	86100	59102	85289	1.46	1.01
8-5-90-0-i-2.5-2-18	A	1	3	5380	19.50	100200	71515	102355	1.40	0.98
	B	1	3	5380	17.88	79800	65555	91807	1.22	0.87
8-5-90-0-i-2.5-2-13	A	1	3	5560	13.25	73100	49400	63750	1.48	1.15
	B	1	3	5560	13.50	65200	50332	65257	1.30	1.00
8-8-90-0-i-2.5-2-8	A	1	3.25	8780	8.00	38000	37481	39917	1.01	0.95
	B	1	3.25	8780	8.00	37700	37481	39917	1.01	0.94
8-8-90-0-i-2.5-2-10	A	1	3.25	7700	9.75	50000	42778	49206	1.17	1.02
	B	1	3.38	7700	9.50	52900	41681	48339	1.27	1.09
8-8-90-0-i-2.5-2-8	A	1	3.25	7910	8.88	54700	39466	44092	1.39	1.24
	B	1	3.38	7910	8.00	45200	35575	39300	1.27	1.15
8-12-90-0-i-2.5-2-9	A	1	3.25	11160	9.00	50800	47538	49580	1.07	1.02
	B	1	3.13	11160	9.00	54800	47538	48885	1.15	1.12
8-5-90-0-i-3.5-2-18	A	1	4.25	5380	19.00	96000	69681	112911	1.38	0.85
	B	1	3.88	5380	18.00	105100	66014	101988	1.59	1.03
8-5-90-0-i-3.5-2-13	A	1	4.13	5560	13.38	69400	49866	72718	1.39	0.95
	B	1	3.88	5560	13.38	68300	49866	71035	1.37	0.96
8-8-90-0-i-3.5-2-8	A	1	4.13	8780	8.50	41200	39823	47107	1.03	0.87
	B	1	4.25	8780	8.00	42900	37481	44141	1.14	0.97
8-8-90-0-i-3.5-2-8(1)	A	1	4	7910	7.75	43700	34464	40234	1.27	1.09
	B	1	4.25	7910	7.75	44000	34464	41159	1.28	1.07
8-8-90-0-i-3.5-2-10	A	1	4.25	7700	8.75	55200	38390	47529	1.44	1.16
	B	1	4.25	7700	10.75	71900	47165	61477	1.52	1.17
8-12-90-0-i-3.5-2-9	A	1	4	11160	9.00	61400	47538	53594	1.29	1.15
	B	1	4.25	11160	9.00	68500	47538	54827	1.44	1.25
11-5-90-0-i-2.5-2-14	A	1.41	3.455	4910	13.50	67200	47298	69282	1.42	0.97
	B	1.41	3.455	4910	15.25	81400	53429	80685	1.52	1.01
11-5-90-0-i-2.5-2-26	A	1.41	3.645	5360	26.00	165700	95176	164507	1.74	1.01
	B	1.41	3.205	5360	26.00	146800	95176	156759	1.54	0.94
11-12-90-0-i-2.5-2-25	A	1.41	3.205	13330	24.88	205100	143598	193180	1.43	1.06
	B	1.41	3.205	13330	24.38	198100	140712	188339	1.41	1.05
11-12-90-0-i-2.5-2-17	A	1.41	3.455	13330	17.63	123600	101745	129167	1.21	0.96
	B	1.41	3.205	13330	17.75	125600	102467	126694	1.23	0.99
11-5-90-0-i-3.5-2-14	A	1.41	4.455	4910	14.75	82600	51678	85132	1.60	0.97
	B	1.41	4.585	4910	15.25	69000	53429	89717	1.29	0.77
11-5-90-0-i-3.5-2-17	A	1.41	4.705	5600	18.13	105000	67818	116790	1.55	0.90
	B	1.41	4.585	5600	17.63	117600	65947	111689	1.78	1.05
11-5-90-0-i-3.5-2-26	A	1.41	4.455	5960	26.00	198300	100361	182906	1.98	1.08
	B	1.41	4.455	5960	26.00	181700	100361	182906	1.81	0.99

Table C.1 cont. Ratios of measured and calculated ultimate bar forces

Specimen		d_b in.	c_b in.	f'_c psi	ℓ_{eh} in.	T lb	T_{ACI} lb	T_{calc} lb	T/T_{ACI}	T/T_{calc}
5-5-90-5#3-i-2.5-2-7	A	0.625	3.06	5230	5.63	32100	36321	34061	0.88	0.94
	B	0.625	3.06	5230	7.00	31300	45199	38075	0.69	0.82
5-12-90-5#3-i-2.5-2-5	A	0.625	2.94	10410	5.13	33900	46688	34925	0.73	0.97
	B	0.625	2.94	10410	5.75	34900	52381	36879	0.67	0.95
5-5-90-5#3-i-3.5-2-7	A	0.625	3.69	5190	7.50	44300	48242	39504	0.92	1.12
	B	0.625	3.81	5190	6.75	35200	43418	37317	0.81	0.94
5-12-90-5#3-i-3.5-2-10	A	0.625	3.81	11090	11.00	46000	103429	53636	0.44	0.86
	B	0.625	3.81	11090	11.25	46000	105779	54423	0.43	0.85
8-5-90-5#3-2.5-2-10a	B	1	3.00	5270	10.50	82800	68058	66735	1.22	1.24
8-5-90-5#3-2.5-2-10b	A	1	3.25	5440	10.25	78800	67500	65774	1.17	1.20
	B	1	3.13	5440	10.50	66700	69147	66947	0.96	1.00
8-5-90-5#3-2.5-2-10c	A	1	3.00	5650	10.50	68900	70469	67201	0.98	1.03
	B	1	3.00	5650	10.50	69600	70469	67201	0.99	1.04
8-5-90-5#3-i-2.5-2-15	A	1	3.25	4850	15.25	77100	94825	88202	0.81	0.87
	B	1	3.00	4850	15.81	72600	98323	90810	0.74	0.80
8-5-90-5#3-i-2.5-2-13	A	1	3.00	5560	13.75	93100	91542	82366	1.02	1.13
	B	1	2.88	5560	13.50	81300	62915	81191	1.29	1.00
8-8-90-5#3-i-2.5-2-8	A	1	3.38	8290	7.25	56000	58938	53932	0.95	1.04
	B	1	3.25	8290	7.25	51200	58938	53932	0.87	0.95
8-12-90-5#3-i-2.5-2-9	A	1	3.00	11160	9.00	66500	84890	64376	0.78	1.03
	B	1	3.13	11160	9.00	63100	84890	64376	0.74	0.98
8-5-90-5#3-i-3.5-2-15	A	1	4.06	4850	15.75	81200	97934	90520	0.83	0.90
	B	1	4.00	4850	15.75	87100	97934	90520	0.89	0.96
8-5-90-5#3-i-3.5-2-13	A	1	3.88	5570	13.25	89600	88293	80031	1.01	1.12
	B	1	4.00	5570	13.00	76000	86627	78856	0.88	0.96
8-8-90-5#3-i-3.5-2-8	A	1	4.00	7910	8.00	55400	63527	57330	0.87	0.97
	B	1	4.13	7910	8.00	56200	63527	57330	0.88	0.98
8-12-90-5#3-i-3.5-2-9	A	1	3.75	11160	9.00	68800	84890	64376	0.81	1.07
	B	1	3.88	11160	9.00	82200	84890	64376	0.97	1.28
11-5-90-6#3-i-2.5-2-20	A	1.41	3.33	5420	20.00	153100	131465	149891	1.16	1.02
	B	1.41	3.33	5420	20.00	135000	131465	149891	1.03	0.90
11-12-90-6#3-i-2.5-2-16	A	1.41	3.21	13710	14.75	115100	154203	126394	0.75	0.91
	B	1.41	3.21	13710	16.00	127500	167271	135459	0.76	0.94
11-12-90-6#3-i-2.5-2-22	A	1.41	3.58	13710	21.88	200100	228691	178065	0.87	1.12
	B	1.41	3.83	13710	21.50	199200	224770	175345	0.89	1.14
11-5-90-6#3-i-3.5-2-20	A	1.41	4.46	5420	20.00	150200	131465	149891	1.14	1.00
	B	1.41	4.58	5420	20.00	135300	131465	149891	1.03	0.90

Table C2 Calculated and normalized ultimate bar forces

Specimen	Hook	Bend Angle	d_b in.	c_b in.	f'_c psi	ℓ_{eh} in.	T lb	T_{ACI} lb	T_n lb
5-5-90-0-i-2.5-2-7	A	90°	0.625	2.8125	5190	6.88	26600	24764	26314
	B	90°	0.625	2.8125	5190	7.00	26100	25215	25819
5-5-90-0-i-2.5-2-10	A	90°	0.625	3.0625	5230	9.38	37400	33899	36915
	B	90°	0.625	2.9425	5230	9.38	32900	33899	32474
5-8-90-0-i-2.5-2-6	A	90°	0.625	2.8125	9080	6.13	21700	29182	18252
	B	90°	0.625	2.8125	9080	6.50	25000	30969	21028
5-8-90-0-i-2.5-2-6	A	90°	0.625	3.0625	8450	6.75	27600	31024	23704
	B	90°	0.625	2.9425	8450	6.75	32100	31024	27569
5-8-90-0-i-2.5-2-8	A	90°	0.625	2.8125	8580	8.00	31900	37051	27276
	B	90°	0.625	3.0625	8580	7.50	35900	34736	30696
5-12-90-0-i-2.5-2-10	A	90°	0.625	2.6925	10290	10.00	40800	35504	33095
	B	90°	0.625	2.8125	10290	11.00	42500	55792	34474
5-12-90-0-i-2.5-2-5	A	90°	0.625	2.9425	11600	5.13	19400	27599	15199
	B	90°	0.625	2.9425	11600	4.75	18000	25580	14102
5-5-90-0-i-3.5-2-7	A	90°	0.625	3.6925	5190	7.50	27200	27016	26907
	B	90°	0.625	3.8125	5190	7.63	25900	27466	25621
5-5-90-0-i-3.5-2-10	A	90°	0.625	3.8125	5190	10.50	43200	37822	42735
	B	90°	0.625	3.8125	5190	10.38	41100	37372	40658
5-8-90-0-i-3.5-2-6	A	90°	0.625	4.0625	9300	6.50	24400	31342	20381
	B	90°	0.625	4.0625	9300	6.63	27500	31945	22971
5-8-90-0-i-3.5-2-6(1)	A	90°	0.625	3.9425	8580	6.25	25100	28946	21462
	B	90°	0.625	3.8125	8580	6.38	29100	29525	24882
5-8-90-0-i-3.5-2-8	A	90°	0.625	3.9425	8380	8.63	39100	39478	33662
	B	90°	0.625	3.8125	8380	8.50	34300	38905	29529
5-12-90-0-i-3.5-2-5	A	90°	0.625	3.9425	10410	5.50	22000	28058	17785
	B	90°	0.625	3.9425	10410	5.38	23200	27420	18755
5-12-90-0-i-3.5-2-10	A	90°	0.625	3.8125	11600	10.13	46000	54525	36038
	B	90°	0.625	3.8125	11600	10.00	46000	53852	36038
8-5-90-0-i-2.5-2-9.5	A	90°	1	3.25	5140	9.00	44600	32262	44244
	B	90°	1	3	5140	10.25	65800	36743	65275
8-5-90-0-i-2.5-2-12.5	A	90°	1	3.25	5240	13.25	65300	47957	64418
	B	90°	1	3.25	5240	13.25	69900	47957	68956
8-5-90-0-i-2.5-2-16	A	90°	1	3.25	4980	16.00	83300	56455	83397
	B	90°	1	3.25	4980	16.75	86100	59102	86200
8-5-90-0-i-2.5-2-18	A	90°	1	3	5380	19.50	100200	71515	98094
	B	90°	1	3	5380	17.88	79800	65555	78123
8-5-90-0-i-2.5-2-13	A	90°	1	3	5560	13.25	73100	49400	70884
	B	90°	1	3	5560	13.50	65200	50332	63223
8-8-90-0-i-2.5-2-8	A	90°	1	3.25	8780	8.00	38000	37481	32275
	B	90°	1	3.25	8780	8.00	37700	37481	32021
8-8-90-0-i-2.5-2-10	A	90°	1	3.25	7700	9.75	50000	42778	44115
	B	90°	1	3.38	7700	9.50	52900	41681	46674
8-8-90-0-i-2.5-2-8	A	90°	1	3.25	7910	8.88	54700	39466	47887
	B	90°	1	3.38	7910	8.00	45200	35575	39570
8-12-90-0-i-2.5-2-9	A	90°	1	3.25	11160	9.00	50800	47538	40248
	B	90°	1	3.13	11160	9.00	54800	47538	43417
8-5-90-0-i-3.5-2-18	A	90°	1	4.25	5380	19.00	96000	69681	93982
	B	90°	1	3.88	5380	18.00	105100	66014	102891
8-5-90-0-i-3.5-2-13	A	90°	1	4.13	5560	13.38	69400	49866	67296
	B	90°	1	3.88	5560	13.38	68300	49866	66229
8-8-90-0-i-3.5-2-8	A	90°	1	4.13	8780	8.50	41200	39823	34993
	B	90°	1	4.25	8780	8.00	42900	37481	36437
8-8-90-0-i-3.5-2-8(1)	A	90°	1	4	7910	7.75	43700	34464	38257
	B	90°	1	4.25	7910	7.75	44000	34464	38520
8-8-90-0-i-3.5-2-10	A	90°	1	4.25	7700	8.75	55200	38390	48703
	B	90°	1	4.25	7700	10.75	71900	47165	63438
8-12-90-0-i-3.5-2-9	A	90°	1	4	11160	9.00	61400	47538	48646
	B	90°	1	4.25	11160	9.00	68500	47538	54271
11-5-90-0-i-2.5-2-14	A	90°	1.41	3.455	4910	13.50	67200	47298	67555
	B	90°	1.41	3.455	4910	15.25	81400	53429	81830
11-5-90-0-i-2.5-2-26	A	90°	1.41	3.645	5360	26.00	165700	95176	162393
	B	90°	1.41	3.205	5360	26.00	146800	95176	143870
11-12-90-0-i-2.5-2-25	A	90°	1.41	3.205	13330	24.88	205100	143598	154336
	B	90°	1.41	3.205	13330	24.38	198100	140712	149068
11-12-90-0-i-2.5-2-17	A	90°	1.41	3.455	13330	17.63	123600	101745	93008
	B	90°	1.41	3.205	13330	17.75	125600	102467	94513
11-5-90-0-i-3.5-2-14	A	90°	1.41	4.455	4910	14.75	82600	51678	83036
	B	90°	1.41	4.585	4910	15.25	69000	53429	69364
11-5-90-0-i-3.5-2-17	A	90°	1.41	4.705	5600	18.13	105000	67818	101605
	B	90°	1.41	4.585	5600	17.63	117600	65947	113798
11-5-90-0-i-3.5-2-26	A	90°	1.41	4.455	5960	26.00	198300	100361	188453
	B	90°	1.41	4.455	5960	26.00	181700	100361	172677
5-8-180-0-i-2.5-2-7	A	180°	0.625	2.81	9080	7.38	26700	44284	22458
	B	180°	0.625	2.94	9080	7.13	35200	42783	29607
5-8-180-0-i-3.5-2-7	A	180°	0.625	3.94	9080	7.38	34100	44284	28682
	B	180°	0.625	3.69	9080	7.25	31400	43534	26411
8-5-180-0-i-2.5-2-11	A	180°	1.00	3.50	4550	11.00	45600	38526	46864
	B	180°	1.00	3.25	4550	11.00	50500	38526	51900
8-5-180-0-i-2.5-2-14	A	180°	1.00	3.25	4840	14.00	49400	49337	49868
	B	180°	1.00	3.13	4840	14.00	69400	49337	70058
8-8-180-0-i-2.5-2-11.5	A	180°	1	3.50	8630	9.25	62800	34538	53607
	B	180°	1	3.50	8630	9.25	80200	34538	68459
8-5-180-0-i-3.5-2-11	A	180°	1.00	4.25	4550	11.63	58600	40715	60225
	B	180°	1.00	4.25	4550	11.63	60500	40715	62178
8-5-180-0-i-3.5-2-14	A	180°	1.00	4.38	4840	14.38	63700	50658	64304
	B	180°	1.00	4.25	4840	13.88	78000	48896	78739

Table C.2 cont. Calculated and normalized ultimate bar forces

Specimen	Hook	Bend Angle	d_b in.	c_b in.	f'_c psi	ℓ_{eh} in.	T lb	T_{ACI} lb	T_n lb
5-5-90-2#3-i-2.5-2-8	A	90°	0.625	2.81	5860	8.00	27900	28737	27408
	B	90°	0.625	2.81	5860	7.50	38900	26941	38215
5-5-90-2#3-i-2.5-2-6	A	90°	0.625	2.94	5800	6.00	31800	21530	31276
	B	90°	0.625	2.94	5800	5.75	29200	20633	28719
5-8-90-2#3-i-2.5-2-6	A	90°	0.625	3.06	8580	6.00	33500	22390	31534
	B	90°	0.625	3.19	8580	6.00	30900	22390	29087
5-8-90-2#3-i-2.5-2-8	A	90°	0.625	2.94	8380	8.25	39800	30714	37563
	B	90°	0.625	2.81	8380	8.50	40500	31645	38224
5-12-90-2#3-i-2.5-2-5	A	90°	0.625	2.81	11090	5.75	25200	22015	23049
	B	90°	0.625	3.06	11090	5.75	29400	22015	26891
5-5-90-2#3-i-3.5-2-6	A	90°	0.625	3.69	5230	6.00	21500	21309	21392
	B	90°	0.625	3.69	5230	5.75	22400	20421	22287
5-5-90-2#3-i-3.5-2-8	A	90°	0.625	3.69	5190	7.94	43700	28168	43518
	B	90°	0.625	3.81	5190	7.50	45700	26616	45510
5-8-90-2#3-i-3.5-2-8	A	90°	0.625	3.81	8710	7.13	38000	26628	35710
	B	90°	0.625	3.81	8710	7.00	28600	26161	26876
5-8-90-2#3-i-3.5-2-6	A	90°	0.625	3.81	8580	6.50	29900	24256	28145
	B	90°	0.625	4.06	8580	6.00	30100	22390	28334
5-12-90-2#3-i-3.5-2-5	A	90°	0.625	4.06	10410	5.63	27900	21401	25700
	B	90°	0.625	3.81	10410	5.25	28900	19974	26621
5-10-90-2#3-i-3.5-2-10	A	90°	0.625	3.81	11090	10.75	46000	41159	42074
	B	90°	0.625	3.94	11090	10.63	46000	40680	42074
5-12-90-5#3-i-3.5-2-5	A	90°	0.625	2.69	11090	5.25	25200	20101	23049
	B	90°	0.625	2.81	11090	4.75	29400	18186	26891
8-5-90-2#3-i-2.5-2-9.5	A	90°	1	3.00	5140	9.00	54900	31908	54730
	B	90°	1	3.00	5140	9.25	53600	32794	53434
8-5-90-2#3-i-2.5-2-12.5	A	90°	1	3.25	5240	12.00	74100	42626	73712
	B	90°	1	3.25	5240	12.00	76300	42626	75900
8-5-90-2#3-i-2.5-2-16	A	90°	1	3.25	4810	15.00	80000	52828	80348
	B	90°	1	3.38	4810	15.75	92800	55469	93204
8-8-90-2#3-i-2.5-2-8	A	90°	1	3.50	7700	8.00	46200	29532	44019
	B	90°	1	3.38	7700	8.50	55400	31378	52785
8-8-90-2#3-i-2.5-2-10	A	90°	1	3.25	8990	9.88	60700	37023	56840
	B	90°	1	3.25	8990	9.50	67000	35617	62739
8-12-90-2#3-i-2.5-2-9	A	90°	1	3.38	11160	9.00	61800	34480	56485
	B	90°	1	3.13	11160	9.00	60300	34480	55114
8-5-90-2#3-i-3.5-2-13	A	90°	1	3.75	5570	17.50	102600	62543	101367
	B	90°	1	4.00	5570	17.00	88600	60756	87535
8-5-90-2#3-i-3.5-2-17	A	90°	1	3.63	5560	13.75	81200	49132	80240
	B	90°	1	4.13	5560	13.50	86900	48239	85873
8-8-90-2#3-i-3.5-2-8	A	90°	1	4.13	8290	8.00	48300	29751	45641
	B	90°	1	4.25	8290	8.13	49300	30216	46586
8-8-90-2#3-i-3.5-2-10	A	90°	1	4.13	8990	8.75	54000	32805	50566
	B	90°	1	4.25	8990	8.75	53800	32805	50379
8-12-90-2#3-i-3.5-2-9	A	90°	1	4.13	11160	9.00	50300	34480	45974
	B	90°	1	4.50	11160	9.00	49300	34480	45060
11-5-90-2#3-i-2.5-2-14	A	90°	1.41	3.46	4910	13.50	77700	47643	77858
	B	90°	1.41	3.58	4910	13.75	77200	48525	77357
11-5-90-2#3-i-2.5-2-17	A	90°	1.41	3.21	5600	17.38	108400	62130	107033
	B	90°	1.41	3.33	5600	17.75	103200	63471	101898
11-12-90-2#3-i-2.5-2-17	A	90°	1.41	3.21	13710	18.00	133200	70394	118971
	B	90°	1.41	3.21	13710	17.50	129900	68438	116023
11-5-90-2#3-i-3.5-2-14	A	90°	1.41	4.46	4910	14.50	92700	51172	92889
	B	90°	1.41	4.58	4910	13.38	81800	47202	81967
11-5-90-2#3-i-3.5-2-17	A	90°	1.41	4.33	7070	17.50	107800	64053	103698
	B	90°	1.41	4.33	7070	17.75	111500	64968	107257
5-5-180-2#3-1.5-2-11.25	A	180°	0.625	1.94	4420	11.63	48300	64955	48972
	B	180°	0.625	1.81	4420	11.50	43000	64257	43598
5-5-180-2#3-i-2.5-2-6	A	180°	0.625	2.94	5860	5.75	26900	33047	26426
	B	180°	0.625	2.94	5860	5.50	26900	31610	26426
5-5-180-2#3-i-2.5-2-8	A	180°	0.625	2.81	5670	8.00	34000	45828	33524
	B	180°	0.625	2.81	5670	8.00	34500	45828	34018
5-8-180-2#3-i-2.5-2-7	A	180°	0.625	2.81	9080	7.00	34600	42032	32363
	B	180°	0.625	2.81	9080	7.25	28700	43534	26845
5-8-180-2#3-i-3.5-2-7	A	180°	0.625	3.69	9080	6.75	29300	40531	27406
	B	180°	0.625	3.81	9080	6.88	32600	41282	30493
8-5-180-2#3-i-2.5-2-11	A	180°	1	3.25	4550	10.75	64200	37650	64882
	B	180°	1	3.00	4550	10.50	61900	36775	62557
8-5-180-2#3-i-2.5-2-14	A	180°	1	3.25	4870	13.50	87100	47604	87357
	B	180°	1	3.25	4870	14.00	76900	49367	77127
8-8-180-2#3-i-2.5-2-11.5	A	180°	1	3.25	8810	10.50	70100	39287	65791
	B	180°	1	3.25	8810	10.25	59500	38351	55842
8-5-180-2#3-i-3.5-2-11	A	180°	1	3.88	4300	10.13	57200	35261	58174
	B	180°	1	4.00	4300	10.63	54900	37003	55835
8-5-180-2#3-i-3.5-2-14	A	180°	1	4.13	4870	13.50	68300	47604	68502
	B	180°	1	4.25	4870	13.63	73000	48045	73216

Table C.2 cont. Calculated and normalized ultimate bar forces

Specimen	Hook	Bend Angle	d_b in.	c_b in.	f'_c psi	ℓ_{eh} in.	T lb	T_{ACI} lb	T_n lb
5-5-90-5#3-i-2.5-2-7	A	90°	0.625	3.06	5230	5.63	32100	36321	31956
	B	90°	0.625	3.06	5230	7.00	31300	45199	31160
5-12-90-5#3-i-2.5-2-5	A	90°	0.625	2.94	10410	5.13	33900	46688	31503
	B	90°	0.625	2.94	10410	5.75	34900	52381	32432
5-5-90-5#3-i-3.5-2-7	A	90°	0.625	3.69	5190	7.50	44300	48242	44135
	B	90°	0.625	3.81	5190	6.75	35200	43418	35069
5-12-90-5#3-i-3.5-2-10	A	90°	0.625	3.81	11090	11.00	46000	103429	42478
	B	90°	0.625	3.81	11090	11.25	46000	105779	42478
8-5-90-5#3-2.5-2-10a	B	90°	1	3.00	5270	10.50	82800	68058	82366
8-5-90-5#3-2.5-2-10b	A	90°	1	3.25	5440	10.25	78800	67500	78138
	B	90°	1	3.13	5440	10.50	66700	69147	66140
8-5-90-5#3-2.5-2-10c	A	90°	1	3.00	5650	10.50	68900	70469	68063
	B	90°	1	3.00	5650	10.50	69600	70469	68755
8-5-90-5#3-i-2.5-2-15	A	90°	1	3.25	4850	15.25	77100	94825	77335
	B	90°	1	3.00	4850	15.81	72600	98323	72821
8-5-90-5#3-i-2.5-2-13	A	90°	1	3.00	5560	13.75	93100	91542	92117
	B	90°	1	2.88	5560	13.50	81300	62915	80441
8-8-90-5#3-i-2.5-2-8	A	90°	1	3.38	8290	7.25	56000	58938	53239
	B	90°	1	3.25	8290	7.25	51200	58938	48676
8-12-90-5#3-i-2.5-2-9	A	90°	1	3.00	11160	9.00	66500	84890	61369
	B	90°	1	3.13	11160	9.00	63100	84890	58232
8-5-90-5#3-i-3.5-2-15	A	90°	1	4.06	4850	15.75	81200	97934	81448
	B	90°	1	4.00	4850	15.75	87100	97934	87366
8-5-90-5#3-i-3.5-2-13	A	90°	1	3.88	5570	13.25	89600	88293	88638
	B	90°	1	4.00	5570	13.00	76000	86627	75184
8-8-90-5#3-i-3.5-2-8	A	90°	1	4.00	7910	8.00	55400	63527	52916
	B	90°	1	4.13	7910	8.00	56200	63527	53680
8-12-90-5#3-i-3.5-2-9	A	90°	1	3.75	11160	9.00	68800	84890	63492
	B	90°	1	3.88	11160	9.00	82200	84890	75858
11-5-90-6#3-i-2.5-2-20	A	90°	1.41	3.33	5420	20.00	153100	131465	151870
	B	90°	1.41	3.33	5420	20.00	135000	131465	133915
11-12-90-6#3-i-2.5-2-16	A	90°	1.41	3.21	13710	14.75	115100	154203	104056
	B	90°	1.41	3.21	13710	16.00	127500	167271	115267
11-12-90-6#3-i-2.5-2-22	A	90°	1.41	3.58	13710	21.88	200100	228691	180901
	B	90°	1.41	3.83	13710	21.50	199200	224770	180087
11-5-90-6#3-i-3.5-2-20	A	90°	1.41	4.46	5420	20.00	150200	131465	148993
	B	90°	1.41	4.58	5420	20.00	135300	131465	134213

APPENDIX D ANALYSIS ON COMBINED 90° AND 180° HOOK TEST DATA

As discussed in Section 4.5, the anchorage strength of 180° hooks is nearly equivalent to the anchorage strength of 90° hooks. Therefore, it would make good sense to combine 90° and 180° hooks for analysis. The purpose of this appendix is to develop equations that characterize the relationship between ultimate bar force T, embedment length ℓ_{eh}, concrete compressive strength f_c', bar diameter d_b, and side cover to the center of the bar c_b for 90° and 180° hooks without confining transverse reinforcement and hooks with two No. 3 ties as confining transverse reinforcement in the same manner that is done for 90° hooks alone in Section 4.3. Though the 180° hooks confined by two No. 3 ties had ties spaced at $3d_b$, no comparison between the 90° and 180° hooks with ties spaced at $3d_b$ was made because 180° hooks require ties spaced at $3d_b$ to be placed perpendicular to the bar being developed – the ties in this study were placed parallel to the bar being developed – to qualify for the 0.8 reduction factor in accordance with Section 12.5.3(c) in ACI 318-11.

D.1 90° and 180° Hooks with No Confining Transverse Reinforcement

Figure D1 shows ultimate bar force at failure T as a function of embedment length ℓ_{eh}. This and other figures in this section show the results for 86 hooked bars, 16 for No. 5 bars with 2.5-in. side cover (2 being 180° hooks), 16 for No. 5 bars with 3.5-in. side cover (2 being 180° hooks), 24 for No. 8 bar with 2.5-in. side cover (6 being 180° hooks), 16 for No. 8 bar with 3.5-in. side cover (4 being 180° hooks), 8 for No. 11 bars with 2.5-in. side cover, and 6 for No. 11 bars with 3.5-in. side cover. No 180° No. 11 hooks have been tested. Embedment lengths range from 4.75 to 26 in. and ultimate bar force T ranges from 18,000 to 205,000 lb, which increases with increases in embedment length and bar size. The dummy variables analysis, without normalizing for concrete compressive strength, shows no difference in T as a function of side cover for No. 5 hooks, a higher T for increased side cover for No. 8 hooks, and a lower T for increased side cover for No. 11 hooks.

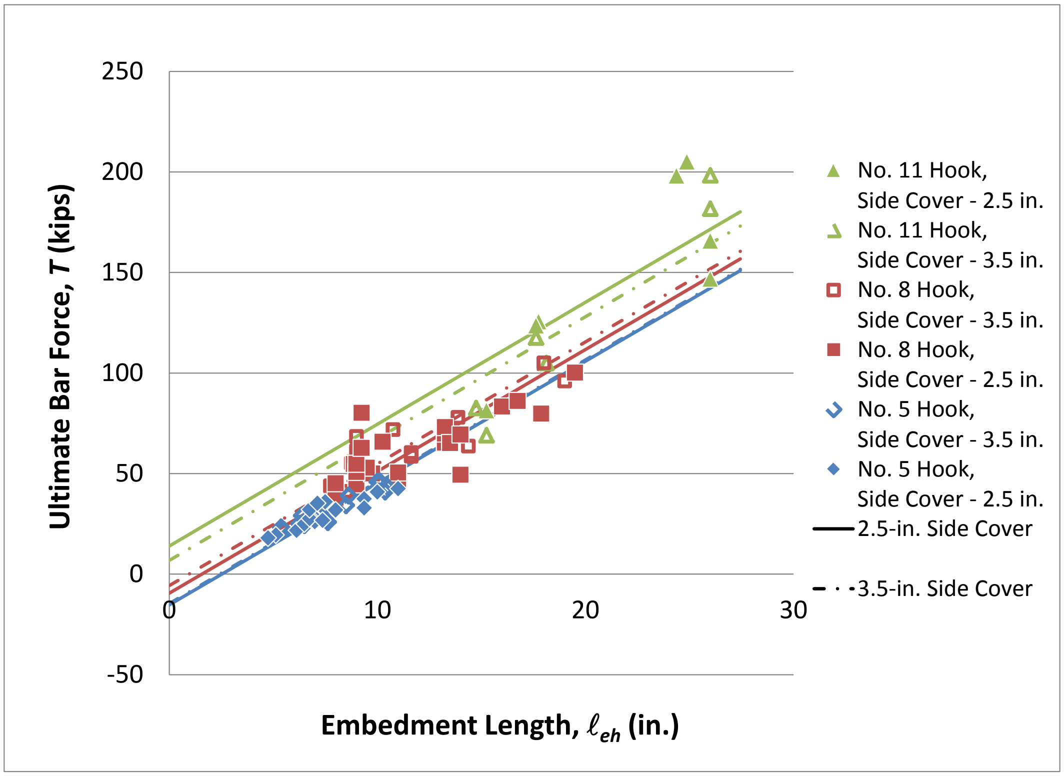

Figure D1 Ultimate bar force versus embedment length for 90° and 180° hooks with no confining transverse reinforcement

Using the process described in Section 4.3, a linear equation is developed that minimizes the scatter in $T/f_c'^{\,p_1}$ as a function of $d_b^{p_2}$ and $c_b^{p_3}$. The result of the analysis is represented by the closely spaced lines in Figure D2. Using the average intercept of the lines, the linear expression for the best fit with the data is

$$\frac{T}{f_c'^{\,1/3}} = 241\ell_{eh} d_b^{0.15} c_b^{0.3} - 749 \tag{D.1}$$

where,

T = ultimate bar force, lb

f_c' = concrete compressive strength, psi

ℓ_{eh} = embedment length, in.

c_b = side cover to the center of the bar, in.

d_b = bar diameter, in.

The parallel dummy variables analysis lines have the following intercepts, -788 for No. 5 bars with 2.5-in. side cover, -764 for No. 5 bars with 3.5-in. side cover, -651 for No. 8 bars with 2.5-in. side cover, -800 for No. 8 bars with 3.5-in. side cover, -776 for No 11 bars with 2.5-in side cover and -773 for No. 11 bars with 3.5-in. side cover. As for the 90° hook data alone, the negative intercept in Eq. (D.1) as well as the spread in the data points suggest a nonlinear relationship between T and ℓ_{eh}. The nonlinear relationship is shown in Eq. (D.2) and Figure D2.

$$\frac{T}{f_c'^{1/3}} = 109\left(\ell_{eh} d_b^{0.15} c_b^{0.3}\right)^{1.20} \tag{D.2}$$

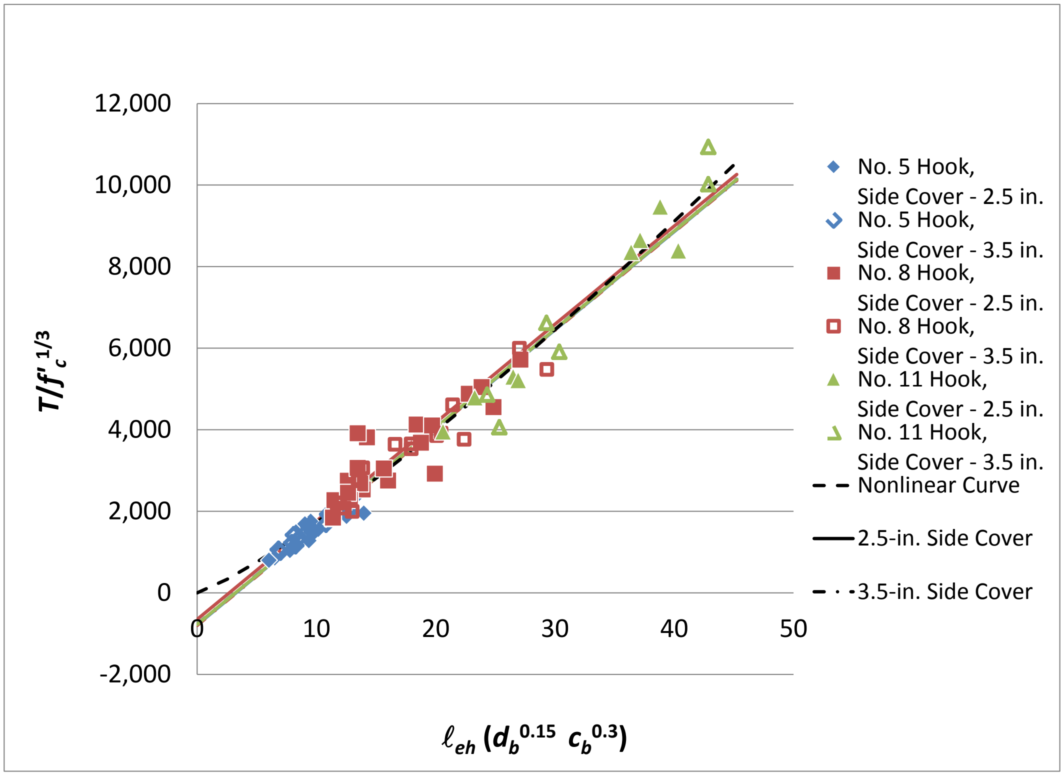

Figure D2 Development of an equation for 90° and 180° hooks with no confining transverse reinforcement

The powers p_1=1/3, p_2=0.15, and p_3=0.3 in Eq. (D.1) and (D.2) compare to the respective powers of 0.29, 0.1, and 0.3 for 90° hooks alone, as shown in Eq. (6) and (7). The ratios of the measured ultimate bar forces to those calculated using Eq. (D.2) T/T_{calc} are plotted in Figure D3 versus f_c'. The mean ratio is 0.994, standard deviation is 0.054, and the ratio ranges from 0.925 to 1.065. The zero slope of the dummy variables lines based on bar size and side cover indicates that the 1/3 power captures the average effect of concrete compressive strength on bar force *T*. The intercept for No. 5 hooks with 2.5-in. side cover is 0.925, for No. 5 hooks with 3.5-in. side cover is 0.947, for No.8 hooks with 2.5-in. side cover is 1.065, for No. 8 hooks with 3.5-in. side cover is 1.016, for No. 11 hooks with 2.5-in. side cover is 0.987, and for No. 11 hooks with 3.5-in. side cover is 0.970.

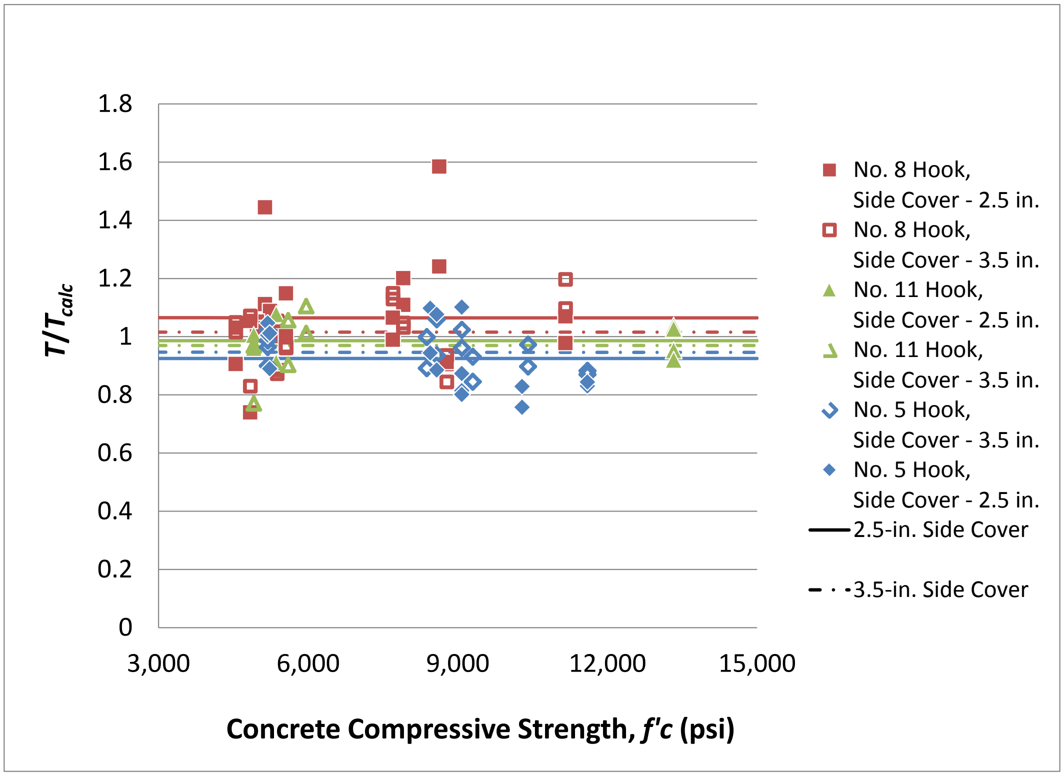

Figure D3 Ratio of test ultimate bar force to calculate ultimate bar force T/T_{calc} versus concrete compressive strength for 90° and 180° hooks with two No. 3 ties as confining transverse reinforcement

Equations (D.3) and (D.4) can be converted to "design style" equations by substituting development length ℓ_{dh} for embedment length ℓ_{eh} and the product $A_b f_y$ for T, and solving for ℓ_{dh}. The resulting equations are

$$\ell_{eh} = \frac{\dfrac{A_b f_y}{f_c'^{1/3}} + 749}{241 d_b^{0.15} c_b^{0.3}} \tag{D.3}$$

$$\ell_{dh} = \frac{\left(\dfrac{A_b f_y}{109 f_c'^{1/3}}\right)^{\frac{5}{6}}}{d_b^{0.15} c_b^{0.3}} \tag{D.4}$$

where,

A_b = ultimate bar force, lb

f_y = yield strength of the bar, psi

f_c' = concrete compressive strength, psi

ℓ_{dh}= development length, in.

c_b = side cover to the center of the bar, in.

d_b = bar diameter, in.

D.2 90° and 180° Hooks with Two No. 3 Ties as Confining Transverse Reinforcement

The figures in this section show the results for 74 hooked bars, 16 of which are No. 5 bars with 2.5-in. side cover (6 being 180° hooks), 16 are No. 5 bars with 3.5-in. side cover (2 being 180° hooks), 18 are No. 8 bars with 2.5-in. side cover (6 being 180° hooks), 14 are No. 8 bars with 3.5-in. side cover (4 being 180° hooks), 6 are No. 11 bars with 2.5-in. side cover, and 4 are No. 11 bars with 3.5-in. side cover. Figure D4 shows embedment length ℓ_{eh} as a function of ultimate bar force at failure T. Embedment lengths range from 4.75 to 18 in. and ultimate bar forces range from 21,500 to 133,200 lb. Ultimate bar force at failure increases with increases in embedment length and bar size. There is no effect for side cover shown for No. 5 hooks, but No. 8 and No. 11 hooks show a decrease in anchorage strength as side cover increases.

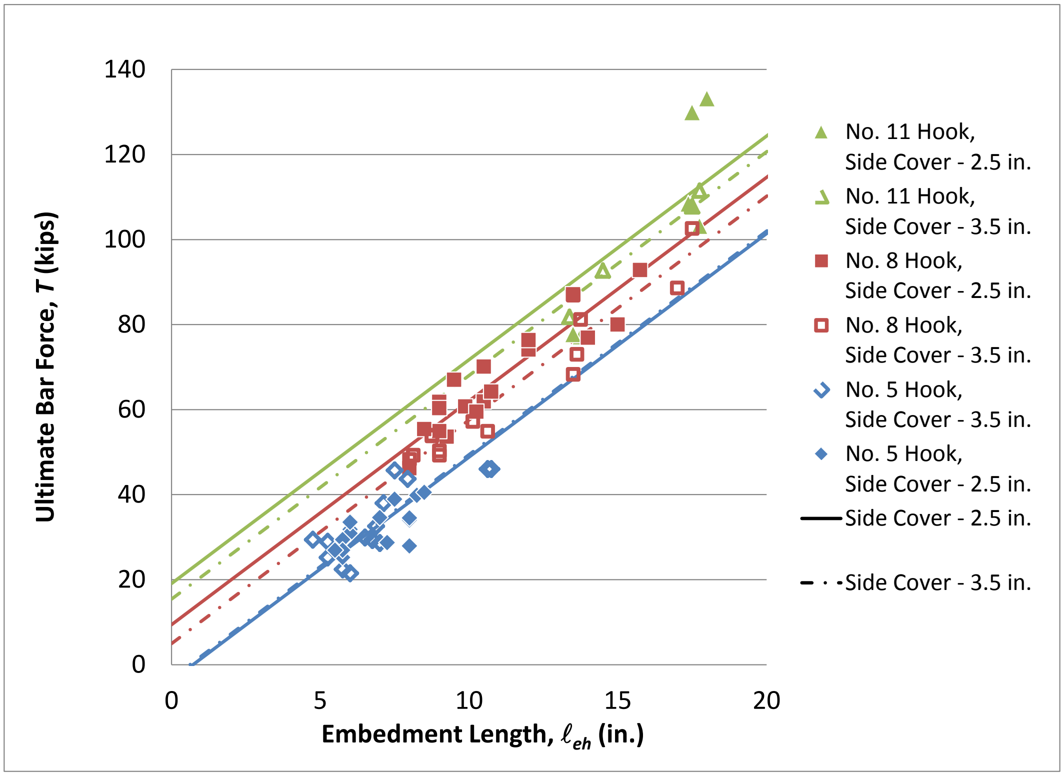

Figure D4 Ultimate bar force versus embedment length for 90° and 180° hooks with two No. 3 ties as confining transverse reinforcement

Using the same process as before, the dummy variables lines are condensed as shown in Figure D5. The intercepts are as follows, -538 for No. 5 bars with 2.5-in. side cover, -510 for No. 5 bars with 3.5-in. side cover, 2,249 for No. 8 bars with 2.5-in. side cover, 524 for No. 8 bars with 3.5-in. side cover, 617 for No 11 bars with 2.5-in side cover and 553 for No. 11 bars with 3.5-in. side cover. A linear expression is found relating ultimate bar force to embedment length, bar diameter, concrete compressive strength, and cover to the center of the bar. Using the average intercept of the lines, this equation is

$$\frac{T}{f_c'^{\,0.114}} = 2065\ell_{eh}d_b^{0.3} + 482 \tag{D.5}$$

where,

T = ultimate bar force, lb

f'_c = concrete compressive strength, psi

ℓ_{eh}= embedment length, in.

c_b = side cover to the center of the bar, in.

d_b = bar diameter, in.

In this case, the powers p_1=0.114, p_2=0.3, and p_3=0 compare to the respective powers for 90° hooks alone of 0.112, 0.3, and 0.05 in Eq. (14).

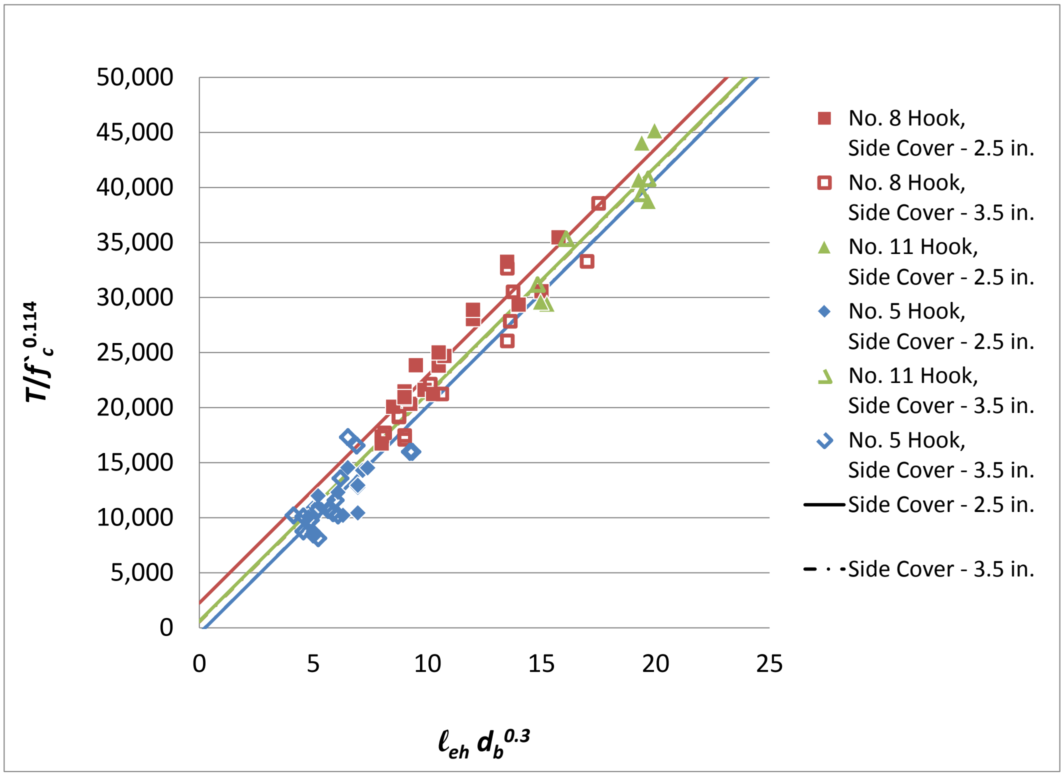

Figure D5 Development of an equation for 90° and 180° hooks with two No. 3 ties as confining transverse reinforcement

Replacing embedment length ℓ_{eh} with development length ℓ_{dh} and T with the product $A_b f_y$ in Eq. (D.5) and solving for ℓ_{dh} gives

$$\ell_{dh} = \frac{\dfrac{A_b f_y}{f_c'^{\,0.114}} - 482}{2065 d_b^{0.3}} \tag{D.6}$$

The ratios of the measured failure loads to those calculated using Eq. (D.5) are plotted in Figure D6. The mean ratio is 0.988, the standard deviation is 0.113, and the ratio ranges from 0.703 to 1.242. The zero slope in Figure D6 indicates that the 0.114 power captures the average effect of concrete compressive strength on bar force T. The average intercepts are 0.926 for No. 5 bars with 2.5-in. side cover, 0.928 for No. 5 bars with 3.5-in. side cover, 1.078 for No. 8 bars with 2.5-in. side cover, 1.000 for No. 8 bars with 3.5-in. side cover, 0.998 for No. 11 bars with 2.5-in. side cover, and 1.003 for No. 11 bars with 3.5-in. side cover.

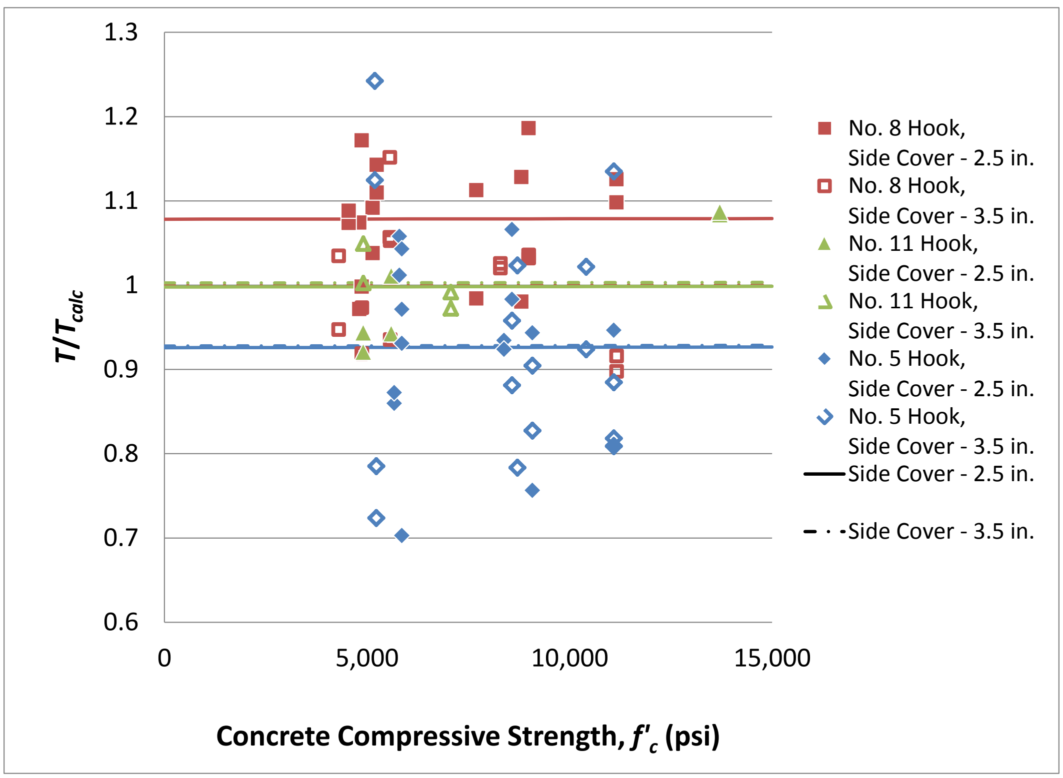

Figure D6 Ratio of test ultimate bar force to calculate ultimate bar force T/T_{calc} versus concrete compressive strength for 90° and 180° hooks with two No. 3 ties as confining transverse reinforcement