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

By

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Abstract

This report describes the initial tests on the anchorage strength of standard hooked bars in concrete. The goal of the testing is to determine the effects embedment length, side cover, tail cover, quantity of transverse reinforcement, location of longitudinal reinforcement, concrete strength, bar size, and bar bend on the anchorage strength of hooked bars in concrete. Initial tests have been performed on No. 5 and No. 8 bars, with 90° and 180° hooks, cast in concrete with a nominal compressive strength of 5000 psi. Further testing will also include No. 11 bars and concrete strengths up to 15,000 psi. The goal of this study is to gain a firm understanding of the anchorage strength of hooked bars in concrete as a function of the key variables and use the data to establish reliability-based design expressions for development length.

Thus far, the testing apparatus has been fabricated, the testing procedures have been established, and the initial specimens have been tested. The test results agree qualitatively with those in previous studies and show that hook strength increases with increased embedment length, side cover, and confining reinforcement. The results also show that hook strength is greater for hooks anchored within a column core than for hooks anchored outside of the core. The latter case is appropriate to hooks anchoring bars at the end of cantilever beams.

Keywords: anchorage, development, hooks, reinforced concrete

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TABLE OF CONTENTS Page

Chapter 1: Introduction 1

1.1: Objective 1

1.2: Definition of the Problem 1

Chapter 2: Experimental Work 3

2.1: Specimens 3

2.1.1: Specimen Design 3

2.1.2: Casting Specimens 9

2.2: Material Properties 11

2.3: Loading Systems 12

2.3.1 Testing Apparatus 12

2.3.2: Hooked Bar Grips 15

2.3.3: Super Washers 18

2.4: Instrumentation 19

2.4.1: Load Cells 19

2.4.2: External Slip Measurement 22

2.4.3: Internal Slip Measurement 24

2.5: Testing Procedure 27

Chapter 3: Evaluation of Test Results 35

3.1: Test Results 35

3.2: Crack Patterns 39

3.3: Failure Modes 40

3.4: Data Trends 42

Chapter 4: Summary 46

References 47

List of Figures Page

Figure 1: Top view of hook region for No. 5 bars placed inside longitudinal reinforcement 4

Figure 2: Top view of hook region for No. 5 bars placed outside longitudinal reinforcement 5

Figure 3: Side view of a specimen with No. 5 hooks 6

Figure 4: Shear reinforcement placed inside of hooks 7

Figure 5: Typical joint regions in specimens 8

Figure 6: Front and back view of forms 9

Figure 7: Assembled forms with hooks supported 10

Figure 8: Testing apparatus 12

Figure 9: Test frame: (a) Back view; (b) Front view 13

Figure 10: Forces on test specimen 14

Figure 11: Hooked bars extending through the jacks with load cells supported by platform 16

Figure 12: Close up of hook extensions 17

Figure 13: Nuts tightened onto the threaded bars of the hook extensions 17

Figure 14: Super washers 18

Figure 15: Threaded bar attached to super washer 19

Figure 16: Load cells placed on hooked bars 20

Figure 17: Load cells measuring axial compression 21

Figure 18: Covered LVDTs fixed to the apparatus 22

Figure 19: Close up of steel extension 23

Figure 20: Wire for internal slip measurement attached to hook 25

Figure 21: Wire protruding from specimen and attached to string pot 26

Figure 22: Frame holding string pot 26

Figure 23: Hydraulic jacks affixed to the testing apparatus 27

Figure 24: Bottom cross beam placed below the base plate 28

Figure 25: Weather stripping on the specimen 29

Figure 26: Placing Hydro-Stone between specimen and apparatus 30

Figure 27: Channel sections tightened to the specimen 31

Figure 28: Threaded bar with proper length placed on specimen 32

Figure 29: (a) Placing top cross beam with crane; (b) Bottom load cells in place 33

Figure 30: Cracks propagating from the hooked bars 39

Figure 31: Vertical cracks forming a conical shape 40

Figure 32: Breakout failure 41

Figure 33: Side splitting failure 41

Figure 34: Side blowout failure 42

Figure 35: Ultimate bar stress versus embedment length for 90° No. 5 hooked bars with no transverse reinforcement 43

Figure 36: Ultimate bar stress versus embedment length for 90° No. 5 hooked bars with 5 No. 3 bars transverse reinforcement 44

Figure 37: Ultimate bar stress for No. 8 bar 90° hooks with 10.25-in. nominal embedment length and 2.5-in. nominal side cover 45

List of Tables Page

Table 1 - Example group of specimens 5

Table 2- Concrete mixture proportions 11

Table 3- Hooked bar properties 11

Table 4 - Specimen properties and test results 37

Table 4 Continued – Specimen properties and test results 38

Chapter 1: Introduction

1.1: Objective

This report describes ongoing research on the anchorage strength of bars with standard hooks in concrete. The principal variables are embedment length (ℓ_{eh}) which is the distance from the back of the hooked bar to the face of the concrete, side cover, tail cover, quantity of transverse reinforcement, location of longitudinal reinforcement, concrete strength, bar size, and bar bend angle. Testing is focused on No. 5, No. 8, and No. 11 hooked bars with nominal yield strengths of 60, 80, 100, and 120 ksi cast in concrete with nominal compressive strengths of 5000, 8000, 12,000, and 15,000 psi. Most tests involve hooks with bend angles of 90° and 180°; some tests with 135° hooks are also planned. The goal of this study is to gain a firm understanding of the anchorage strength of hooked bars in concrete as a function of the key variables and use the data to establish reliability-based design expressions for development length.

1.2: Definition of the Problem

To date, there has been minimal research done on the anchorage strength of hooked bars in concrete, especially high-strength hooked bars and hooks in high-strength concrete. Previous research on full scale specimens includes studies done by Marques and Jirsa (1975), Pinc et al. (1977), Soroushian et al. (1988), Hamad et al. (1993), and Ramirez and Russell (2008). Of these tests only Hamad (1993) and Ramirez and Russell (2008) used concrete strengths above 6,050 psi, which include a total of 13 tests on uncoated hooks.

Current provisions in the ACI 318 Building Code (2011), the ACI 349 Code Requirements for Nuclear Safety-Related Concrete Structures (2006), and the AASHTO Bridge Specifications (2012) for the development length (ℓ_{dh}) of bars with standard hooks are based on 22 tests reported by Marques and Jirsa (1975), which used neither high-strength steel nor high-strength concrete. Reinforcing steel for these tests had yield strengths of 64 and 68 ksi, and the compressive strengths of the concrete were between 3,750 and 5,100 psi. Recently, the use of both high-strength reinforcing steel and concrete has become much more common. Current design expressions are allowed to be used for the higher-strength steels, but without sufficient information, the safety in doing so is unknown. While the ACI Code does limit the use of compressive strength in design equations to 10,000 psi, the accuracy of this limit has not been verified. Also, with such a small data base, it is difficult to confidently evaluate the true contribution of side cover, confinement, bar size, or embedment length on the anchorage strength of hooked bars.

Chapter 2: Experimental Work

2.1: Specimens

2.1.1: Specimen Design

The specimens are designed to determine the effects of the different variables on the anchorage strength of hooked bars. Each specimen contains two hooks. The principal variables being studied are embedment length, side cover, quantity of transverse reinforcement, location of longitudinal reinforcement, concrete strength, bar size, and bar bend angle. The tail cover on all specimens is 2 in., corresponding to provision 12.5.3 of the ACI 318 Building Code (2011). The spacing between hooks is constant for each hook size. For No. 5 bars, the outside to outside spacing is 8 in. For No. 8 bars, the outside to outside spacing is 12 in.

Specimen designations are based on the variables. For example, a specimen may be titled 8-5-90-1#3-I-2.5-2-9.5b: where 8 indicates the hooked bar size, 5 indicates the nominal concrete compressive strength in ksi, 90 indicates the bend angle in degrees of the hook, 1#3 indicates a confinement by 1 No. 3 bar in the hook region (to indicate no confinement a 0 is used), I indicates that the hooks are inside the longitudinal reinforcement (an O is used to indicate that the hooks are outside of the longitudinal reinforcement), 2.5 indicates the side cover to the hook in in., 2 indicates the tail cover on the hook in in., 9.5 indicates the embedment length to the nearest quarter in., and b indicates the second test done with the designation (either the letter a or no letter at the end of the designation implies it is the first and sometimes the only test done with the designation).

Figure 1 shows typical hook regions for No. 5 bars placed inside of the longitudinal reinforcement, both with and without transverse reinforcement. Since the outside to outside

spacing of the No. 5 bars is constant for all specimens, the width of No. 5 specimens with 2.5-in. side cover and 1.5-in. side cover will always be 13 in. and 11 in., respectively. Embedment length is varied by changing the depth of the specimen.

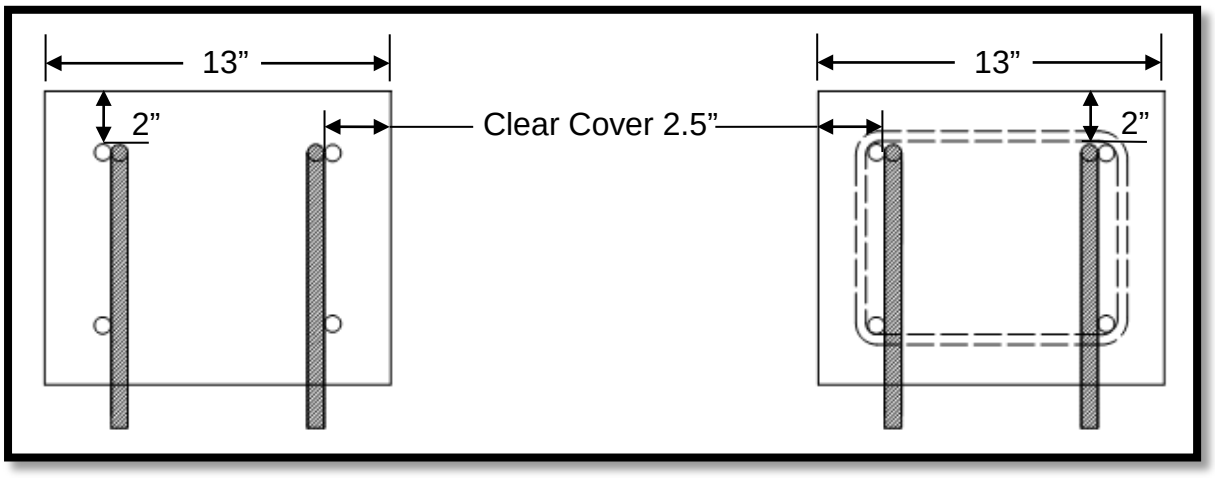

Figure 1: Top view of hook region for No. 5 bars placed inside longitudinal reinforcement

Figure 2 shows typical hook regions of No. 5 bars placed outside of the longitudinal reinforcement. To vary the side cover on hooks, the spacing between hooks is not changed. Instead, the width of the specimen is changed.

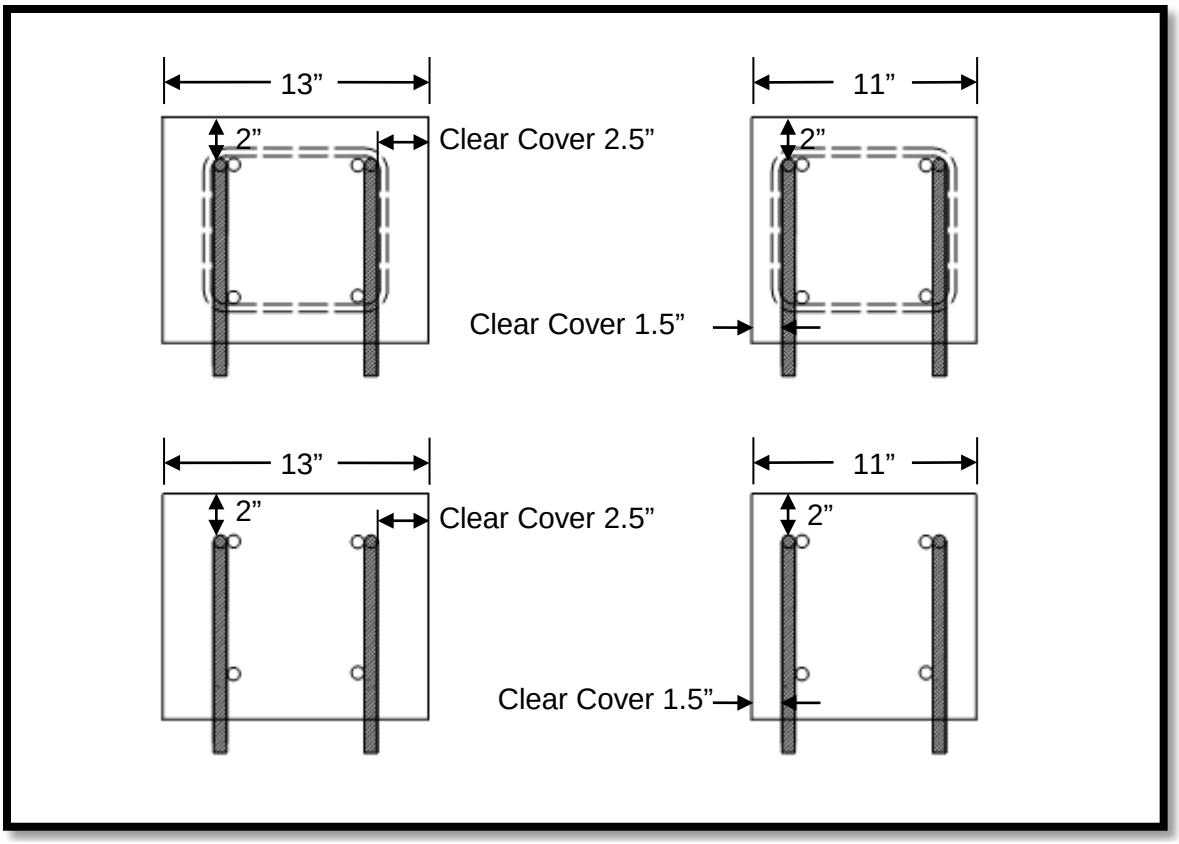

Figure 2: Top view of hook region for No. 5 bars placed outside longitudinal reinforcement

Specimens are fabricated and cast in groups. To better compare the effect of other variables, constant embedment lengths are typically used for all specimens in a group. Table 1 shows a group of four specimens. In this group, the bar size, concrete strength, hook bend angle, location of hooks, and embedment length are constant, while confinement and side cover are varied.

Table 1 - Example group of specimens

Specimen
5-5-90-0-O-1.5-2-5
5-5-90-0-O-2.5-2-5
5-5-90-5#3-O-1.5-2-5
5-5-90-5#3-O-2.5-2-5

Choosing only a few variables for each group gives a good indication of the effect of those variables on the anchorage strength. An embedment length for the group is used that will

ensure a hook failure, rather than a bar failure, for all specimens. For the specimens described in the report, this is accomplished by using 80% of the hook development length, ℓ_{dh}, based on the ACI 318 Building Code for the strongest specimen in the group.

Specimens are designed to represent an exterior beam-column joint and column. The depth of the column is determined based on ℓ_{eh} and the tail cover, and the width is based on the out-to-out hook spacing and side cover. The height of the column is selected so that the support reactions at the top and bottom of the apparatus do not interfere with the hook region. The shortest height that can be accommodated by the testing apparatus that meets these criteria is selected. Figure 3 shows a specimen sized to fit into the smallest size allowable by the testing apparatus for No. 5 bars.

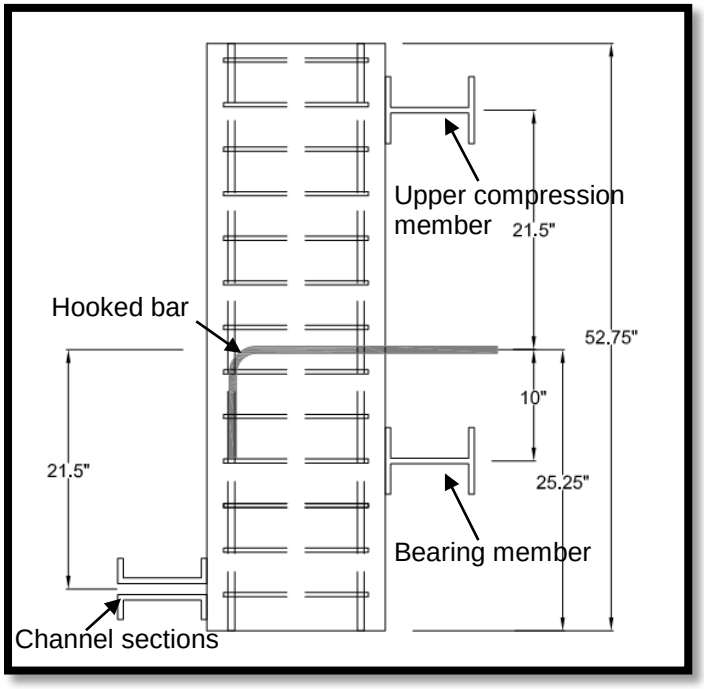

Figure 3: Side view of a specimen with No. 5 hooks

After the dimensions of the specimen are selected, the maximum moment and shear in the specimen are determined by assuming that both hooks will reach their planned failure loads simultaneously. These forces determine the amount of longitudinal and transverse reinforcing

steel needed in the specimen. If the shear reinforcement required exceeds the amount of confining reinforcement desired in the joint region, stirrups are placed inside the hooks, as shown in Figure 4.

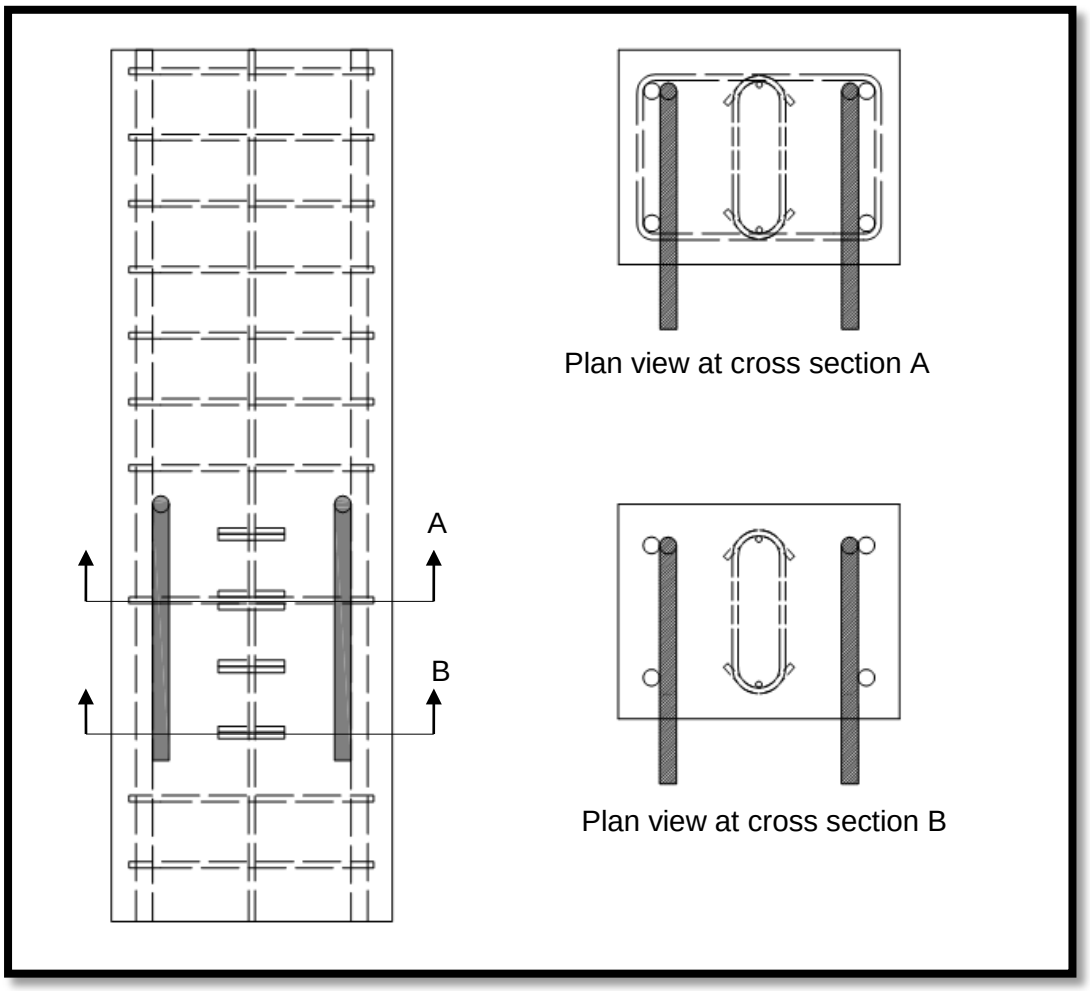

Figure 4: Shear reinforcement placed inside of hooks

Figure 5 shows front, side and plan views of typical joint regions. The joint regions have 2 in. tail cover and include specimens with both 1.5 and 2.5 in. side cover, hooks inside and outside of longitudinal reinforcement, and hooks with and without transverse reinforcement. Appropriate dimensions are included. As stated previously, spacing between hooks is dependent on hook size.

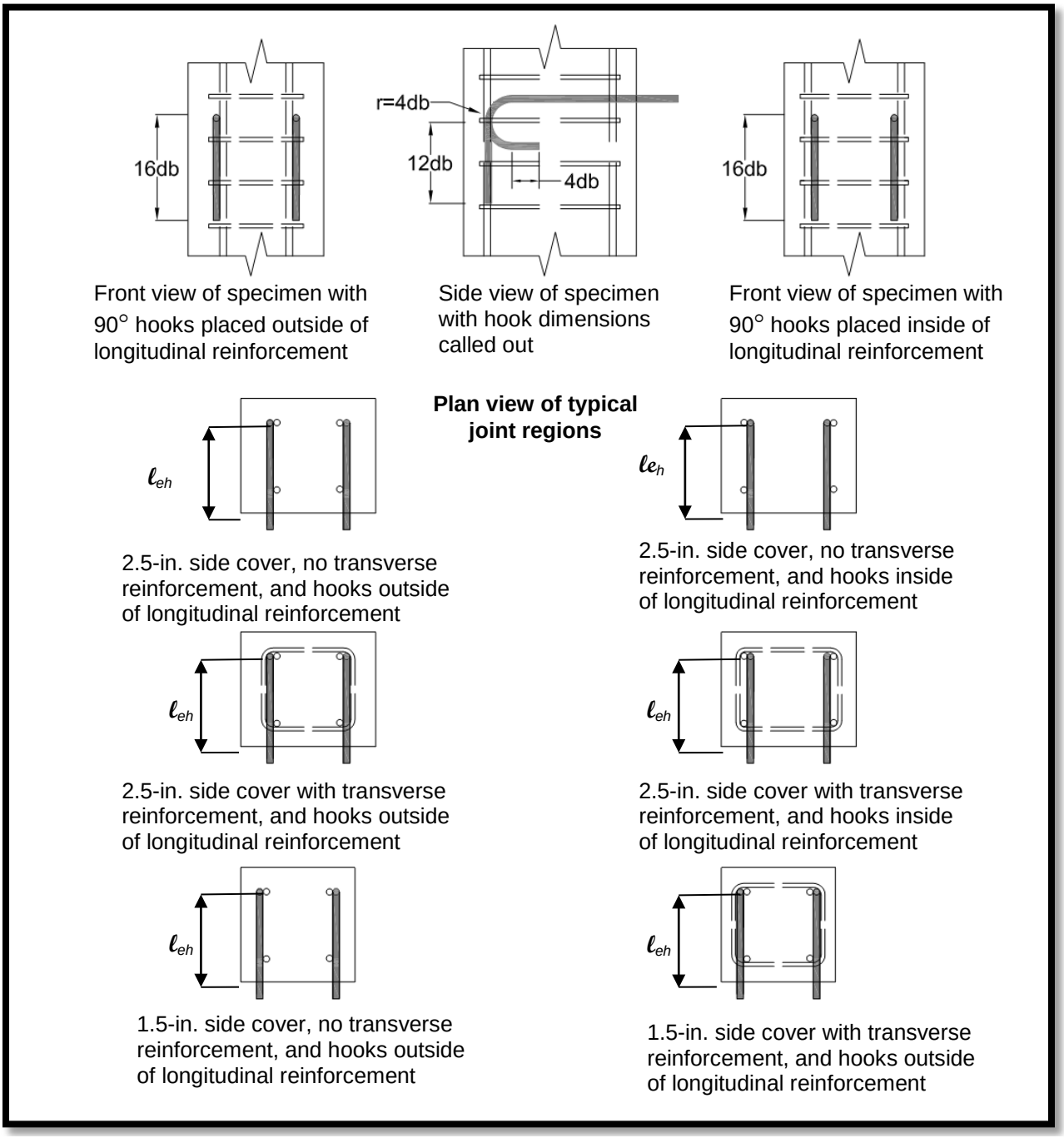

Figure 5: Typical joint regions in specimens

2.1.2: Casting Specimens

Forms are built so that embedment lengths can be varied, allowing each form to be used multiple times, rather than for just one specimen (Figure 6). The front of each form has holes allowing the hooks to extend out of the specimen. The hooks are supported outside of the specimen to maintain the desired hook spacing, embedment length, and side cover throughout the casting process (Figure 7). Reinforcement is tied in place within the form to minimize unwanted movement during casting. Any movement of the hooks that occurs during the casting process, however, needs to be accounted for. This is done by marking the hooked bars at a known distance from the tail. After casting, the distance from the mark on the hook to the specimen face is measured to determine the actual embedment length of the hook.

Figure 6: Front and back view of forms

Figure 7: Assembled forms with hooks supported

Multiple specimens are cast at one time. Specimens are placed in three lifts, with the hook region in the second lift. After casting, the tops of the specimens are finished, and then covered with saturated burlap and plastic to cure. Concrete samples taken after the first and second lift.

2.2: Material Properties

The specimens were fabricated using non-air-entrained ready-mix concrete. The specimens described in this report have a nominal compressive strength of 5000 psi. The concrete contained Type I/II portland cement, ¾-in. maximum size crushed limestone, and Kansas River sand. The water-cement ratio is 0.44. Adva 140, a Type A/F superplasticizer, was used to improve workability. The concrete mixture proportions are listed in Table 2.

The majority of the hooked bars used in the initial specimens were fabricated using ASTM A1035 reinforcing bars. The specimens containing hooked bars fabricated using ASTM A615 bars were 5-5-90-0-O-1.5-2-11, 5-5-90-0-O-2.5-2-7, 5-5-90-2#3-O-1.5-2-11, 5-5-90-2#3-O-2.5-2-7, 5-5-90-0-O-2.5-2-6.5, 5-5-90-0-O-1.5-2-8, 5-5-90-5#3-O-1.5-2-8, 5-5-90-5#3-O-2.5-2-8, 5-5-90-0-O-2.5-2-8, 5-5-90-5#3-O-1.5-2-6.5, 5-5-90-0-O-2.5-2-6.5, and 5-5-90-5#3-O-2.5-2-6.5. Deformation properties for A615 hooks were not measured. The specific bar properties of the ASTM 1035 steel are listed in Table 3. All longitudinal and transverse reinforcement has been fabricated using Grade 60 ASTM A615 reinforcing bars.

Table 2- Concrete mixture proportions

Material	Quantity (SSD)
Type I/II Cement	600 lb/yd^3
Water	263 lb/yd^3
Crushed Limestone	1734 lb/yd^3
Kansas River Sand	1396 lb/yd^3
Estimated Air Content	1%
Type A/F Superplasticizer (Adva 140)	24 fl oz (US)

Table 3- Hooked bar properties

Bar Size	ASTM Designation	Nominal Yield Strength, ksi	Nominal Diameter, in.	Rib Spacing, in.	Rib Height		Gap Width		Relative Rib Area
					ASTM, in.	Average, in.	Side 1, in.	Side 2, in.	
5	A615	88	0.625	0.42	0.79	0.74	0.18	0.17	0.060
5	A1035	130	0.625	0.39	0.96	0.86	0.20	0.17	0.073
8	A1035	130*	1	0.57	1.45	1.31	0.16	0.16	0.078

2.3: Loading Systems

Full details of the loading system are presented by Al-Khafaji et al. (2012)

2.3.1 Testing Apparatus

The testing apparatus provides a self-reacting system designed to simulate the axial, tensile, and compressive forces acting on a beam-column joint (Figures 8 and 9). The system is a modified version of the test apparatus used by Marques and Jirsa (1975).

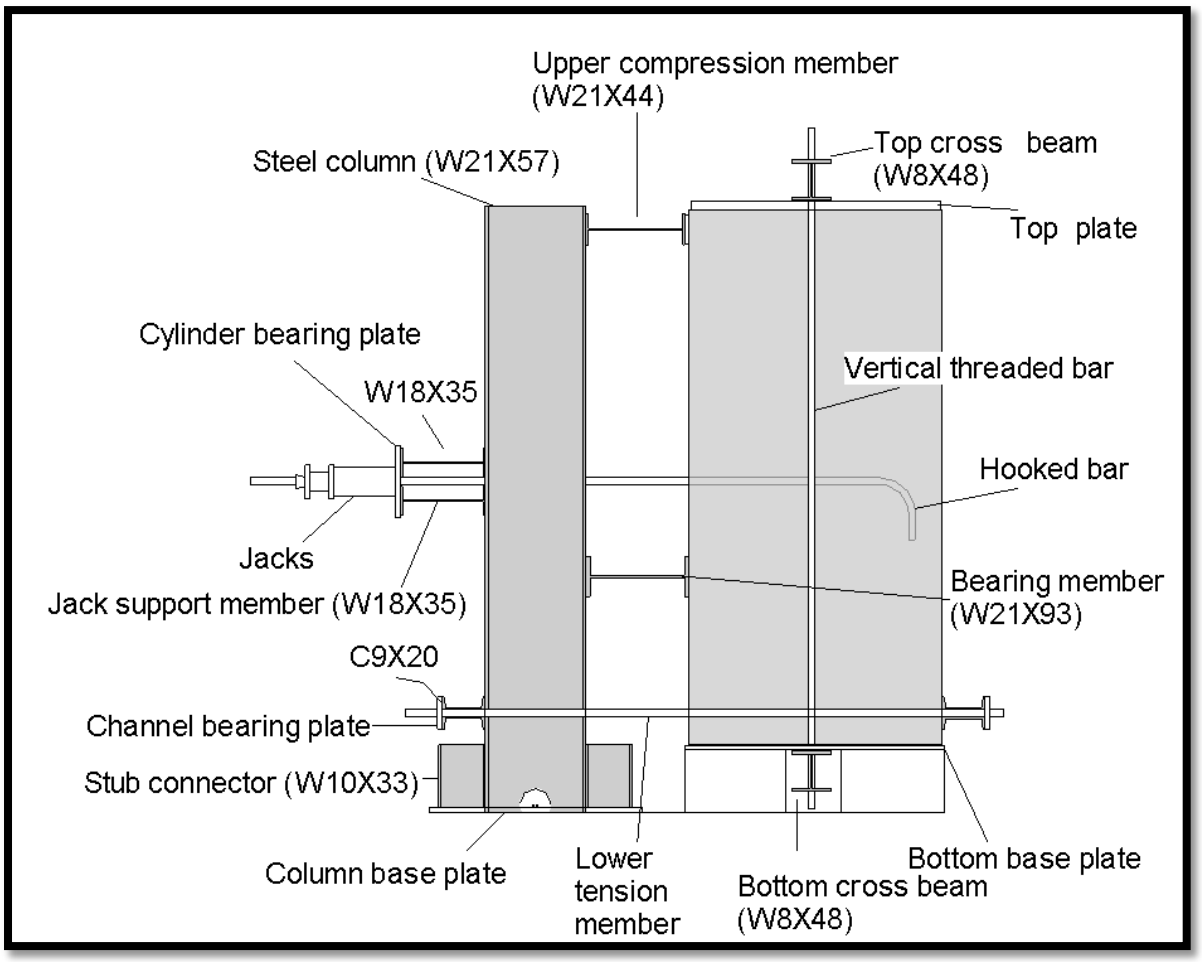

Figure 8: Testing apparatus

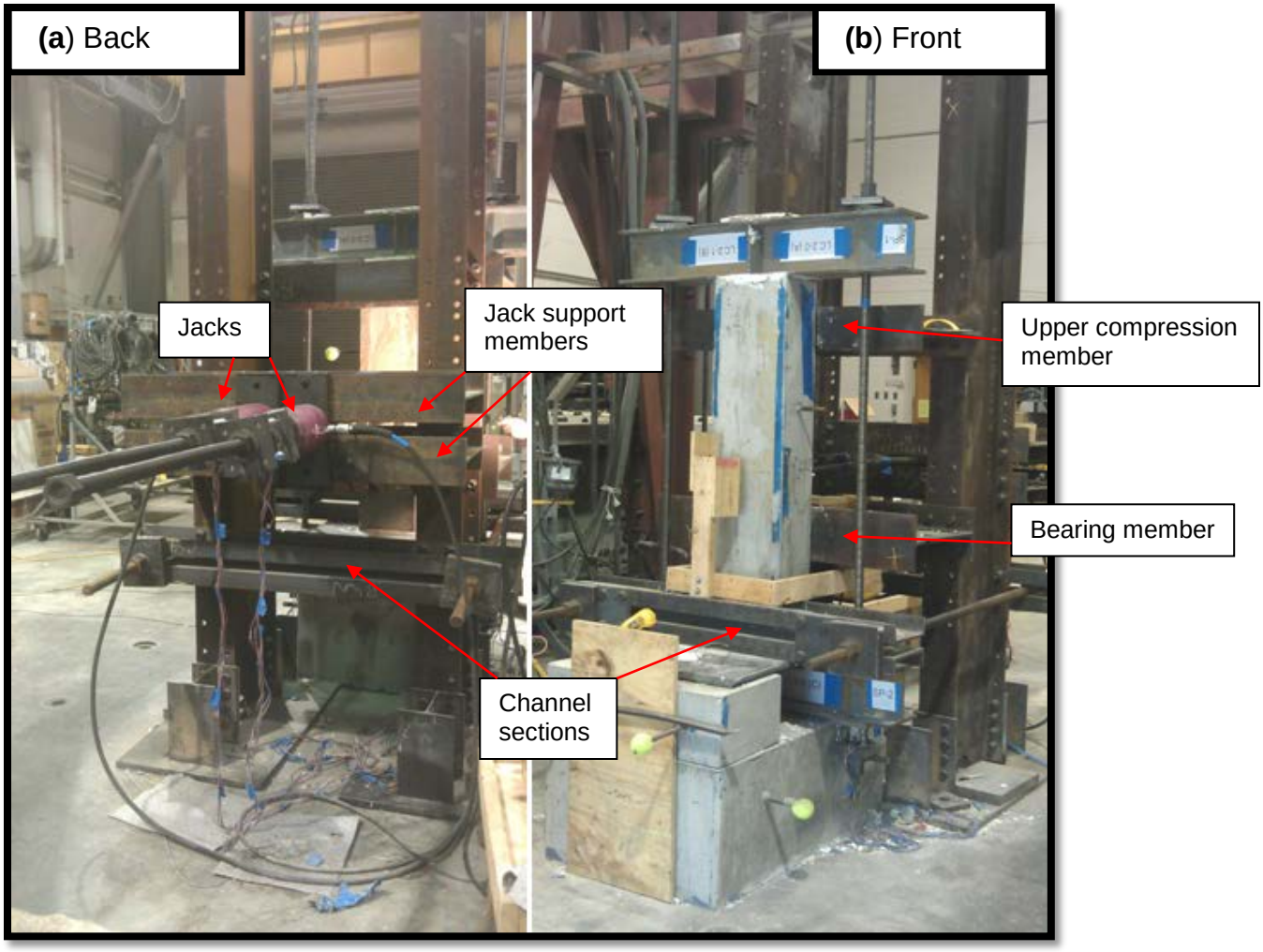

Figure 9: Test frame: (a) Back view; (b) Front view

Tensile forces are applied to the hooked bars, simulating the tension in the reinforcement at the face of a beam-column joint. This pulls the concrete specimen against the apparatus, resulting in reactions at three points (Figure 10). The main reaction, at the bearing member, is designed to simulate compression at the face of the beam at the connection. The reactions at the upper compression member and channel sections prevent rotation of the specimen. The apparatus is sized using strength design based on the shears and moments developed by loading

two No. 11 hooked bars to 150 ksi, 25% higher than the maximum of 120 ksi planned for the project.

Axial compression is applied to the specimen to simulate axial loading of a column (figure 10). The value of the axial load is not a variable in this study, because Marques and Jirsa (1975) found that changing the axial load resulted in negligible change in the anchorage strength of the hook.

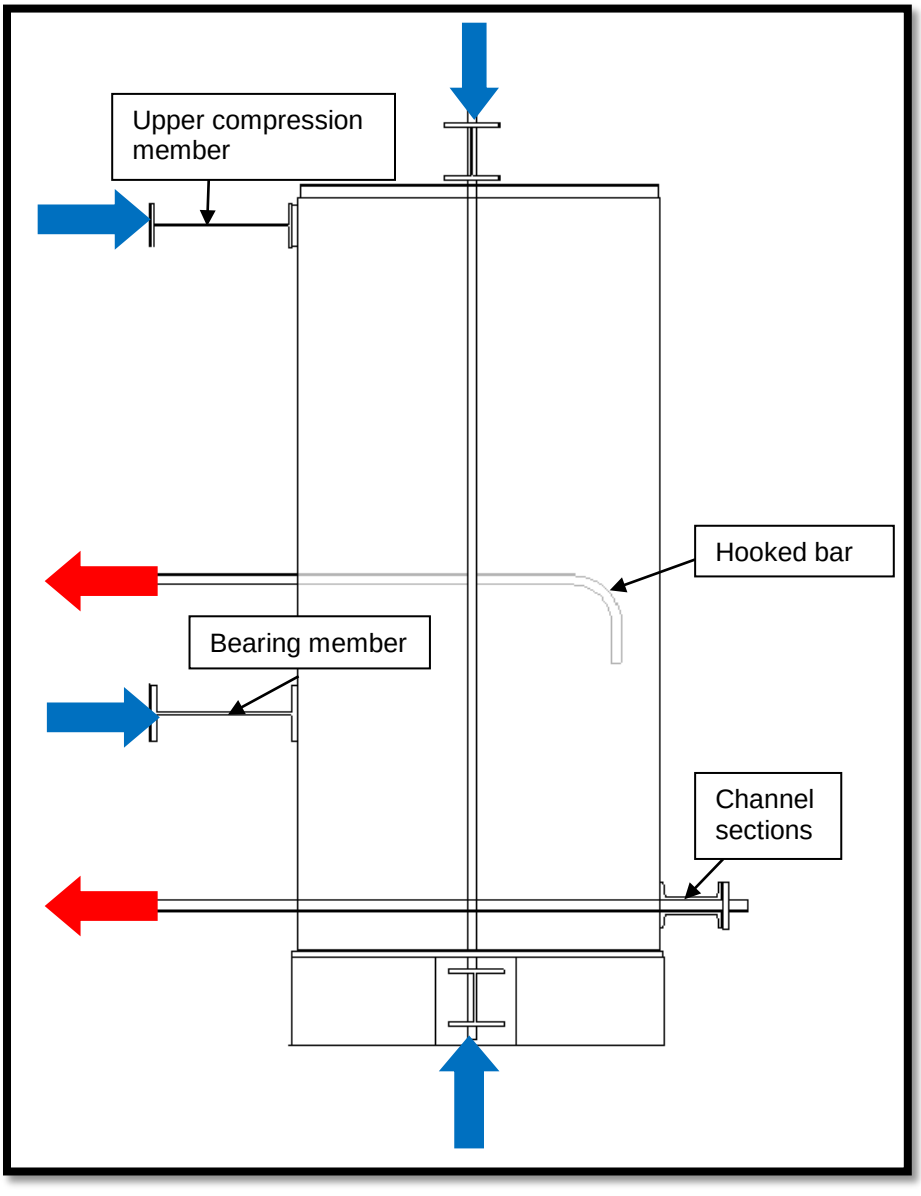

Figure 10: Forces on test specimen

Considerations in the design of the specimens and apparatus included keeping the support reactions outside of the testing region, keeping the hooks at a reasonable height, maintaining the ability to mark cracks on all faces of the specimen, and being able to test a large variety of specimen sizes. To prevent the support reactions from interfering with the testing region, supports needed to be placed at least a distance of ℓ_{eh} above and below the hook. Because ℓ_{eh} in the initial test matrix ranged from 5 in. to greater than 40 in., the apparatus was designed to accommodate multiple specimen sizes. Thus, specimens with a large ℓ_{eh} can be tall enough to keep the support reactions from interfering with the test region, and specimens with a small ℓ_{eh} can be shorter to minimize the quantity of concrete and allow for easier handling. The apparatus allows the hooked bar to be located approximately at eye level for all test configurations.

2.3.2: Hooked Bar Grips

Two different configurations have been used for gripping the hooked bars. The preferred method is to have long extensions on the hooked bars so they extend from the specimen, all the way through the loading jacks (Figure 11). This way, once the bars pass through the loading jacks, the jacks can be adjusted so there is no eccentric loading on the hook. After the jacks are adjusted, load cells are placed on the bar, followed by the grips. The grips consist of a hollow tapered tube, which slides over the bar, and wedges, which are placed between the hollow tube and the bar. An adjustable platform is raised high enough to support the load cells so no vertical load is placed on the bars. The bars are adjusted vertically to prevent any eccentric loading. A hand pump is then used to apply the load.

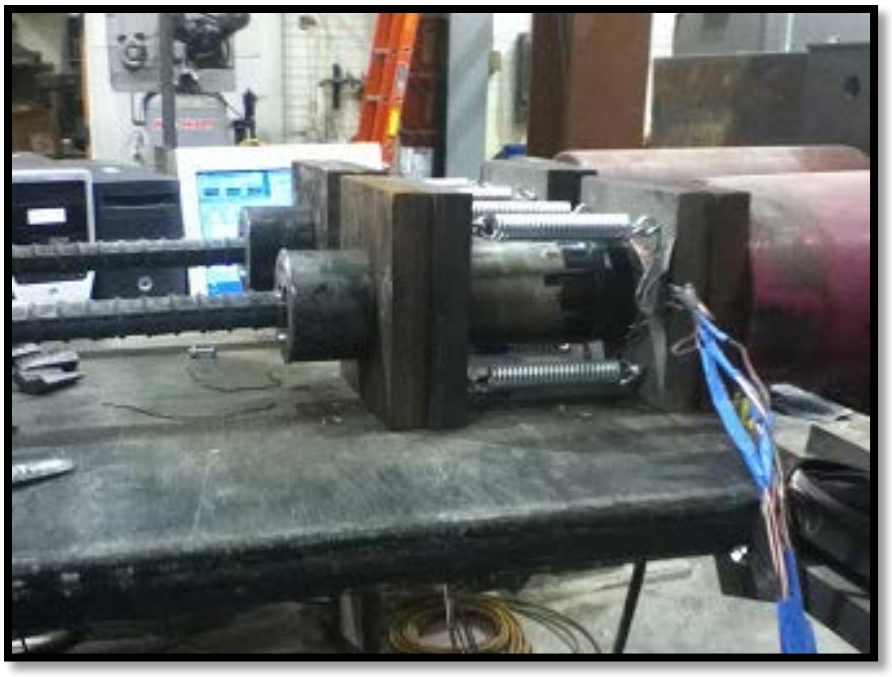

Figure 11: Hooked bars extending through the jacks with load cells supported by platform

An alternative procedure is used for gripping the hooked bars when the bars are not long enough to extend through the jacks. An extension is used to grip the hooked bars near the specimen and extend through the jacks (Figure 12). The extension consists of three No. 5 bars welded to a No.11 bar on one side and a wedge grip on the other. The No. 11 bar is welded to a threaded bar. The grip is placed onto the hooked bar, and the threaded end of the No. 11 bar is passed through the jacks. The load cells are placed on the threaded bar and nuts are tightened up to the load cells (Figure 13). When the jack is loaded, it pushes the threaded bar away from the specimen causing the wedges to tighten on the bar in the grip.

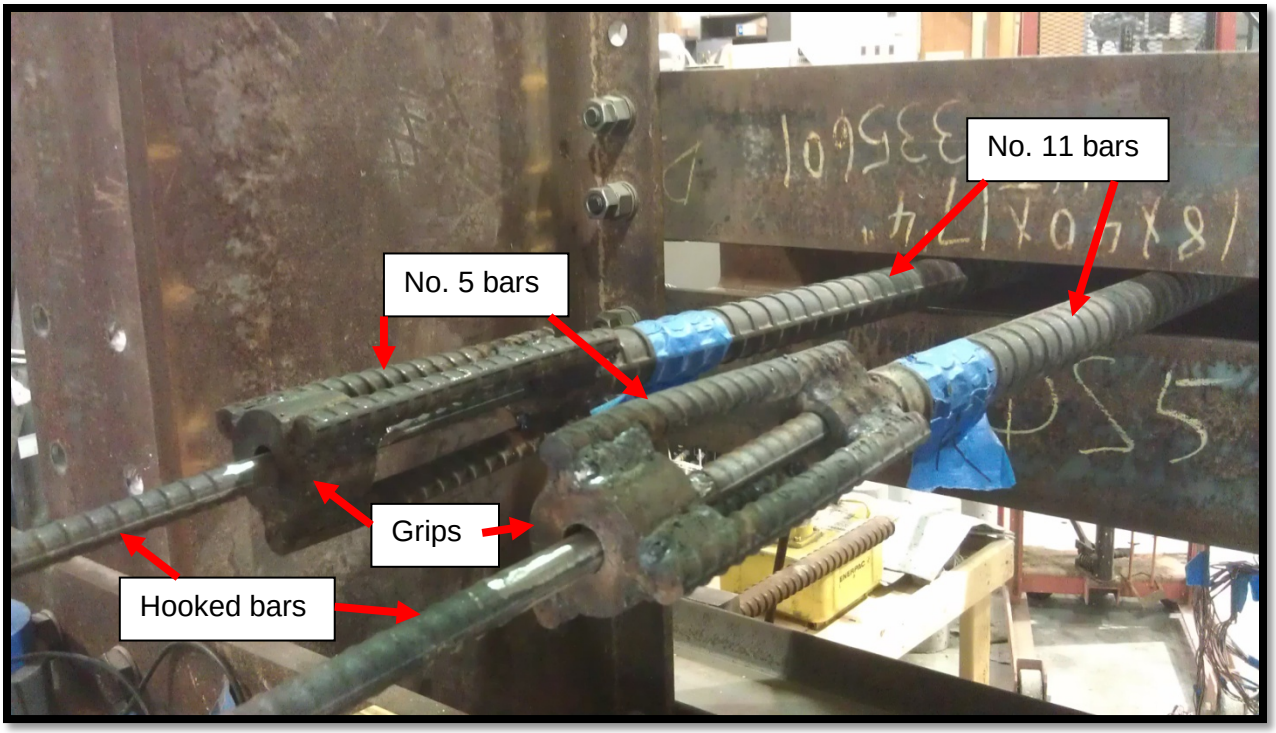

Figure 12: Close up of hook extensions

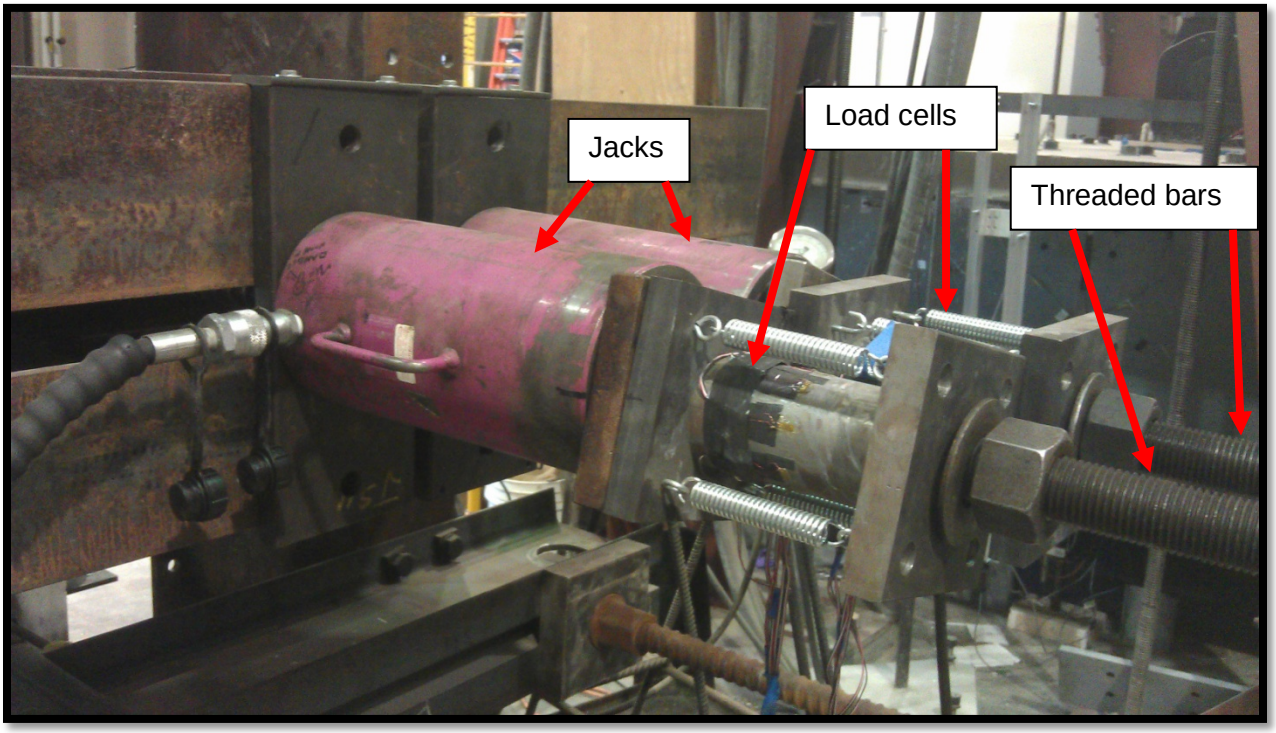

Figure 13: Nuts tightened onto the threaded bars of the hook extensions

2.3.3: Super Washers

Two super washers are used to apply axial compression to the specimen during testing (Figure 14). The super washers are made of 6×6×1-in. steel plates with a 1.75-in. diameter hole in the center, allowing a threaded bar to pass through. Eight holes are drilled and tapped in a circular pattern around the center hole for 1-in. socket set screws.

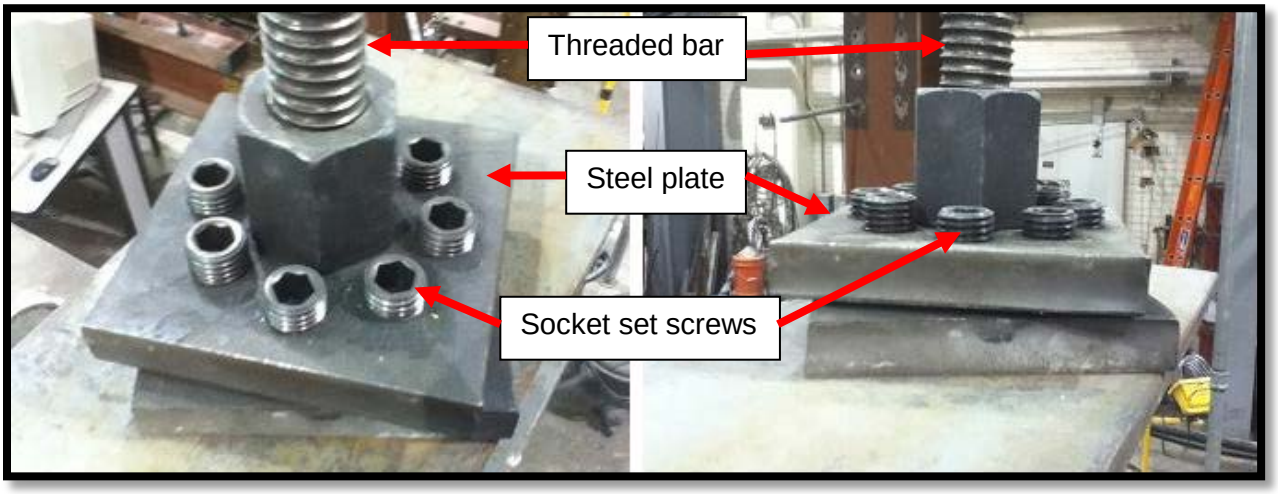

Figure 14: Super washers

To apply a load using a super washer, the threaded bar to be loaded is passed through the center hole of the super washer and a nut on the bar is hand tightened onto the super washer. The other end of the threaded bar is anchored below the specimen (Figure 15). The eight socket set screws are then tightened one by one in a circular pattern acting to elongate the threaded bar. This places the threaded bar in tension and, in turn, places a compression force on the specimen.

Figure 15: Threaded bar attached to super washer

2.4: Instrumentation

2.4.1: Load Cells

Four load cells were manufactured from steel pipes and are used on the testing apparatus. One load cell is placed on each hooked bar between the hydraulic jack and the wedge grip or nut (Figure 16), and one load cell is used on each of the threaded bars to measure the vertical axial compression force applied by the super washers (Figure 17). Each load cell contains eight 120-Ω strain gauges, four oriented perpendicular and four oriented parallel to the direction of loading.

The strain gauges are evenly spaced around the circumference of the load cell with alternating orientation (Figure 16).

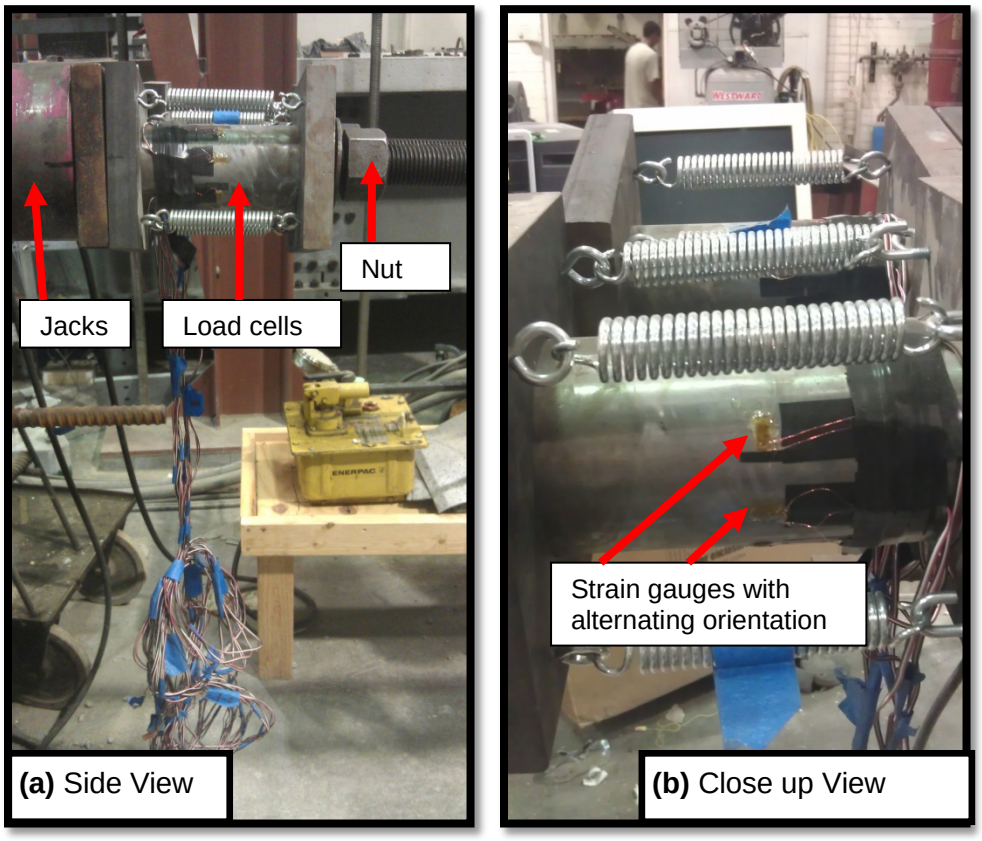

Figure 16: Load cells placed on hooked bars

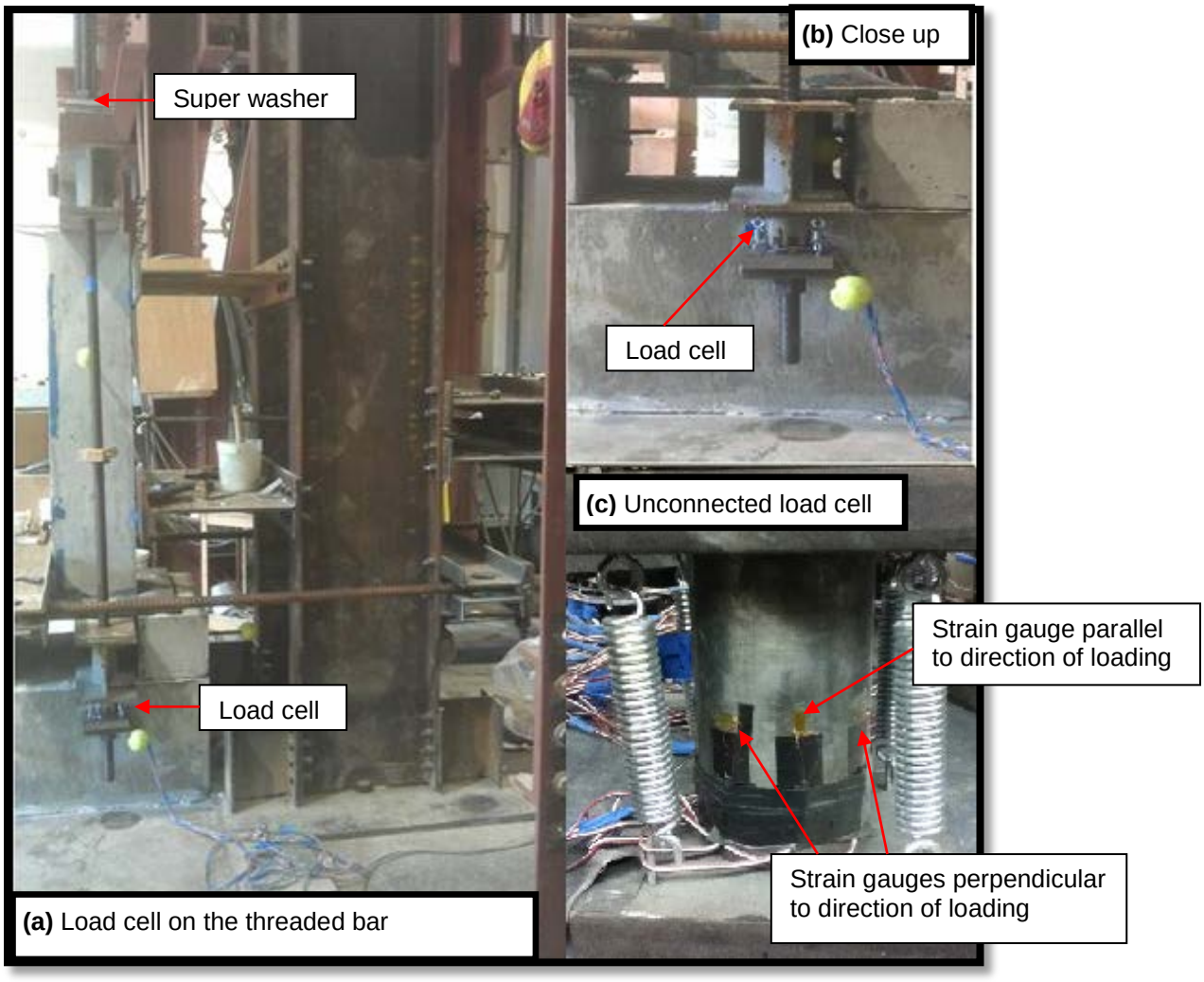

Figure 17: Load cells measuring axial compression

Each load cell is calibrated three times using the data acquisition system used during testing in a Baldwin hydraulic loading frame. A least-squares linear regression analysis of force versus voltage output is used to determine a calibration coefficient. The load cell calibrations are checked after every third series of tests.

2.4.2: External Slip Measurement

Linear variable differential transformers, or LVDTs, are used to measure the loaded-end slip of the hooks. The LVDTs are fixed to the bearing member directly below the hooks (Figure 18). The assumption is that once the specimen is pulled tight against the apparatus, the specimen will not displace with respect to the apparatus. The LVDTs are covered with plywood to protect them from debris (Figure 18).

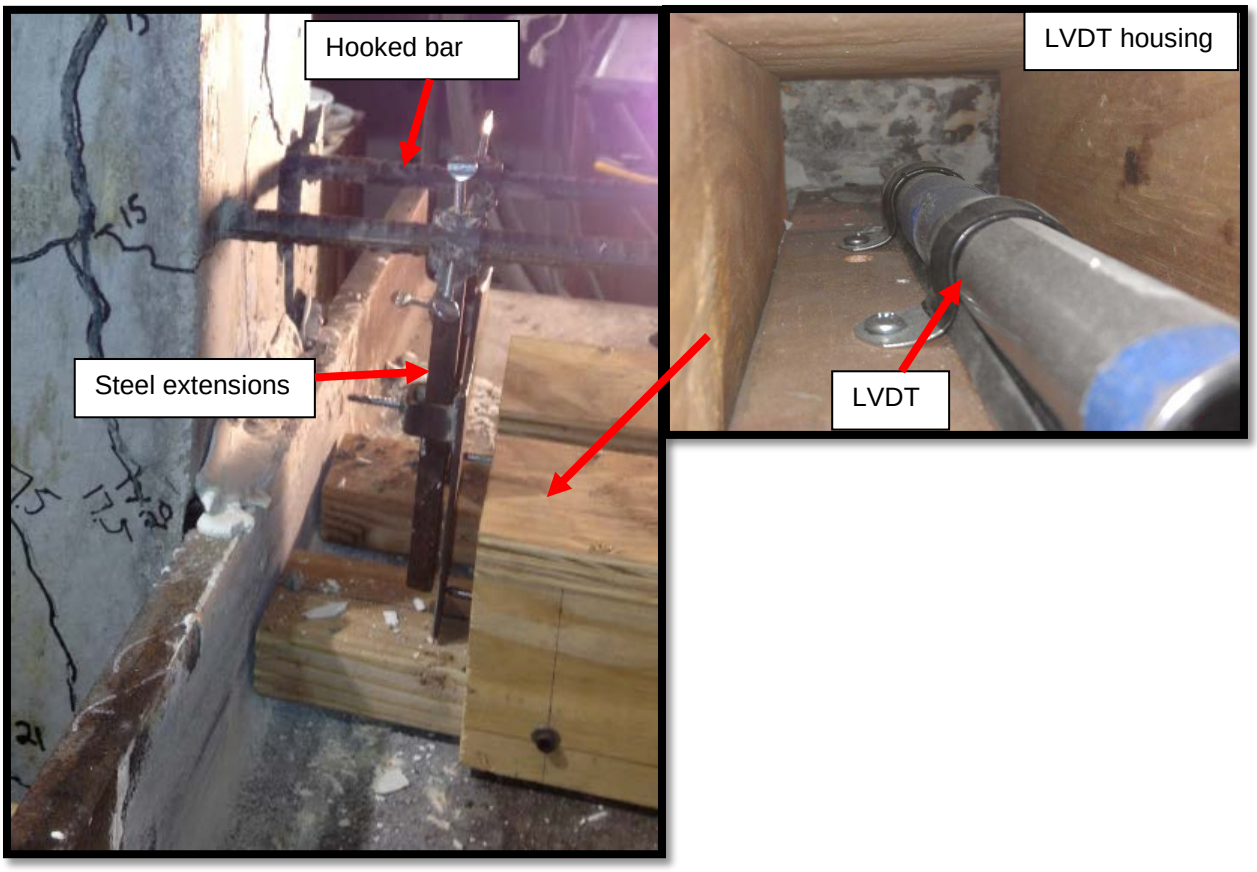

Figure 18: Covered LVDTs fixed to the apparatus

Steel extensions (Figure 19) are connected to each hooked bar so that, as the bar slips forward, the extensions will displace the LVDTs. The steel extensions are made by welding a square rod to a 2-in. long steel pipe. Holes are drilled and tapped in the steel pipe, allowing it to

be slid onto the hooked bar and tightened. A 2×5×$^{1}/_{8}$-in. steel plate is attached to the bottom of the square rod, creating a larger surface area for the LVDT to press against.

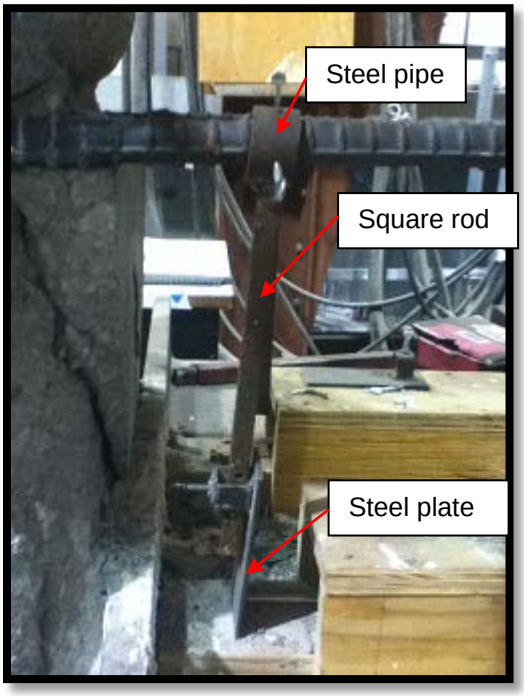

Figure 19: Close up of steel extension

The distance from the center of the bolts on the steel extension to the face of the specimen is measured to account for elongation of the hooked bar in this region. Each LVDT is calibrated by connecting it to the data acquisition system used during testing, then displacing the LVDT on a calibrated Baldwin test frame. Three calibration cycles are used. The displacement measured on the testing machine is recorded with the corresponding voltage output from the LVDT. Using a least-squares linear regression analysis on displacement versus voltage output, a calibration coefficient is determined for each LVDT. The LVDT calibrations are checked after every third series of tests.

2.4.3: Internal Slip Measurement

The internal slip of the hooks with respect to the concrete is measured with a string pot, using a method similar to that used by Marques and Jirsa (1975). This is accomplished by attaching a 0.029-in. diameter fishing wire to the hooked bar (Figure 20). The wire extends out of the specimen and connects to the wire on the string pot. Internal slip is measured on one of the two hooks of each specimen. To attach the wire, a $^{1}/_{16}$-in. hole is drilled into the top of the hooked bar just before the bend. The depth of the hole equals the radius of the bar. The wire is glued inside the hole and placed parallel to the direction the bar is expected to slip. A $^{1}/_{16}$-in. diameter plastic tube is placed over the wire to ensure free movement of the wire inside the concrete. A small amount of silicone caulk is used to fix the plastic tube to the bar at the connection of the wire and the hook. The amount of caulk is small enough to consider the loss of bond in the area negligible, considering that the inside of the hook bears directly on the concrete when the bar is loaded.

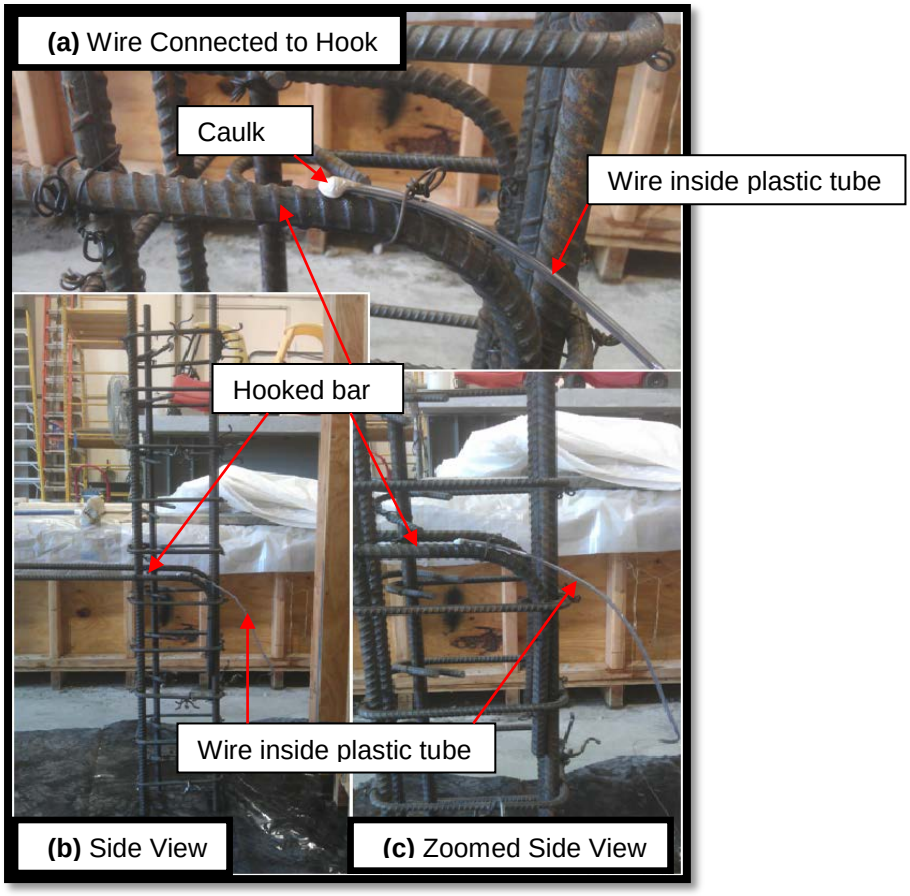

Figure 20: Wire for internal slip measurement attached to hook

During testing, the wire is attached to a string pot (Figure 21). A frame was built to hold the string pot directly behind the specimen, where the wire protrudes (Figure 22). The frame holding the string pot is fixed to the bearing member directly below the hook. This operation is based on the assumption that once the specimen is pulled tight against the testing apparatus, the specimen will not displace with respect to the testing apparatus. The string pot is calibrated using the data acquisition system used during testing. It is displaced using a Baldwin hydraulic testing frame. Three calibration cycles are used, and a least-squares linear regression analysis of displacement versus voltage output is used to establish the calibration coefficient. The calibration coefficient is checked after every third set of tests.

Figure 21: Wire protruding from specimen and attached to string pot

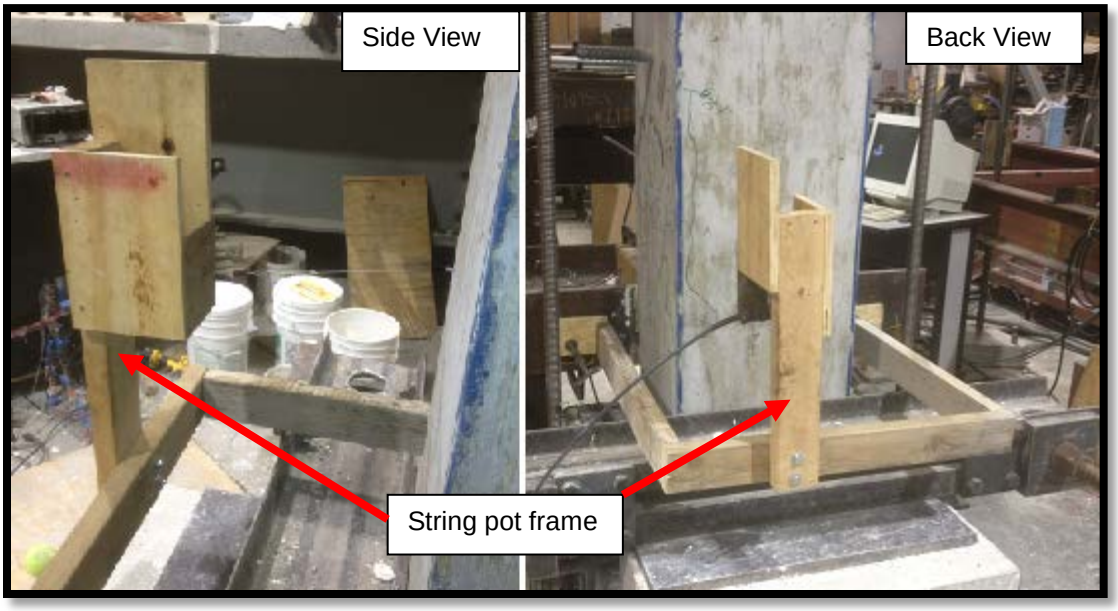

Figure 22: Frame holding string pot

2.5: Testing Procedure

1. Prior to each test, the location of each component of the loading apparatus and the height and location of the base plate are checked to ensure they are correctly positioned. All bolts on the apparatus are double nutted and checked for tightness, including the bolts attaching the loading apparatus to the strong floor.
2. The data acquisition system for the LVDTs, load cells, and string pot is checked prior to each test. This includes ensuring all wires are connected and that load cells, LVDTs, and the string pot are working properly.
3. The hydraulic jacks are attached to the testing apparatus and connected to the hand pump (Figure 23).

Figure 23: Hydraulic jacks affixed to the testing apparatus

4. The bottom cross beam is placed underneath the base plate (Figures 8 and 24).

Figure 24: Bottom cross beam placed below the base plate

5. The steel extensions used to measure external slip are placed on the hooks of the specimen being tested. This is done prior to placing the specimen on the loading apparatus, because once the hooks extend through the jacks, it is no longer possible to slide the extensions onto the hooked bar.
6. Using the lab crane, the specimen is placed on the testing apparatus approximately 6 in. from the bearing and upper compression members, with the bars passing through the jacks.
7. $^{3}/_{8}$-in. sponge rubber weather stripping is used to create U-shapes on the specimen at the height of the bearing and upper compression members (Figure 25). When the specimen is snug to the bearing and upper compression members, the weather stripping allows

Hydro-Stone (a high-strength gypsum grout) to be placed between the specimen and the bearing members.

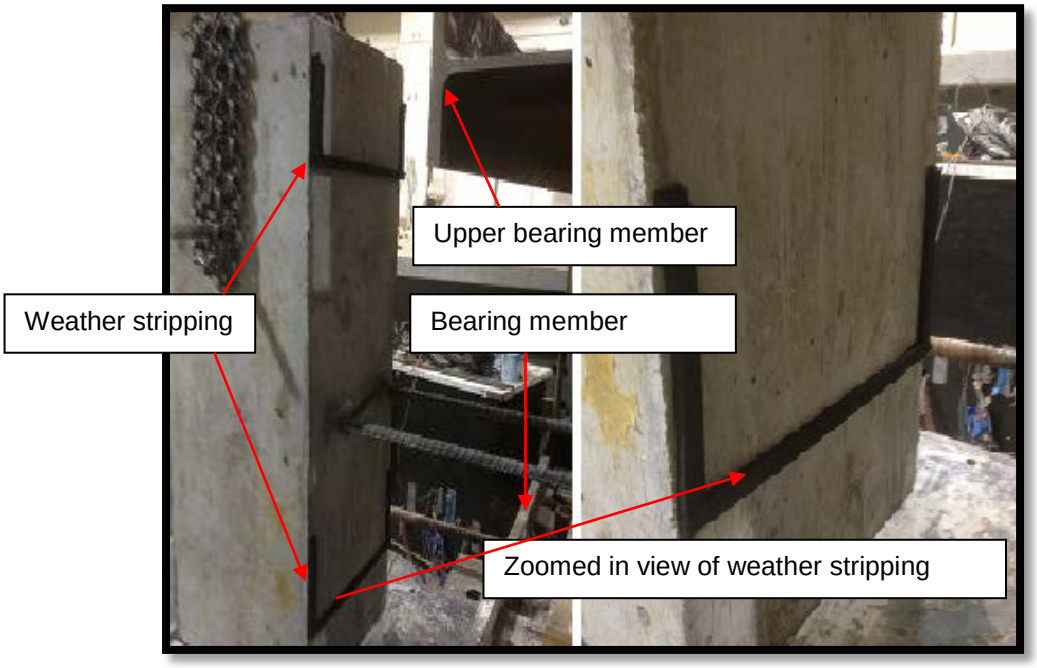

Figure 25: Weather stripping on the specimen

8. The specimen is lifted off of the base plate using the crane, and Hydro-Stone is placed on the base plate to ensure even loading of the base, when axial compression is applied to the specimen.
9. The specimen is moved forward to the testing apparatus then lowered onto the Hydro-Stone, while ensuring that the weather stripping is pressing against the testing apparatus, creating a tight seal.
10. The jacks are moved horizontally, as needed, on the jack support member, to ensure the hooks will not be loaded eccentrically.
11. Hydro-Stone is placed in the voids between the specimen and the bearing members, created by the weather stripping to ensure even loading during the test (Figure 26).

Figure 26: Placing Hydro-Stone between specimen and apparatus

12. The channel sections are supported behind the specimen and threaded rods are passed through both sets of channels. Nuts are then hand-tightened on the threaded bars (Figure 27).

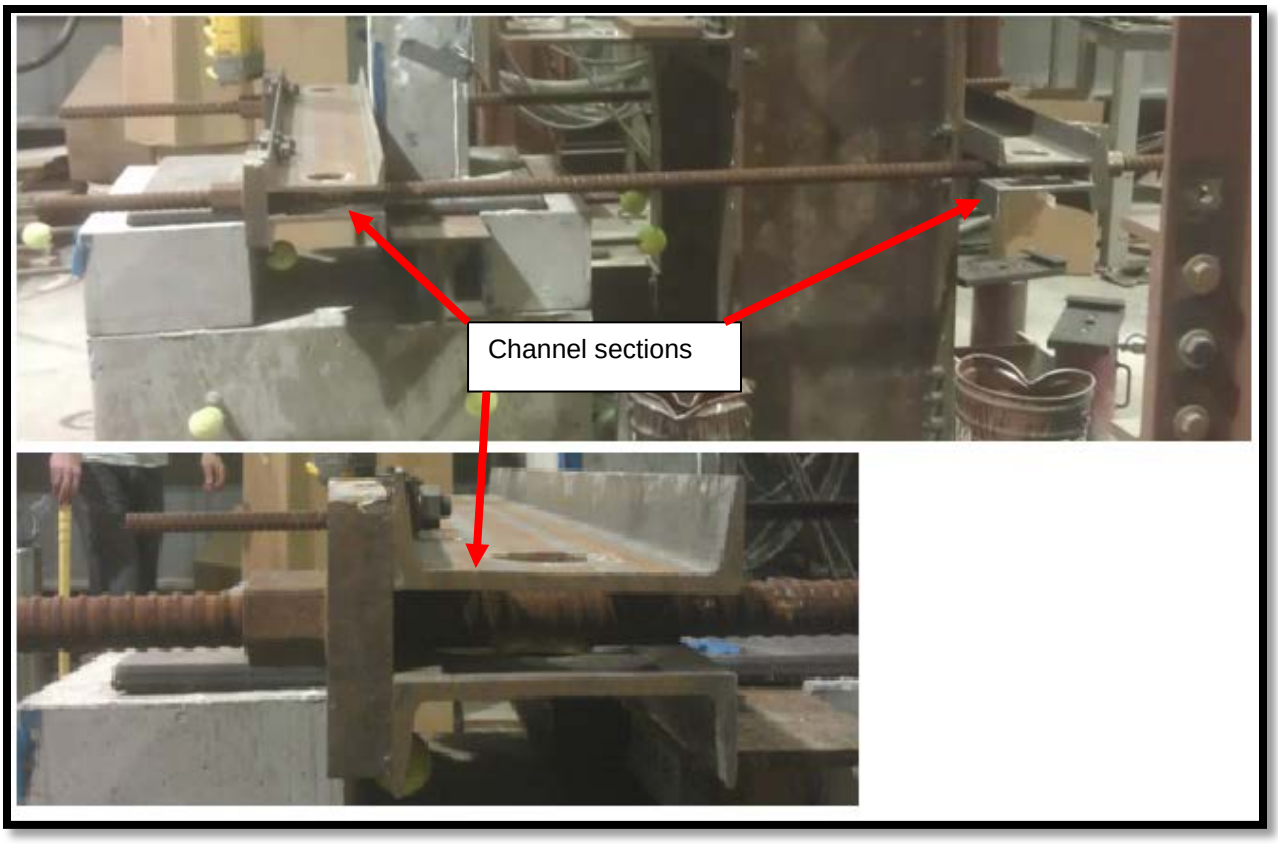

Figure 27: Channel sections tightened to the specimen

13. While the top cross beam (Figure 8) is still on the ground, threaded bars are placed through the holes with proper length to pass through the bottom cross beam and load cell, when the top cross beam is on the specimen (Figure 28).

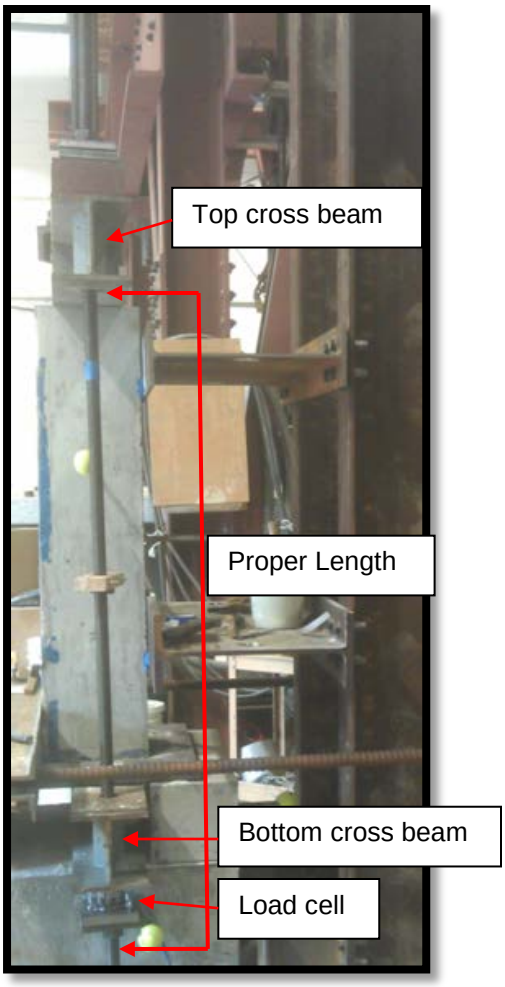

Figure 28: Threaded bar with proper length placed on specimen

14. Once the threaded bars have the proper length, a super washer is slid onto the top of each threaded bar, and a nut is hand tightened on the super washer.
15. The top cross beam is then lifted with the crane and lowered onto the top of the specimen while guiding the threaded bars through the holes on the bottom cross beam (Figure 29a). Hydro-Stone is placed between the specimen and top cross beam to ensure even loading of the axial compression.
16. Load cells are placed on the threaded rod below the bottom cross beam and nuts are hand-tightened below the load cells (Figure 29b).

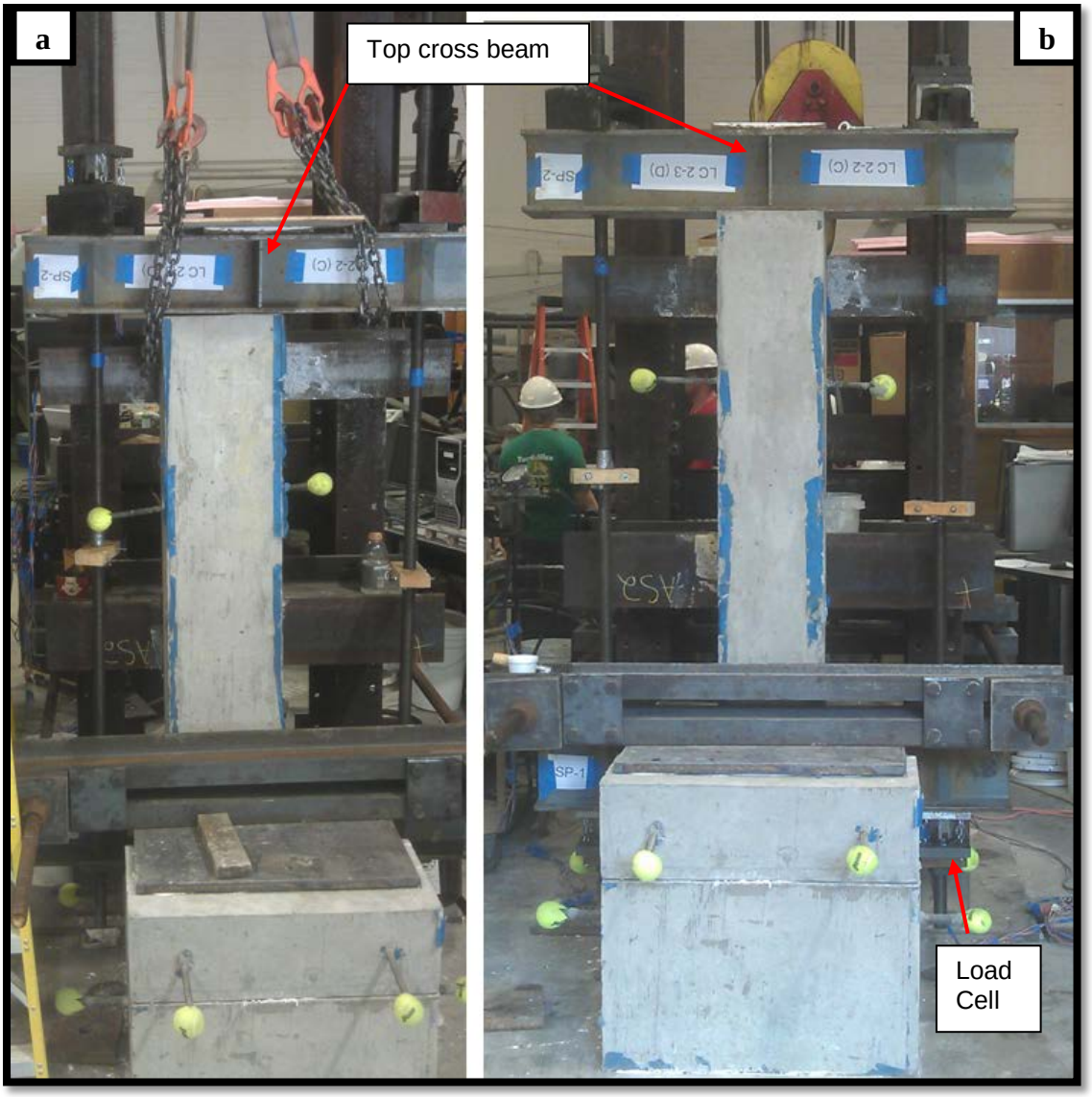

Figure 29: (a) Placing top cross beam with crane; (b) Bottom load cells in place

17. A total axial load of 80 kips is applied to the specimen by simultaneously tightening the super washers on each bar.
18. The LVDTs are fixed to the bearing member directly below the hooks, and the steel extensions are tightened to each hook so that as the hooks slip forward, the extensions will displace the LVDTs.

19. The string pot fixture is clamped to the bearing member, holding the string pot directly behind the internal slip measurement wire protruding from the specimen. This wire is then connected to the string pot.
20. The load cells are placed on the hooked bars and placed tight to the jacks, followed by wedge grips.
21. The adjustable height platform is raised high enough to support the load cells so that no weight is placed on the hooked bars. The platform is adjusted vertically to ensure that the bars are tensioned perpendicular to the specimen without any eccentric loading.
22. Measurements of the specimen are recorded, including the center-to-center spacing of hooked bars, side cover, distance from the specimen face to LVDTs, and dimension used to establish the actual value of ℓ_{eh}.
23. Load is applied to the hooks using the jacks, pausing to mark cracks at 5 kip intervals.
24. After the failure of one or both of the hooks, cracks, failure load, and failure type are documented.
25. If one of the hooks has not yet failed, the jack for the failed hook is shut off and incremental loading of the other hook is resumed.
26. Upon failure of the second hook, cracks, failure load, and failure type are documented.
27. After failure of both hooks, the specimen is removed and later autopsied.

Chapter 3: Evaluation of Test Results

3.1: Test Results

Results for the first 26 specimens in this study are described in this chapter. Each specimen contained two hooks. Some of the No. 5 bars in the early tests yielded before an anchorage failure occurred. The results from those hooks are included, but not used in the analysis of the results. Bar properties are summarized in Table 3 (Chapter 2). Specimen properties and test results are summarized in Table 4.

Test results include 17 specimens with No. 5 hooked bars and nine specimens with No. 8 hooked bars, all cast with 5 ksi concrete.

The No. 5 hook tests include specimens with 90° and 180° hooks, side covers of 1.5 in. and 2.5 in., transverse reinforcement consisting of 5 No. 3 bars, 2 No. 3 bars, or no transverse reinforcement, and embedment lengths ranging from 5 in. to 11.25 in. These specimens were cast with the hooks outside of the longitudinal reinforcement.

The No. 8 hook test specimens included three sets of three identical specimens. All specimens were cast in 5 ksi concrete, with 90° hooks, 2.5-in. side cover, and a 10-in. embedment length. The variables of these specimens were the location of the hook, both inside and outside of the longitudinal reinforcement, and the quantity of transverse reinforcement, 5 No. 3 bars or no transverse reinforcement confining the hook.

Notation:

A_h	Bar area of hook
A_{tr}	Area of transverse bars in hook region
b	Column width
c_b	Cover of reinforcement being developed, measured to tension face of member, in.
c_{th}	Clear cover measured from the tail of the hook to the back of the column
c_{so}	Clear cover measured from the side of the hook to the side of the column
c_h	Clear spacing between hooked bars, inside-to-inside spacing
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_{cl}	Height measured from the center of the hook to the top of the compression block
h_c	Height of compression plate
ℓ_{eh}	Embedment length of the hook
N_h	Number of hooks loaded simultaneously
N_{tr}	Number of stirrups/ties crossing the hook
T	Load at failure
R_r	Relative rib area
s_{tr}	Center-to-center spacing of stirrups/ties around the hook

Failure types described further in Section 3.3

K	Kick out of the hook tail at failure
B	Breakout failure
SB	Side blowout failure
SS	Side splitting failure

Specimen identification

A-B-C-D#E-F-G-H-Ix

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, blank (or a), b, c, etc.

Table 4 - Specimen properties and test results

Specimen	Hook	Bend Angle	Radius of Bend In.	Transverse Reinf. Orientation	ℓ_{dh} in.	f'_c psi	Age days	f_y ksi	d_b in.	R_r	b in.	h_{cl} in.	h_c in.
5-5-90-0-O-1.5sc-2tc-11	A	90°	1 7/8	Horizontal	10.6	3950	*	60	0.625	*	11	5.25	8.375
	B	90°	1 7/8	Horizontal	10.6	3950	*	60	0.625	*	11	5.25	8.375
5-5-90-0-O-2.5sc-2tc-7	A	90°	1 7/8	Horizontal	7.4	3950	*	60	0.625	*	11	5.25	8.375
	B	90°	1 7/8	Horizontal	7.4	3950	*	60	0.625	*	11	5.25	8.375
5-5-90-2#3-O-1.5sc-2tc-11	A	90°	1 7/8	Horizontal	10.6	4080	*	60	0.625	*	11	5.25	8.375
	B	90°	1 7/8	Horizontal	10.6	4080	*	60	0.625	*	11	5.25	8.375
5-5-90-2#3-O-2.5sc-2tc-7	A	90°	1 7/8	Horizontal	7.4	4080	*	60	0.625	*	11	5.25	8.375
	B	90°	1 7/8	Horizontal	7.4	4080	*	60	0.625	*	11	5.25	8.375
5-5-90-0-O-1.5-2-5	A	90°	1 7/8	Horizontal	5.00	4930	4	60	0.625	0.077	11	5.25	8.375
	B	90°	1 7/8	Horizontal	5.00	4930	4	60	0.625	0.077	11	5.25	8.375
5-5-90-0-O-2.5-2-5	A	90°	1 7/8	Horizontal	4.75	4930	4	60	0.625	0.077	13	5.25	8.375
	B	90°	1 7/8	Horizontal	4.75	4930	4	60	0.625	0.077	13	5.25	8.375
5-5-90-5#3-O-1.5-2-5	A	90°	1 7/8	Horizontal	5.00	5205	5	60	0.625	0.077	11	5.25	8.375
	B	90°	1 7/8	Horizontal	5.00	5205	5	60	0.625	0.077	11	5.25	8.375
5-5-90-5#3-O-2.5-2-5	A	90°	1 7/8	Horizontal	5.19	4930	4	60	0.625	0.077	13	5.38	8.375
	B	90°	1 7/8	Horizontal	5.13	4930	4	60	0.625	0.077	13	5.25	8.375
5-5-90-0-O-1.5-2-6.5	A	90°	1 7/8	Horizontal	6.50	5650	6	120	0.625	0.077	11	5.25	8.375
	B	90°	1 7/8	Horizontal	5.88	5650	6	120	0.625	0.077	11	5.25	8.375
5-5-90-0-O-1.5-2-8	B	90°	1 7/8	Horizontal	7.88	5650	6	120	0.625	0.077	11	5.25	8.375
	B	90°	1 7/8	Horizontal	7.88	5650	6	120	0.625	0.077	11	5.25	8.375
5-5-90-5#3-O-1.5-2-8	A	90°	1 7/8	Horizontal	8.00	5650	6	120	0.625	0.077	11	5.25	8.375
	B	90°	1 7/8	Horizontal	7.75	5650	6	120	0.625	0.077	11	5.25	8.375
5-5-90-5#3-O-2.5-2-8	A	90°	1 7/8	Horizontal	7.50	5650	6	120	0.625	0.077	13	5.25	8.375
	B	90°	1 7/8	Horizontal	7.50	5650	6	120	0.625	0.077	13	5.25	8.375
5-5-90-0-O-2.5-2-8	A	90°	1 7/8	Horizontal	9.00	5780	7	120	0.625	0.077	13	5.25	8.375
	B	90°	1 7/8	Horizontal	9.00	5780	7	120	0.625	0.077	13	5.25	8.375
5-5-90-5#3-O-1.5-2-6.5	A	90°	1 7/8	Horizontal	6.50	5780	7	120	0.625	0.077	11	5.25	8.375
	B	90°	1 7/8	Horizontal	6.50	5780	7	120	0.625	0.077	11	5.25	8.375
5-5-90-0-O-2.5sc-2tc-6.5	A	90°	1 7/8	Horizontal	6.5	5780	7	120	0.625	0.077	11	5.25	8.375
	B	90°	1 7/8	Horizontal	6.5	5780	7	120	0.625	0.077	11	5.25	8.375
5-5-90-5#3-O-2.5sc-2tc-6.5	A	90°	1 7/8	Horizontal	6.5	5780	7	120	0.625	0.077	11	5.25	8.375
	B	90°	1 7/8	Horizontal	6.5	5780	7	120	0.625	0.077	11	5.25	8.375
5-5-180-2#3-O-2.5-2-9.5	A	180°	2	Horizontal	9.13	4420	7	120	0.625	0.077	13	5.25	8.375
	B	180°	2	Horizontal	9.25	4420	7	120	0.625	0.077	13	5.25	8.375
5-5-180-0-O-1.5-2-9.5	A	180°	2	Horizontal	9.63	4420	7	120	0.625	0.077	11	5.25	8.375
	B	180°	2	Horizontal	9.25	4420	7	120	0.625	0.077	11	5.25	8.375
5-5-180-2#3-1.5-2-11.25	A	180°	2	Horizontal	11.63	4420	7	120	0.625	0.077	11	5.25	8.375
	B	180°	2	Horizontal	11.50	4420	7	120	0.625	0.077	11	5.25	8.375
5-5-180-0-O-2.5-2-9.5	A	180°	2	Horizontal	9.50	4520	8	120	0.625	0.077	13	5.25	8.375
	B	180°	2	Horizontal	9.50	4520	8	120	0.625	0.077	13	5.25	8.375
5-5-180-2#3-O-1.5-2-9.5	A	180°	2	Horizontal	8.75	4520	8	120	0.625	0.077	11	5.25	8.375
	B	180°	2	Horizontal	8.75	4520	8	120	0.625	0.077	11	5.25	8.375
5-5-180-2#3-O-2.5-2-11.25	A	180°	2	Horizontal	11.13	4520	8	120	0.625	0.077	13	5.25	8.375
	B	180°	2	Horizontal	11.38	4520	8	120	0.625	0.077	13	5.25	8.375
5-5-180-0-O-1.5-2-11.25	A	180°	2	Horizontal	11.25	4520	8	120	0.625	0.077	11	5.25	8.375
	B	180°	2	Horizontal	11.25	4520	8	120	0.625	0.077	11	5.25	8.375
8-5-90-0-O-2.5-2-10a	A	90°	3 1/16	Horizontal	10.25	5270	7	120	1	0.084	17	10.50	8.375
	B	90°	3 1/16	Horizontal	10.50	5270	7	120	1	0.084	17	10.50	8.375
8-5-90-0-O-2.5-2-10b	A	90°	3 1/16	Horizontal	9.25	5440	8	120	1	0.084	17	10.50	8.375
	B	90°	3 1/16	Horizontal	10.25	5440	8	120	1	0.084	17	10.50	8.375
8-5-90-0-O-2.5-2-10c	A	90°	3 1/16	Horizontal	10.75	5650	9	120	1	0.084	17	10.50	8.375
	B	90°	3 1/16	Horizontal	10.50	5650	9	120	1	0.084	17	10.50	8.375
8-5-90-5#3-O-2.5-2-10a	A	90°	3 1/16	Horizontal	10.25	5270	7	120	1	0.084	17	10.50	8.375
	B	90°	3 1/16	Horizontal	10.50	5270	7	120	1	0.084	17	10.50	8.375
8-5-90-5#3-O-2.5-2-10b	A	90°	3 1/16	Horizontal	10.50	5440	8	120	1	0.084	17	10.50	8.375
	B	90°	3 1/16	Horizontal	10.50	5440	8	120	1	0.084	17	10.50	8.375
8-5-90-5#3-O-2.5-2-10c	A	90°	3 1/16	Horizontal	11.25	5650	9	120	1	0.084	17	10.50	8.375
	B	90°	3 1/16	Horizontal	10.50	5650	9	120	1	0.084	17	10.50	8.375
8-5-90-5#3-I-2.5-2-10a	A	90°	3 1/16	Horizontal	10.50	5270	7	120	1	0.084	17	10.50	8.375
	B	90°	3 1/16	Horizontal	10.50	5270	7	120	1	0.084	17	10.50	8.375
8-5-90-5#3-I-2.5-2-10b	A	90°	3 1/16	Horizontal	10.25	5440	8	120	1	0.084	17	10.50	8.375
	B	90°	3 1/16	Horizontal	10.50	5440	8	120	1	0.084	17	10.50	8.375
8-5-90-5#3-I-2.5-2-10c	A	90°	3 1/16	Horizontal	10.50	5650	9	120	1	0.084	17	10.50	8.375
	B	90°	3 1/16	Horizontal	10.50	5650	9	120	1	0.084	17	10.50	8.375

* Not available

Table 4 Continued – Specimen properties and test results

Specimen	Hook	c_b in.	c_{so} in.	c_{th} in.	c_h in.	N_h	A_{h_2} in.^{2}	f_{yt} ksi	d_{tr} in.	A_{tr_2} in.^{2}	N_{tr}	s_{tr} in.	T kip	f_{su} ksi	Loaded-End Slip at Failure in.	Failure Type
5-5-90-0-O-1.5sc-2tc-11	A	-	1.50	2.00	6.63	2	0.31	60	-	0	0	-	20.8	67.00	-	Yield
	B	-	1.50	2.00	6.63	2	0.31	60	-	0	0	-	20.8	67.00	-	Yield
5-5-90-0-O-2.5sc-2tc-7	A	-	2.50	2.00	6.63	2	0.31	60	-	0	0	-	20.8	67.00	-	Yield
	B	-	2.50	2.00	6.63	2	0.31	60	-	0	0	-	20.8	67.00	-	Yield
5-5-90-2#3-O-1.5sc-2tc-11	A	-	1.50	2.00	6.63	2	0.31	60	0.375	0.22	2	3	20.8	67.00	-	Yield
	B	-	1.50	2.00	6.63	2	0.31	60	0.375	0.22	2	3	20.8	67.00	-	Yield
5-5-90-2#3-O-2.5sc-2tc-7	A	-	2.50	2.00	6.63	2	0.31	60	0.375	0.22	2	3	20.8	67.00	-	Yield
	B	-	2.50	2.00	6.63	2	0.31	60	0.375	0.22	2	3	20.7	67.00	-	Yield
5-5-90-0-O-1.5-2-5	A	-	1.50	2.00	6.75	2	0.31	60	-	0	0	-	14.1	45.48	-	B/SB
	B	-	1.75	2.00	6.75	2	0.31	60	-	0	0	-	19.6	63.23	-	B/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	62.90	-	B/SB
	B	-	2.50	2.13	6.38	2	0.31	60	-	0	0	-	23.5	75.81	-	B/SB
5-5-90-5#3-O-1.5-2-5	A	-	1.50	2.00	6.50	2	0.31	60	0.375	0.55	5	1.9	26.0	83.90	-	SB
	B	-	1.50	2.00	6.50	2	0.31	60	0.375	0.55	5	1.9	22.0	70.97	-	B/SB
5-5-90-5#3-O-2.5-2-5	A	-	2.63	1.88	6.63	2	0.31	60	0.375	0.55	5	1.9	22.0	70.97	-	B/SB
	B	-	2.63	1.88	6.63	2	0.31	60	0.375	0.55	5	1.9	29.0	93.55	-	B/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	67.10	-	B
	B	-	1.63	2.75	6.63	2	0.31	60	-	0	0	-	18.2	58.71	-	B/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	75.81	-	No Failure
	B	-	1.50	2.13	6.63	2	0.31	60	-	0	0	-	23.5	75.81	-	SB
5-5-90-5#3-O-1.5-2-8	A	-	1.56	2.25	6.38	2	0.31	60	0.375	0.55	5	1.9	25.2	81.29	-	B/SB
	B	-	1.50	2.63	6.38	2	0.31	60	0.375	0.55	5	1.9	30.4	98.06	-	B/SB
5-5-90-5#3-O-2.5-2-8	A	-	2.56	2.13	6.50	2	0.31	60	0.375	0.55	5	1.9	28.4	91.61	-	B
	B	-	2.56	2.13	6.50	2	0.31	60	0.375	0.55	5	1.9	23.0	74.19	-	Yield
5-5-90-0-O-2.5-2-8	A	-	2.56	1.50	6.63	2	0.31	60	-	0	0	-	30.3	97.74	-	SB
	B	-	2.56	1.50	6.63	2	0.31	60	-	0	0	-	30.6	98.70	-	Yield
5-5-90-5#3-O-1.5-2-6.5	A	-	1.56	2.00	6.50	2	0.31	60	0.375	0.55	5	1.9	26.2	84.52	-	B/SB
	B	-	1.56	2.00	6.50	2	0.31	60	0.375	0.55	5	1.9	20.9	67.42	-	B/SB
5-5-90-0-O-2.5sc-2tc-6.5	A	-	2.63	2.00	6.63	2	0.31	60	-	0	0	-	30.0	96.70	-	Yield
	B	-	2.63	2.00	6.63	2	0.31	60	-	0	0	-	30.0	96.70	-	Yield
5-5-90-5#3-O-2.5sc-2tc-6.5	A	-	2.50	2.00	6.63	2	0.31	60	0.375	0.55	5	1.9	25.0	80.60	-	Yield
	B	-	2.63	2.00	6.63	2	0.31	60	0.375	0.55	5	1.9	25.0	80.60	-	Yield
5-5-180-2#3-O-2.5-2-9.5	A	-	2.50	2.13	6.63	2	0.31	60	0.375	0.22	2	2	35.5	114.52	-	B/SB
	B	-	2.50	2.00	6.63	2	0.31	60	0.375	0.22	2	2	43.9	141.61	-	B
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	113.55	-	B
	B	-	1.63	2.13	6.38	2	0.31	60	-	0	0	-	30.4	98.06	-	B/SB
5-5-180-2#3-1.5-2-11.25	A	-	1.63	1.88	6.63	2	0.31	60	0.375	0.22	2	2	48.3	155.81	-	B/SB
	B	-	1.50	1.88	6.63	2	0.31	60	0.375	0.22	2	2	43.0	138.71	-	B/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	130.32	-	B
	B	-	2.50	1.75	6.63	2	0.31	60	-	0	0	-	34.0	109.68	-	B
5-5-180-2#3-O-1.5-2-9.5	A	-	1.63	2.38	6.63	2	0.31	60	0.375	0.22	2	2	30.0	96.70	-	No Failure
	B	-	1.63	2.38	6.63	2	0.31	60	0.375	0.22	2	2	20.3	65.48	-	B/SB
5-5-180-2#3-O-2.5-2-11.25	A	-	2.50	2.50	6.63	2	0.31	60	0.375	0.22	2	2	43.6	140.65	-	B
	B	-	2.75	2.13	6.63	2	0.31	60	0.375	0.22	2	2	42.5	137.10	-	B/SB
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	104.52	-	B/SB
	B	-	1.75	2.25	6.63	2	0.31	60	-	0	0	-	35.0	112.90	-	No Failure
8-5-90-0-O-2.5-2-10a	A	-	2.50	2.00	10.00	2	0.79	60	-	0	0	-	40.6	51.39	-	B/SS
	B	-	2.63	1.75	10.00	2	0.79	60	-	0	0	-	46.6	58.99	0.186	SS/B
8-5-90-0-O-2.5-2-10b	A	-	2.50	3.25	10.00	2	0.79	60	-	0	0	-	47.9	60.63	-	B/SS
	B	-	2.50	2.25	10.00	2	0.79	60	-	0	0	-	30.6	38.73	-	SS/B
8-5-90-0-O-2.5-2-10c	A	-	2.50	1.50	10.00	2	0.79	60	-	0	0	-	62.7	79.37	-	B/SS
	B	-	2.50	1.75	10.00	2	0.79	60	-	0	0	-	54.6	69.11	0.132	SS/B/K
8-5-90-5#3-O-2.5-2-10a	A	-	2.63	1.75	9.88	2	0.79	60	0.375	0.55	5	3	55.7	70.51	-	SS
	B	-	2.63	2.00	9.88	2	0.79	60	0.375	0.55	5	3	55.8	70.63	0.213	SB
8-5-90-5#3-O-2.5-2-10b	A	-	2.50	2.00	9.88	2	0.79	60	0.375	0.55	5	3	66.4	84.05	0.203	B/SB
	B	-	2.63	2.00	9.88	2	0.79	60	0.375	0.55	5	3	69.5	87.97	0.235	SB/B
8-5-90-5#3-O-2.5-2-10c	A	-	2.63	1.25	9.88	2	0.79	60	0.375	0.55	5	3	80.6	102.03	-	SS/B
	B	-	2.50	2.00	9.88	2	0.79	60	0.375	0.55	5	3	57.7	73.04	-	SS/B
8-5-90-5#3-I-2.5-2-10a	A	-	2.50	1.75	9.75	2	0.79	60	0.375	0.55	5	3	82.8	104.81	-	No Failure
	B	-	2.50	1.75	9.75	2	0.79	60	0.375	0.55	5	3	82.8	104.81	0.164	B/SS
8-5-90-5#3-I-2.5-2-10b	A	-	2.75	2.00	9.88	2	0.79	60	0.375	0.55	5	3	78.8	99.75	0.129	B/SS
	B	-	2.63	1.75	9.88	2	0.79	60	0.375	0.55	5	3	66.7	84.43	-	B
8-5-90-5#3-I-2.5-2-10c	A	-	2.50	2.00	10.00	2	0.79	60	0.375	0.55	5	3	68.9	87.22	-	B/SS
	B	-	2.50	2.00	10.00	2	0.79	60	0.375	0.55	5	3	69.6	88.10	-	B/SS

3.2: Crack Patterns

Crack patterns were similar for most of the specimens. The first cracks appear on the loaded face of the specimen radiating from the hooks (Figure 30). These cracks propagate from the face, around the edge and then onto the sides of the specimen. Once cracks have reached the sides of the specimen, vertical cracks begin to propagate and grow both above and below the transverse cracks. As the cracks on the sides of the specimen propagate vertically, they also angle towards the loaded face of the specimen, resulting in a conical shape within the failure region (Figure 31). Cracks continue to grow larger until failure occurs. In some tests, cracks appear on the back of the specimen behind the hooks, though this does not always happen and is much more common for No. 8 bars than No. 5 bars.

Figure 30: Cracks propagating from the hooked bars

Figure 31: Vertical cracks forming a conical shape

3.3: Failure Modes

The specimens failed in three ways: breakout failure (Figure 32), side splitting failure (Figure 33), and side blowout failure (Figure 34). Breakout failures are defined by a section of concrete around the hook being pulled forward out of the specimen at failure. Side splitting failures occur when cracks in the plane of the hooks on the side of the specimen continue to grow until the hook loses anchorage strength. Side blowout failures are similar to side splitting failures, in that they are also a result of excessive cracking on the side of the specimen in the plane of the hook. The difference is primarily in the degree of cracking, with side blowout failures exhibiting significant spalling at failure. Breakout failures often occur in conjunction with side splitting and side blowout failures. Kickout also occurs from some hooks. Kickout occurs when the tail of the hooked bar breaks the concrete cover and is exposed on the back side

of the specimen. Kickout of hooked bars has occurred, but only in conjunction with other types of failure. It has not yet been observed as the cause of failure.

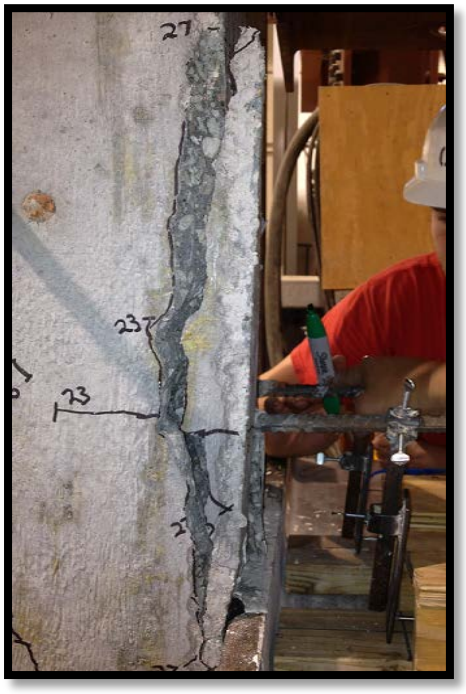

Figure 32: Breakout failure

Figure 33: Side splitting failure

Figure 34: Side blowout failure

3.4: Data Trends

The 17 No. 5 hook tests focused on the effects of side cover, embedment length, and confinement on anchorage strength. The effect of these variables is shown in Figures 35 and 36.

Figures 35 and 36 compare ultimate bar stress versus embedment length for specimens with No. 5 hooked bars, with 1.5 and 2.5-in. nominal side covers. The specimens in Figure 35 have no transverse reinforcement confining the hook, while those in Figure 36 contain hooks confined by 5 No. 3 transverse bars. Comparing hook strengths in the two figures, the hooks in Figure 36 have higher anchorage strengths. The strengths of most hooks with no transverse reinforcement cluster between 60 to 80 ksi, while the anchorage strength of most hooks confined by 5 No. 3 bars cluster between 70 and 100 ksi. Since both graphs compare hooks with similar

side covers and embedment lengths, this shows that increasing confinement in the hook region increases anchorage strength. Also, both figures show that increasing embedment length increases anchorage strength, and hooks with 2.5-in. side cover are stronger than hooks with 1.5-in. side cover. These observations agree with those in studies by Marques and Jirsa (1975), Pinc et al. (1977), Soroushian et al. (1988), Hamad et al. (1993), and Ramirez and Russell (2008). One of the principal goals of this study is to quantify the effects of these variables on anchorage strength.

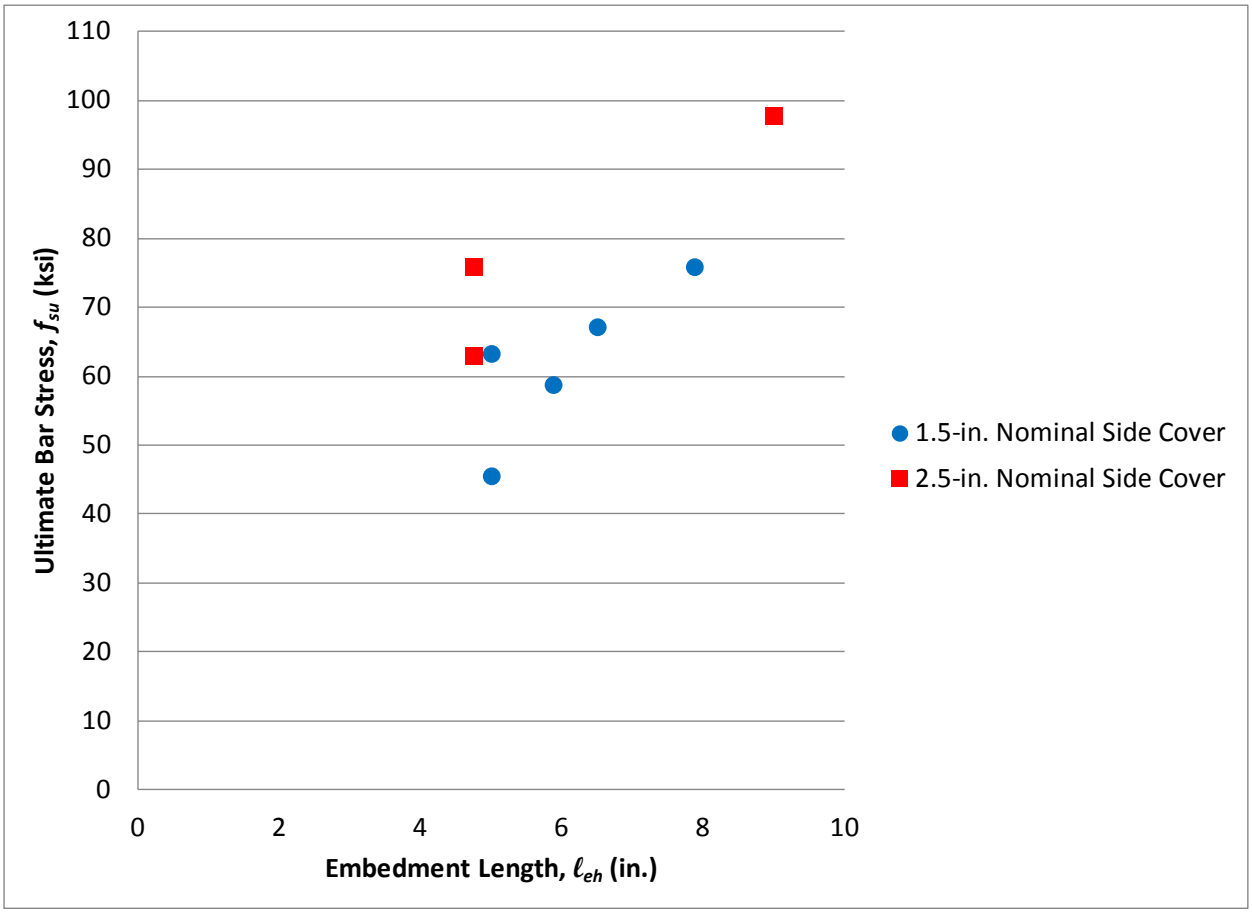

Figure 35: Ultimate bar stress versus embedment length for 90° No. 5 hooked bars with no transverse reinforcement

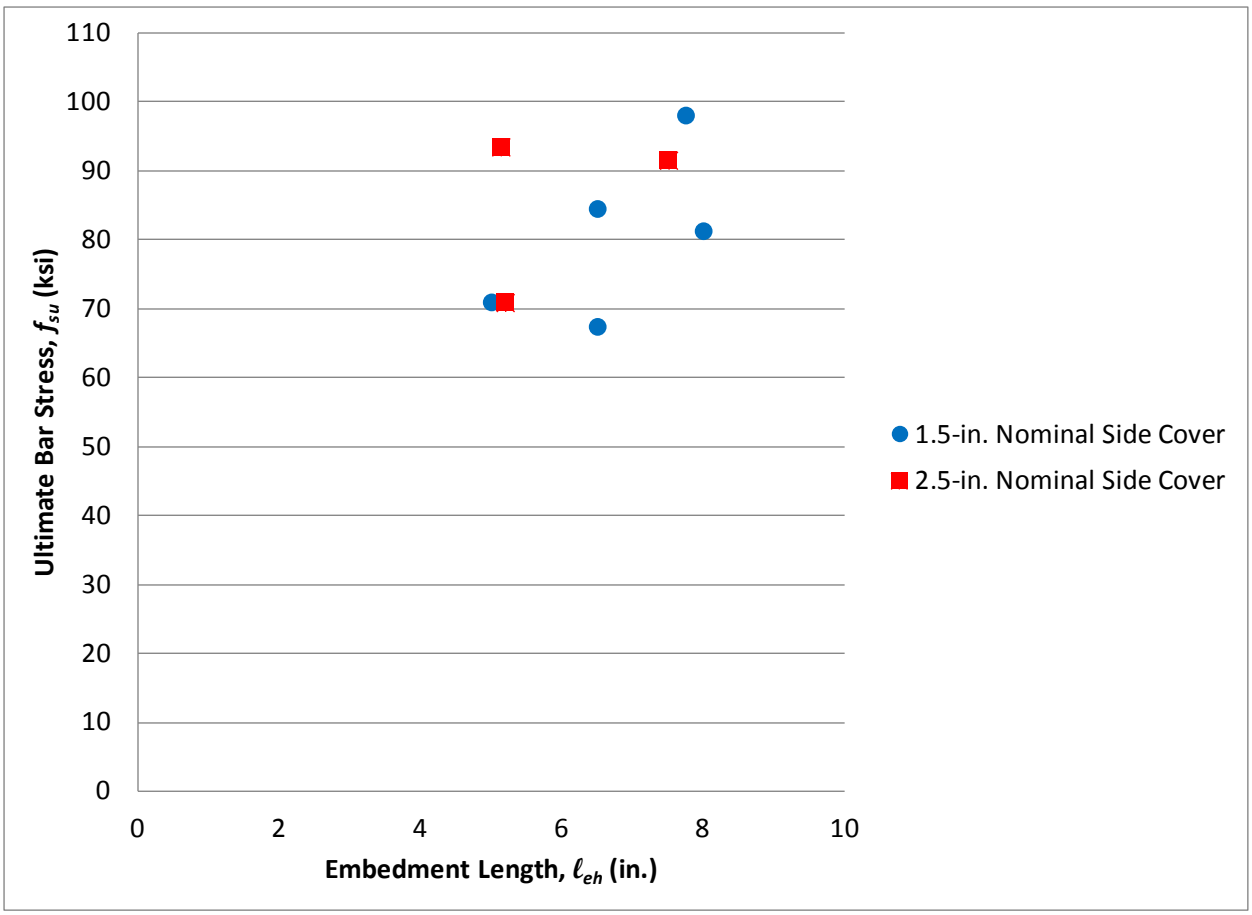

Figure 36: Ultimate bar stress versus embedment length for 90° No. 5 hooked bars with 5 No. 3 bars transverse reinforcement

The No. 8 bar tests were intended to provide an initial evaluation of the effect of hook location with respect to the core of a column on anchorage strength. In previous studies, hooked bars confined by transverse reinforcement have been cast both inside and outside of the longitudinal reinforcement, that is, inside and outside of the core of the test column. Casting the hooks outside of the longitudinal reinforcement contrasts with requirements in ACI 318 for beam-column joints, which requires hooks to be anchored within the column core. Tests of hooks outside of a core are appropriate, however, for cantilever beams, such as shown in the Fig. R12.5.4 of the ACI 318 (2011). The specimens contain 90° hooks with the same embedment length, side cover, and tail cover. Specimens differ in the location of the longitudinal and

transverse reinforcement with respect to the hooks. Three specimens were cast with the hook outside of both the transverse and longitudinal reinforcement, three were cast with the hooks inside the transverse reinforcement but outside the longitudinal reinforcement, and three were cast with the hooks inside both the longitudinal and transverse reinforcement. A nominal clear side cover of 2.5 in. was used for all specimens.

Figure 37 shows the average values and ranges of ultimate bar strengths in these tests. The figure demonstrates that having hooks inside the core of a column increases anchorage strength compared to hooks outside of the longitudinal reinforcement. The results also show that hooks confined by transverse reinforcement are stronger than hooks without transverse reinforcement. These results are consistent with those for the No. 5 bars.

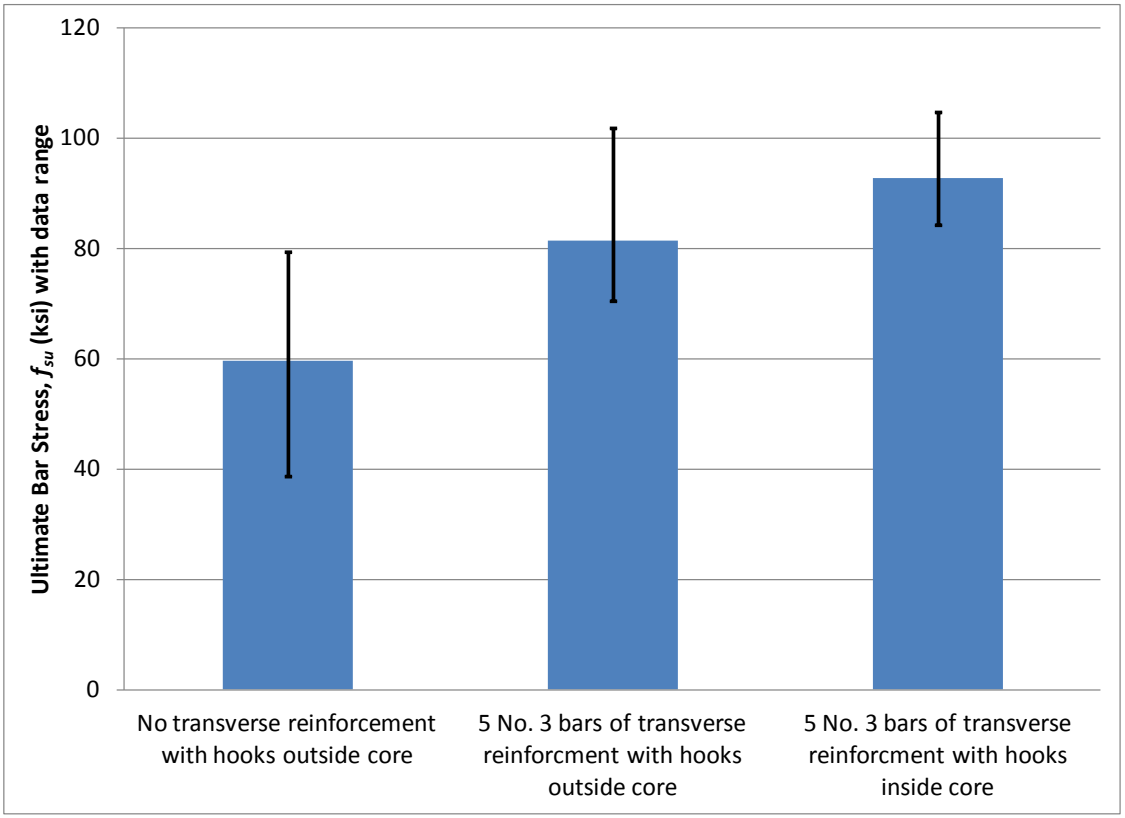

Figure 37: Ultimate bar stress for No. 8 bar 90° hooks with 10.25-in. nominal embedment length and 2.5-in. nominal side cover

Chapter 4: Summary

One goal of this study is to determine the effects of embedment length, side cover, confinement, bar size, concrete strength, and hook geometry on the anchorage strength of hooked bars. Concrete strengths of up to 15,000 psi will be used, as well as hooked bars with yield strengths in excess of 100 ksi.

Thus far, the testing apparatus has been fabricated, the testing procedures have been established, and the initial specimens have been tested. The test results agree qualitatively with those in previous studies and show that hook strength increases with increased embedment length, side cover, and confining reinforcement. The results also show that hook strength is greater for hooks anchored within a column core than for hooks anchored outside of the core. The latter case is appropriate to hooks anchoring bars at the end of cantilever beams.

Testing will continue, to provide data that will be used to establish reliability-based design expressions for development length of bars with standard hooks.

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