

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

By
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A Report on Research Sponsored by

The Charles Pankow Foundation,
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Precast/Prestressed Concrete Institute,
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Structural Engineering and Engineering Materials
SL Report 20-3
February 2020



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

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ABSTRACT

The reaction frame to be used to test No. 14 and No. 18 bar beam-column joint specimens, the modified reaction frame used to test initial No. 11 beam-column joint specimens, and the design of beam-column joint specimens are described. Concrete strengths of 5,000 psi to 15,000 psi will be used with bar sizes of No. 11, No. 14, and No. 18 with bar stresses at anchorage failure in excess of 100 ksi in future work.

Thus far, the testing apparatus has been designed, test procedures have been established, and initial specimens have been tested. The initial test results show that the descriptive equation used to calculate the anchorage strength of headed bars presented by Shao et al. (2016) is accurate for No. 11 bars.

Testing will continue using the apparatus and procedures described in this report, and the results will be added to the database developed at The University of Kansas to better understand how large high-strength headed and hooked bars behave in beam-column joints.

Keywords: anchorage, embedment length, beam-column joints, hooked bars, headed bars, high-strength concrete, high-strength steel

ACKNOWLEDGEMENTS

This report is based on a report submitted by Matthew Blessent in partial fulfillment of the requirements for the MSCE degree from the University of Kansas. Funding and substantial material support for this research were provided by the Charles Pankow Foundation, BarSplice Products, Headed Reinforcement Corporation, nVent, the CRSI Education and Research Foundation, the Precast/Prestressed Concrete Institute, the Commercial Metals Company, and Nucor. Additional material support was provided by Dayton Superior.

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CHAPTER 1: INTRODUCTION

1.1: Objective and Scope

This report describes ongoing research on the anchorage strength of large headed and standard hooked bars as a function of embedment length, bar size and spacing, and confining reinforcement. For headed bars, the embedment length is the distance from the critical section to the bearing face of the head. For standard hooked bars, the embedment length is the distance from the critical section to the back of the hook. This report focuses on No. 11 and No. 14 bars in beam-column joint specimens containing concrete with nominal strengths of 15,000 psi, the design of the loading system used to test beam-column joint specimens is also discussed. The goal of this study is to build on previous research to permit the use of No. 14 and No 18 headed bars and to provide improved design provisions for No. 14 and No. 18 hooked bars.

1.2: Definition of Problem

There has been minimal research performed on the anchorage strength of hooked and headed bars larger than No. 11 bars. Previous studies on No. 11 and smaller hooked bars include those by Marques and Jirsa (1975), Pinc et al. (1977), Joh et al. (1993, 1996), Ramirez and Russel (2008), and at the University of Kansas, Sperry et al. (2015a, 2015b), Yasso et al. (2017), and Ajaam et al. (2017). Previous studies on No. 11 and smaller headed bars includes these by Bashandy (1996), Chun et al. (2009), Kang et al. (2010), and at the University of Kansas, Shao et al. (2016) and Ghimire (2018, 2019a, 2019b). The studies at the University of Kansas included beam-column joints with headed bars and hooked bars with 90- and 180-degree bends, test bars with up to 120 ksi yield strength, concrete with strengths up to 16,000 psi, high and low side and tail cover, wide and closely spaced test bars, two to four test bars in a single row, up to six bars in two rows, and different quantities of confining reinforcement within the joint region.

Twenty-six beam-column joint specimens containing No. 14 and No. 18 hooked bars and 27 beam-column joint specimens containing No. 14 and No. 18 headed bars were tested by Chun et al. (2017). Tests were conducted on joints with and without transverse reinforcement. The specimens without transverse reinforcement in the joint contained bars located outside of the column core. Specimens with transverse reinforcement in the joint contained bars located inside the column core. The stresses in the hooked bars ranged from 33.6 to 88.3 ksi, with concrete compressive strengths ranging from 5,450 psi to 10,600 psi. Stresses in the headed bars ranged from 43.1 to 93.4 ksi, with concrete compressive strengths ranging from 5,870 to 11,770 psi. In the test configuration used, the compression reaction of the simulated beam was placed a distance of just two-thirds of the embedment length away from the test bar, much less than what typically occurs in practice. This short distance puts a compressive strut on the bar being developed, which in all likelihood resulted in the high anchorage strengths observed in these specimens.

The current provisions for the development length of hooked and headed bars in Sections 25.4.3 and 25.4.4, respectively, of ACI 318-19 have limits. The hooked bar provisions do not take advantage of concrete strengths over 10,000 psi and do not consider the effect of confining reinforcement for bars larger than No. 11. The headed bar also do not take advantage of concrete strengths over 10,000 psi provisions, and do not permit bars larger than No. 11. The limit on bar size is due to the lack of research on No. 14 and No. 18 headed bars in realistic configurations.

CHAPTER 2: EXPERIMENTAL WORK

2.1: Specimens

2.1.1: Specimen Design

The specimens in this study are designed to find the effects of key variables on the anchorage strength of reinforcement in beam-column joints. These key variables are embedment length, bar spacing, area of confining reinforcement in the joint region, bar size, and concrete strength. The specimens described in this report contained either two No. 11 headed bars with a center-to-center spacing of 14.1 in. or two No. 14 hooked or headed bars with a center-to-center spacing of 18 in. The nominal concrete strength of each specimen is 15,000 psi. Of the two No. 11 specimens tested, one had confining reinforcement within the joint and the other had no confining reinforcement within the joint. Confining reinforcement consists of steel ties within the joint region, parallel to the test bar. Designations for headed bar specimens follow that used by Shao et al. (2016), shown in Figure 1.

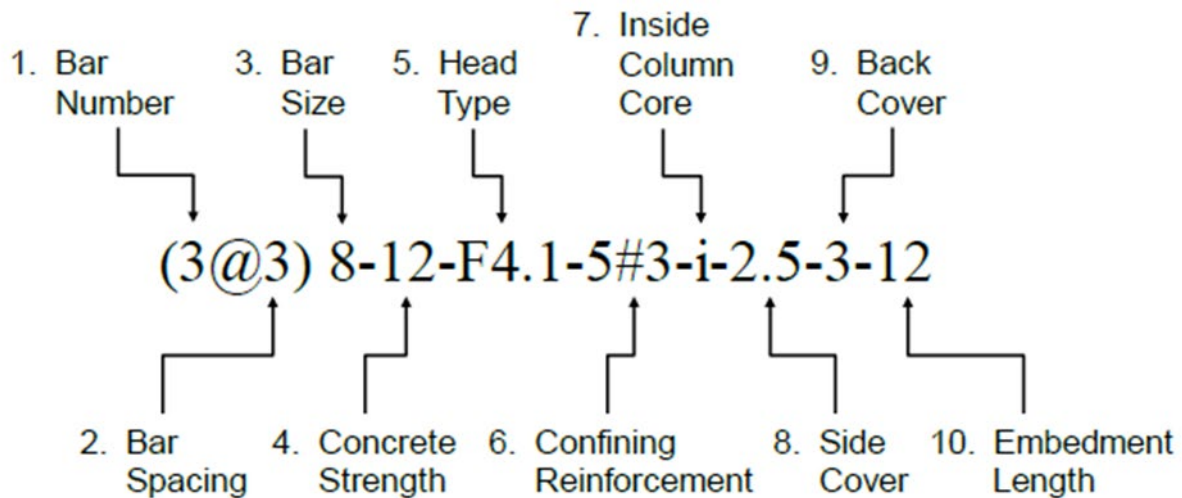


Figure 1 – Headed bar specimen naming designation

Specimens were designed to simulate exterior beam-column joints and proportioned so that an anchorage failure occurred in the joint region. The embedment lengths were calculated using the descriptive equations presented in Ajaam et al. (2017) and Shao et al. (2016) for the anchorage strength of hooked and headed bars, shown in Eq. (1) and (2), respectively. The second term on the right side of Eq. (1) and (2) represents the effect of spacing between test bars. Specimens without confining reinforcement were designed to reach a target stress of 100 ksi in each test bar; paired specimens with confining reinforcement were designed with the same embedment length. Based on the embedment length and bar spacing, column dimensions were chosen for each specimen. Longitudinal reinforcement and transverse reinforcement outside of the joint region were designed to resist the flexural and shear stresses based on the assumption that both bars reach the maximum load simultaneously.

$$T_h = \left(294 f_{cm}^{0.295} \ell_{eh}^{1.0845} d_b^{0.47} + 55,050 \left(\frac{A_{th}}{n} \right)^{1.0175} d_b^{0.73} \right) \left(0.0516 \frac{c_{ch}}{d_b} + 0.6572 \right) \quad (1)$$

$$\left(0.0516 \frac{c_{ch}}{d_b} + 0.6572 \right) \leq 1.0$$

$$T_h = \left(781 f_{cm}^{0.24} \ell_{eh}^{1.03} d_b^{0.35} + 48,800 \frac{A_u}{n} d_b^{0.88} \right) \left(0.0622 \frac{s}{d_b} + 0.5428 \right) \quad (2)$$

$$\left(0.0622 \frac{s}{d_b} + 0.5428 \right) \leq 1.0$$

The dimensions shown in Figure 2 represent the No. 11 headed bar specimen dimension proportions. These proportions are based on previous tests conducted at the University of Kansas by Shao et al. (2016). The No. 11 bars specimens had a center-to-center spacing s of 14.1 in. to conform to the definition of widely bars (center-to-center bar spacing of $8d_b$ or greater, where d_b

is the diameter of the test bar). The headed bars in the initial No. 11 bar specimens had a side and back cover of 3.5 in. Side cover c_{so} is defined as the distance from the side face of the concrete column to the outside of the test bar, and back cover c_{bc} is defined as the distance from the back face of the concrete column to the back of the head, as shown in Figure 3.

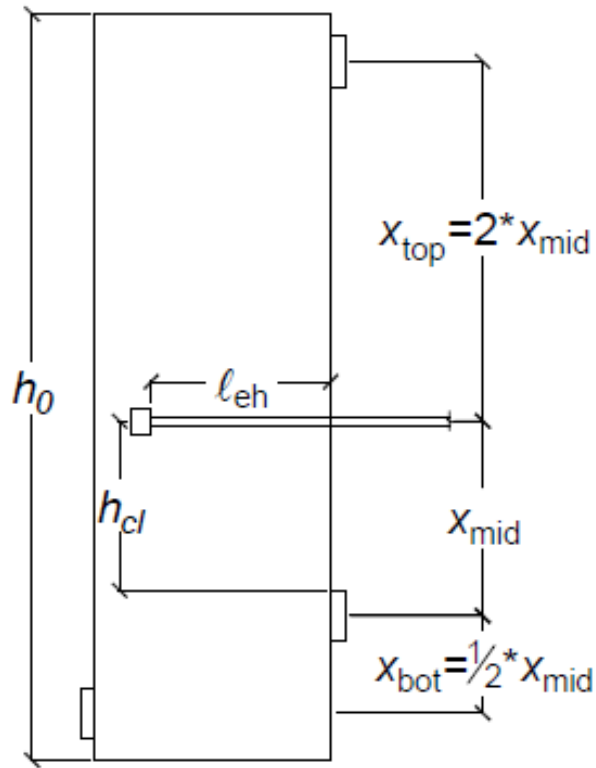


Figure 2 – Initial No. 11 elevation proportions

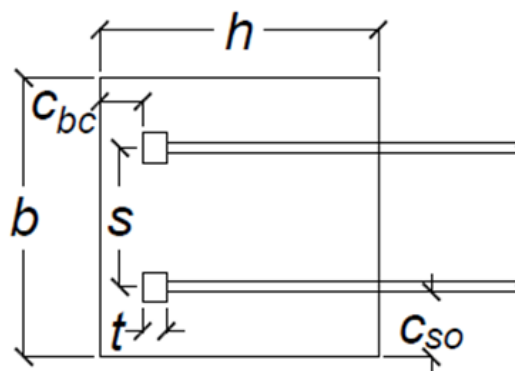
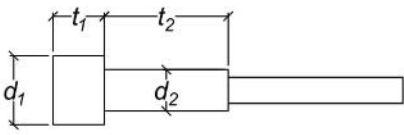
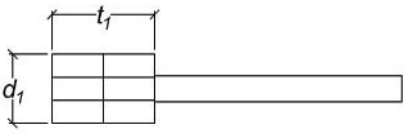


Figure 3 – Initial No. 11 bar specimen cross-sectional dimension guidelines

The dimensions of the heads on the test bars are given in Table 1. The heads used in the No. 11 bar tests and No. 14 bar columns are shown in Figures 4 and 5, respectively.

Table 1 - Specimen head dimensions

Specimen	Head Type	Bar Size	d_1 (in.)	t_1 (in.)	d_2 (in.)	t_2 (in.)	Net Bearing Area
	O4.5	No. 11	3.75	2.125	2.25	6.75	$4.5A_b^*$
	B4.9	No. 14	4.125	4.5	-	-	$4.9A_b$

* A_b = nominal bar area



Figure 5 - Head on No. 11 test bars



Figure 4 - Head on No. 14 test bars

For each specimen strain gauges were attached to the test bar and transverse reinforcement in the joint region (when present). The reinforcement, along with the location of strain gauges, used in the No. 11 bar specimen with confining reinforcement is shown in Figures 6 and 7. The

dimension x_{mid} equaled 24.5 in. for the No. 11 bar specimens, with a total column height of 8 ft. The ‘B1’ strain gauges were mounted to a single test bar just inside the front face of the column, the ‘H1’ strain gauges were mounted 1 in. away from the obstruction on the bar (see Figure 4), the ‘O1’ strain gauges were mounted on the obstruction in front of the head, and the ‘T1’ strain gauges were mounted on the hoop above the test bars, centered on the front face of the column. ‘S’ strain gauges were mounted on the hoops above the test bars, centered on the front face of the column. ‘S’ strain gauges were mounted on the hoops within the joint region.

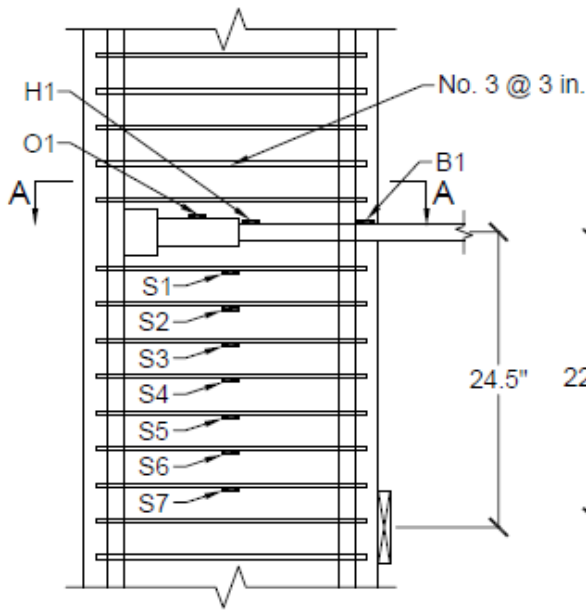


Figure 7 - Elevation of No. 11 bar test specimen showing strain gauge locations

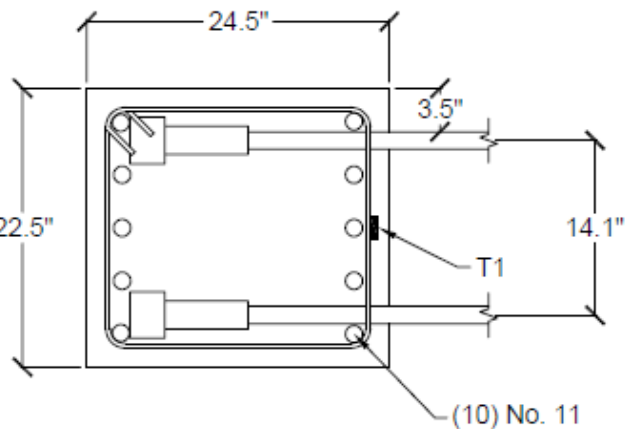


Figure 6 - Cross section A-A of No. 11 bar test specimen showing location of strain gauge T1

The No. 14 bar specimens were designed with the dimensional proportions shown in Figures 8 and 9. The dimension x_{mid} will equal 28.5 in. for No. 14 test bars, and the total column height will equal 14 ft. The proportions were chosen so that eighty percent of the total shear force on the specimen due to the applied moment at the joint would be placed on the joint region to accurately simulate an exterior beam-column joint in a building. For the initial test specimens, the No. 14 hooked bars are spaced 18 in. on center, with back cover of 2 in. and side cover of 3.5 in.

The embedment lengths of the No. 14 bars were calculated using the hooked bar descriptive equation by Ajaam et al. (2017) without confining reinforcement within the joint, headed bars were placed inside specimens with the same dimensions. Since the embedment length for hooked bars is defined differently than headed bars, headed bars have a shorter embedment length than the corresponding hooked bar specimens. Corresponding stresses were calculated using the headed bar descriptive equation. The No. 14 bar specimens to be cast have embedment lengths of 26.6 and 20.6 in. for the hooked and headed bars, respectively. The No. 14 bar specimens, with hooked bars, have calculated design stresses of 100 and 121 ksi, with and without confining reinforcement, respectively; the No. 14 specimens with headed bars have calculated design stresses of 95 and 116 ksi, with and without confining reinforcement, respectively. The dimensions of the head used on the test bar in the No. 14 specimens are given in Table 1.

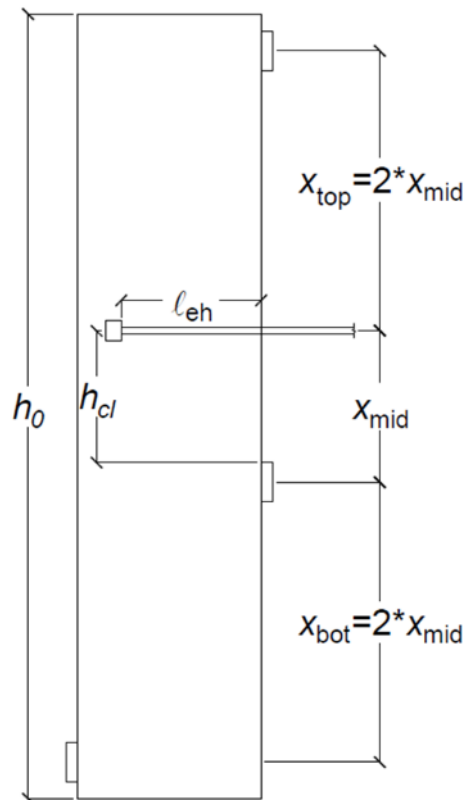


Figure 8 – No. 14 bar test specimen elevation proportions

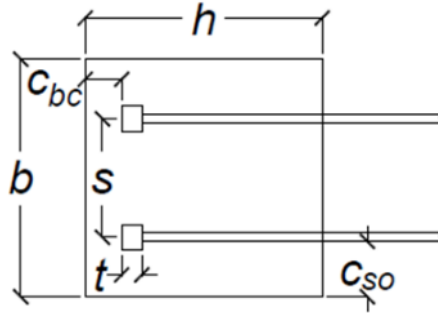


Figure 9 - No. 14 bar test specimen cross-sectional dimensions

The reinforcement and the strain gauge locations for No. 14 bar test specimens with nominal concrete compressive strength of 15,000 psi are shown in Figures 10 and 11, where (8) No. 11 bars are used as longitudinal reinforcement. No. 4 hoops spaced at $3d_b$ within the joint region and No. 4 hoops spaced at 9 in. outside of the joint region are used as transverse reinforcement. Strain gauges were mounted to a single test bar, to the confining reinforcement within the joint region (when present), the two stirrups above the joint region, and to two longitudinal reinforcing bars in each specimen.

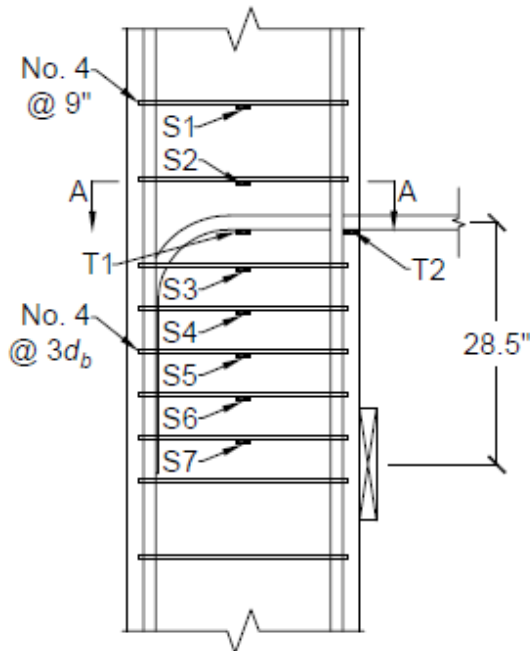


Figure 10 - Elevation of No. 14 bar test specimen showing strain gauge locations

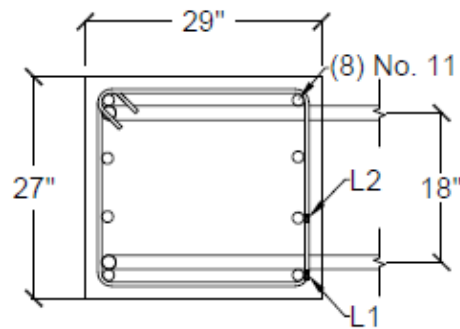


Figure 11 - Cross section A-A of No. 14 bar test specimen showing strain gauge L1 and L2

2.1.2: Specimen Fabrication

Formwork was built so that the depth of the columns could be changed to accommodate different embedment lengths. The formwork was fabricated using 2×4 dimension lumber and $\frac{3}{4}$ -in. thick plywood. To ensure adequate strength, 2×6 dimension lumber was placed on each side of the formwork and clamped together using all-thread rods, as shown in Figure 12. Hoops were bent to the required dimensions and tied to longitudinal reinforcement. Reinforcement chairs were tied to the steel cage to maintain the side and back cover during concrete placement. After the steel cages were placed in the forms, the test bars were tied into the steel cage at the desired spacing and height in the column. Once the test bars were tied in, the front panel was bolted in place with the test bars passing through pre-drilled holes.



Figure 12 - Formwork for the No. 14 bar specimens

The two No. 11 bar specimens with 15,000 psi concrete were cast in the same placement. The specimens were filled in three layers of roughly equal volume. The top surface of the specimens was finished and covered with saturated burlap and plastic sheeting. During casting 4 × 8 in. concrete cylinders were fabricated to allow for the concrete strength to be tracked; 6 × 12 in. concrete cylinders were used to determine the strength on test day. After the concrete reached a strength of 3,000 psi, the formwork was removed and the concrete column was wrapped in saturated burlap and plastic sheeting for further curing. Once the desired strength was reached the burlap and plastic were removed. The No. 14 specimens will be cast simultaneously and in two separate placements. The first placement will fill the column up to the 9 ft mark along the height of the column. This allows for relief of hydrostatic pressure load on the formwork. The upper portion of the specimens will be cast in a second placement, after the lower portion has set. The columns will be cured in the same manner as the No. 11 specimens.

2.1.3: Material Properties

Non-air-entrained ready-mix concrete will be used for the initial specimens. The initial No. 11 bar specimens tested had nominal concrete compressive strengths of 15,000 psi and the No. 14 bar specimens will also be cast using concrete with a nominal strength of 15,000 psi. The concrete mixture proportions include a high-range water reducer and a viscosity modifier to ensure ease of placement and adequate strength. The water-to-cementitious ratio of the mix is 0.21. The concrete contains Type I/II portland cement and Type C fly ash. Crushed granite and Kansas River sand are used as aggregates. The mixture proportions for the concrete are shown in Table 2.

Table 2 - Concrete mixture proportions

Material	Quantity (SSD)
	15,000 psi
Type I/II Cement (lb/yd ³)	800
Water (lb/yd ³)	210
Fly Ash Type C (lb/yd ³)	200
Granite (lb/yd ³)	1430
Kansas River Sand (lb/yd ³)	1430
High Range Water Reducer, ADVA 575 (oz.) (US)	147
Viscosity Modifier (VMAR) (oz.)	20

The specimens were fabricated using ASTM A615 Gr. 60 No. 11, No. 4, or No. 3 reinforcing bars for longitudinal and transverse reinforcement. The No. 11 and No. 14 headed and hooked bars are fabricated from ASTM A1035 Grade 120 steel. The reinforcing test bar properties are shown in Table 3. The head on each headed bar has a net bearing area of at least $4A_b$, where A_b is the area of the bar (see Table 1).

Table 3 - Headed bar material properties

Bar Size	Head Designation	Yield Strength (ksi)	Nominal Diameter (in.)	Rib Spacing (in.)	Average Rib Height (in.)		Average Gap Width (in.)	Relative Rib Area
					ASTM	ACI		
11	O4.5	135	1.41	0.838	0.097	0.092	0.394	0.099
14	B4.9	127	1.69	1.005	0.079	0.069	0.279	0.062

2.2: Testing Apparatus

2.2.1: No. 14 and No. 18 Bar Specimen Reaction Frame

The reaction frame is a modified version of the system used by Shao et al. (2016), shown in Figures 13 and 14. The reaction frame is capable of applying loads up to 1620 kips and allows for a single row of two or three bars, as well as two rows of two or three bars, to be tested simultaneously. The frame can be modified based on the dimensional proportions of No. 11, No. 14, and No. 18 bar specimens. No. 18 bar specimens will be described in future reports.

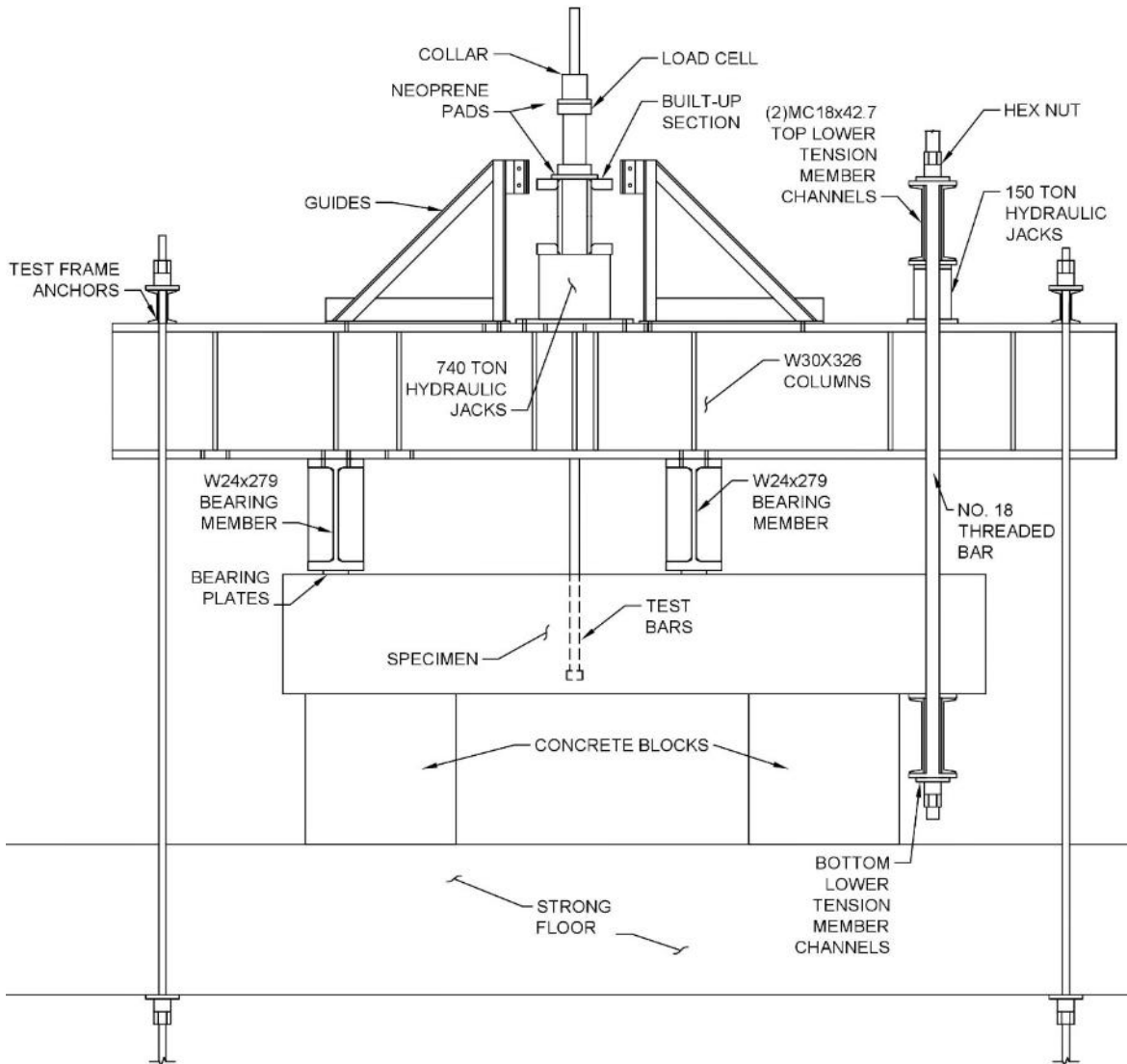


Figure 13 – Reaction frame, side elevation

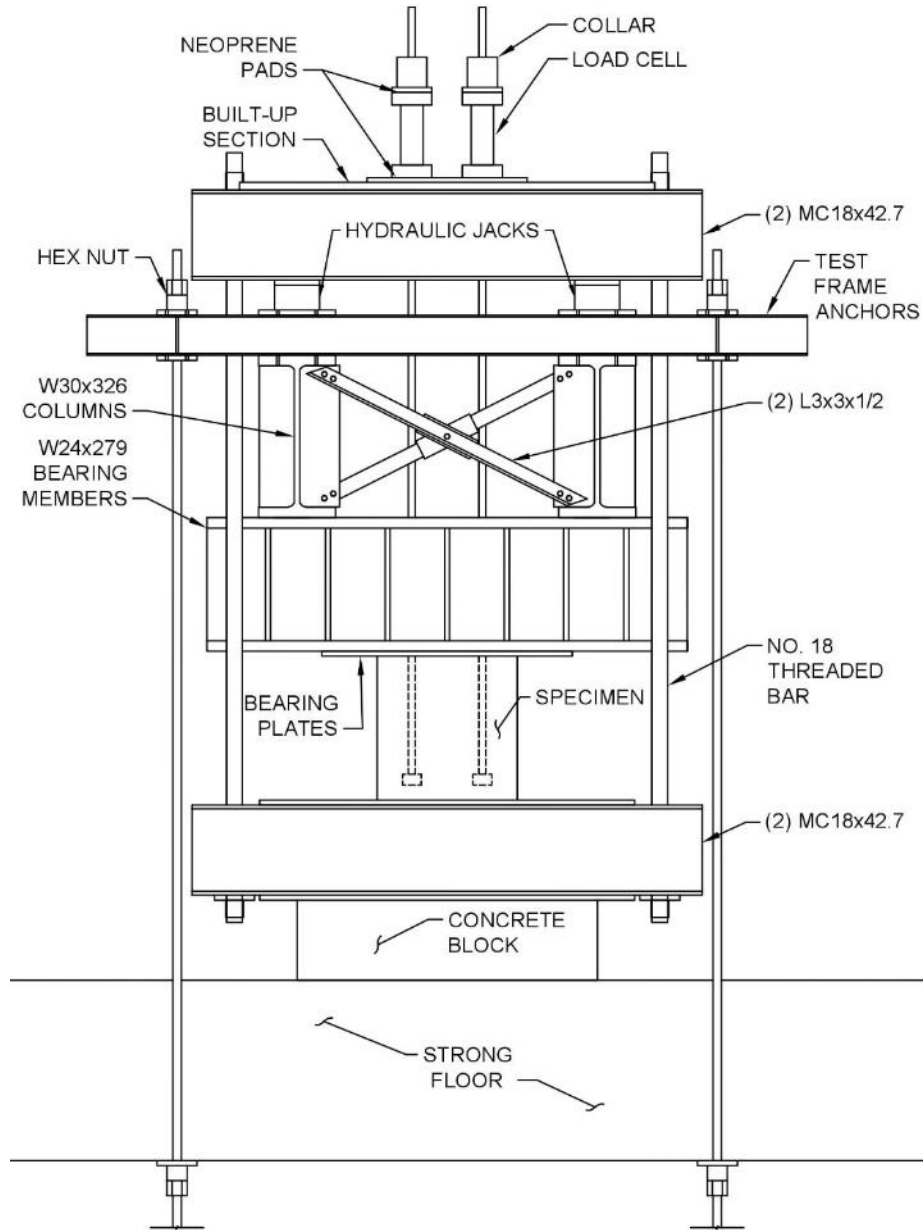


Figure 14 – Reaction frame, end elevation

The applied forces are shown in Figure 15. In this test configuration, the specimen is placed horizontally, with the test bars pointing upward, and lifted onto $3 \times 3 \times 5$ ft concrete blocks. The concrete blocks are placed so that a tail kick out can occur in hooked bar specimens. The two $W24 \times 279$ bearing members contact the specimen in accordance with the dimensional proportions

shown in Figure 8. The one bearing member represents the compression reaction in the virtual beam and remains at the same location for all testing configurations. The other bearing member changes in location as a function of the bar size is being tested to maintain dimensional proportions.

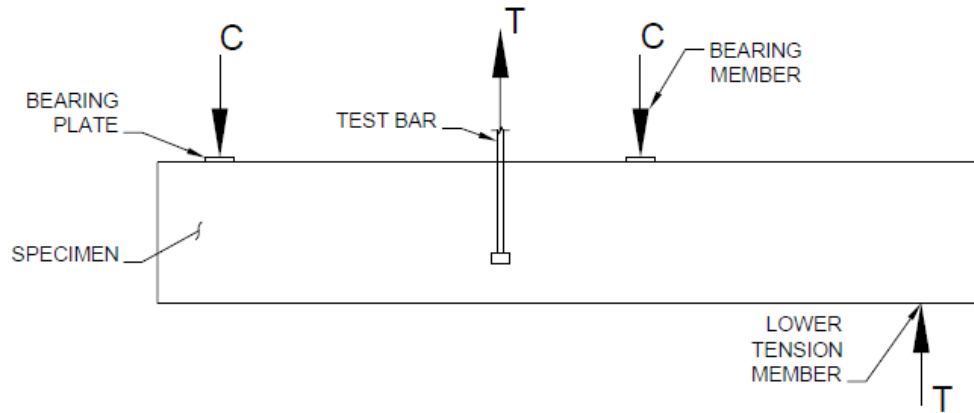


Figure 15 – Applied forces on the test specimen from the reaction frame

Forces are applied in the test by 740-ton hydraulic jacks located between a built-up section (Figure 16), which loads the test bars, and W30 × 326 members, referred to as “columns.” The columns have stiffeners welded to them at locations that are based on the testing configuration. The columns are bolted to the top of the bearing members, spaced at 60 in. on-center. The 60-in. spacing allows for all possible test bar spacings. Two sets of cross bracing, consisting of two L3 × 3 × 1/2 angles, are bolted to the stiffeners of the W30 × 326 columns at the same location as the bearing members. Hydraulic jacks are placed on each of the W30 × 326 columns, aligned with the test bars. The built-up section, which consists of 1 in. and 2.5 in. steel plates welded together, is placed on top of the hydraulic jacks and is shown in detail in Figures 16 and 17. The built-up section has a hollow mid-section and stiffeners spaced 6 in. on center that allows that test bars to pass through. The built-up section can be offset so that specimens with two and three test bars can be tested with 6, 12, or 18 in. spacing.

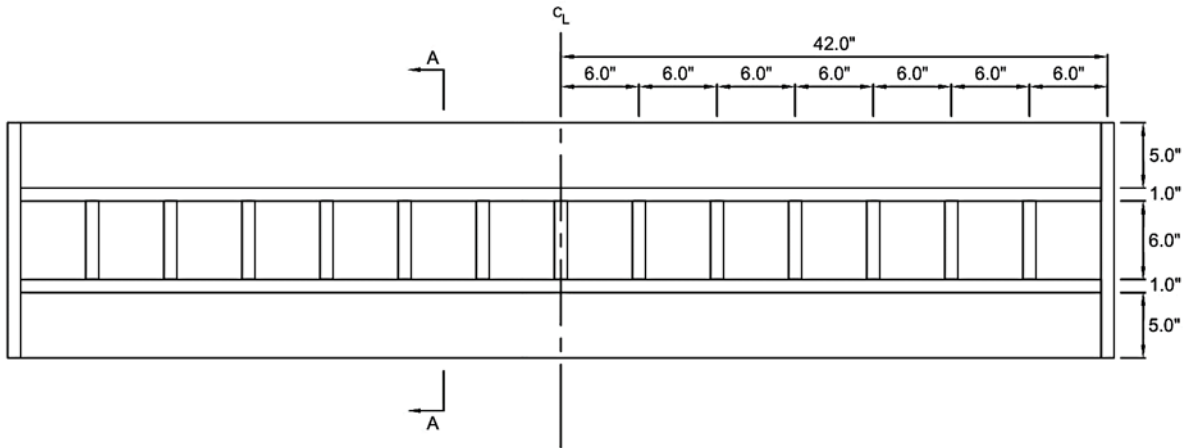


Figure 16 – Built-up section plan view

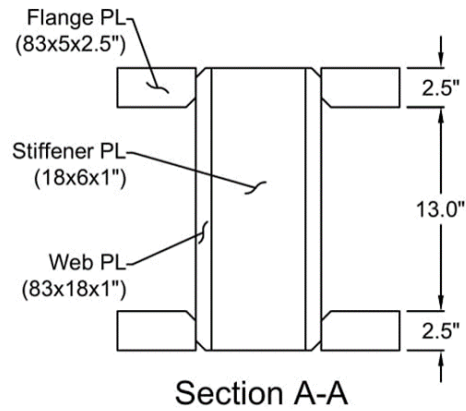


Figure 17 – Built-up section, A-A

Load cells are placed on the far side of the built-up section over each test bar to measure the applied force. Neoprene pads are placed above and below the load cells for level bearing. A steel washer plate, with holes drilled throughout for each testing configuration, is attached to the built-up section, as shown in Figure 18. This washer plate allows for a solid bearing between the built-up section and the load cells. The load cells are fixed against the test bars.

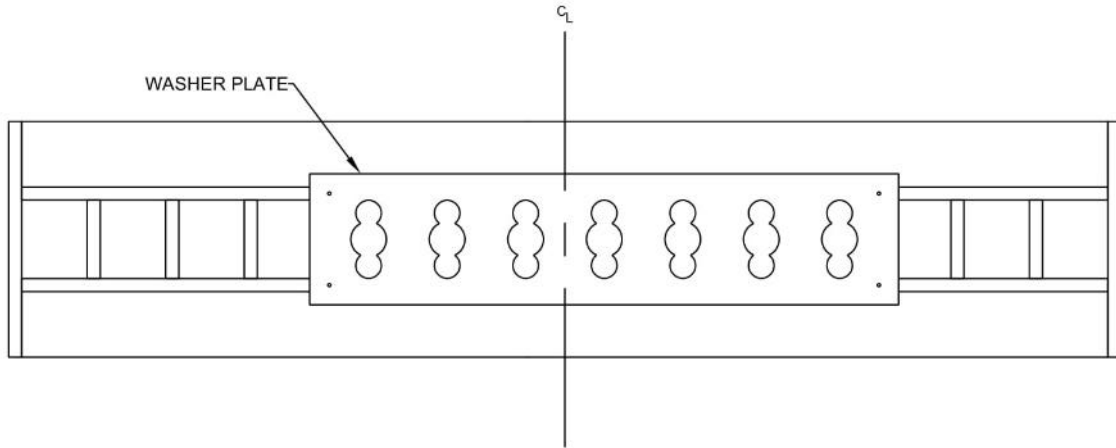


Figure 18 – Built-up section with washer plate attached

Hydraulic jacks with a capacity of 150 tons, approximately one-fifth of the size of the 740-ton jacks placed on the reaction frame, are bolted to each of the $W30 \times 326$ columns. The location of the smaller hydraulic jacks are a function the size of test bar due to dimensional differences. Two sets of two $MC18 \times 42.7$ channels, the smaller hydraulic jacks, and No. 18 threaded bar make up the lower tension member. One set of channels is placed on top of the smaller hydraulic jacks and the second set of channels is in contact with the back face of the specimen. The two sets of channels are connected together by two No. 18 threaded bars.

The reaction frame is tied into the strong floor using the test frame anchors. The guides are used to guide the built-up section during testing. The test frame anchors and guides do not apply any load to the specimen. Load is applied through an electric hydraulic pump.

2.2.2: Modified Reaction Frame for Initial Specimens

Specimens with No. 11 headed bars, were tested using a modified version of the reaction frame described above, as shown in Figures 19 and 20. These initial specimens did not have the same dimensional proportions as planned for the balance of the study. The built-up section was placed directly on the $W30 \times 326$ columns and hydraulic through jacks with a capacity of 150 tons

were placed on top of the built-up section with the test bars passing through each jack. The smaller jacks were used to load the test bars because the hydraulic pump for the larger hydraulic jacks had not been shipped to the lab at that time.

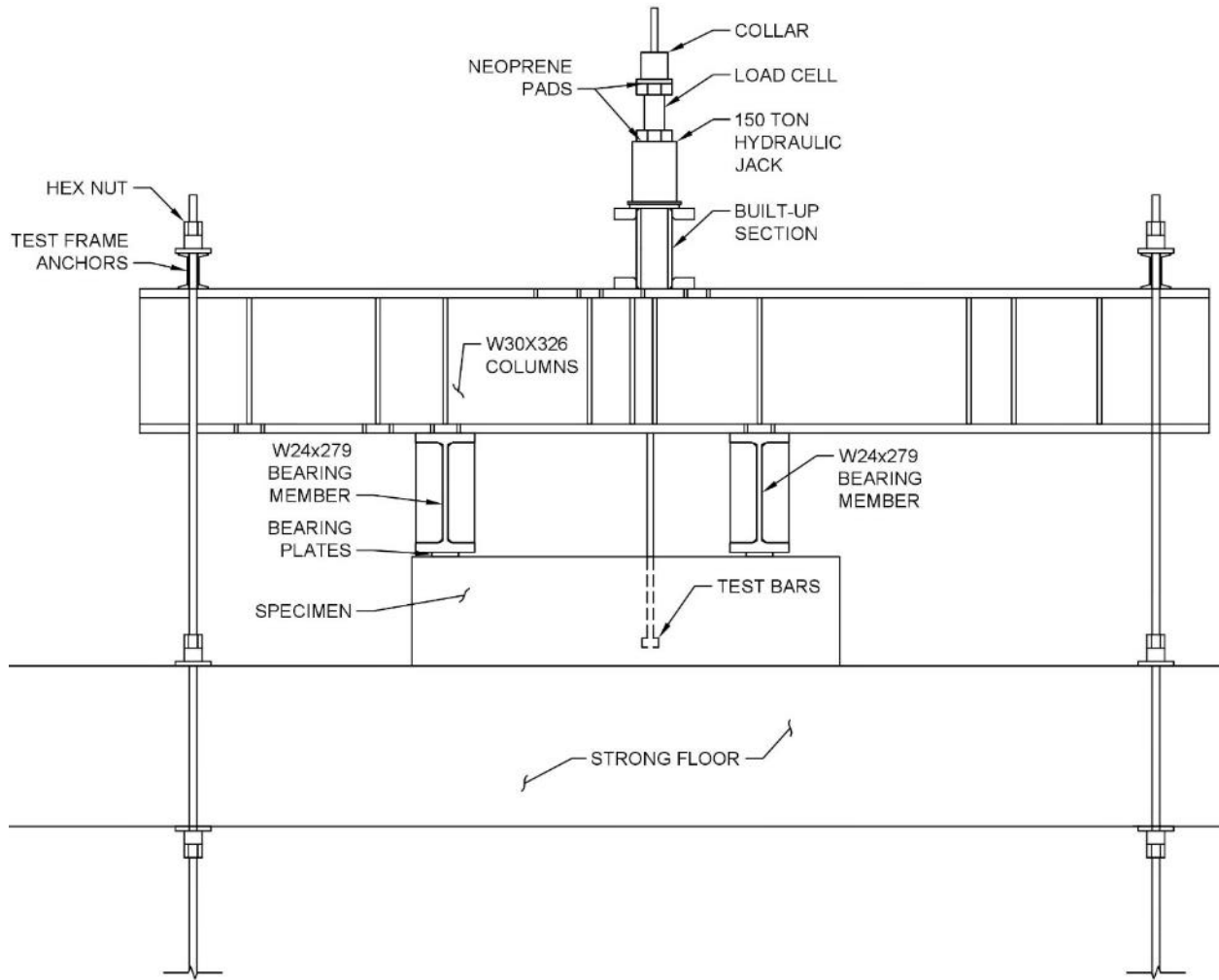


Figure 19 – Modified reaction frame for the initial specimens, side elevation

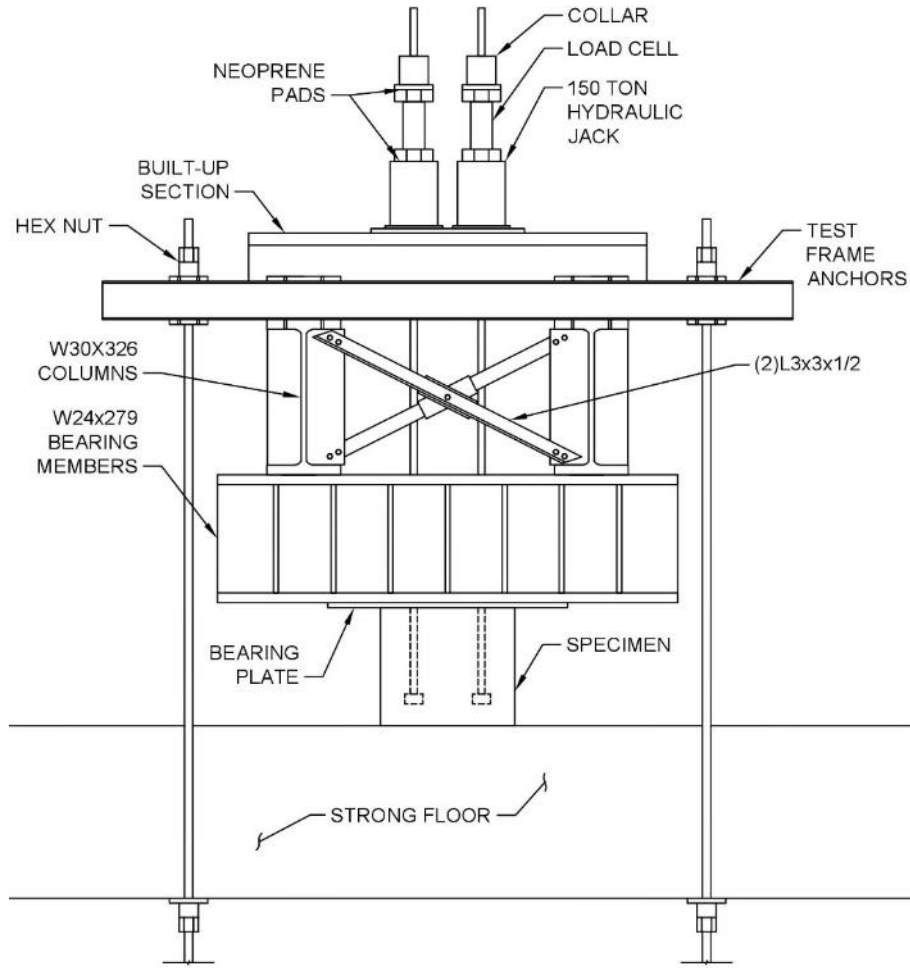


Figure 20 - Modified reaction frame for the initial specimens, end elevation

A modified washer plate, shown in Figure 21, was used for these initial specimens. This washer plate allowed for solid bearing between the built-up section and the hydraulic jacks. Load cells were placed on each test bar with neoprene above and below each load cell. The load cells are fixed against the test bars.

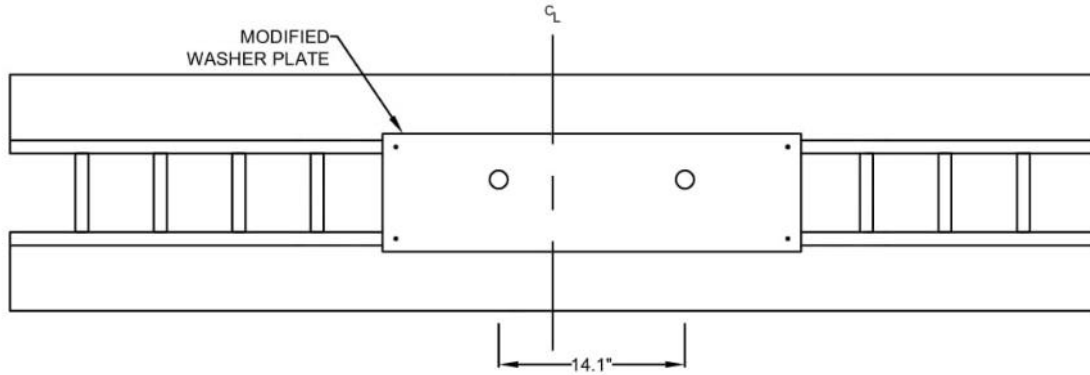


Figure 21 – Initial specimen modified washer plate

2.2.3: Bearing Plates

Steel plates, 1 in. thick by 48-in. long, are placed between the test specimen and each of the bearing members. To more accurately represent the dimension of the neutral axis c of the simulated concrete beam, compared to the flange of the bearing member, the width of the plate is based on c . Plates with 6, 9, and 12 in. widths are used, as shown in Table 4. The bearing plates are placed at predetermined locations using hydrostone between the specimen for leveling.

Table 4 - Bearing plate size table

Calculated Neutral Axis Depth, c (in.)	Bearing Plate Size (in.)
$c \leq 6$	6
$6 < c \leq 9$	9
$9 < c \leq 12$	12

2.2.4 External Slip Measurement

The slip of each test bar is measured using a linear variable differential transformer (LVDT). The LVDTs are attached to 2×4 lumber and wedged into placed between the flanges of the lower bearing member, as shown in Figures 22 and 23. The 2×4 is then clamped to a stiffener on the lower bearing member to secure it. A hollow square steel section (HSS) with a ring and bolts on one end is attached to each test bar and tightened in place. At the opposite end of the ring;

a flat 1/8 in. thick steel plate is attached to the HSS using a bolt. This plate gives the LVDT a larger bearing area to react against during testing.



Figure 22 - LVDT clamped to the lower bearing member



Figure 23 - LVDT HSS attachment to the test bar

2.2.5 Load Cells

Four load cells were fabricated for the No. 11 bars, four load cells were fabricated for the No. 14 and No. 18 single row tests, and four load cells were fabricated for the No. 14 and No. 18 two row tests. The No. 14 and No. 18 load cells will be used in future tests. Each load cell consists of a steel pipe with a thickness that depends on the anticipated maximum load. The steel pipe is connected to a plate on the top and bottom through a spring and eye bolt at the corner of each plate. The pipes for the No. 14 and No. 18 bars load cells underwent a heating and quenching process to increase the yield and tensile strength of the steel. The steel plates for the No. 14 and No. 18 bar load cells are dimensioned so that test bars can be spaced at 6 in. on center and not interfere with one another. Each No. 11 bar load cell has four 120-ohm strain gauges mounted in a full bridge to the steel pipe at mid-height, while the No. 14 and No. 18 bar load cells have four 350-ohm strain gauges mounted in a full bridge to the steel pipe at mid-height. Two strain gauges are oriented parallel to the loading direction while the other two are oriented in the transverse direction. The parallel and transverse strain gauges are alternated around the circumference of the pipe at 90-degree intervals. The strain gauges are then wired into a data acquisition system (DAQ) as a full Wheatstone bridge. The load cells are calibrated in a hydraulic loading frame while wired into the DAQ. The load cells are shown in Figures 24 through 26.



Figure 24 - No. 14 and No. 18 bar single-row load cell



Figure 25 - No. 14 and No. 18 bar two-row load cell



Figure 26 - Initial No. 11 bar load cell

2.3: Testing Procedure

2.3.1: No. 14 and No. 18 Bar Specimen Test Procedure

- 1) The reaction frame is assembled in a staging area, separate from the specimen staging area, where the anchor rods can pass through the strong floor, shown in Figure 27.



Figure 27 - Reaction frame staging area

- 2) The reaction frame is checked so that each component is in the proper location or the location of items that will be installed individually (described in following steps) is known before testing, dependent on what size bar is being tested. This includes the bearing members, guides, and the lower tension member.
- 3) The strong floor is marked to show where the concrete blocks will be placed relative to the holes in the strong floor. For hooked bars, the concrete block should not block the hook extension on the back face of the column in case a tail kickout failure occurs.

- 4) The concrete specimen is laid horizontally, lifted onto the concrete blocks, and aligned so that the reaction frame can be placed onto the specimen.
- 5) The bearing plates, described in Table 4, are placed on the specimen at the locations of the upper and lower bearing members, with hydrostone between the specimen and the plate, to ensure they are level on the specimen.
- 6) The LVDT bearing plate attachments are placed on each test bar.
- 7) All bolts on the reaction frame are tightened.
- 8) The reaction frame, consisting of the upper and lower bearing members, W30 × 326 columns, cross bracing, anchors, hydraulic jack base plates, and guides, is lifted onto the specimen so that the upper and lower bearing members bare on the bearing plates.
- 9) The anchor rods are guided through a washer and into the holes in the strong floor. A washer and nut are used above and below the strong floor to lock the bars in place, securing the reaction frame.
- 10) The nuts that attach the anchors to the reaction frame are then loosened to ensure no load is applied.
- 11) The 740-ton hydraulic jacks are then lifted and placed on hydraulic jack base plates, assuring the ports for the hydraulic lines are in the proper position for testing.
- 12) The 150-ton jacks are lifted and set at the predetermined location of the lower tension member and bolted into place.
- 13) The built-up section is then lifted onto the 740-ton hydraulic jacks with the test bars passing through the designated holes.
- 14) The No. 14 and No. 18 bar washer plate is placed on the built-up section to allow for bearing of the load cells.

- 15) A neoprene pad is placed on the washer plate, over the test bars.
- 16) The load cells are lifted onto each of the test bars. A neoprene pad, along with a ½-in. steel plate with a center hole, are placed on top of each of the load cells.
- 17) A collar and wedges are used to fix each test bar to the load.
- 18) The pair of top lower tension member channels, with No. 18 threaded bars passing through, is lifted onto the 150-ton hydraulic jacks.
- 19) The pair of bottom lower tension member channels is lifted so that the No. 18 threaded bars pass through the designated location, until the top of the steel beam is touching the back face of the concrete specimen.
- 20) A nut is then screwed onto the No. 18 threaded bar to lock the bottom lower tension member channels in place.
- 21) The LVDTs are clamped to the lower bearing member.
- 22) The LVDT extension devices, coming off of the test bars, are placed so that they are applying pressure on the LVDTs and tightened to the test bar.
- 23) All measurement devices including the load cells, LVDTs, and all strain gauges are wired into the DAQ.
- 24) Measurements of embedment length of each test bar, distances from the test bars to the upper and lower bearing member, and center-to-center bar spacing are recorded.
- 25) Load is applied to the test bars at predetermined intervals of force using an electric pump. Cracks are marked and pictures are taken after each interval.
- 26) Once the specimen has reached 80% of the expected failure load, it is loaded continuously to failure.

- 27) After failure, the failure type and maximum load are recorded and photos of the specimen are taken.
- 28) The load frame is then disassembled in the reverse order that it is assembled. More photos of the specimen are taken for further examination.
- 29) The specimen is then dissected for further examination.

2.3.2: No. 11 Bar Specimen Modified Procedure

- 1) Steps 1 through 9 remain the same as for testing No. 14 and No. 18 bar specimens, except the specimen is not lifted onto concrete blocks but is laid on the strong floor. The placement of the bearing plates and the reaction frame lifted onto the specimen are shown in Figures 28 and 29, respectively.



Figure 28 - Bearing plates placed on the specimen with hydrostone



Figure 29 - Reaction frame lifted onto the specimen

- 2) The built-up section is then lifted onto the $W30 \times 326$ columns with the test bars passing through its through holes.
- 3) A washer plate is screwed onto the built-up section to allow for bearing of the hydraulic jacks, shown in Figure 30.



Figure 30 - Washer plate attached to the built-up section

- 4) Two 150-ton hydraulic through jacks are lifted onto the test bars, and hydraulic hoses connecting to the manual pump station are attached.
- 5) A steel plate, with a center hole, is placed onto the test bars and placed to bear on the hydraulic jacks.
- 6) A neoprene pad, with a center hole, is then placed on the steel plate with the test bar passing through
- 7) The load cells are then lifted onto the test bar and set on the neoprene pad.
- 8) Another neoprene pad, with a center hole, is placed on top of the load cells.
- 9) A collar and wedges are used to fix each test bar to the load. Completed steps 3-9 are shown in Figure 31.



Figure 31 - Hydraulic jack, load cells, and grips on the test bars

10) Steps 18-20 are not used for the No. 11 bar specimens. A completed set up of the modified reaction frame is shown in Figures 32 and 33.

11) Steps 21 through 29 are the same as for the No. 14 and No. 18 bar test specimens, except that load is applied with a manual pump and not an electric pump.



Figure 32 - Reaction frame completed set up top view



Figure 33 - Reaction frame completed set up side view

CHAPTER 3: INITIAL TESTS

3.1: Test Results and Analysis

Results for the initial No. 11 specimens in this study are described in this chapter. Each specimen contained two No. 11 headed bars. Bar properties are shown in Table 3 in Section 2.1.3 and the reinforcement layouts are shown in Figure 6 and 7 in Section 2.1.2. The test results for these specimens are shown in Table 5.

Table 5 - Test results of initial No. 11 beam-column joint tests

Specimens	l_{ch} (in.)	f_{cm} (psi)	$\frac{A_{brg}}{A_b}$	T (kips)	T_h (kips)	$\frac{T}{T_h}$
(2@10)11-15-O4.5-i- 3.5-3.5-18.25	18.5	16,210	4.5	163.0	182.5	0.89
	18.5	16,210	4.5	163.0	182.5	0.89
(2@10)11-15-O4.5-7#3-i- 3.5-3.5-18.25	18.5	15,850	4.5	221.0	210.6	1.05
	18.5	15,850	4.5	221.0	210.6	1.05

Two specimens were tested, one with confining reinforcement within the joint region and one without, with a nominal concrete strength 15,000 psi. Table 5 compares the strengths measured in the tests, identified as T , the average test bar force, with strengths calculated using the descriptive equations for anchorage strength of headed bars presented by Shao et al. (2016), identified as T_h . The anchorage strength of the headed bars increased with the presence of confining reinforcement within the joint region. The test-calculated ratio T/T_h was 0.89 for specimen (2@10)11-15-O4.5-i-3.5-3.5-18.25 without confining reinforcement and 1.05 for specimen (2@10)11-15-O4.5-7#3-i- 3.5-3.5-18.25 with confining reinforcement. Both ratios are within the expected range based on the coefficients of variation of the descriptive equations of approximately 12%.

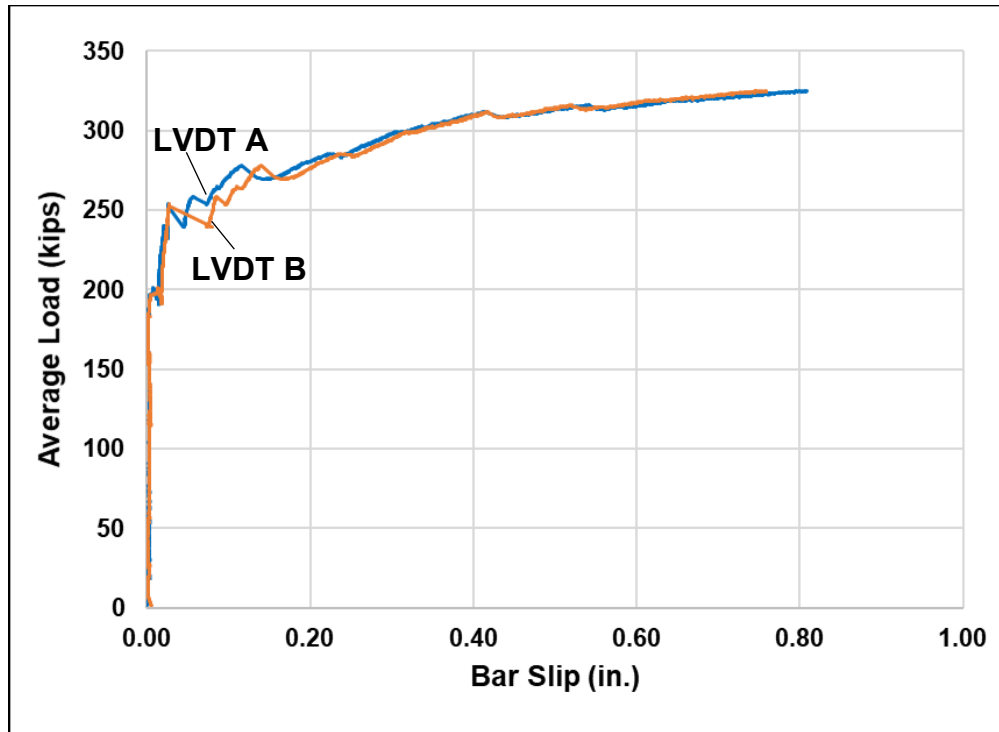


Figure 34 - Load vs. bar slip of specimen (2@10)11-15-O4.5-i-3.5-3.5-18.25

The average load in a single test bar vs. bar slip is shown in Figure 34. The bar exhibits no significant slip until roughly 200 kips. From there, slip increases rapidly as the load increases to a maximum slip of 0.81 in. at failure.

The load vs. strain plots for specimens (2@10)11-15-O4.5--i-3.5-3.5-18.25 and (2@10)11-15-O4.5-7#3 -i-3.5-3.5-18.25 are shown in Figures 35 and 36, respectively. Figure 35 shows the load vs. strain on the test bar, and Figure 36 shows the strain in the confining reinforcement within the joint region. The strain gauges are identified in Figures 6 and 7. As expected, the strain in gauge B1, just inside the front face of the column, had a higher strain than gauge H1, mounted 1 in. away from the obstruction on the bar – the difference due to the force transferred by bond along the length of the bar. For a total load greater than about 150 kips, however, the strain in gauge B1 became erratic and eventually dropped below the strain in gauge H1, suggesting that the gauge was no longer functioning. As observed by Shao et al. (2016), the strain developed in the ties is a

function of their location; confining reinforcement closest to the test bars starts to exhibit strain at early loads and continues to develop strain with increasing load, while reinforcement farthest away from the bars exhibits minimal strain.

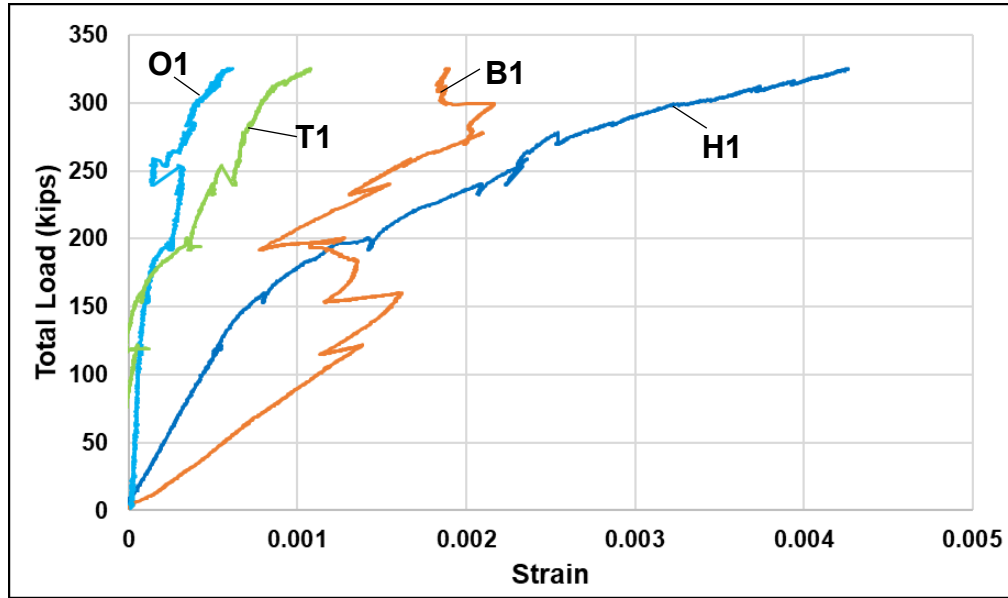


Figure 35 - Total load vs. strain in test bar on specimen (2@10)11-15-O4.5-i-3.5-3.5-18.25

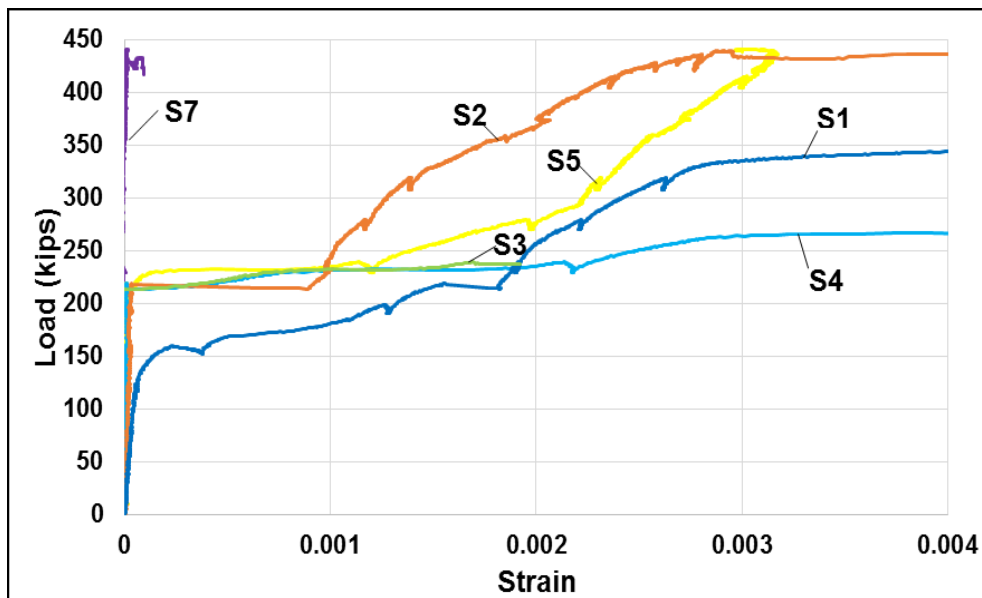


Figure 36 - Total load vs. strain in confining reinforcement on specimen (2@10)11-15-O4.5-7#3-i-3.5-3.5-18.25

3.2: Cracking Behavior and Failure Modes

The first cracks observed in both specimens were due to bar slip on the front face of the column, starting at the headed bar and then propagating towards the sides of the column as shown in Figure 37.

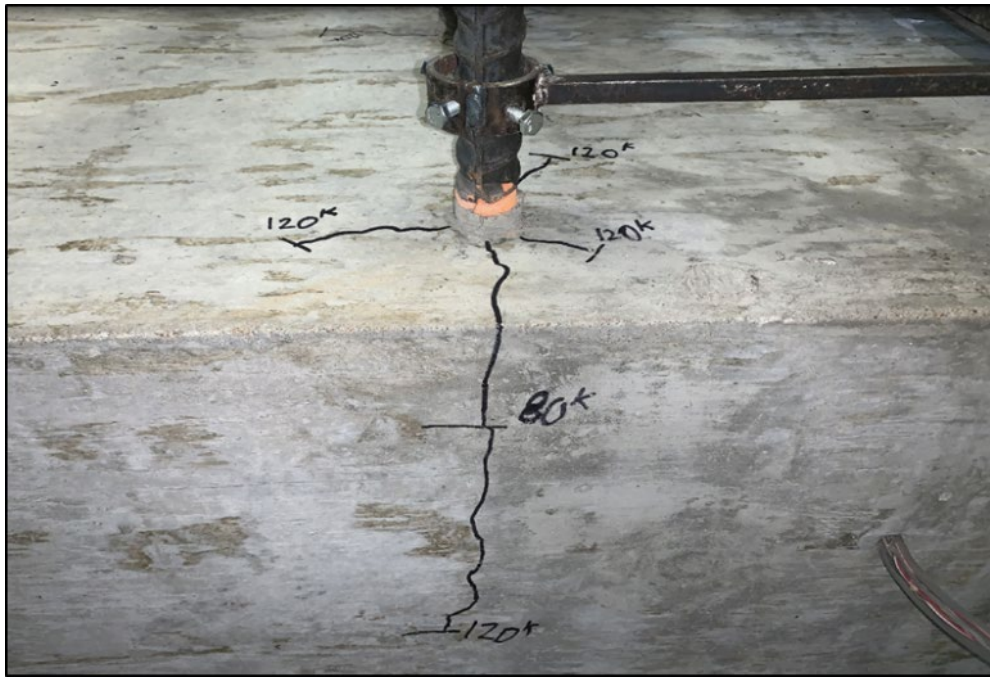


Figure 37 - Bar slip cracking

At higher loads the cracks began to propagate toward the upper and lower bearing members. The cracks below the headed bars grew through the joint, growing toward the lower bearing member, while the cracks above the headed bars grew toward the upper bearing member but never reached it. These patterns are shown in Figure 38. Both specimens exhibited a front breakout failure, as shown in Figure 39 for specimen (2@10)11-15-O4.5-i-3.5-3.5-18.25. Both specimens exhibited a sudden failure.

CHAPTER 4: SUMMARY

The reaction frame to be used to test No. 14 and No. 18 bar beam-column joint specimens, the modified reaction frame used to test No. 11 beam-column joint specimens, and the design of these beam-column joint specimens are described. Nominal concrete strengths of 5,000 psi to 15,000 psi will be used with bar sizes of No. 11, No. 14, and No. 18 with bar stresses at anchorage failure in excess of 100 ksi in future work.

The testing apparatus has been designed, test procedures have been established, and initial specimens have been tested. The initial test results show that the descriptive equation used to calculate the anchorage strength of headed bars presented by Shao et al. (2016) is accurate for No. 11 bars.

Testing will continue using the apparatus and procedures described in this report, and the results will be added to the database developed at The University of Kansas to better understand how large high-strength headed and hooked bars behave in beam-column joints.

Notation:

A_b	Nominal area of a bar
A_{th}	Total cross-sectional area of confining reinforcement within the joint region within $10d_b$ below the center of the hooked test bar
A_{brg}	Net bearing area of the headed deformed bar
A_{tt}	Total cross-sectional area of confining reinforcement within the joint region within $10d_b$ below the center of the headed test bar
b	Width of column
c	Effective depth of neutral axis from the extreme compression fiber
c_{bc}	Clear cover measured from the back of the head to the back of the member
c_{ch}	Center-to-center spacing between hooked bars
c_{so}	Clear cover measured from the side of the headed bar to the side of the member
d_b	Nominal diameter of a bar
f'_c	Specified concrete compressive strength
f_{cm}	Measured concrete compressive strength at time of test
f_y	Specified yield strength of a headed or hooked bar
h	Depth of column
h_o	Total height of a beam-column joint specimen
h_{cl}	Height measured from the center of the test bar to the top of the lower bearing member
ℓ_{eh}	Embedment length measured from the bearing face of the head to the front face of the specimen for headed bars and embedment length of a standard hook measured from the outside of the hook to the front face of the specimen for hooked bars
n	Number of bars being tested simultaneously
T	Average load on a headed bar at failure
T_h	Calculated force in a headed or hooked bar per the corresponding descriptive equation
s	Center-to-center spacing between headed test bars
x_{bot}	Height measured from the center of the test bar to the center of the lower tension member
x_{mid}	Height measured from the center of the test bar to the center of the lower bearing member
x_{top}	Height measured from the center of the test bar to the center of the upper bearing member

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