Load Distribution and Load-Deflection Behavior of Hooked Reinforcing Bars Loaded in Tension

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Abstract

The purpose of this capstone design project report is to discuss the behavior of a hooked bar in concrete carrying a tension force. The cover and bonded length are varied to observe the effect on the load distribution between the hook portion and the bonded length portion of a hooked bar. Each specimen had 1 or 2 inches of cover. Each specimen had a bonded length of 8, 12, or 16 inches. Straight rebar was also tested to provide a control and comparison to the hooked bars with similar cover and bond length variables.

All hooked specimens experienced a steel failure. The straight bar specimens with 8 inch bond length and the straight bar specimen with 12 inch bond length and 1 inch cover experienced a concrete failure in splitting. The straight bar specimen with 12 inch bond length and 2 inch cover and the straight bar specimens with 16 inch bond length experienced a steel failure.

The addition of the hook adds enough strength to prevent concrete failure when compared to the straight rebar with similar bond length and cover. With bond lengths less than 12 inches and minimal cover, the addition of the hook adds enough strength for the steel to reach yield. The hooked bar stiffness was larger than the straight bar stiffness in every specimen except for the straight bar specimen with 16 inches of bonded length and 2 inches of cover.

An interesting trend is the effect of bonded length and cover on load distribution between hook and bond. As the bond length increased, the bond took a greater portion of the load. At shorter bond lengths, the hook takes the greatest portion of the load. An increase in cover increased the load carried by the bond in all cases. This effect was greater at shorter bond lengths since the hook carries the greater portion of the load.

It is suggested in further work to continue to include a load cell, slip measurement, and strain gauges to allow for comparison of maximum loading, load distribution, and stiffness. The method for measuring lead and end slip might be improved. The lead slip in this capstone report was erratic or failed to record due to the LVDT slipping off the angle. The bulk of research conducted on hooks concentrates on a pullout failure. Further research and data will be required to make any statements regarding splitting-controlled hook configurations. The data obtained in this capstone report are not sufficient to create a model that can be applied to the code.

Acknowledgments

I would like to thank my advisor, Dr. DeVries, and my committee, Professor Raebel and Dr. Stahl, for assisting this research through continued guidance and support. I would also like to thank Matt Lepper for spending his valuable time helping during concrete-pour day.

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Hooked Rebar – A steel reinforcing bar with a 90 hook at the end of the bond length.

Straight Rebar – A steel reinforcing bar without any bends.

Bond – The chemical and mechanical connection created between concrete and steel rebar.

Bonded Length – The length of rebar exposed to concrete and allowed to bond resisting load primarily through concrete bearing on the rebar's ribs.

Development Length – The bonded length required for the rebar to reach yield.

Slip – The relative displacement between concrete and reinforcement.

Lead Slip – The slip measured at the specimen face on the loaded end of the bonded length.

End Slip – The slip measured at the specimen face on the non-loaded end of the bonded length.

Splitting Failure – A concrete failure mode where the concrete cover cracks along the bonded length.

Chapter 1 – Introduction

1.1 Background

An important concept in reinforced concrete design is the development length of rebar. The ribs in the rebar work to transfer forces between the concrete and the steel. The development length is the length required for the forces to effectively transfer. It is not possible to achieve the required lengths in every situation—for example, in a beam-end joint. A hooked or bent rebar is utilized in this instance. The rebar ribs bear on the concrete creating the greatest portion of the bond. It also mechanically bonds by friction through the surfaces on the rebar. Lastly, it creates a weak chemical connection similar to adhesive connecting the rebar and concrete. The chemical bond fails during initial slip.

The behavior of straight rebar development length has been researched extensively. The behavior of hooked bars, especially the load distribution between bond length and hook, has had less consideration. The load distribution from the concrete to rebar has been developed through research. Originally, it was believed that the force transferred into the bar ran parallel as seen in Figure 1. Tests utilizing smaller concrete cover proved this theory to be incorrect. These tests displayed a splitting failure in the concrete cover which means some force runs perpendicular to the bar. The current representation of force transfer is seen in Figure 2 with forces applied at a 45° angle.

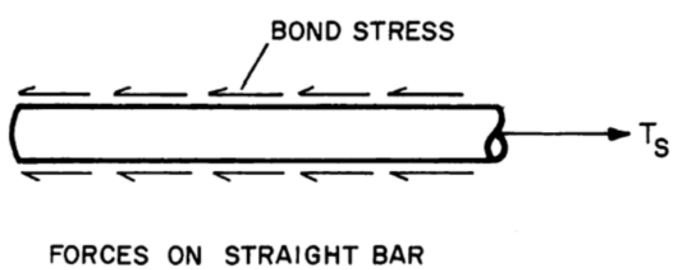


Figure 1 - Probable Forces on Straight Bar [1].

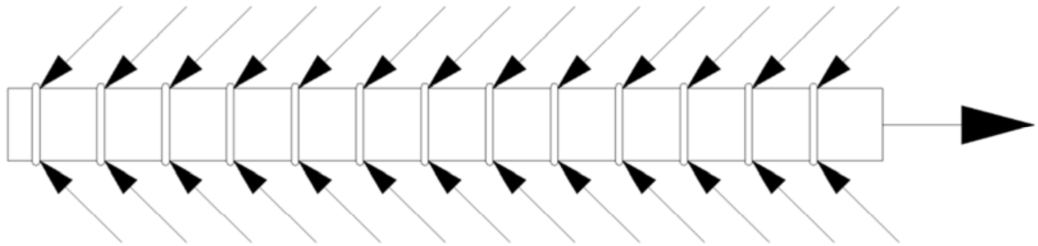


Figure 2 - Current Bar Force Representation.

The hooked bar has undergone a similar understanding. It was believed that the load flowed parallel to the bar all the way through to the hook tail as seen in Figure 3. The belief was that the bar acted like a string in a tube. As the load is applied, the bar straightens out as it is pulled through the concrete. However, both the notions regarding the angle of force and complete straightening of the rebar are incorrect. The current representation applies the force along the straight portion of the bar at a 45° angle and a larger force application at the hooked bend seen in Figure 4.

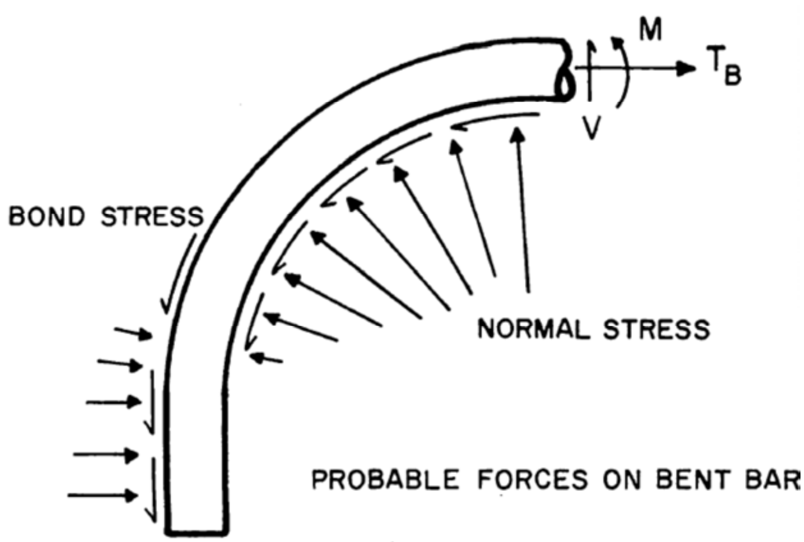


Figure 3 - Probable Forces on Hooked Bar [1].

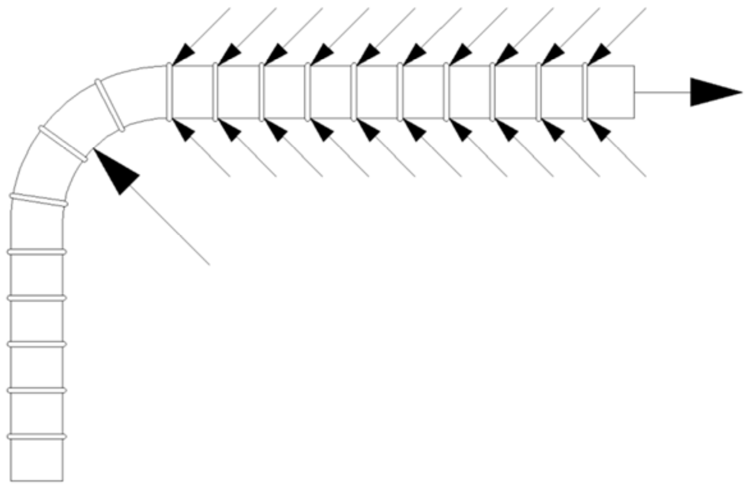


Figure 4 - Current Hooked Bar Force Representation.

The bulk of hooked bar research has focused on hooked bars in mass concrete creating a pullout failure. This research developed the early behavior models. More recent research has observed the splitting failure and created the current behavior model.

1.2 Objective

This testing is part of a larger continuing test program. It is a continuation of research conducted by Delany [2], and it was performed in tandem with Blau [3]. The testing for this capstone report used twelve concrete specimens created simultaneously with Blau's twelve specimens totaling twenty-four specimens created on the concrete-pour day.

The primary objective of this testing is to observe the behavior of hooked bars in concrete by measuring strain, displacement, and load and comparing these measurements to results from tests on straight rebar. Secondly, this testing is to expand Delany's testing by including strain measurements along the bonded length. Delany observed the behavior of straight rebar by varying the bond length and cover which is further discussed in Section 1.3.1. Finally, a literature review was conducted to gather results and pertinent information from other research to compare results.

The capstone report seeks to answer how the hook behaves and carries the force under varying conditions. By varying the cover and the bond length, we can observe the change in load distribution between the hook and bond length. The forces in a member distribute based off of the stiffness of the components in the member. By obtaining the different stiffness values, the load distribution can theoretically be predicted and compared to the load distribution values obtained from the strain gauges.

Chapter 2 - Literature Review

A hooked specimen displays the properties seen in a straight bond specimen and in a hooked specimen. Literature featuring research in both bond length and hook development was reviewed to provide further comparable tests in both the area of bond length and hook strength.

2.1 Delany, 2009

Delany examined the load-deflection behavior of straight rebar [2]. The testing setup used by Delany is the same testing setup used for testing the hooked and straight specimens for this report. This allows a direct comparison between the straight bars tested by Delany and the straight bars tested for this report.

Delany examined 12 beam end specimens measuring 12”x24”x36” with a #8 bar loaded in tension. Delany’s concrete achieved a strength of 4690 psi at 28 days. The clear cover was 1 or 2 inches and the bonded length was 8, 12, or 16 inches. The bond lengths were controlled by using PVC pipe embedded in the concrete. Additional reinforcement included #3 vertical bars resisting shear cracking and #6 longitudinal bars to ease specimen transportation. The free body diagram for Delany’s testing is shown in Figure 5.

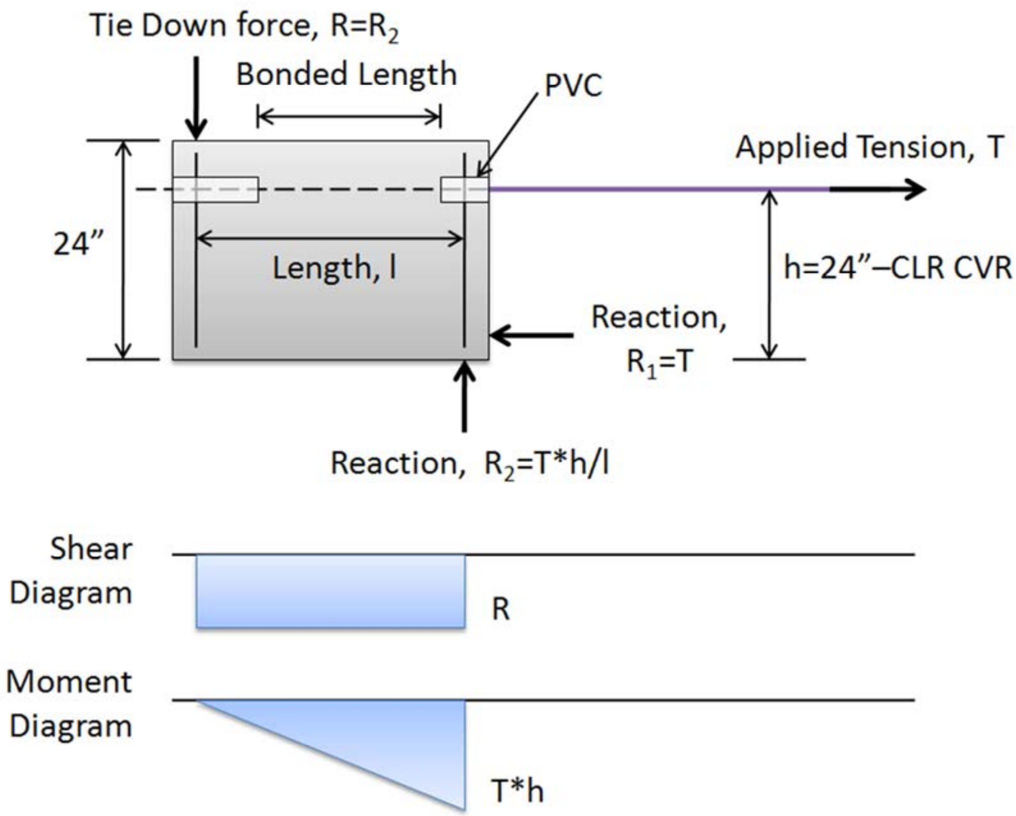


Figure 5 - Free Body Diagram of Experiment Setup with Shear and Moment Diagrams [2].

Load and displacement were recorded during the experiment. Displacement was measured at the end and lead portions of the bond length. Two types of loading methods were employed: repetitive and monotonic. It was hypothesized that the different methods of loading would affect the stiffness results and repetitive loading would lower the specimen stiffness.

This initial hypothesis was incorrect and the stiffness increased instead. It was believed to be due to the specimen settling throughout the repetitive loading process. Most of Delany's specimens experienced a splitting failure to varying extents. The 2-inch cover specimens exhibited little to no concrete cracking. Table 1 lists the stiffness of each specimen. The stiffness of the 1-inch cover specimens was compared to the stiffness of the 2-inch cover specimens. The ratio α was obtained from this comparison and can be seen in Table 2.

Table 1 - Stiffness for Specimens Loaded in Repetitive or Monotonic Loading [2].

	Bonded Length (in.)	Loading	K1 (kips/inch)	Kavg. (kips/inch)
1 db Cover	16	M	376.5	382.4
		R	388.2	
	12	M	285.6	274.4
		R	263.1	
	8	M	162.8	138.1
		R	113.3	
2 db Cover	16	M	600.0	554.0
		R	507.9	
	12	M	349.0	408.7
		R	468.3	
	8	M	407.8	362.1
		R	316.4	

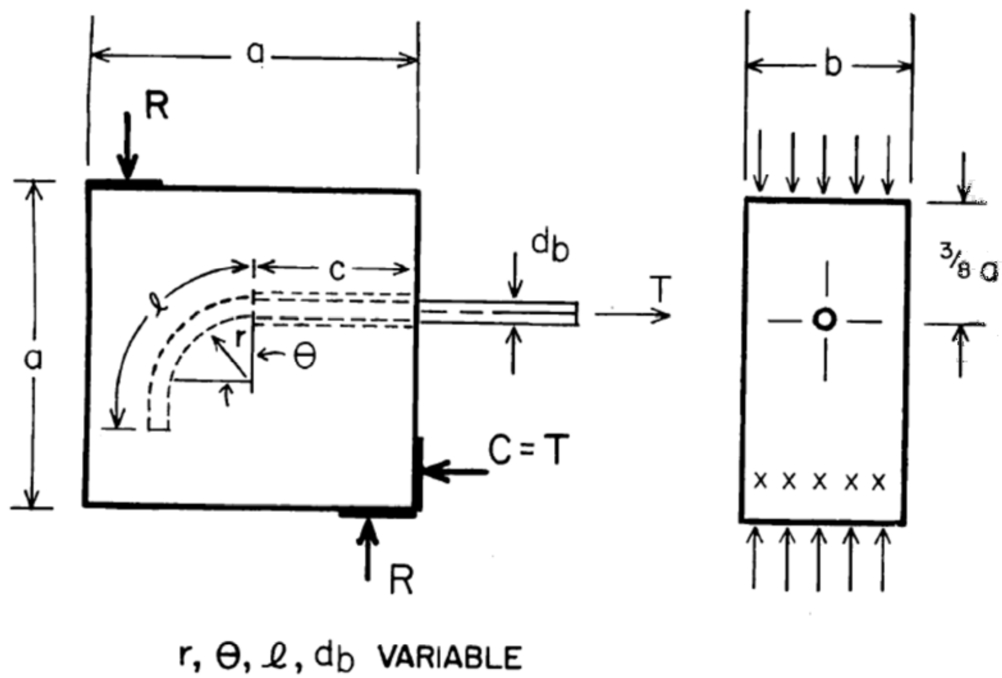
Table 2 - Stiffness Ratio - 2" Cover / 1" Cover [2].

Bonded Length	Stiffness Ratio, α
16"	1.45
12"	1.49
8"	2.62

Delany recommended that repetitive loading be increased from 75% monotonic load closer to 100% monotonic load which might cause a decrease in stiffness and confirm the original hypothesis. Full hysteresis loading loops is also recommended for better real world applicability [2]. One area of uncertainty is the difference between lead and end slips and bar elongation between the slip spots. The recorded lead slip data contained more scatter than the end slip in Delany's experiment.

2.2 Jirsa and Minor, April 1975

Jirsa and Minor's research article, published in April 1975, examines the pullout of bent bars [1]. The specimen configuration seen in Figure 6 included 0°, 45°, 90°, 135°, and 180° bends containing a total of 37 different bar configurations. Deformed, Grade 60 #5, #7, and #9 rebar were used in this test program. These sizes were chosen to best represent typical rebar configuration and still be small enough for testing convenience.



BAR SIZE	DIMENSIONS a	b	c
5	12 in.	8 in.	6 in.
7	16 in.	8 in.	8 in.
9	16 in.	12 in.	7.5 in.

NOTE 1 in. = 2.54 cm.

Figure 6 - Test Specimen [1].

The concrete compressive strength also varied throughout the tests. In comparing the tests, the difference in compressive strength required normalization. Table 3 shows the specimens, compressive strength, and test results. The tests had three failure types: fracture of concrete (F), bar pullout (P), and test termination due to the steel being stressed into the plastic range (T).

Table 3 - Test Specimen and Results [1].

Specimen*	f_c, ksi		Type failure†		Bar stress at failure, ksi		Slip, in. × 10^2 at 60 ksi lead stress		Stress, ksi at 0.01 in. lead slip	
1 2 3 4	A	B	A	B	A	B	A	B	A	B
5-6.0-180-1.5	4.1	4.1	F	F	67	73	6.8	7.3	12	12
5-6.0-135-1.5	4.1	4.1	T	T	—	—	4.3	4.3	20	17
5-6.0-90-1.5	5.1	2.4	F	T	93	—	3.7	—	20	17
5-6.0-90-1.5	5.5	4.3	T	F	—	95	3.2	5.3	20	11
5-6.0-90-1.5	4.6	4.6	T	T	—	—	4.7	3.4	15	33
5-6.0-45-1.5	4.4	4.4	T	T	—	—	3.8	3.6	24	19
5-6.0-0-5	4.1	4.1	T	T	—	—	2.8	2.8	36	36
5-4.5-180-1.0	4.4	4.0	F	F	65	53	8.5	—	18	16
5-4.5-135-1.5	4.8	4.8	F	P	75	73	6.0	6.7	15	15
5-4.5-90-2.5	4.1	4.1	P	P	57	65	—	5.7	14	25
5-4.5-90-2.0	4.2	4.2	P	P	70	58	6.5	—	12	13
5-4.5-90-1.5	5.4	5.4	T	T	—	—	5.4	6.0	16	16
5-4.5-90-1.0	4.1	4.3	F	F	73	77	5.7	6.4	20	17
5-4.5-45-1.5	5.4	5.4	T	T	—	—	3.4	3.3	20	21
5-4.5-0-5	4.4	4.6	P	P	73	56	2.4	—	34	89
5-3.0-90-1.5	4.6	4.8	P	P	53	53	—	—	12	11
5-3.0-90-1.0	4.1	4.1	P	P	54	51	—	—	17	18
5-3.0-45-1.5	4.0	4.0	P	P	55	54	—	—	19	16
5-3.0-0-5	4.3	4.3	P	P	26	21	—	—	14	9
5-3.0-0-5	4.4	4.4	P	P	38	22	—	—	22	13
7-8.5-180-2.0	4.3	4.3	F	F	65	57	5.0	—	30	32
7-8.5-90-2.0	3.8	4.7	T	F	63	68	3.7	3.2	30	23
7-8.5-90-1.5	5.5	5.7	F	T	65	63	4.7	6.6	17	15
7-8.5-90-5	5.0	6.1	F	T	63	93	1.1	1.3	58	55
7-6.4-180-1.5	6.1	6.0	F	F	58	61	—	7.0	19	15
7-6.4-135-2.0	6.0	6.5	F	P	72	75	4.1	2.9	21	29
7-6.4-90-3.0	3.5	4.4	P	F	61	68	7.8	4.7	17	19
7-6.4-90-2.0	5.5	6.4	F	F	67	61	3.7	4.1	21	20
7-6.4-0-5	5.3	5.8	F	F	74	74	2.2	1.6	38	44
7-4.3-90-2.0	5.0	6.2	F	F	57	66	—	3.3	34	30
7-4.3-90-1.5	5.6	5.6	F	F	58	64	—	7.0	21	23
7-4.3-45-4.0	5.1	5.4	P	P	52	53	—	—	24	21
7-4.3-45-3.0	6.2	6.0	F	F	73	64	3.4	3.2	33	33
7-4.3-45-2.0	6.1	6.6	P	P	70	76	4.2	3.6	16	13
7-4.3-0-5	5.6	5.2	F	F	63	63	3.4	2.3	33	43
9-8.3-90-4.5	2.7	3.1	P	T	43	—	—	5.3	12	32
9-8.3-90-3.0	3.3	3.3	F	F	53	57	—	—	10	11
9-8.3-0-5	3.9	3.7	T	P	—	58	3.3	—	33	23

*Specimen notation: (1) bar size, (2) bond length, (3) bend angle, (4) bend radius.
†F-fracture of concrete, P-bar pullout, T-terminated at high stress or large slip.
NOTE: 1 ksi = 70.3 kgf/cm²; 0.01 in. = 0.25 cm.

To record slip, a thin wire encased in a plastic tube was attached to the rebar and cast within the specimen, seen in Figure 7. A dial gauge was attached to the wire at the specimen surface to measure the end slip, seen in Figure 8.

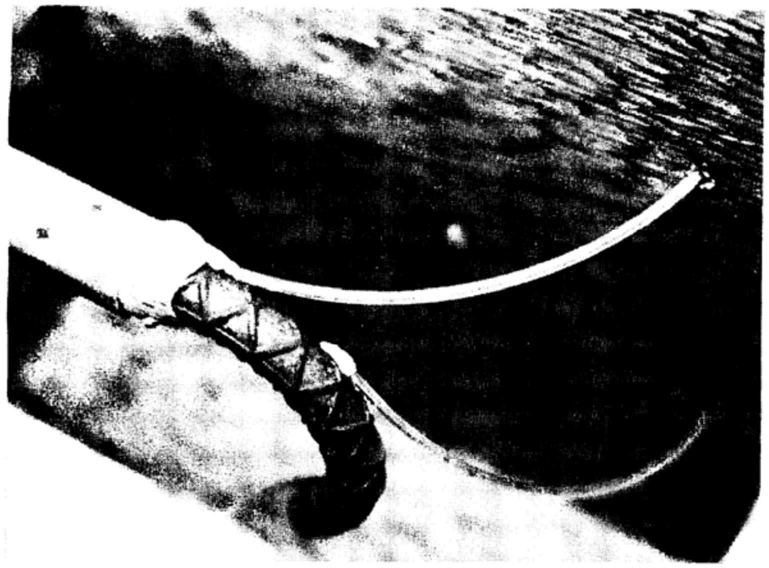


Figure 7 - Wire Encased in Tube and Cast in Specimen [1].

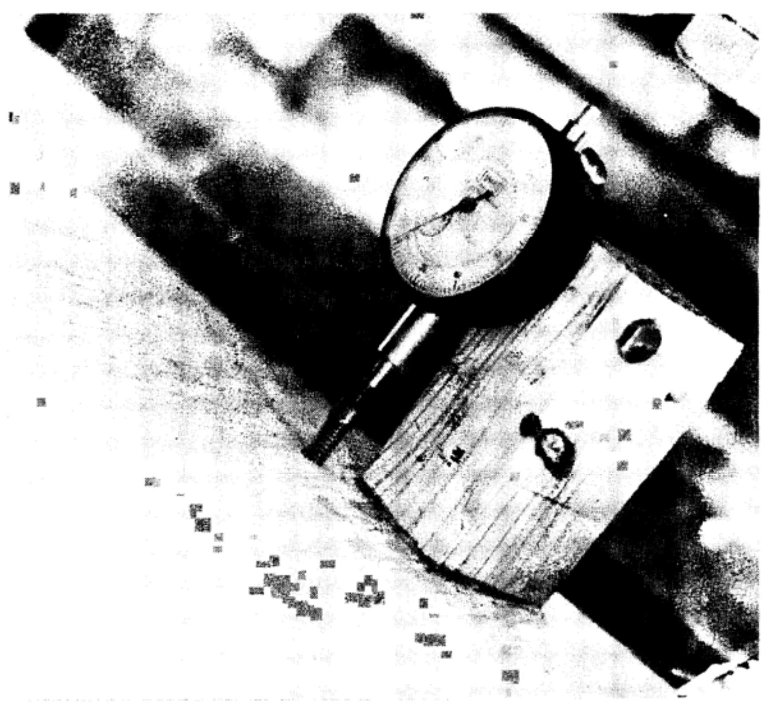


Figure 8 - Dial Gauge Attached to Wire to Record Slip [1].

The specimens were step loaded. Each bar was loaded in 30 to 40 increments to reach failure. The test was terminated at bar yield, pullout, or concrete fracture. The time period between steps was adjusted based on the speed of slip increase. The time period between steps allowed for the rebar slip to stabilize.

Figure 9 compares the lead slip of a straight #5 bar and a bent #5 bar. At larger bonded lengths, both bars are capable of reaching the yield stress. For example, the bar with 6 inches of bonded length reached 80 ksi in both the straight and bent bars, which means the rebar was stressed 20 ksi into the plastic range. As the bonded length decreases, the bend has a greater effect on the strength. For example, the 3-inch bonded length hooked bar develops 15 ksi more stress then the straight bar counterpart. Slip is greater in the bent bar than in the straight bar. The three 90° hooks were further to the right in Figure 9 than their straight bar counterparts. A bent bar tends to slip more than a straight bar, but the bend increases strength as bonded length decreases.

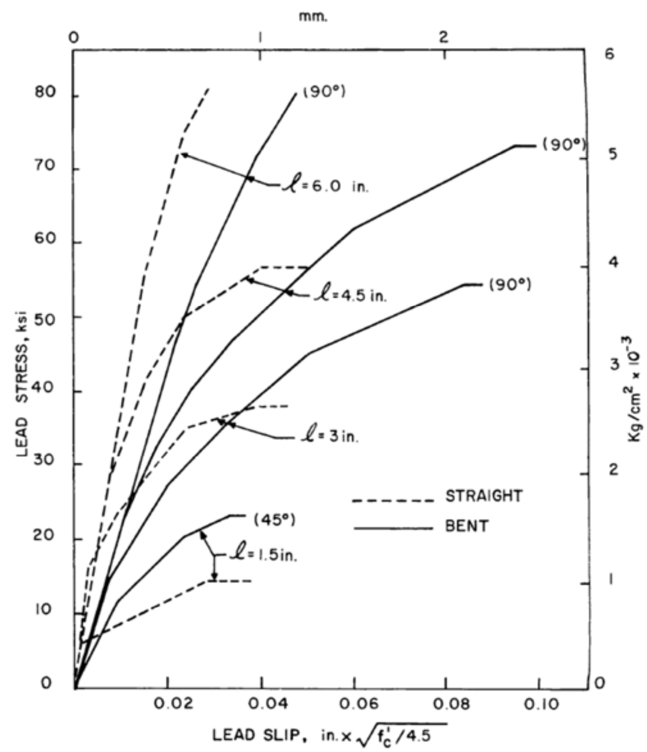


Figure 9 - Comparison of #5 Straight and Bent Bar [1].

Jirsa and Minor hypothesized the stress flow through the bend seen in Figure 10 [1]. A few definitive conclusions were drawn from this testing program. The larger the angle of bend, the greater the resulting slip. The smaller the bend radius, the greater the resulting slip. In a typical bar with a bent section and a straight section, most of the slip occurs at the bend. A difference in strength between straight and bent bars is only realized in shorter bonded lengths, such as 4.5 inch seen in Figure 9. In structural detailing, a 90° bend is preferable to a 180° bend and the radius should be as large as is practical.

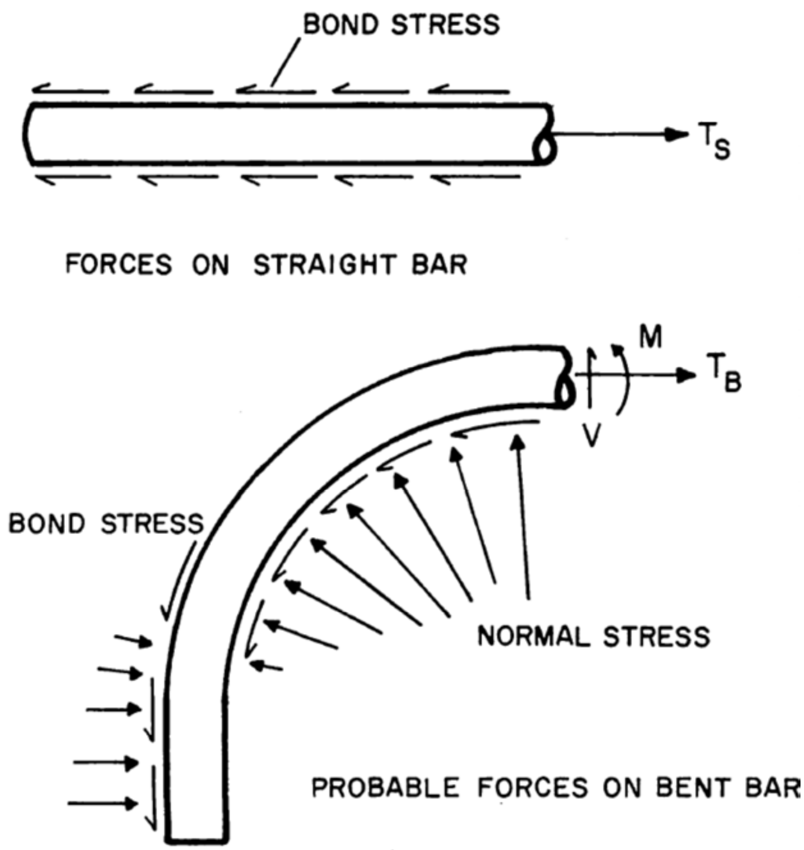


Figure 10 - Probable Stress Flow Through Bent Bar [1].

2.3 Jirsa and Marques, May 1975

Jirsa and Marques' research article, published in the May 1975 *ACI Journal*, uses small concrete blocks and relatively short bonded lengths to insure that a bond failure would occur before the steel yielded [4]. Side cover was sufficient to consider the rebar anchored in mass concrete. Full scale models permitted the use of large diameter hooks, specifically #9 and #11 bars with 90° or 180° hooks. The column size dictated the bonded length of the hooks seen in Figure 11. An average concrete compressive strength of 4500 psi was used.

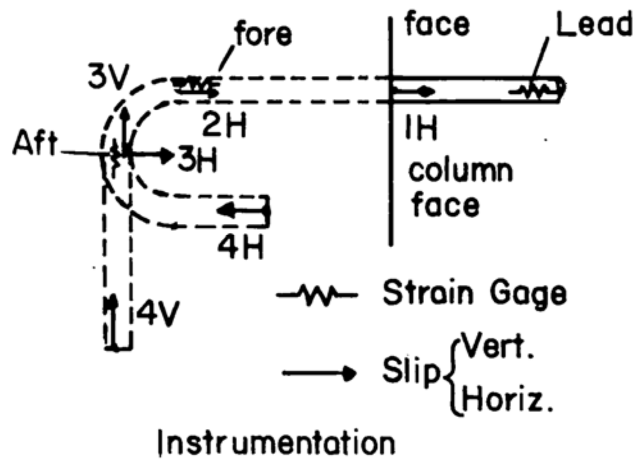


Figure 11 - Instrumentation and Bonded Length Termination at Column Face.

Five different confinement configurations were used representing typical beam-end confinement. These configurations can be seen in Figure 12. Jirsa and Marques state that "three types of confinement were considered. First, the influence of the longitudinal column bars; second, the influence of column ties through the joint; and third, the influence of concrete cover." [4]

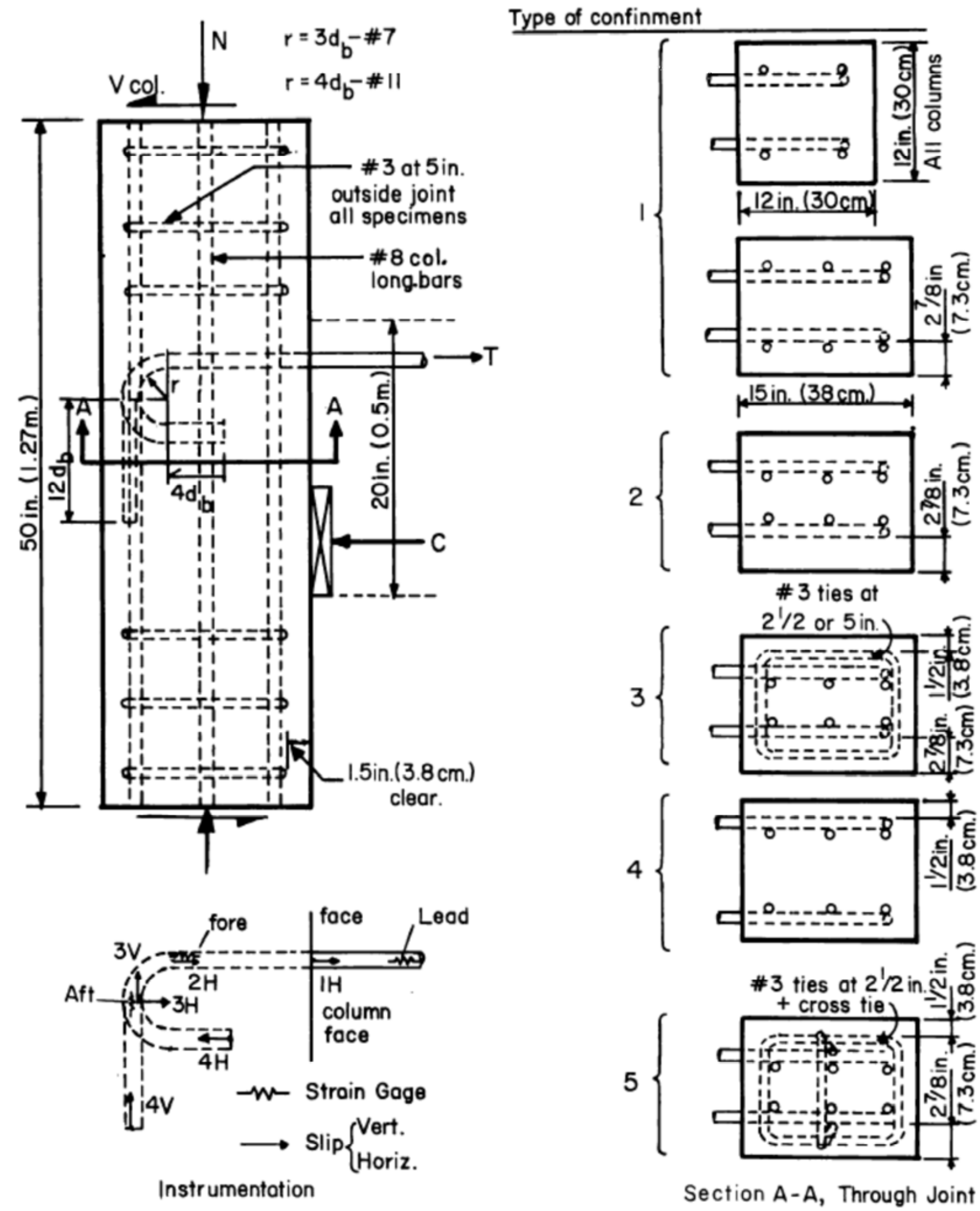


Figure 12 - Test Specimens and Confinement Configurations [4].

An axial load was applied to the column to simulate the beam-end column joint. To test the impact of the axial load, three different loads of 135 kips, 270 kips, and 540 kips were used. In the smaller column, the 540 kip load was reduced to 420 kips to create a comparable stress.

Two center-hole hydraulic rams were placed over the threaded rods to apply the force. The force was applied directly to the threaded rods. The hydraulic ram reaction force traveled through a steel plate placed against the column face to simulate the compression zone of a beam. A horizontal force was applied at the top of the column to resist the moment created by the beam-end loading.

Wires were attached to the rebar to measure slip from the back face of the column. The wires were contained within Neoprene tubes and cast in the concrete. Three strain gauges were attached per bar. The strain gauges were placed at the beginning of the bend, the end of the bend, and where the hooked bar protrudes from concrete.

Table 4 shows a summary of the test results. Most of the slip occurs at the lead end of the hook bar. The #11 bars were about one-third as stiff as the #7 bars. At failure, the lead slip of the #7 bars was about two to three times that of the #11 bars. Stress in the hook tail was generally small until failure was imminent, at which time it increased rapidly. This led to the current hooked bar representation previously seen in Figure 4. The influence of column axial loads appears to be negligible with the hook oriented in the direction of the axial load.

Table 4 - Test Specimen Results [4].

Specimen	Measured results: Stress, ksi, at lead slip of 0.005 in.	0.016 in.	0.05 in.	Stress at failure, f_u, ksi	Approx. slip at failure, in.	Computed results: $(f_h + f_l)$,* ksi	$\frac{f_u}{(f_h + f_l)}$	$(f_h + f_{sh})$,† ksi	$\frac{f_u}{(f_h + f_{sh})}$	Slip at $0.6\ (f_h + f_{sh})$, in.
J7-90-15-1-H	33	55	77	91	0.15	63	1.44	60	1.52	0.006
J7-90-15-1-M	35	61	78	100	0.18	67	1.50	60	1.67	0.005
J7-90-15-1-L	30	52	78	97	0.21	65	1.49	60	1.61	0.006
J7-90-12-1-H	20	31	59	63	0.08	53	1.19	51	1.24	0.015
J7-180-15-1-H	24	45	72	87	0.15	59	1.47	60	1.45	0.012
J7-180-12-1-H	23	38	59	61	0.07	53	1.16	56	1.09	0.012
J7-90-15-2-H	33	52	75	99	0.25	64	1.55	60	1.65	0.007
J7-70-15-2-M	32	46	70	95	0.21	64	1.49	60	1.58	0.008
J7-90-15-3-H	37	65	80	104	0.21	64	1.68	60	1.73	0.005
J7-90-15-3*a*-H	37	63	80	98	0.22	57	1.72	60	1.65	0.005
J7-90-15-4-H	29	54	73	74	0.05	63	1.17	50	1.48	0.006
J11-90-15-1-H	19	33	48	49	0.06	36	1.36	41	1.20	0.009
J11-70-15-1-L	19	29	48	52	0.06	36	1.45	40	1.30	0.012
J11-90-12-1-H	18	30	—	42	0.04	32	1.32	28	1.50	0.005
J11-180-15-1-H	13	25	43	44	0.05	34	1.30	39	1.13	0.015
J11-180-15-1-H	26	37	—	50	0.05	34	1.47	38	1.31	0.009
J11-90-15-2-H	22	35	48	48	0.06	37	1.29	40	1.20	0.007
J11-90-15-2-L	18	28	50	53	0.06	36	1.52	38	1.39	0.011
J11-90-15-3-L	16	28	53	62	0.09	36	1.72	40	1.55	0.014
J11-90-15-3*a*-L	24	42	66	69	0.06	37	1.86	52	1.33	0.010
J11-90-15-4-L	26	39	—	44	0.03	33	1.34	28	1.57	0.003
J11-90-15-5-L	23	39	63	66	0.08	37	1.78	52	1.27	0.011

*ACI 318-71, "other" bar values.
†Using proposed recommendations.

Note: 1 ksi = 70.3 kgf/cm²
0.01 in. = 0.25 mm

The lead slip is greater throughout all stress levels for specimens with shorter bond length. This can be seen in Figure 13. Jirsa and Marques note that "the lead embedment in these tests provided only limited length for stress transfer to the concrete before the hook, especially for large bars. However, with larger lead embedment, the lateral restraint against splitting is improved because a larger area of concrete must spall or split before the bar will fail." [4] Cover reduction did not change the failure curve, but drastically reduced the stress and slip at failure. Closely spaced ties are especially beneficial in large anchored bars. The influence of confinement configuration appeared to be minimal, as seen in Figure 14.

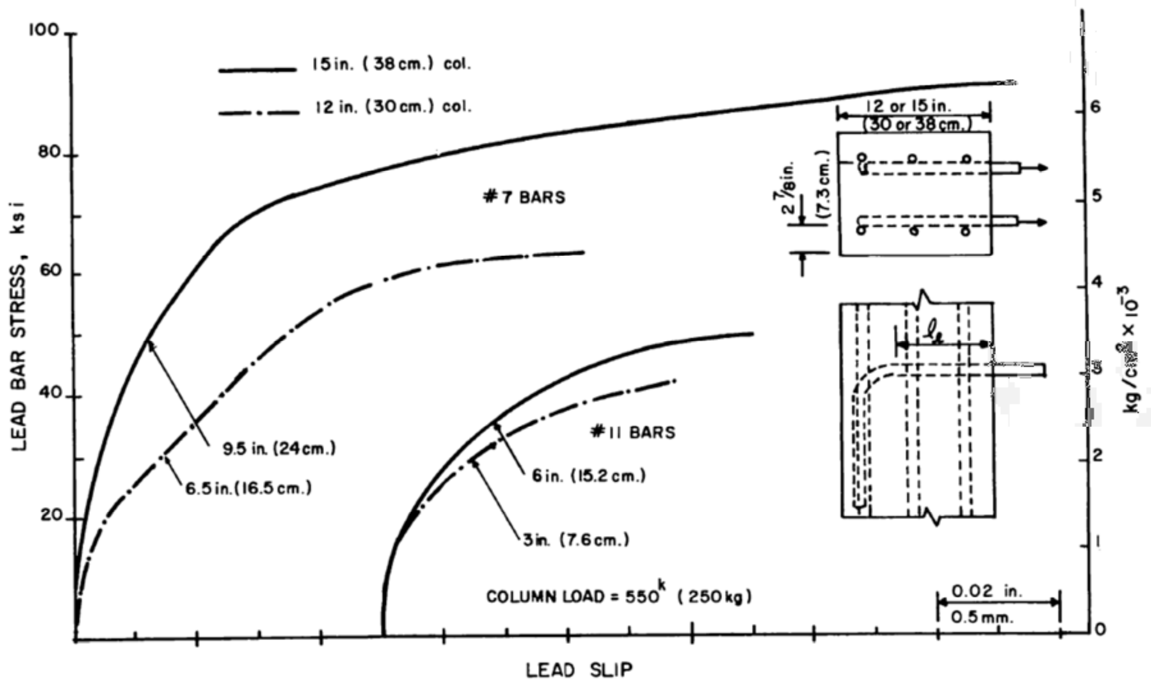


Figure 13 - Influence of Bond Length on Slip [4].

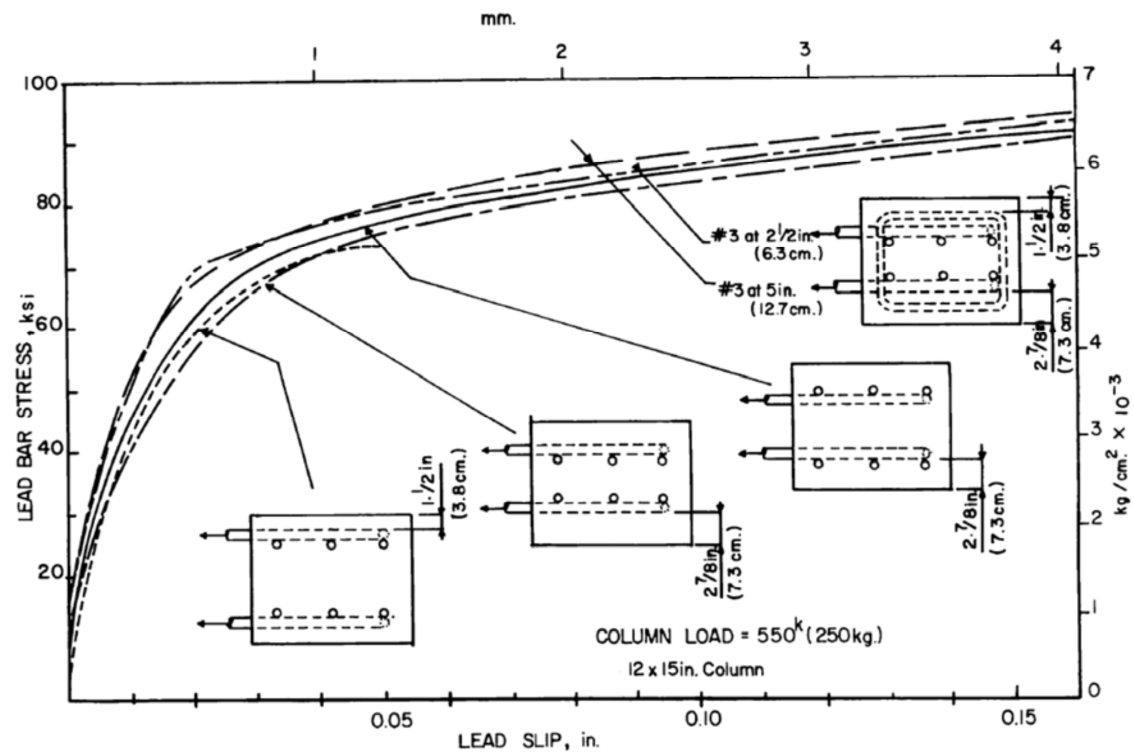


Figure 14 - Influence of Confinement on Slip [4].

Failure was always sudden with the concrete spalling in the side cover. Jirsa and Marques observed that "as the column thickness was increased or ties carried through the joint, some improvement in stress and slip characteristics was noted." [4] The stress characteristic improvement due to column thickness increase is most likely due to the increased cover required to spall before failure. When the radius of the hook is equal or larger than the tie spacing, ties through the joint see the most benefit since the hook joint experiences the most intense lateral pressure. Ultimately, it was found that strength increases as restraint against side splitting is increased.

2.4 Soroushian *et al.*, May-June 1988

Soroushian *et al.* carried out testing that focused on the hook behavior only [5]. The lead embedment length of the hooked bar was enclosed in a plastic tube to prevent bonding. This eliminated the bond resistance leaving only the hook to resist tension. The joints were confined with hoops to satisfy the ACI Building Code requirements for reinforced concrete frames in high-seismic risk zones. To simulate the beam-column connection, a plate was used to imitate the compression zone created by a typical beam.

The configuration of the simulation of a beam-column connection includes inconsistencies. The configuration is seen in Figure 15. In a beam-column joint, the beam carries the load through a compression zone and a tension zone. The tension zone in concrete is ignored and the tension force is transferred through the hook. Subsequently, a tension load should be applied to the hook and a compression zone load should be applied to the column face. Soroushian *et al.*'s configuration contains a compression zone load applied both above and below the tension load applied to the hooked bar. The distance between the tension and compression loads is also smaller than in a typical beam. The small distance between tension and compression also means it will help resist blowout. This test will most likely act similar to a pullout test instead of a beam-column joint. A better representation of a beam-column joint is seen previously in Figure 12 with only one compression zone and tension load and adequate spacing between them.

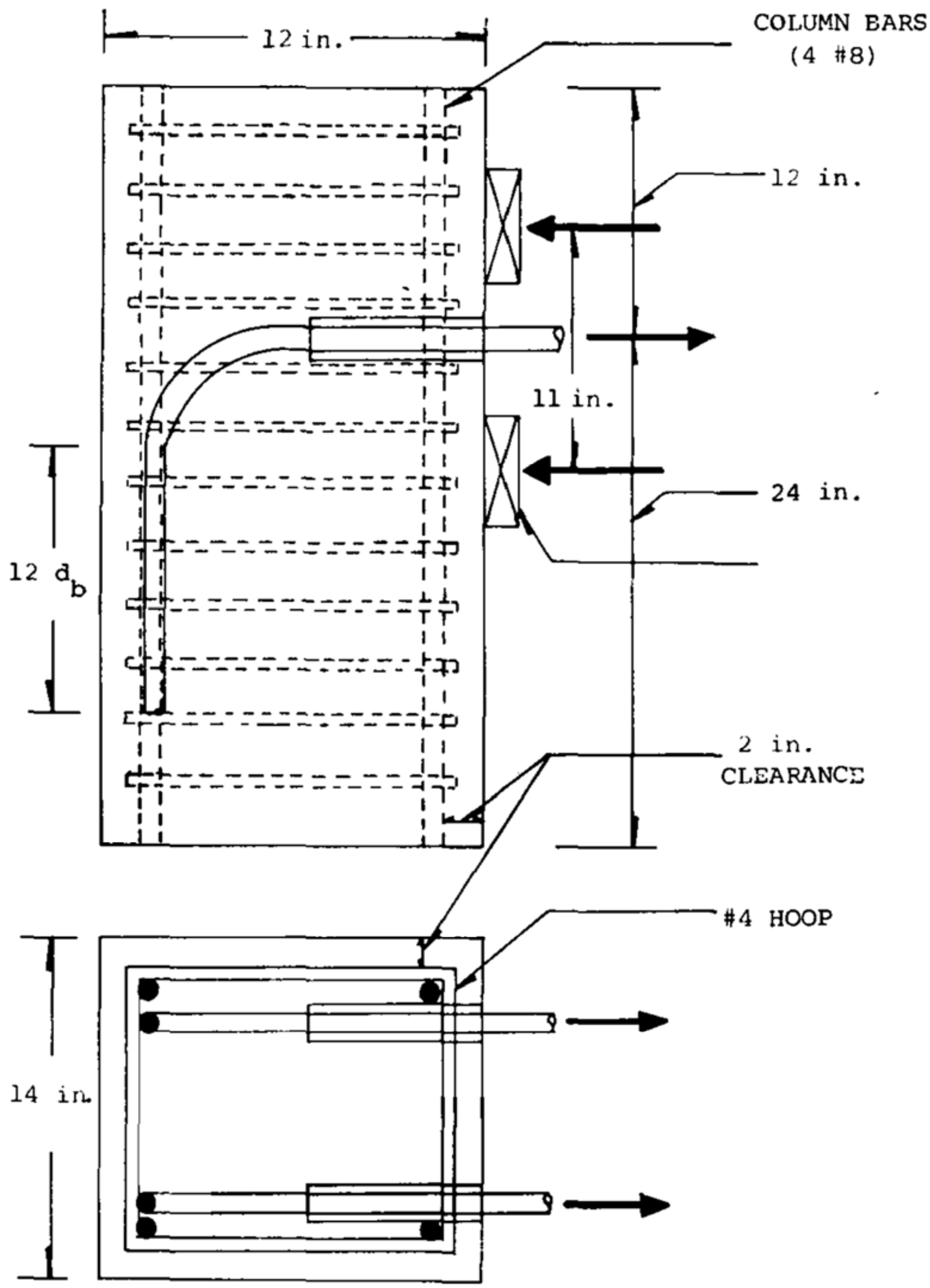


Figure 15 - Specimen Geometry [5].

The test setup is shown in Figure 16. Two hydraulic actuators bear against the concrete column and applied a load in tension. A load cell measured the load and electric displacement transducers were used to measure the displacement 4 inches from the face of the column. The lead slip is equal to the end slip plus strain times length. In Soroushian *et al.*'s testing, the lead slip effectively has 4 inches of extra strain built into the measurement compared to tests which measure slip at the specimen face. This fact might create a negligible difference, but must be realized nonetheless.

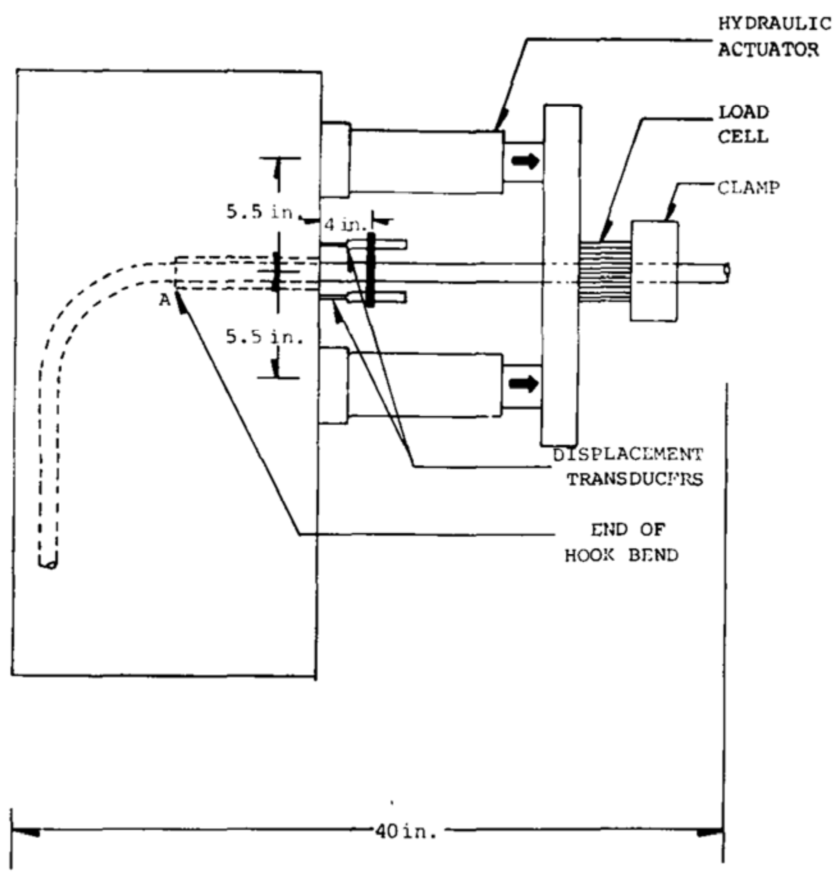


Figure 16 - Test Setup [5].

The specimens tended to expand in the direction normal to the hook tail and fail in concrete blowout. This can be illustrated by the fact that the hooks create a large compressive force at the bend of the hook. The expansion created spalling in the concrete on the face of the column. Soroushian *et al.* observe that “from the test results presented… it may be concluded that the hook initial pullout stiffness, ultimate pullout force, and post-peak resistance increase considerably with increasing bar diameter. This increase is, however, smaller than the corresponding increase in the bar yield force.” [5]

Soroushian *et al.* conclude with the limited test data that pullout strength can be significantly increased if joint confinement satisfies the ACI Building Code requirements for high-risk seismic zones. Without any lead embedment, the hook is able to fully reach tensile yield capacity. However, clear cover below four times the bar diameter may affect this conclusion. An increase in bar diameter increases pullout resistance, but the increase is less than the increase in capacity due to the increased steel area. Confinement of the concrete around the hook is an important factor in the pullout strength of the hook. Finally, the concrete compressive strength did not appear to affect the pullout behavior in this test program. Table 5 lists the specimen properties, Figure 17 shows the effect of hooked bar diameter, and Figure 18 compares the pullout force-displacement curve for both theoretical and experimental specimens.

Table 5 - Test Specimen Configurations [5].

Specimen	Bar size	Lateral confinement	Concrete compressive strength, psi
1 (Standard)	#8	#3 @ 3 in.	3780
2 (Standard)	#8	#3 @ 3 in.	3780
3 (Low confinement)	#8	#3 @ 4 in.	3780
4 (High confinement)	#8	#4 @ 3 in.	3780
5 (High concrete strength)	#8	#3 @ 3 in.	6050
6 (Small hooked bars)	#6	#3 @ 3 in.	3780
7 (Large hooked bars)	#10	#3 @ 3 in.	3780

Note: 1 in. = 2.54 mm; 1 psi = 0.0069 MPa.

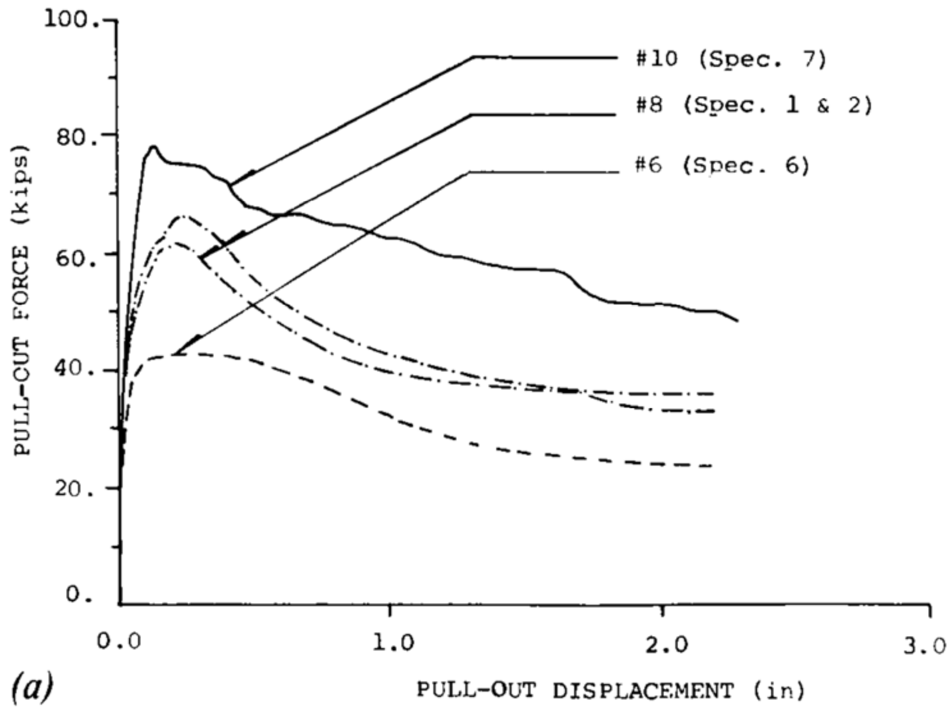


Figure 17 - Displacement versus Force for Varying Bar Diameter [5].

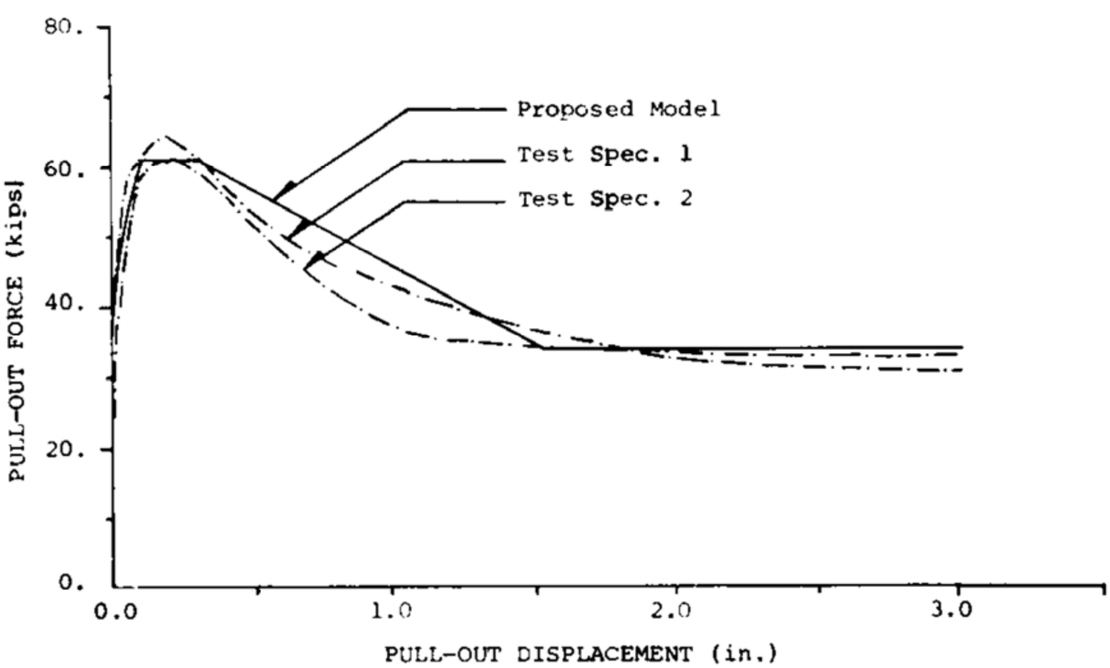


Figure 18 - Force-Displacement Curve of Theoretical and Experimental Models [5].

2.5 Orangun *et al.*, March 1977

Orangun *et al.* pulled information from multiple sources to analyze the data focusing on the comparison of splice length and development length seeking to modify and improve code provisions [6]. Orangun *et al.* observed the V-notch failure which is directly applicable to this capstone report. This failure mode can be seen in Figure 19 where C_s is the side cover and C_b is the bar cover.

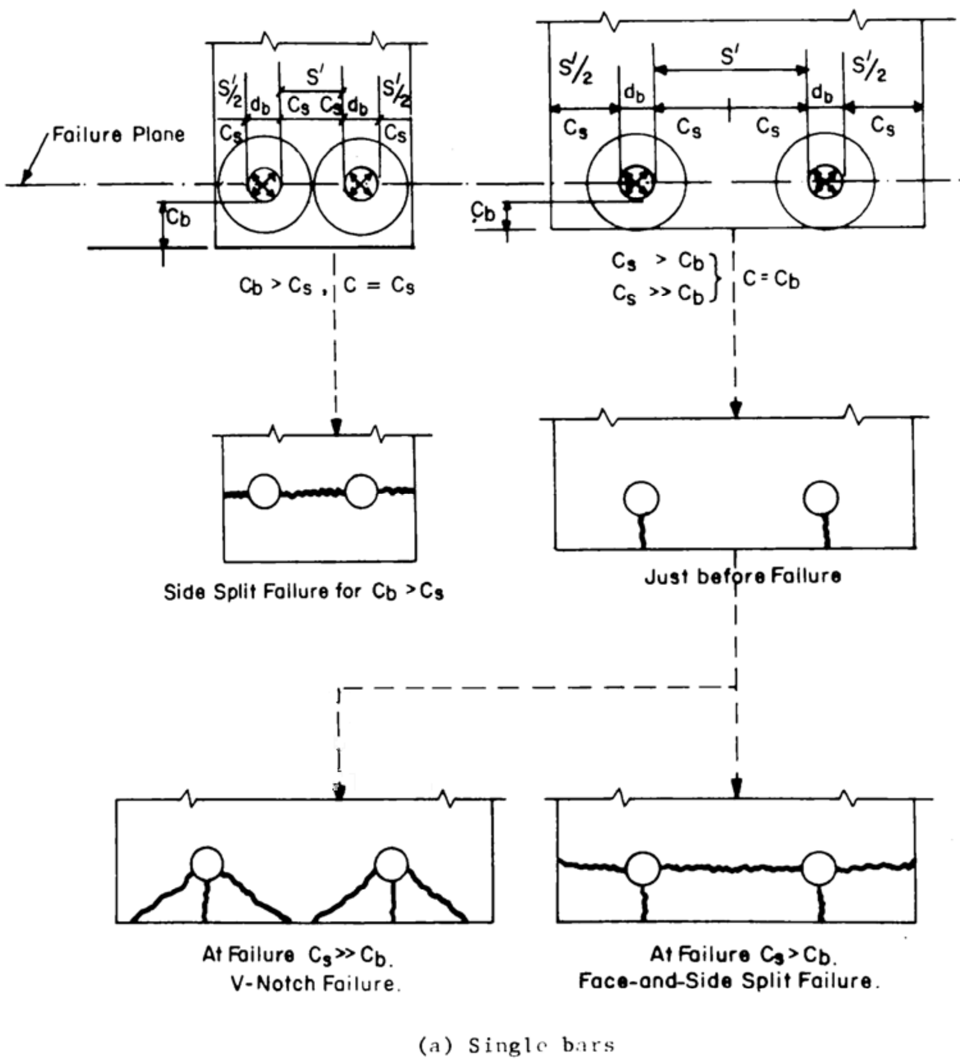


Figure 19 - Failure Patterns of Single Anchored Bar [6]

Orangun *et al.* sought to modify the development length design equation by combining test data from many sources and comparing the current design equation to the design equation proposed in the report. Part of the obtained test data showed that the large side cover or clear spacing between bars restrained splitting across the plane (see side split failure in Figure 19). When this failure mode was restrained, the V-notch failure was observed. The test data became scattered above a $C_s/(C_b{*}d_b)$ ratio of 3. Consequently, Orangun *et al.* suggested that the development length model should be modified when the ratio is above 3.

In the concluding statements, Orangun *et al.* stated that splice length and development length were "found to be identical and could be expressed in terms of steel stress, concrete strength, bar diameter, minimum side or bottom cover, and transverse reinforcement – factors which have been shown by tests to affect the strength of anchored bars." [6] The minimum required cover provisions were unconservative in 1977. The most pertinent finding from this report is the appearance of a splitting failure instead of a pullout failure. Previous to this report, research focused on bars cast in mass concrete and loaded until the bar failed by pulling out of the concrete. The hook tests previously discussed looked at pullout rather than splitting. When the bars are cast near the face of concrete, splitting of the concrete starts to become the limit of strength. With bars typically cast near the face of the concrete, concrete splitting was a topic that required further research.

Chapter 3 – Methods

3.1 Specimen

3.1.1 Configuration

Twelve specimens were created for testing. Six of the specimens were cast with hooked rebar and six were cast with straight rebar. Each specimen block measured 12 inches wide, 24 inches tall, and 32 inches long with a tolerance of a ±1/4 inch. The tensile load was applied to a #8 rebar. Each specimen also had #4 ties to provide concrete shear reinforcement, and four corner bars parallel to the #8 bar to allow for moving the specimen. Figure 20 shows a typical hooked specimen used in the test setup.

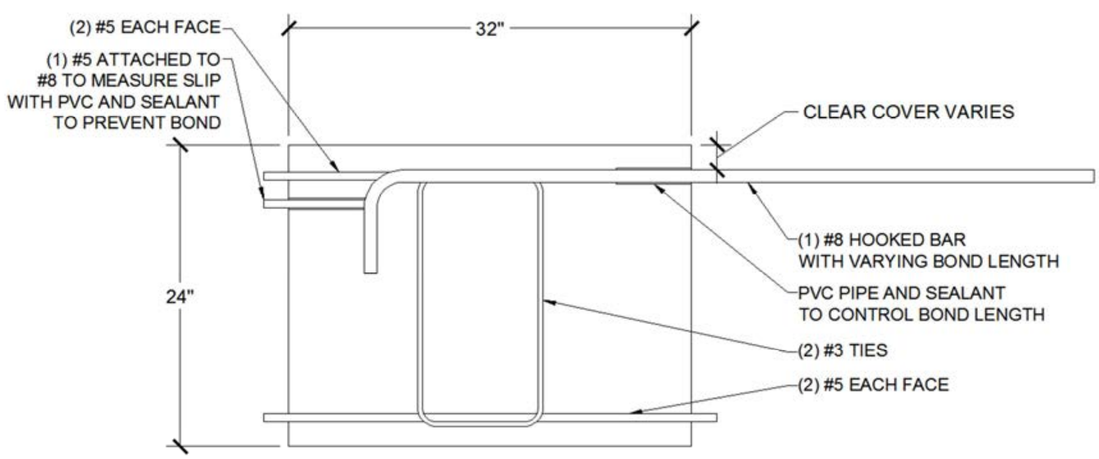


Figure 20 - Experimental Specimen.

Table 6 lists the specimen rebar and strain gauge configurations. The test number is comprised of three identifying components. The letter designates the shape, either hook or straight bar. The first number is the bonded length. The final number following the period is the cover. For example, the test number H8.1 signifies a hooked bar with a bonded length of 8 inches and a cover of 1 inch. As expected, the bond length is not ideally 8 inches, 12 inches or 16 inches. As such, the actual location of the bond length is listed in Table 6 for reference. The strain gauge location is measured from the unloaded end of the bonded length. All of the hooked bars had a strain gauge at a nominal 4 inches from the back of the hook. A visual representation of the strain gauge locations can be seen in Figure 21.

Table 6 - Specimen Test Number and Corresponding Configurations.

Test Number	Shape	Bond Length	Cover	Strain Gauge Location
H8.1	Hook	8.0 in	1.0 in	4.25 in
H8.2	Hook	8.0 in	2.0 in	4.25 in
H12.1	Hook	11.5 in	1.0 in	4.00 in
H12.2	Hook	12.0 in	2.0 in	4.00 in
H16.1	Hook	14.5 in	1.0 in	3.50 in
H16.2	Hook	16.0 in	2.0 in	4.25 in
S8.1	Straight	7.5 in	1.0 in	5.75 in
S8.2	Straight	7.0 in	2.0 in	5.50 in
S12.1	Straight	11.0 in	1.0 in	3.25 in
S12.2	Straight	11.0 in	2.0 in	4.00 in
S16.1	Straight	15.0 in	1.0 in	7.75 in
S16.2	Straight	15.0 in	2.0 in	7.50 in

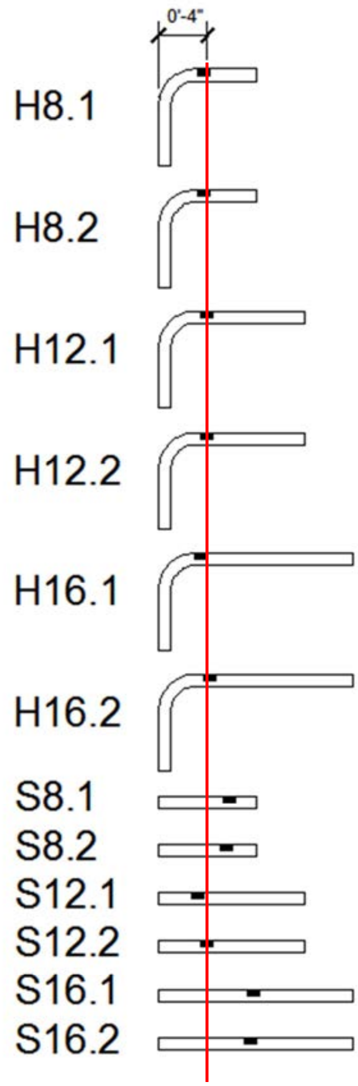


Figure 21 - Strain Gauge Locations.

The specimen rebar configurations were controlled using PVC pipe. The #8 bar was placed through a PVC pipe to control the bond length. Caulk was applied between the bar and PVC pipe end to prevent concrete from leaking into the PVC pipe as seen in Figure 22. The finished specimens are shown in Figure 23. The long bar projecting out of the concrete is the #8 bar that is loaded in tension, and the smaller bars projecting a couple inches out of the concrete were used to maneuver the specimen.

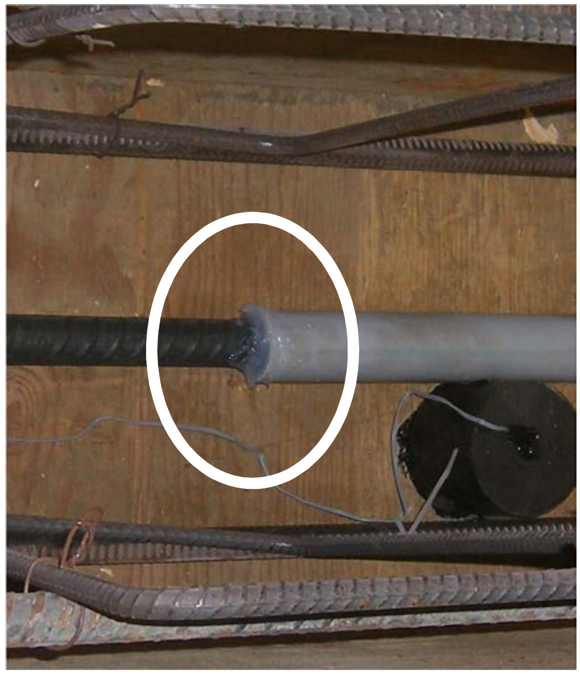


Figure 22 - PVC Pipe and Caulk Terminating Bond Length.

Figure 23 - Finished Specimen Showing Rebar Projection.

3.1.2 Formwork

Several projects made use of the formwork seen in Figure 24 [2]. It was created using plywood, 2"x4" lumber, nails, and screws. The specimen dividers and base were reused from previous years. The end caps had to be newly created because holes were drilled in it to allow the rebar to project out of the concrete.

Figure 24 – Typical Formwork [2].

3.1.3 Concrete

The concrete was designed by a local ready-mix company to meet 4000 psi. Table 7 lists the individual compressive strength results. The quantity of testing cylinders was selected to initially include a day 56 test, but the specimen testing occurred on day 28 and day 29. As such, six cylinders were tested on day 28. Figure 25 displays the compressive strength obtained for day 7, day 14, day 21, and two sets of day 28 breaks. The compressive strength was 4870 psi which was well above the requested 4000 psi.

Table 7 - Individual Cylinder Results.

Day	Individual Test Result (psi)			Average (psi)
3	1998	1984	X	1990
7	3328	2996	2978	3100
14	4276	4495	4283	4350
21	4619	4870	4817	4770
28	5164	4410	4456	4870
28 (v2)	4601	5220	5365	

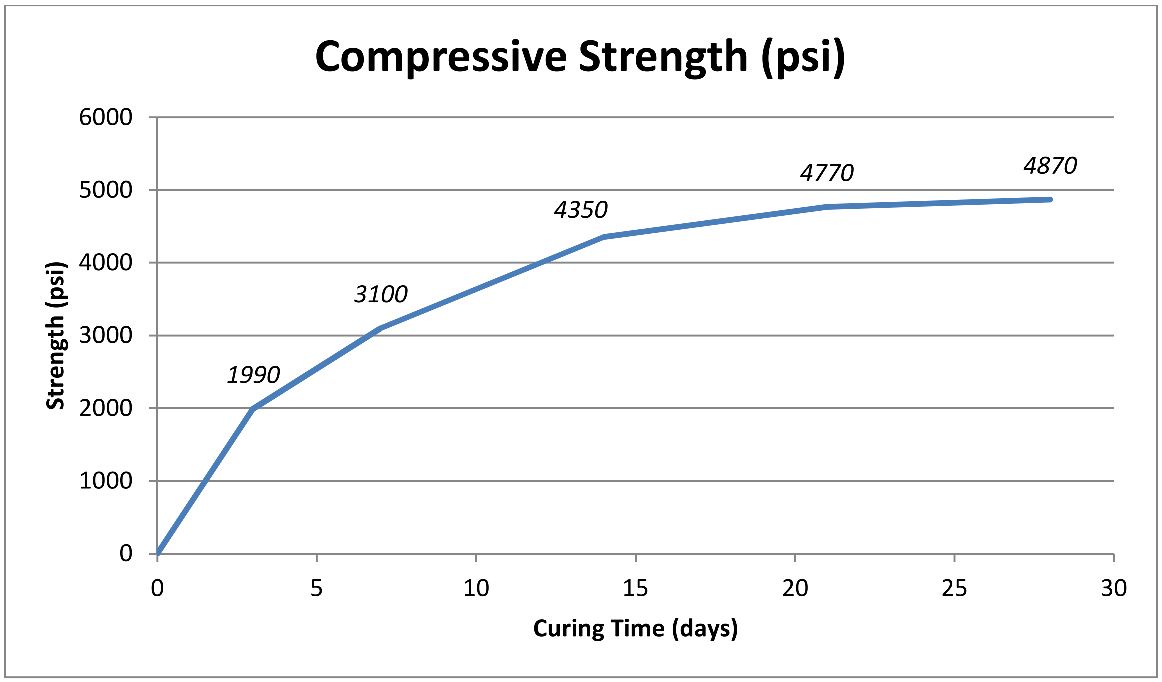


Figure 25 - Cylinder Testing Results.

3.1.4 Steel

All rebar in this report is Grade 60 steel. Subsequently, all stress calculations use a steel yield of 60 ksi. For a #8 bar, the steel yield failure is 47.4 kips. Any force applied above this level stresses the rebar into the plastic range. A force of 42.5 kips was used for 90% yield.

3.2 Setup

3.2.1 Data Acquisition Equipment

The data acquisition equipment configured for each test was composed of two main components: Linear Variable Displacement Transducers (LVDT) and a load cell. The specimen was placed on a W-Flange beam and secured in placed. The #8 bar was placed through the load cell. A LVDT was placed at each end of the #8 bar against an angle clamped to the bar. The strain gauges were cast in the concrete; therefore, the strain gauge wires just required attaching to the computer.

3.2.2 Frame Configuration

Figure 26 shows the forces on the frame setup. The force couple is resisted by the Wide-Flange Beam and a double channel secured using threaded rods. The test setup can be seen in Figure 27 and Figure 28.

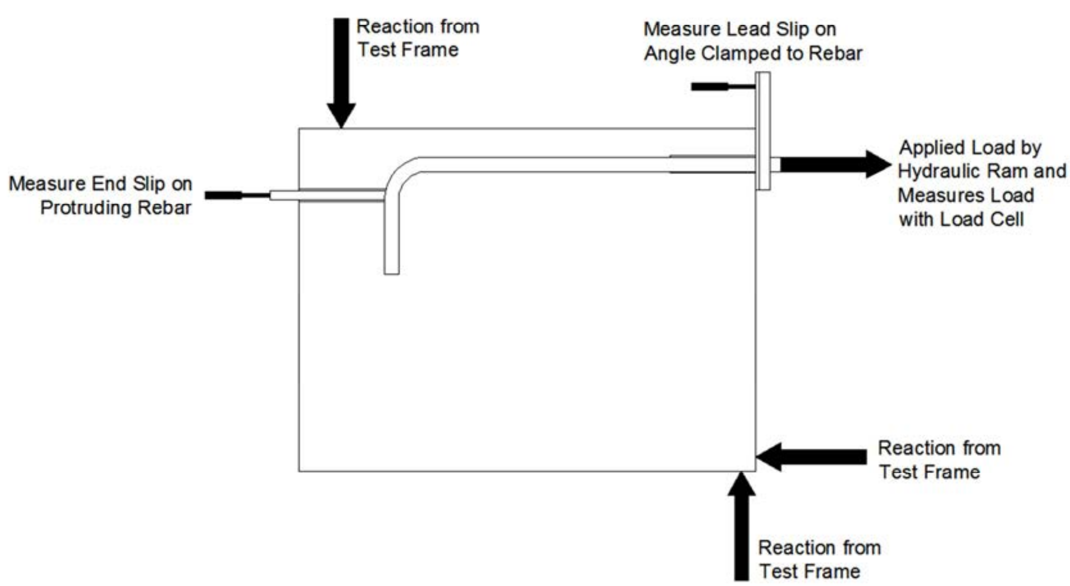


Figure 26 - Specimen Forces.

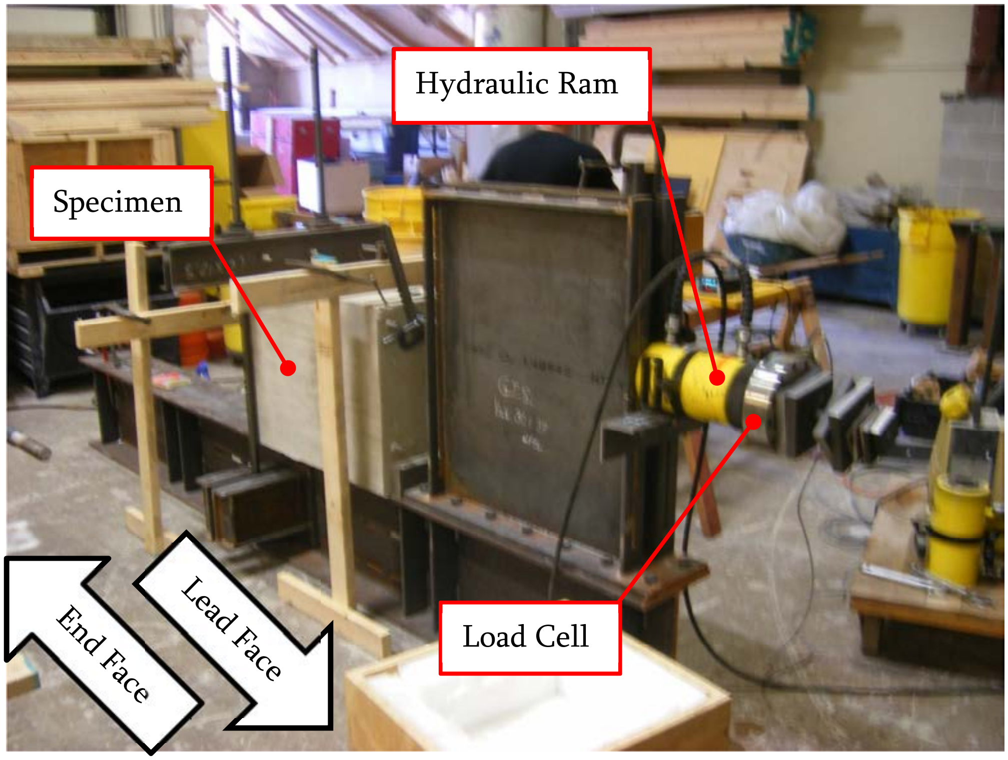


Figure 27 - Test Setup Viewed From Load Cell End.

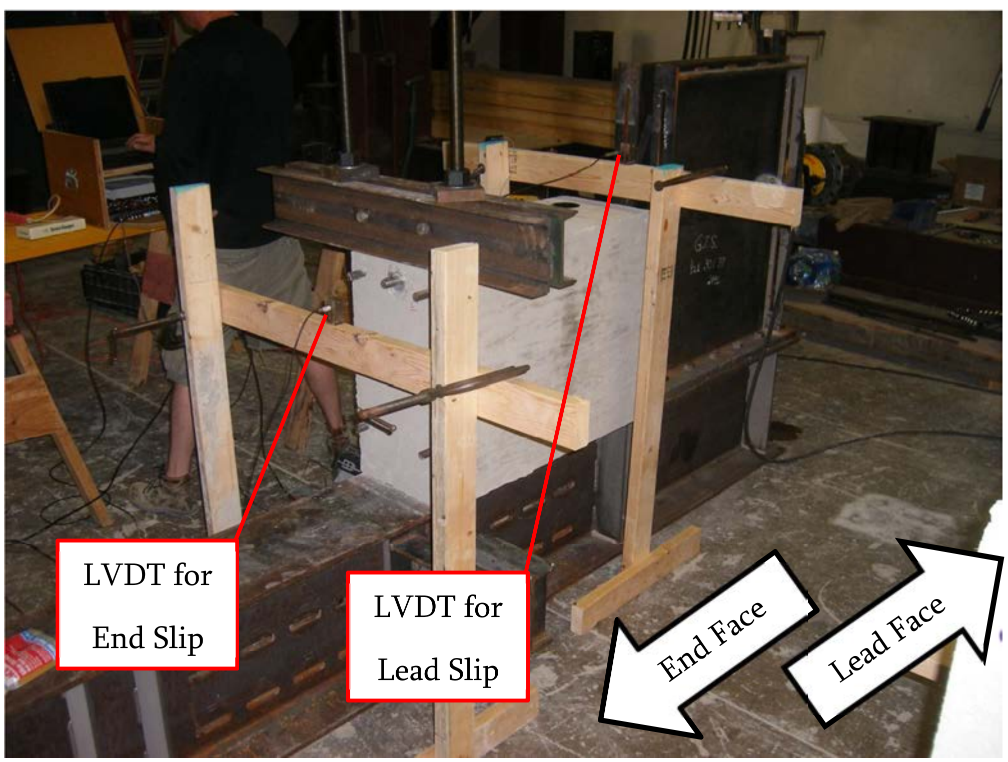


Figure 28 - Test Setup Viewed From Back.

3.3 Procedure

The data were measured using a load cell, Linear Variable Displacement Transducers (LVDT), and strain gauges and then continuously recorded by a computer using Labview. Using the hydraulic ram, the loads were applied monotonically until failure or until the displacement-based ram could not add force. If the ram displacement was increased without the load on the load cell increasing, it meant that the bar was elongating and the test was terminated. In an attempt to prevent the steel from yielding on progressive cycles, the maximum cycle load was set to about 45,000 lbs. If the specimen did not reach failure, the load was applied again. This method was used until the specimen failed or the load was applied repetitiously five times. If the specimen reached the final loading cycle, it was loaded until failure. It most cases, the steel was stressed past yield and loaded into the plastic range.

Chapter 4 – Raw Data Reduction

Data were continually recorded in Labview throughout each loading cycle. A typical load-strain plot and typical load-slip plot are shown in Figure 29 and Figure 30. Within each data file, the data were required to be separated into the loading cycles for each specimen. During data separation, the data points recorded during the removal of the load between cycles were removed. The data could then be separated into single loading cycles. Figure 31 and 32 show the data reduced to the final loading cycle from the typical load versus strain graph, seen in Figure 29, and the typical load versus lead and end slip graph, seen in Figure 30, respectively.

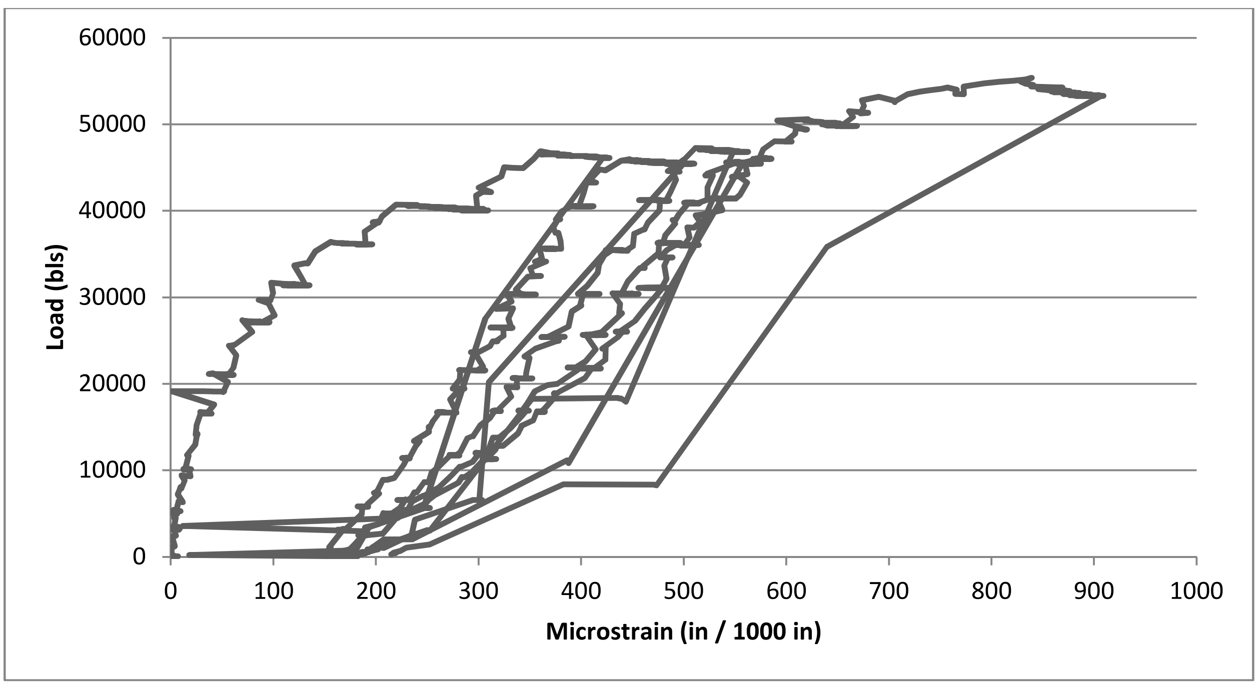


Figure 29 - Raw Data of Load versus Strain.

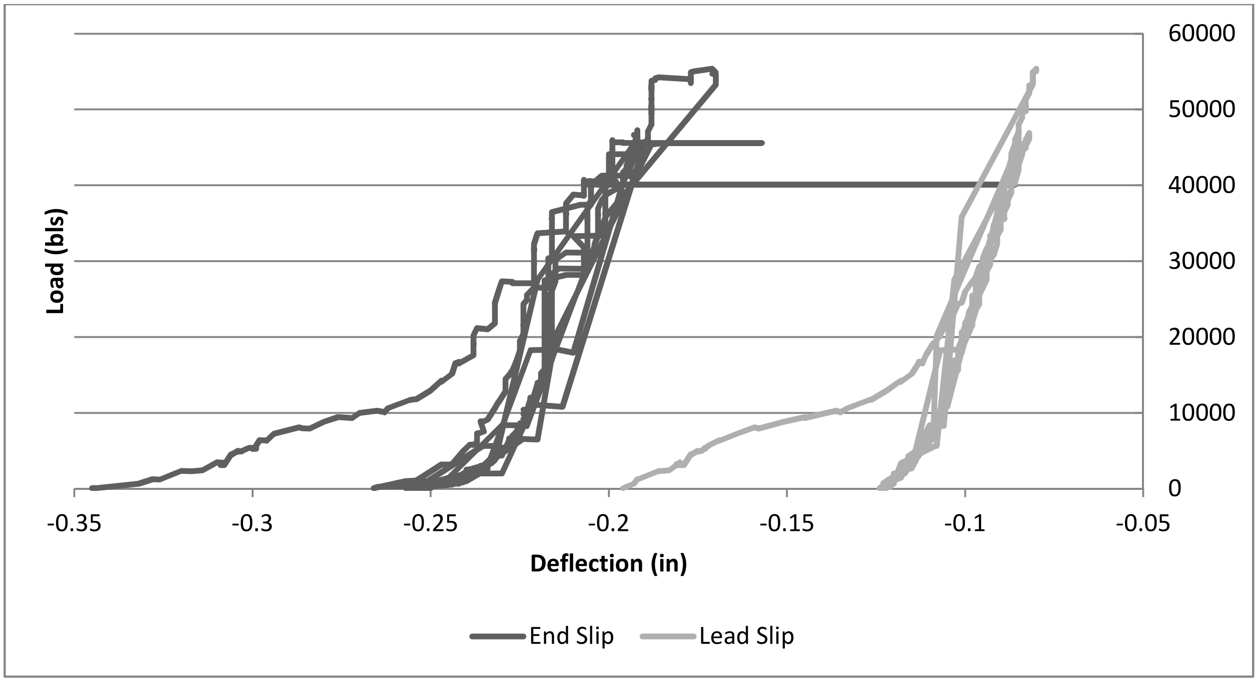


Figure 30 - Raw Data of Load versus Rebar Slip.

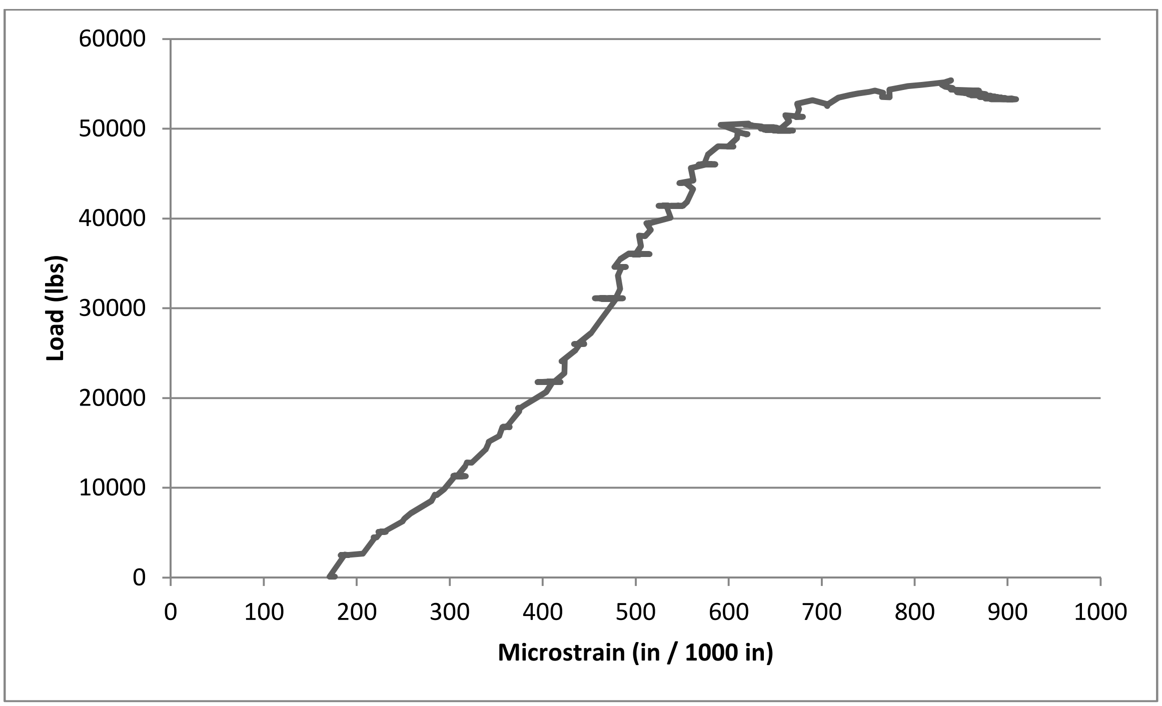


Figure 31 – Typical Final Load Cycle Load versus Strain Graph.

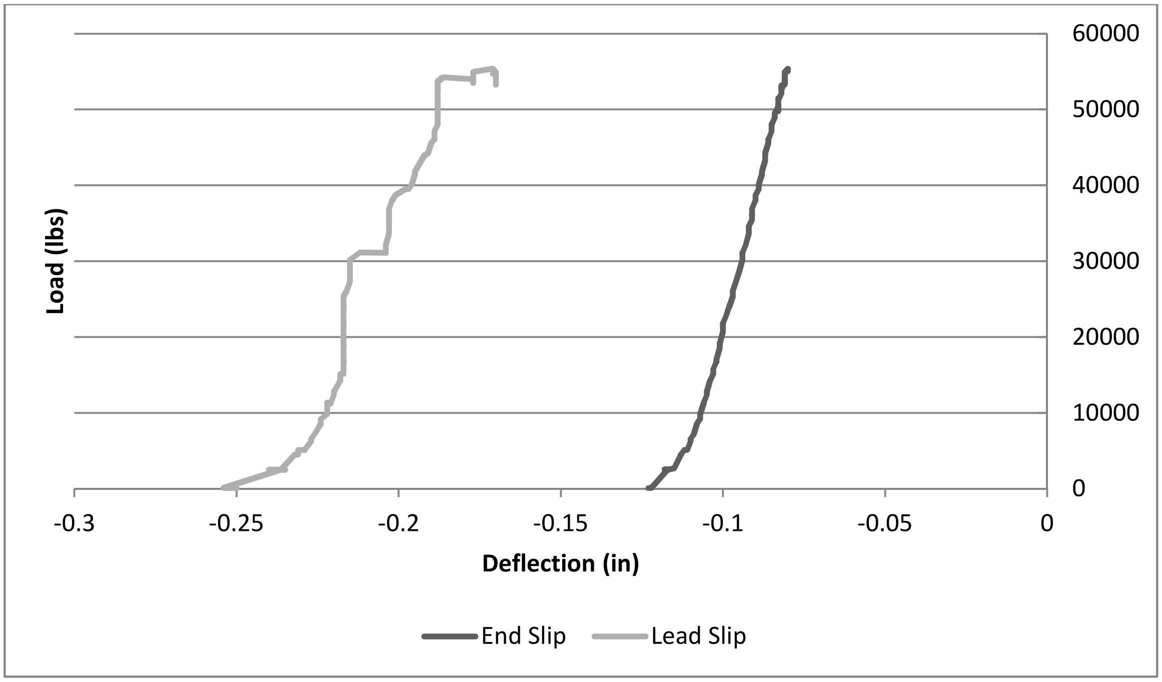


Figure 32 – Typical Final Load Cycle Load versus Lead and End Slip Graph.

Chapter 5 – Results

5.1 Failure Mode

5.1.1 Hooked Specimens

Figure 33 shows the failure modes and ultimate loads of all twelve tests. Every hooked rebar experienced a steel yielding failure regardless of the cover and bond length. Test H16.2 and Test S16.2 were one of the first specimens to be tested and were terminated very close to yield instead of loading into the plastic range as in subsequent tests. These tests were considered to fail in steel yielding.

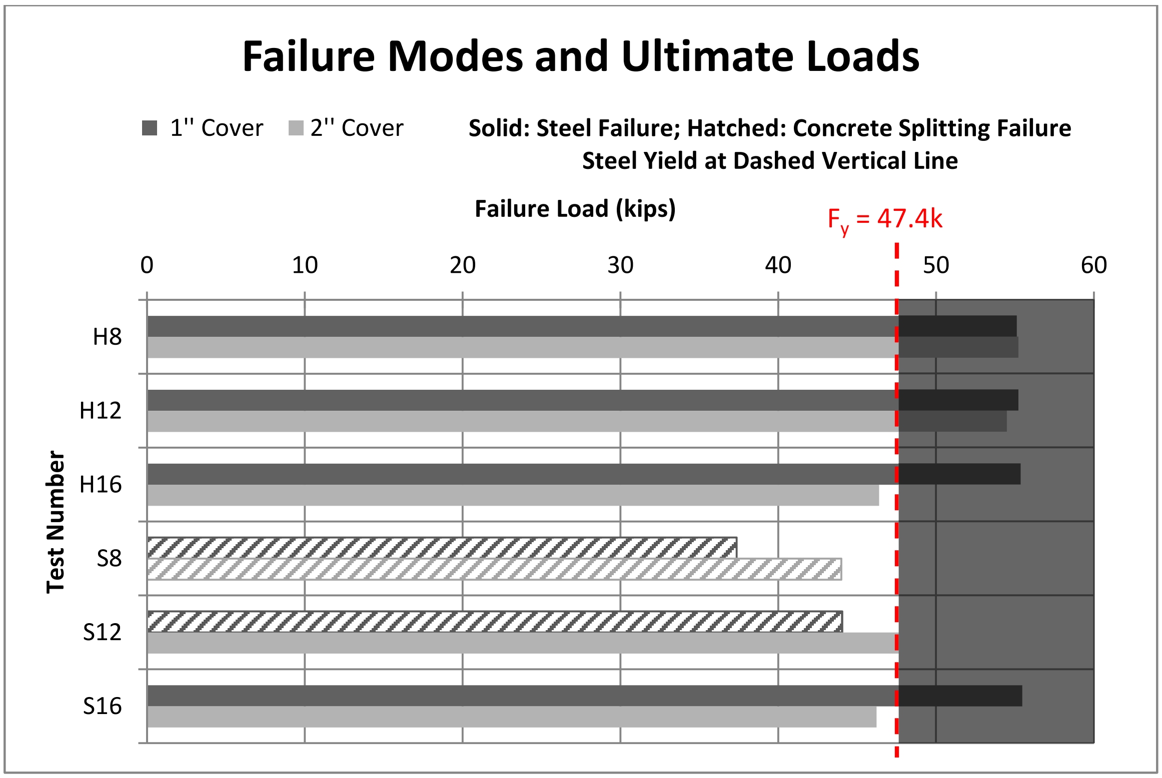


Figure 33 - Graph Showing Failure Loads and Failure Modes.

5.1.2 Straight Specimens

The straight bars exhibited both splitting and steel yield failure. Test S8.1, Test S12.1, and Test S8.2 experienced splitting failures, as seen in Figure 34, Figure 35, and Figure 36, respectively.

Figure 34 - Test S8.1 Failure.

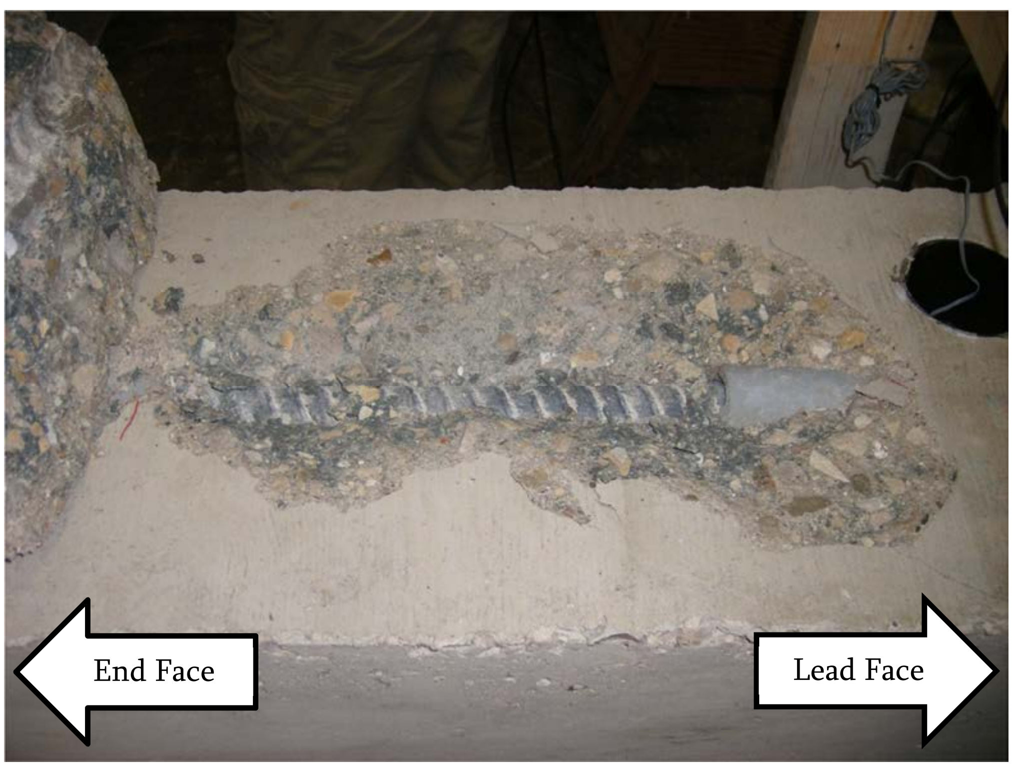


Figure 35 - Test S12.1 Failure.

Test S8.2 exhibits a splitting failure as seen in Figure 36, but failure was not as dramatic as seen in Figure 35 and Figure 34. It is believed that Test S8.2 started failing in splitting, and after the bond weakened, it proceeded to fail in pullout. After the test, the rebar was loose in the specimen and could be freely pulled out by hand. It is worth noting that the initial data collected from Test S16.2 were unusable. The testing was redone and this may have affected the ultimate load.

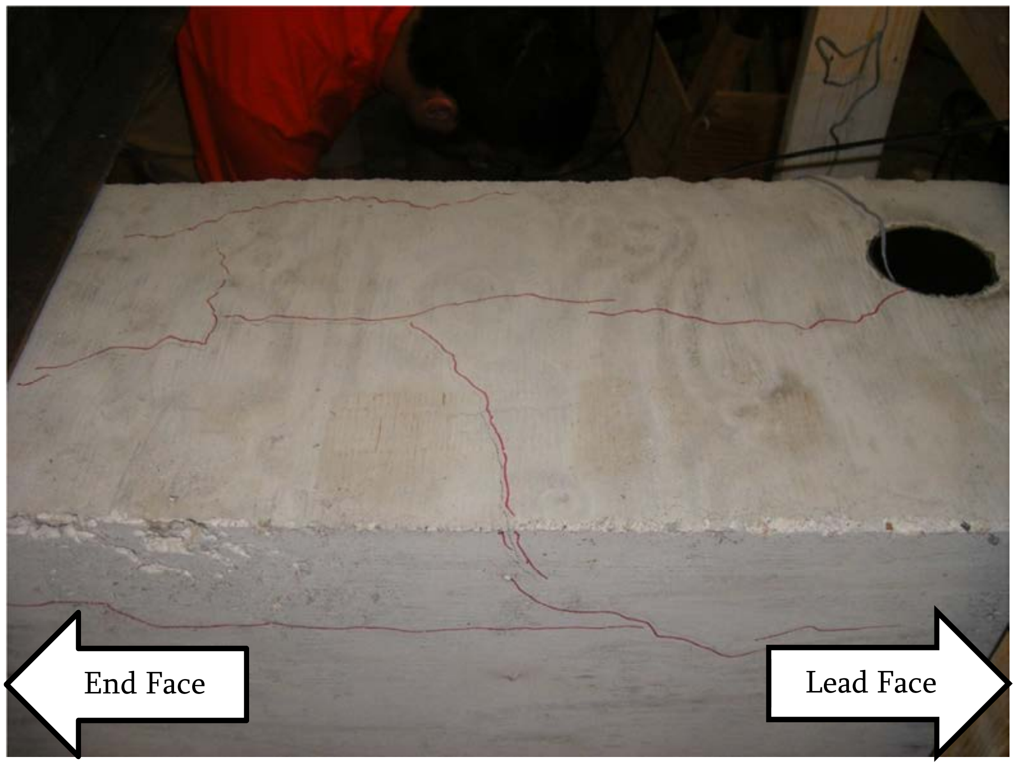


Figure 36 - Test S8.2 Failure.

5.2 Stiffness

The stiffness values are obtained using a linear fit trend line to find the load in kips over the slip in inches (i.e. the slope of the data curve). The stiffness trend lines and values for each test are shown in Figure 37 through Figure 48. Table 8 details the failure mode and stiffness results. The slip scale on Figure 45 is different from the other straight bar stiffness scales. Using the scale from Figure 45 on all graphs would render many of the figures unreadable. This is due to the fact that the slip in Test

S12.1 (seen in Figure 45) is much greater than the other specimen. This large slip decreases the stiffness seen in Table 8. The specimen slipped in the frame upon initial loading so the slip data from the first 10,000 lbs. was removed. Removal of the initial loading slip data allowed for an R correlation of 97% or above for all plots.

Table 8 - Test Specimen Results.

Test Number	Failure Mode	End Slip Stiffness (k/in)
H8.1	Plastic	1630
H8.2	Plastic	1288
H12.1	Plastic	1300
H12.2	Plastic	1385
H16.1	Plastic	1688
H16.2	Yield	1034
S8.1	Splitting	524
S8.2	Splitting	241
S12.1	Splitting	169
S12.2	Yield	373
S16.1	Plastic	822
S16.2	Yield	1327

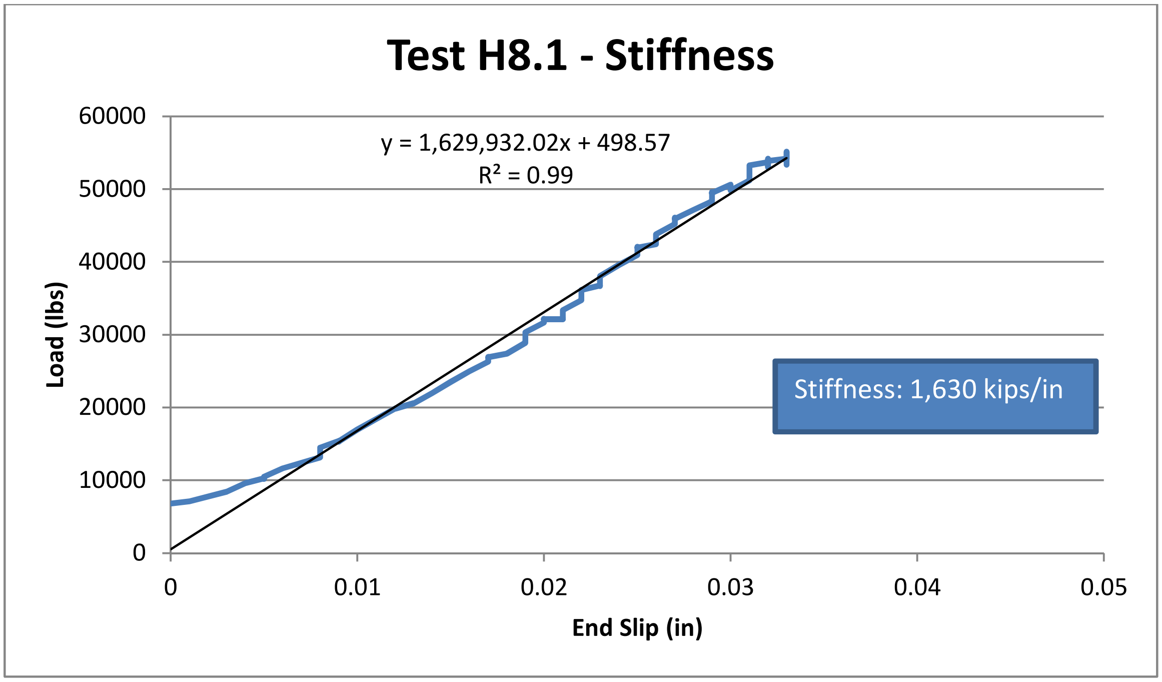


Figure 37 - H8.1 Stiffness.

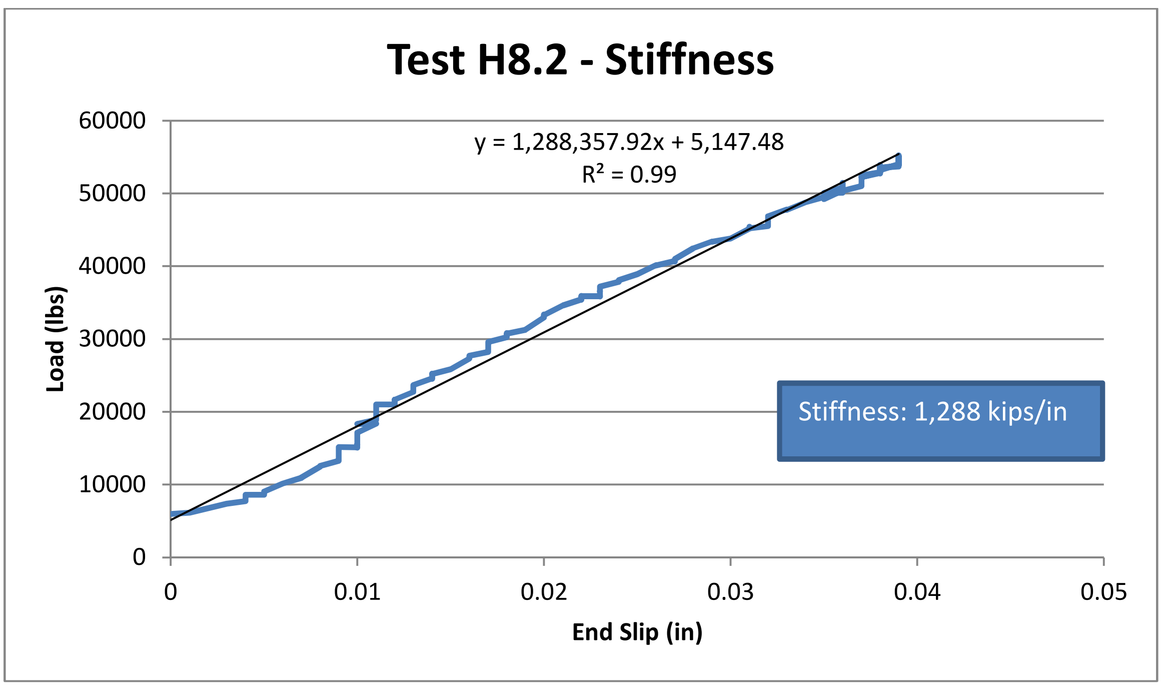


Figure 38 - H8.2 Stiffness.

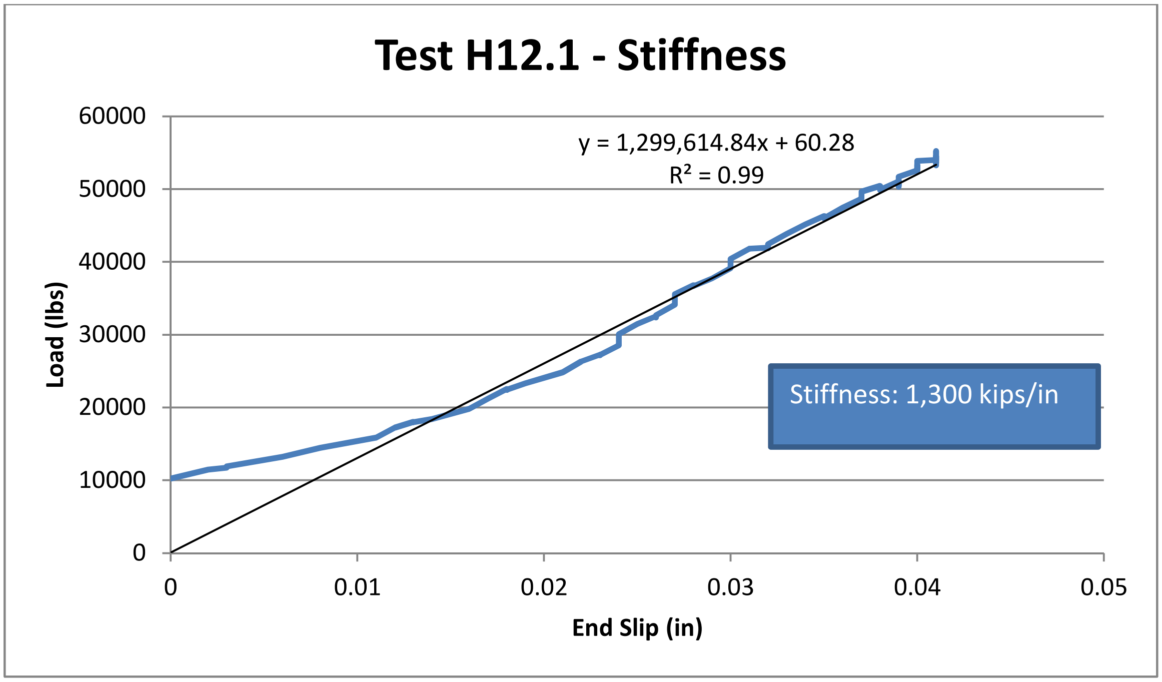


Figure 39 - H12.1 Stiffness.

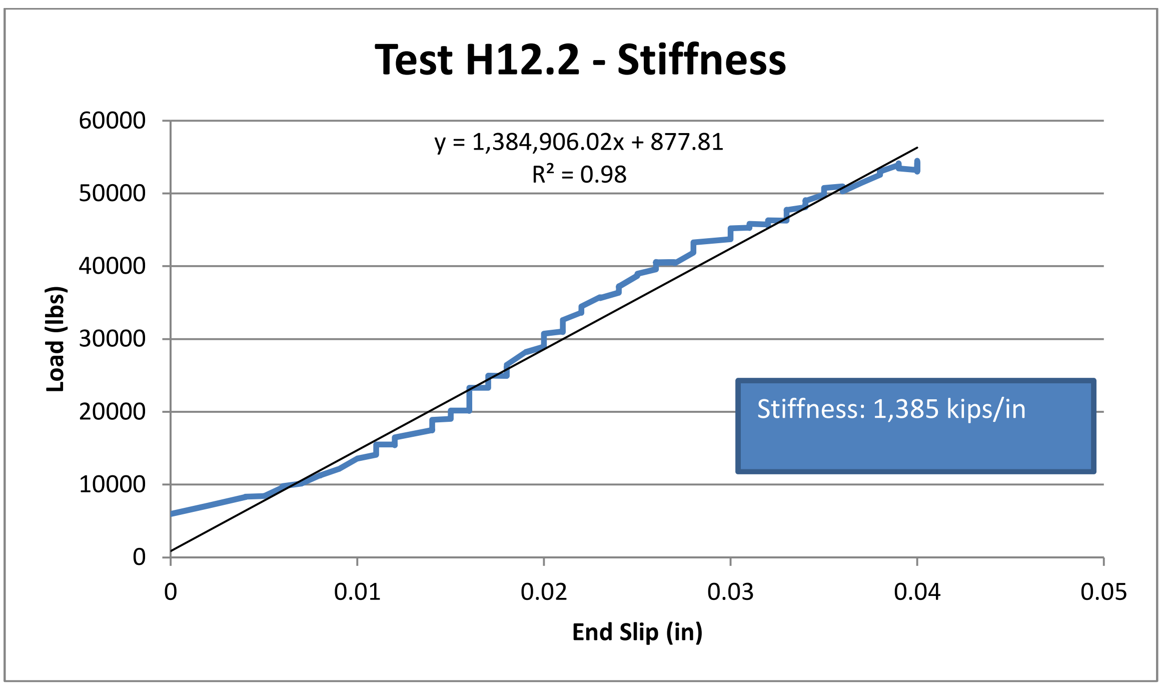


Figure 40 - H12.2 Stiffness.

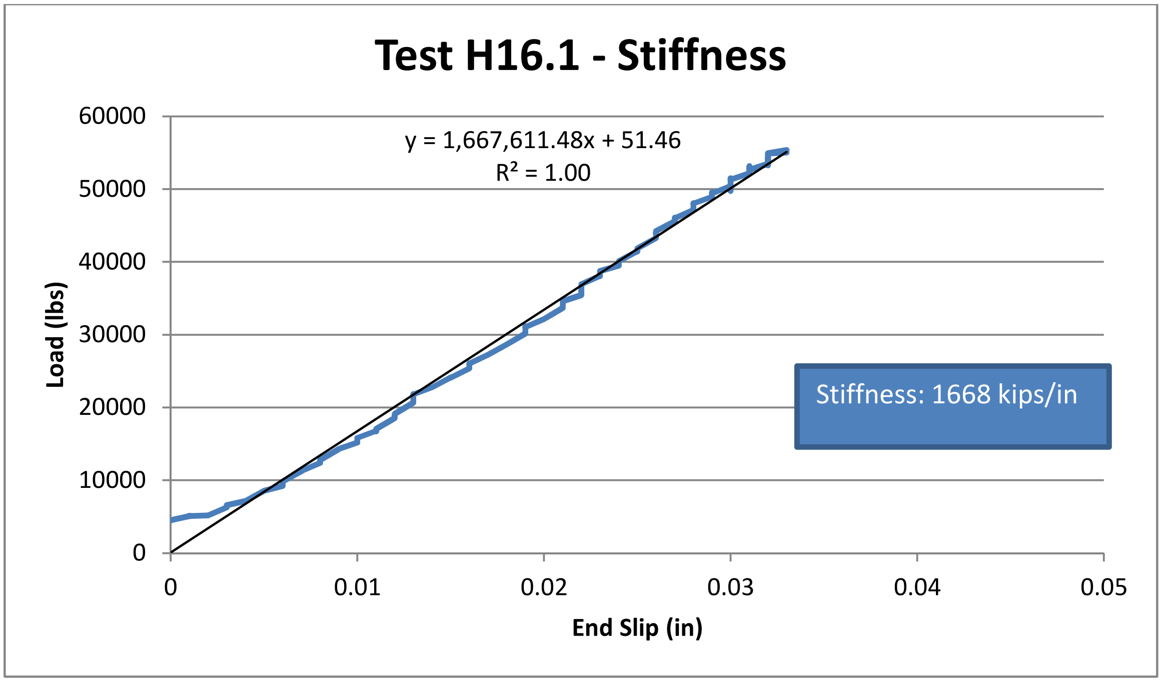


Figure 41 - H16.1 Stiffness.

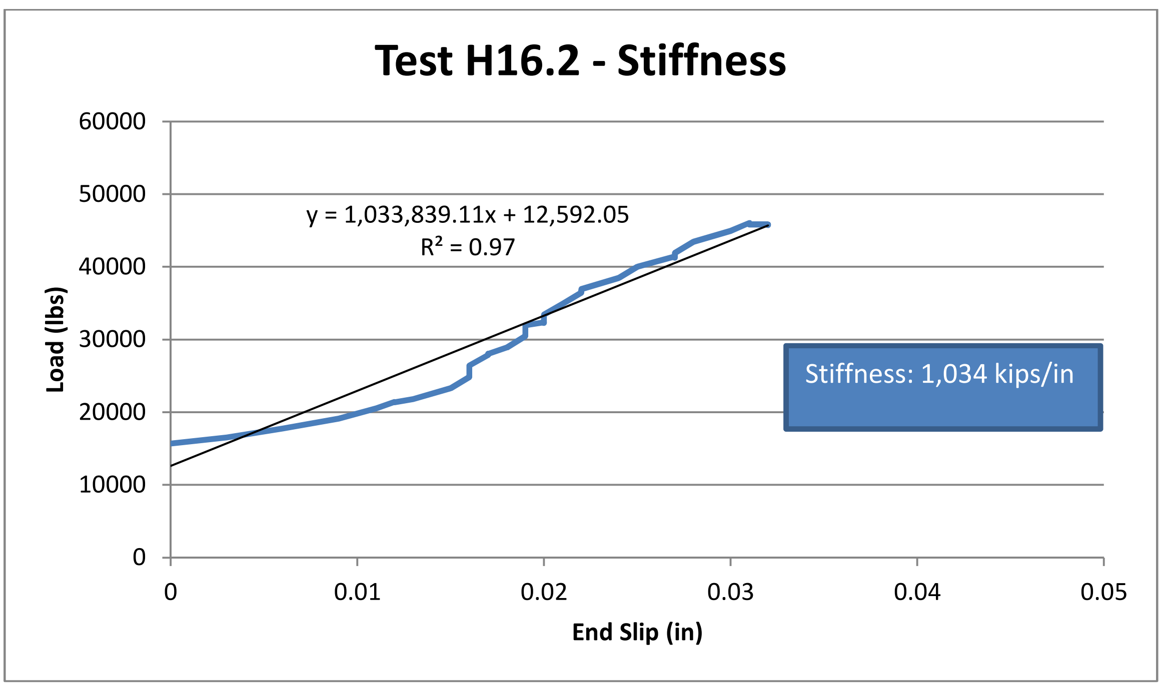


Figure 42 - H16.2 Stiffness.

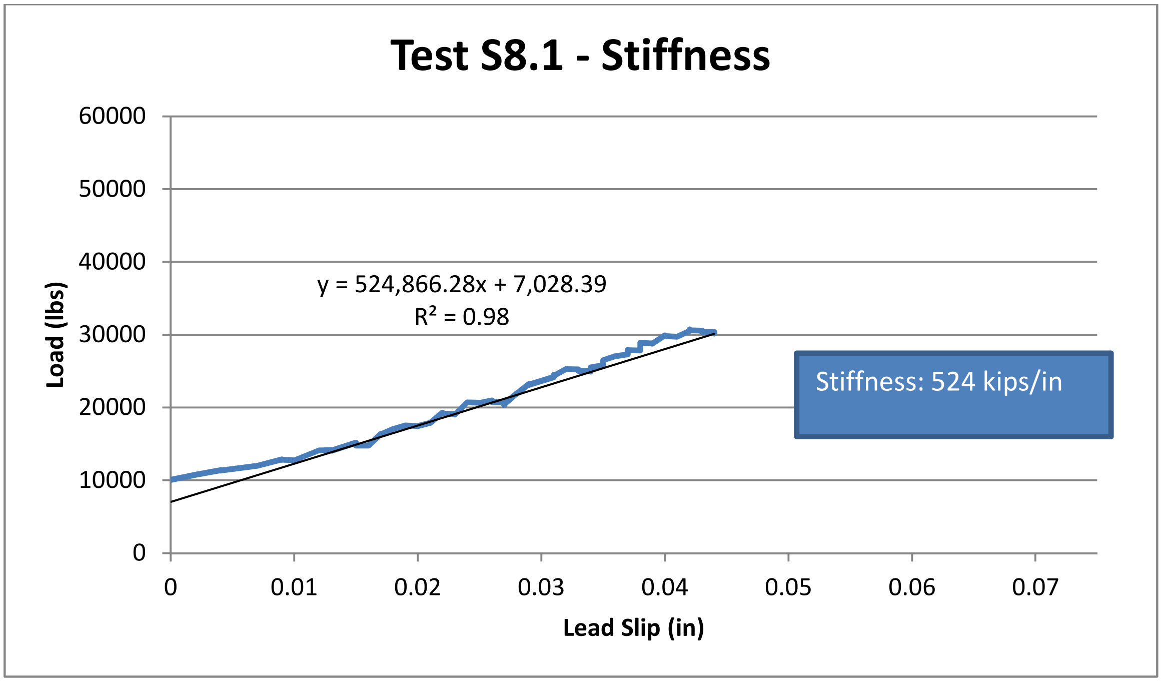


Figure 43 - Straight Bar With 8" Bond Length and 1" Cover - Reached Failure on First Cycle.

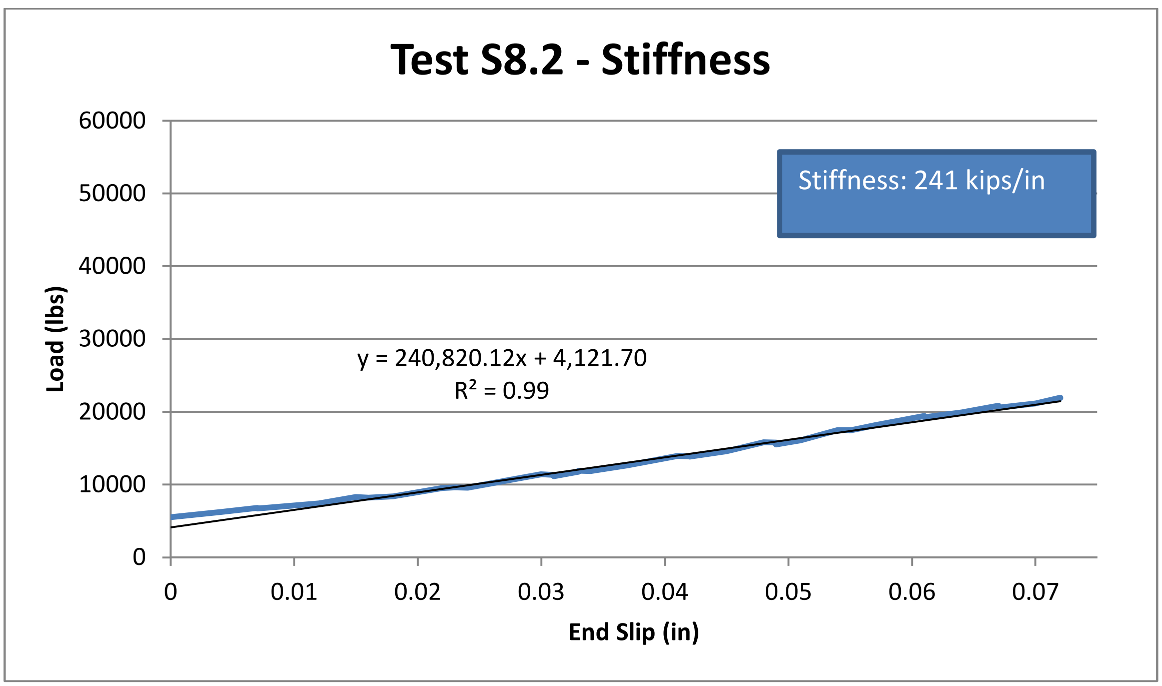


Figure 44 - Straight Bar With 8" Bond Length and 2" Cover - Reached Failure on First Cycle - LVDT Reached Full Stroke During Test Without Being Reset.

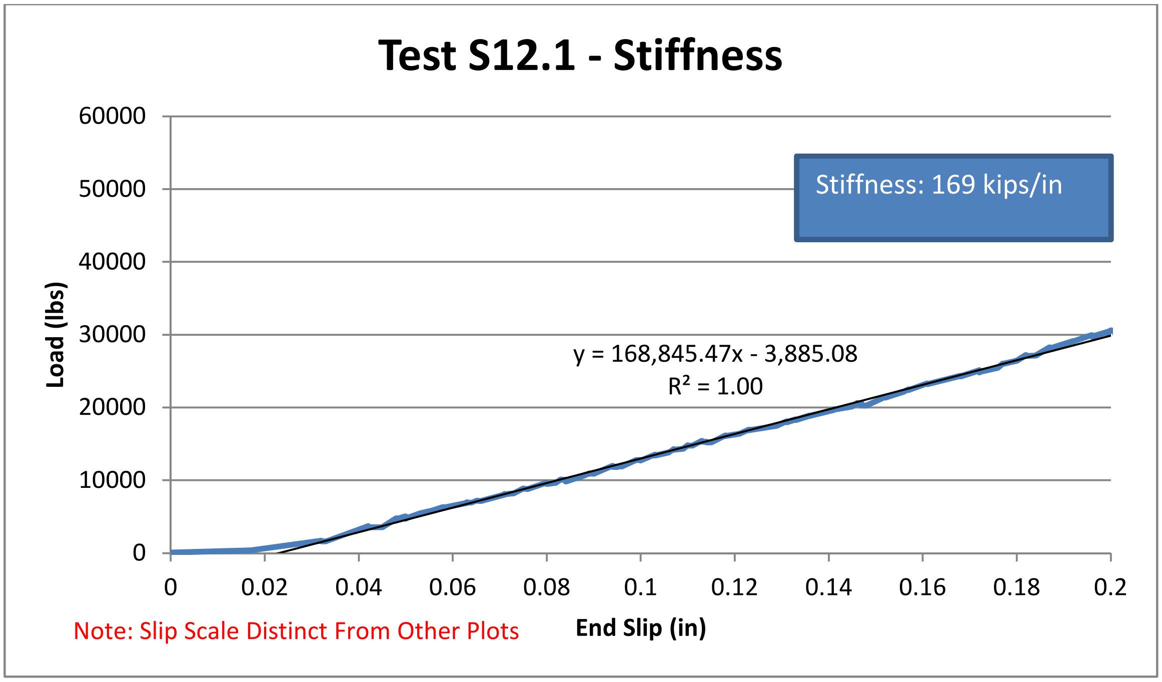


Figure 45 – Straight Bar With 12" Bond Length and 1" Cover – Reached Failure on First Cycle.

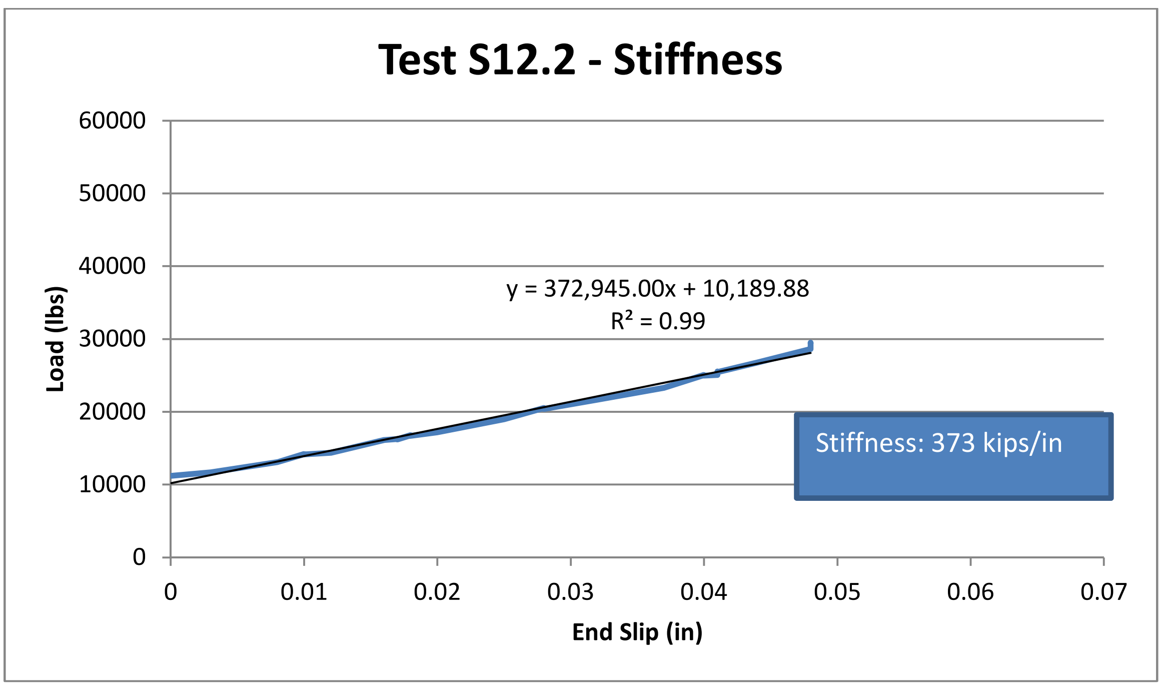


Figure 46 - Straight Bar With 12" Bond Length and 2" Cover - LVDT Reached Full Stroke During Test Without Being Reset.

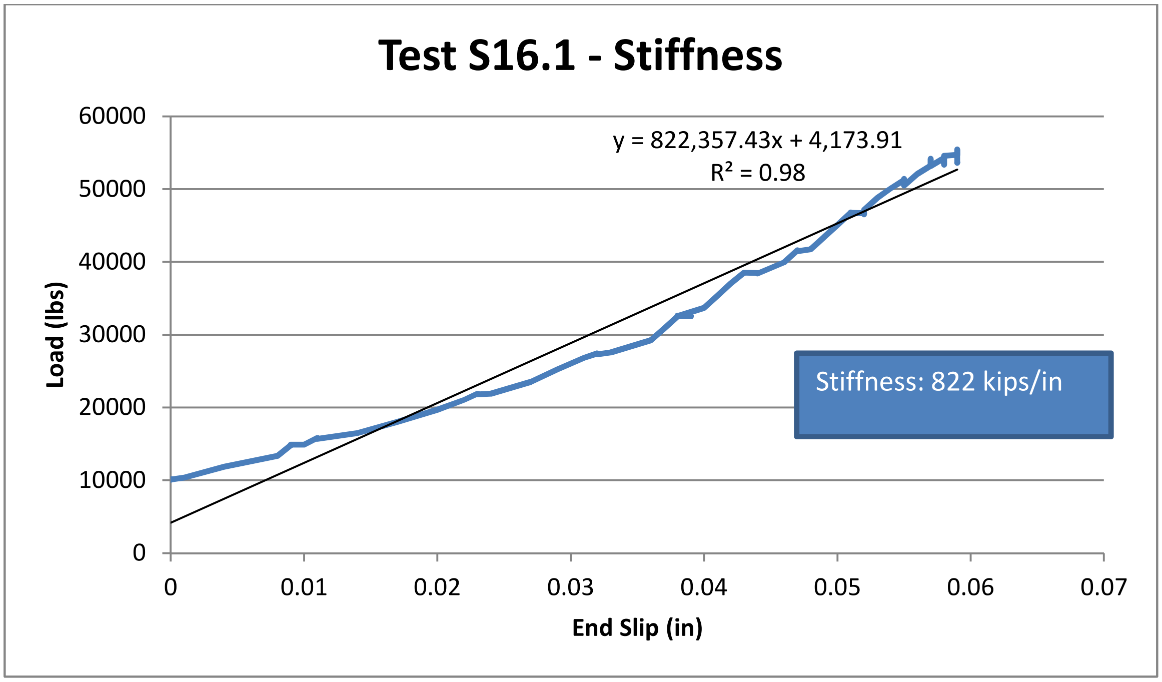


Figure 47 - Straight Bar With 16" Bond Length and 1" Cover.

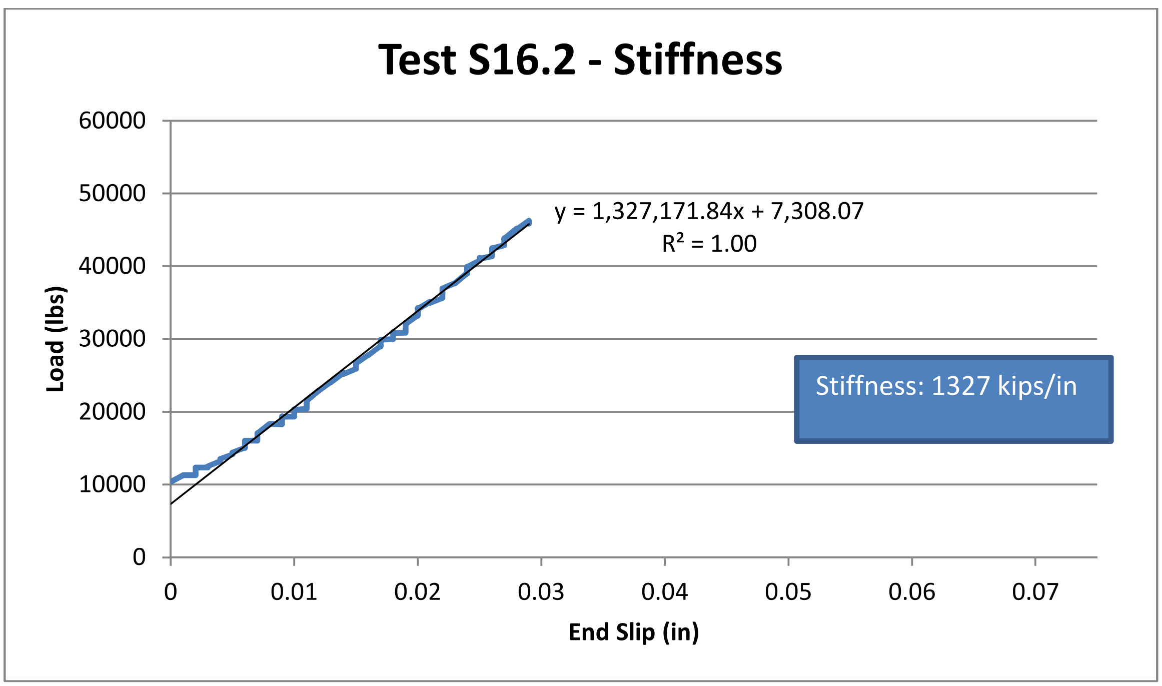


Figure 48 - Straight Bar With 16" Bond Length and 2" Cover.

5.3 Load Distribution

The strain gauges were placed at the end of the developed rebar and the start of the hook, as seen in Figure 49. The total tensile load on the rebar was recorded by the load cell. Using the stress-strain relationship and the area of the rebar, the load carried by the hook of the rebar can be calculated. Taking the total load and removing the load carried by the hook will provide the load carried by the developed rebar. Using this information, a graph can be created for each test showing the relationship between carrying capabilities of the developed bar and the hook (see Figure 51 through Figure 56).

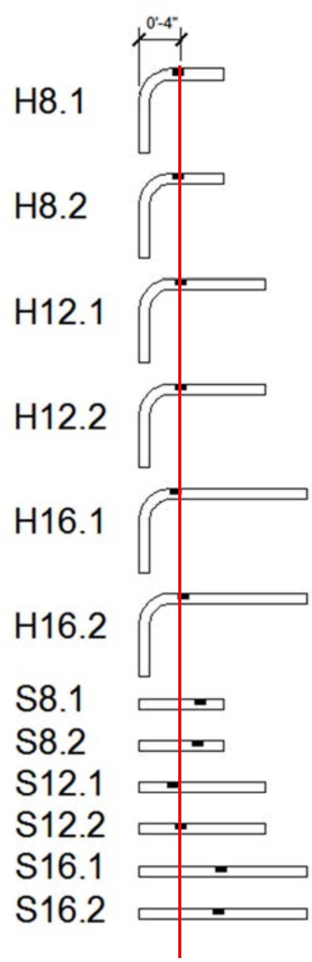


Figure 49 - Strain Gauge Locations.

All strain gauges were placed near the hook end as seen in Figure 50. The strain gauges on the straight bars were located in approximately the same location as the corresponding hook bar. The strain gauge on Test H16.1 was the only exception, being accidentally located closer to the hook end than in Test H16.2.

Figure 50 - Example Strain Gauge Location.

Using the strain data, the modulus of elasticity of steel, and the area of the bar, the load can be found at the location of the strain gauge. This load value represents the load carried by the hook or end portion of the bar. Subtracting this value from the total load will obtain the load carried in the bonded length or lead portion of the bar. The load distribution between the hook and bond at 90% Yield (42.5 kips) can be seen in Table 9. The relationship between the load carrying capabilities of the bonded length and the hook are shown in Figure 51 through Figure 56.

Table 9 - Failure Mode and Load Distribution of Specimens.

Test Number	Failure Mode	Ultimate Load (lbs)
H8.1	Plastic	55,127
H8.2	Plastic	55,225
H12.1	Plastic	55,225
H12.2	Plastic	54,492
H16.1	Plastic	55,371
H16.2	Yield	46,387

	Force Carried at 90% Yield (42.5k)	
Test Number	By Hook (lbs)	By Bond (lbs)
H8.1	33,489	9,011
H8.2	26,319	16,181
H12.1	17,836	24,664
H12.2	15,795	26,705
H16.1	8,880	33,620
H16.2	2,879	39,621

	Percent Carried at 90% Yield (42.5k)	
Test Number	By Hook	By Bond
H8.1	78.80%	21.20%
H8.2	61.93%	38.07%
H12.1	41.97%	58.03%
H12.2	37.16%	62.84%
H16.1	20.89%	79.11%
H16.2	6.77%	93.23%

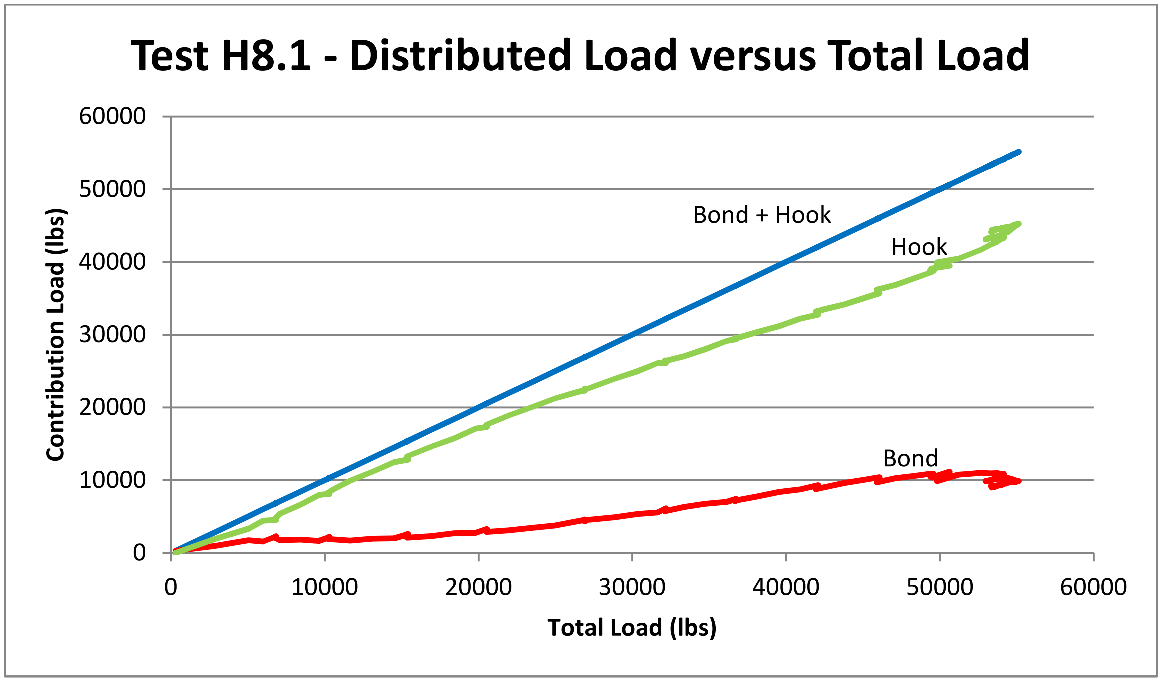


Figure 51 - Bond and Hook Distributed With 8" Bond Length and 1" Cover.

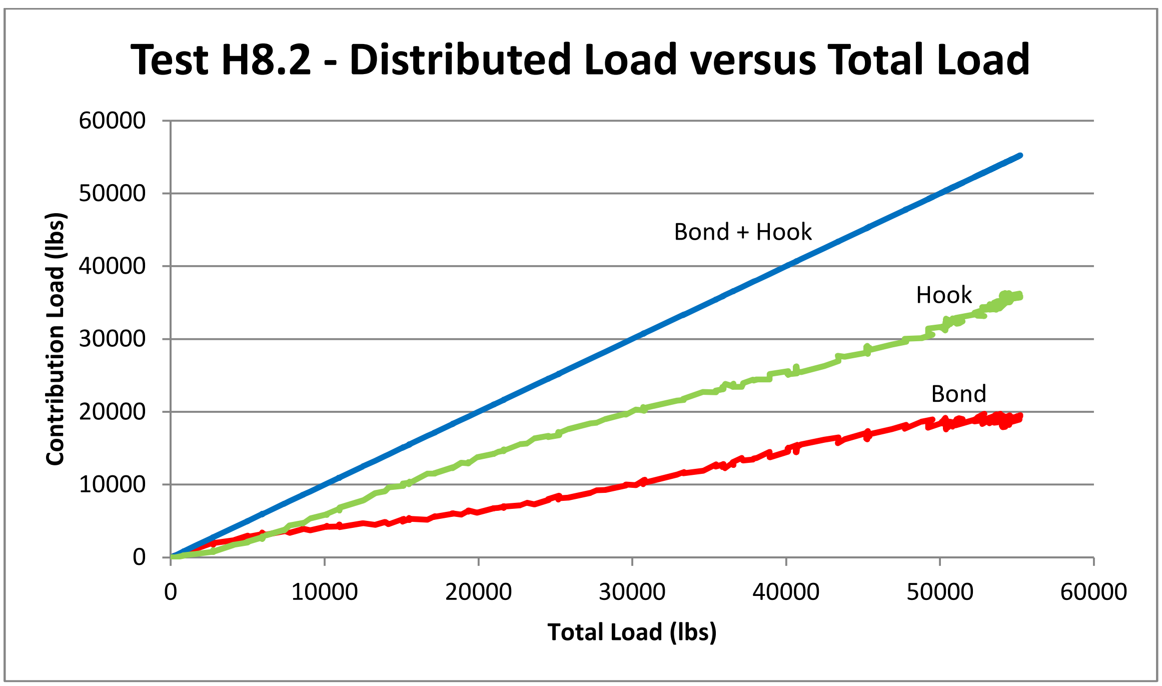


Figure 52 - Bond and Hook Distributed With 8" Bond Length and 2" Cover.

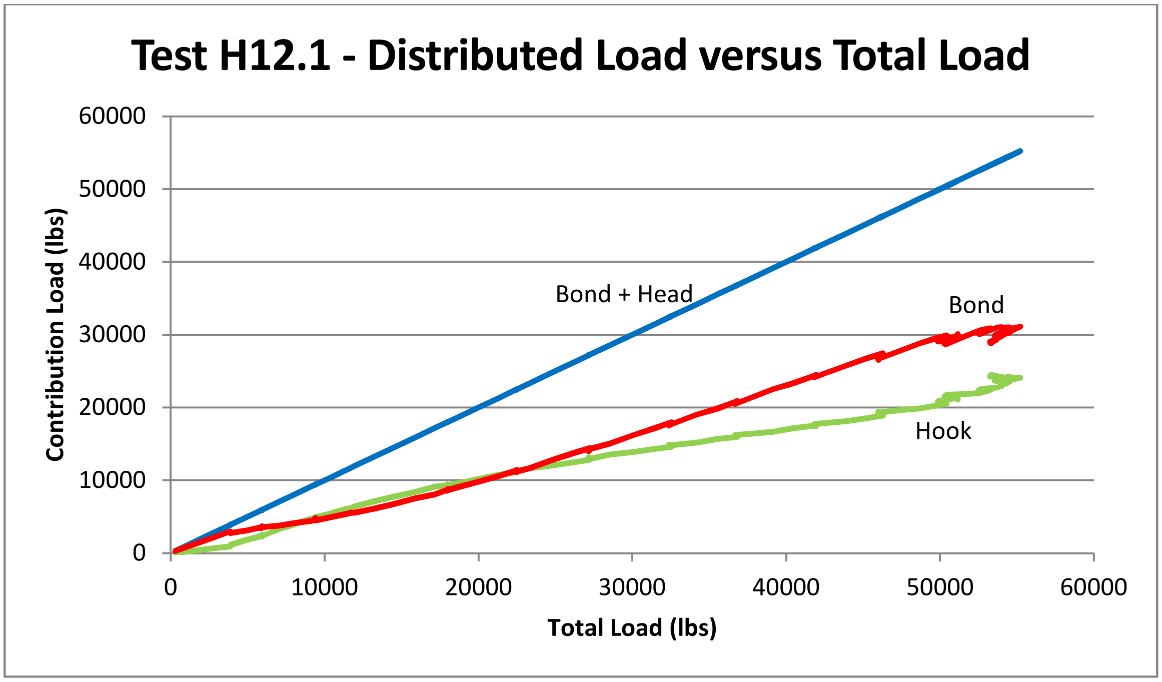


Figure 53 - Bond and Hook Distributed With 12" Bond Length and 1” Cover.

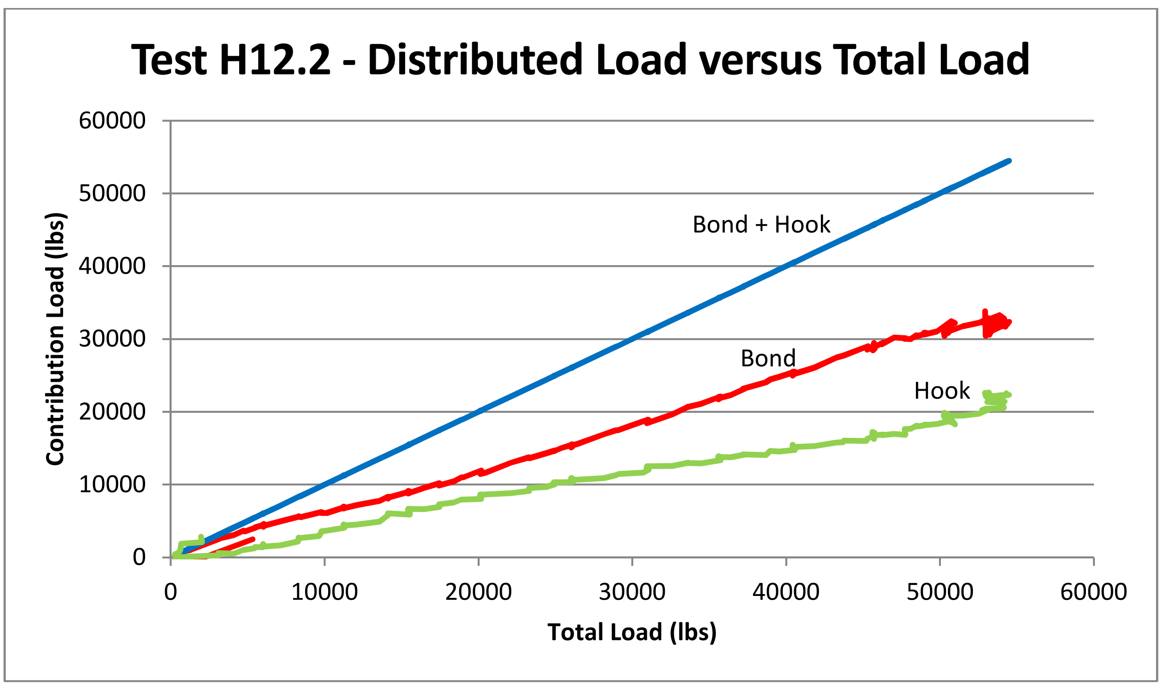


Figure 54 - Bond and Hook Distributed With 12" Bond Length and 2" Cover.

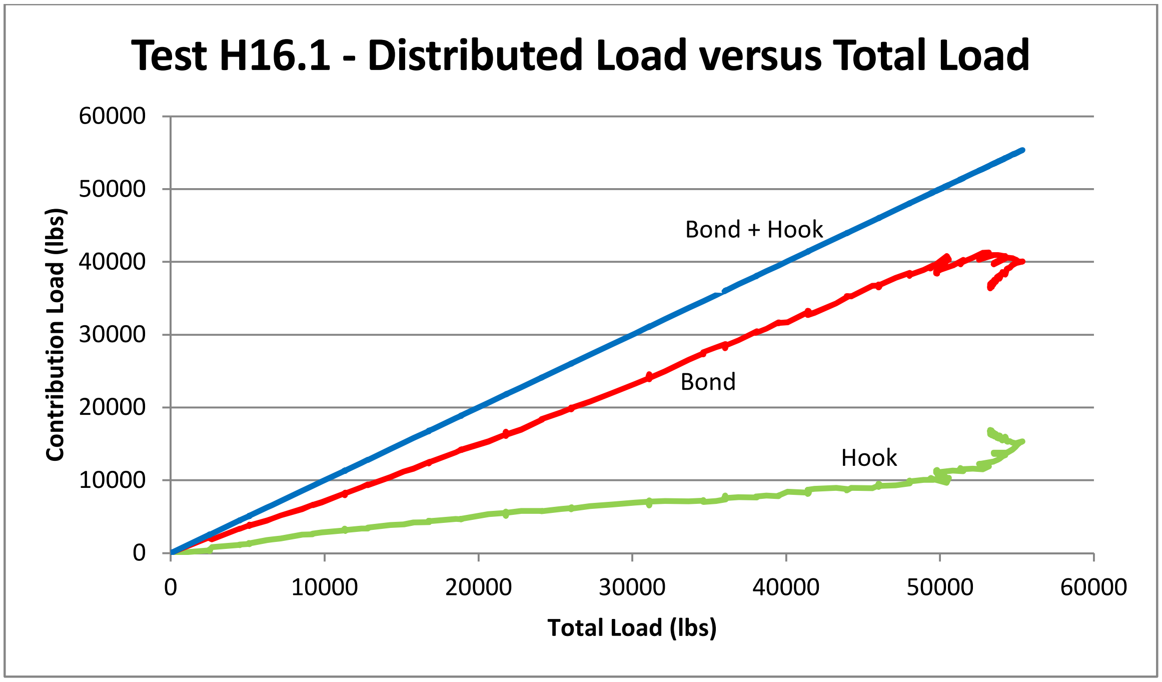


Figure 55 - Bond and Hook Distributed With 16" Bond Length and 1” Cover.

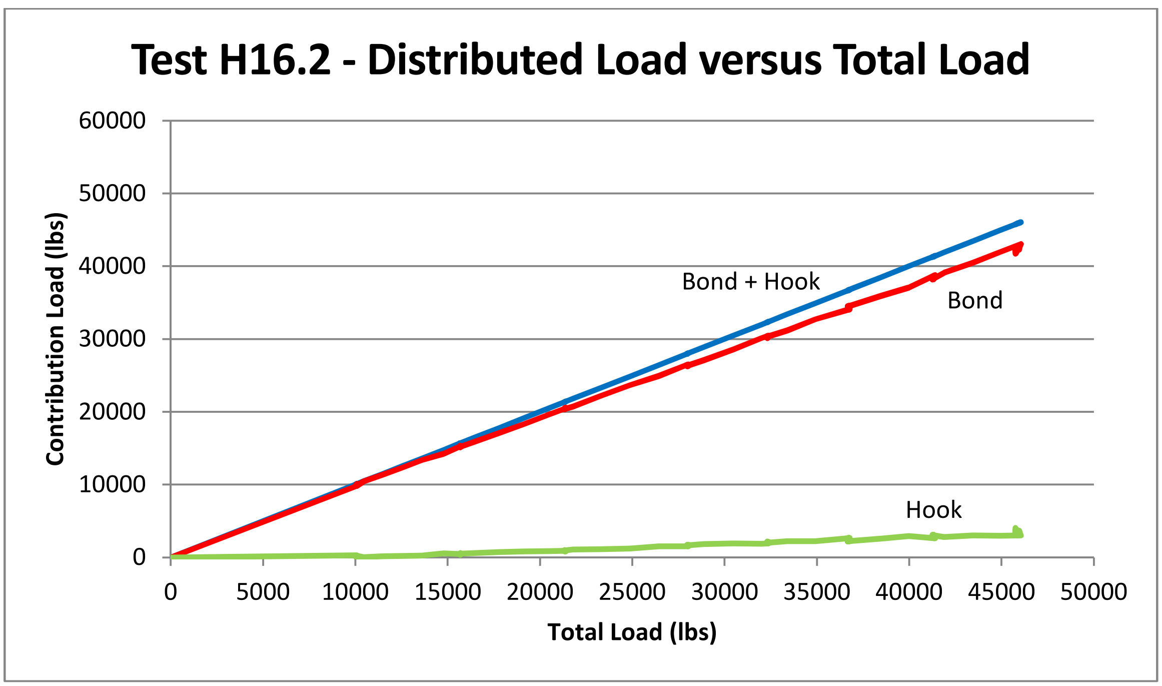


Figure 56 - Bond and Hook Distributed With 16" Bond Length and 2" Cover.

CHAPTER 6 – DISCUSSION

6.1 Introduction

The effect of the variables on specimen strength, stiffness, and load distribution are discussed in this section. Many of the specimens reached steel yield and were loaded into the plastic range. Only three specimens exhibited a concrete failure: S8.1, S8.2, and S12.1. This result makes it difficult to adequately compare the specimen strength. The results are also compared with Blau's headed bars, since headed bars and hooked bars may behave similarly [3]. Finally, the results are compared to results obtained from the literature review.

6.2 Effect of Variables on Strength

6.2.1 Hook Bar Strength Versus Straight Bar Strength

Most of the tests reached yield and were loaded into the plastic range. It is not useful to compare the ultimate loads since test termination after yield was not decided experimentally. Test S8.1, Test S8.2, and Test S12.1 were the three tests that failed before reaching yield, seen in Figure 57 and Figure 58. The hooked bar with 8 inches of bonded length reached yield where the straight bar failed about 20 kips under yield. This result shows that the addition of a hook allows the 8- and 12-inch bonded length bars to reach yield. However, this increase in strength cannot be accurately defined because the comparable hooked bars reached yield.

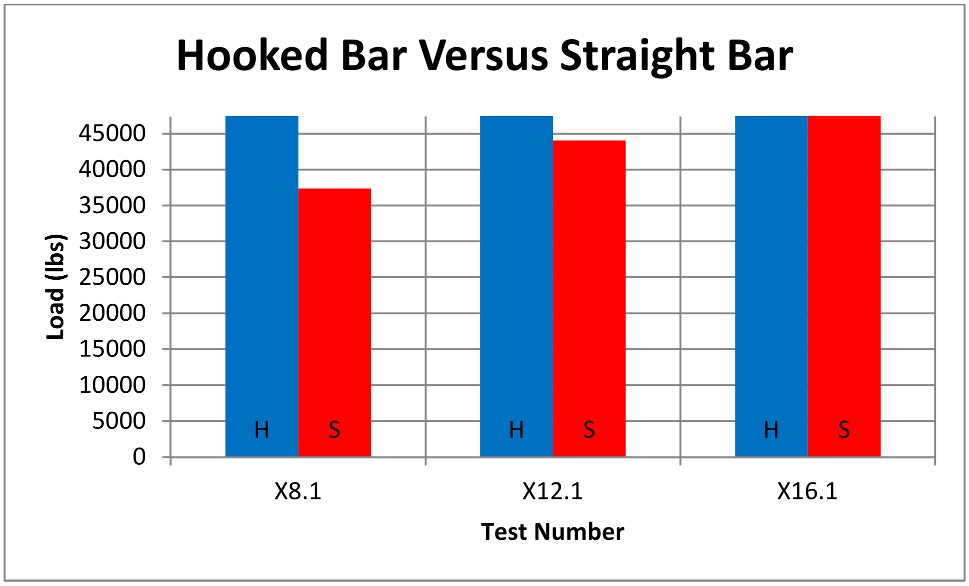


Figure 57 - Hooked Bar versus Straight Bar with 1” Cover.

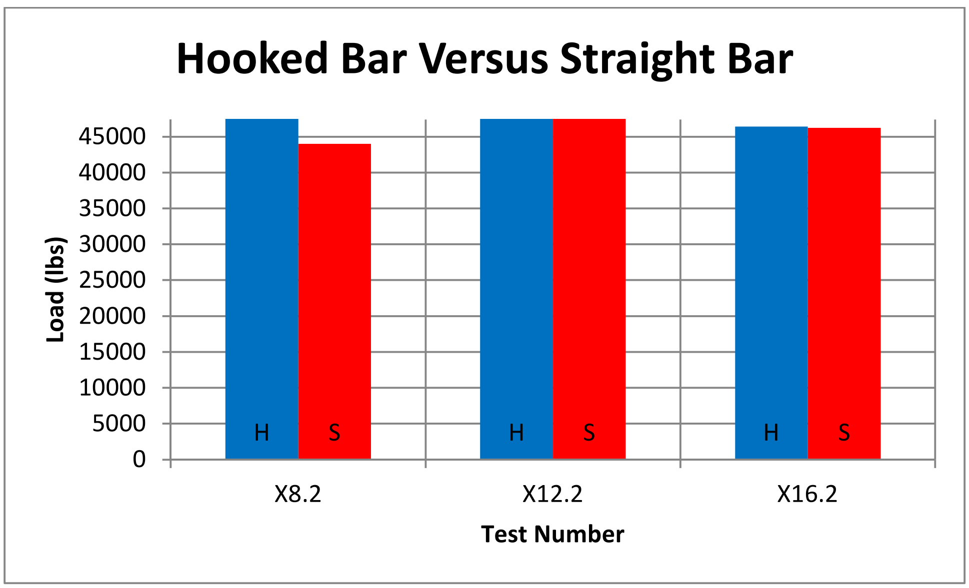


Figure 58 - Hooked Bar versus Straight Bar with 2” Cover.

6.2.2 Effect of Bonded Length on Strength

The effect of bonded length on strength can be seen in Figure 59 and Figure 60. The increase in strength due to bonded length was difficult to observe since all of the hooked bars reached yield. The straight bars with 1-inch cover displayed the most observable increase.

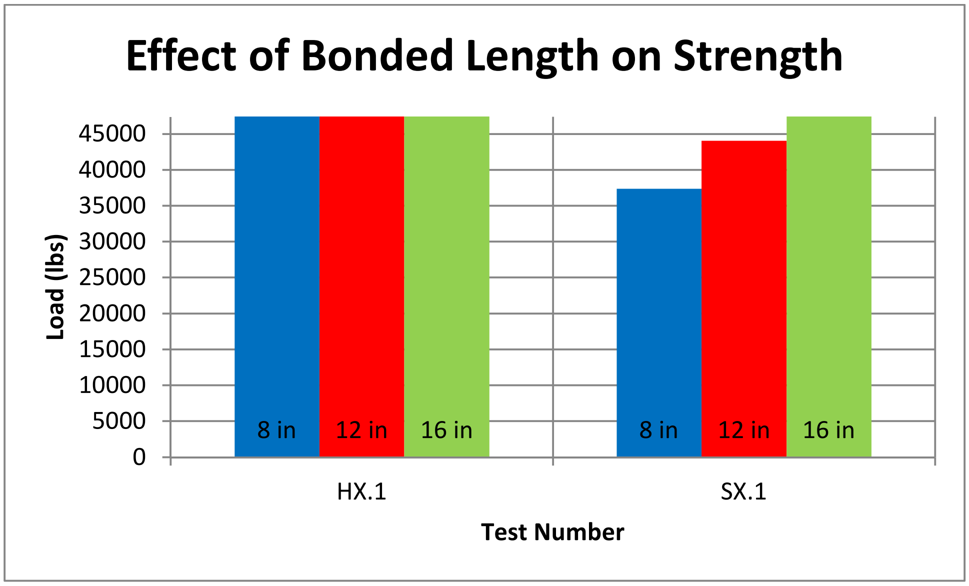


Figure 59 - Effect of Bonded Length on Strength With 1" Cover Specimens.

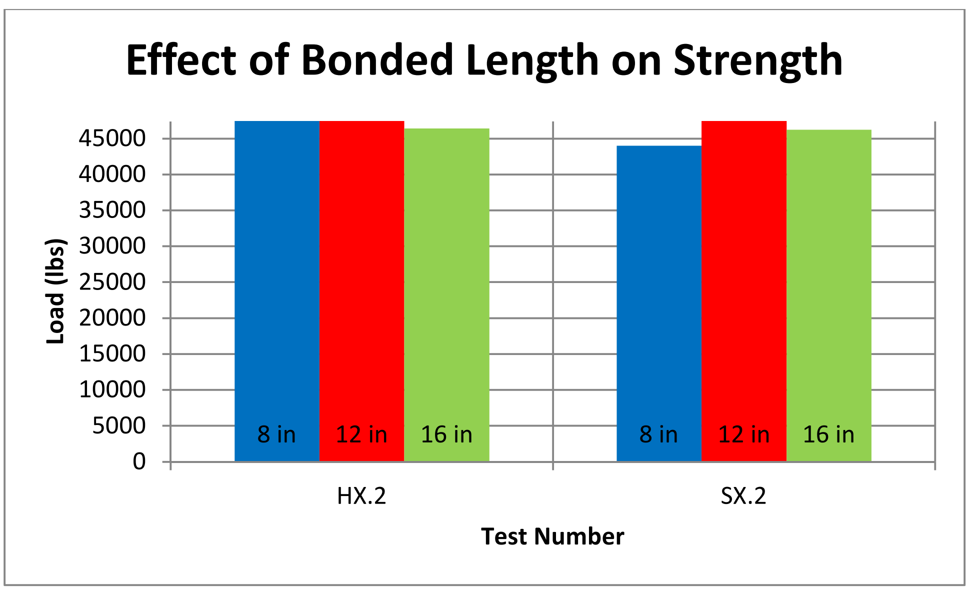


Figure 60 - Effect of Bonded Length on Strength With 2" Cover Specimens.

6.2.3 Effect of Cover on Strength

The only observable increase in strength is seen in the straight bar with 8 inches of bonded length. The increased cover added approximately 7 kips of strength, seen in Figure 61. The rest of the specimens reached yield or near yield, so no viable conclusions can be drawn. The effect of cover on strength for 8, 12, and 16 inches of bonded length can be seen in Figure 61, 62, and 63, respectively.

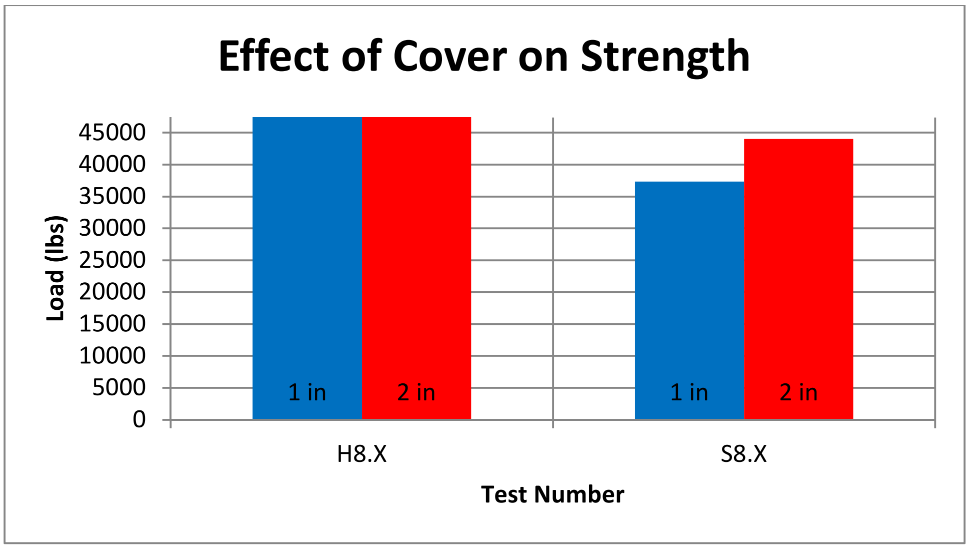


Figure 61 - Effect of Cover on Strength for 8” Bonded Length.

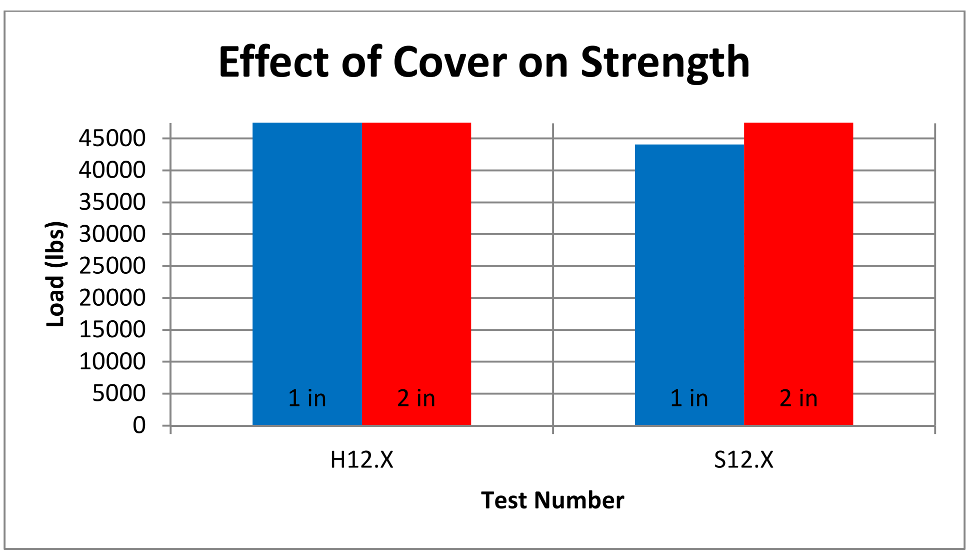


Figure 62 - Effect of Cover on Strength for 12” Bonded Length.

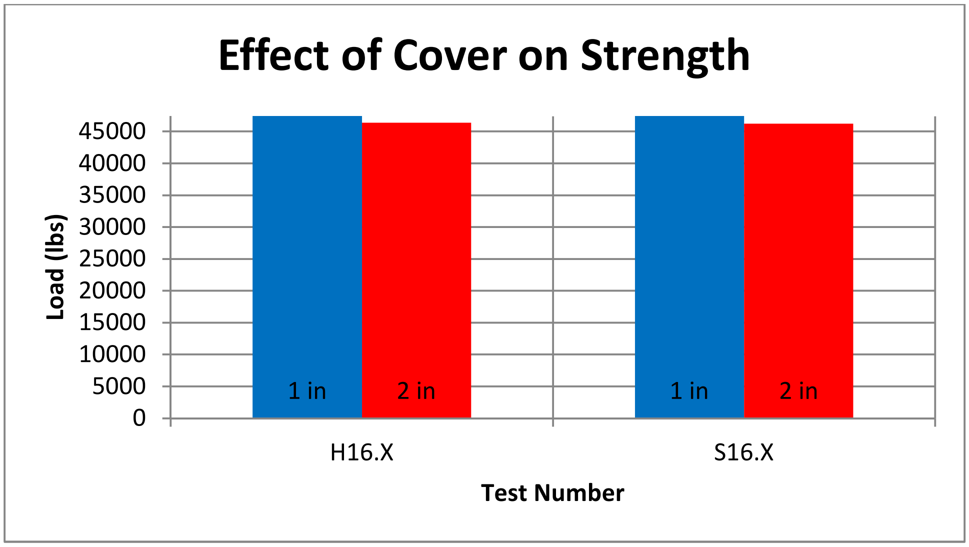


Figure 63 - Effect of Cover on Strength for 16" Bonded Length.

6.2.4 Comparison to ACI

The American Concrete Institute (ACI) defines the development length as the length of bar required to reach yield. The length is defined for both straight bars and hooked bars. To compare these values to those in this report, a ratio is created from the bonded lengths used in the specimens divided by the development length required by ACI. Multiplying this ratio by the yield load (i.e. 47.4 kips) calculates the amount of load the bonded length can carry as defined by ACI.

The hooked bars and straight bars in this report are compared to the ACI load in Figure 64 and Figure 65. The experimental results are significantly greater in every test. The three straight bar tests each experienced a splitting failure with values that were 72% to 82% greater than the values calculated from the ACI development length requirement.

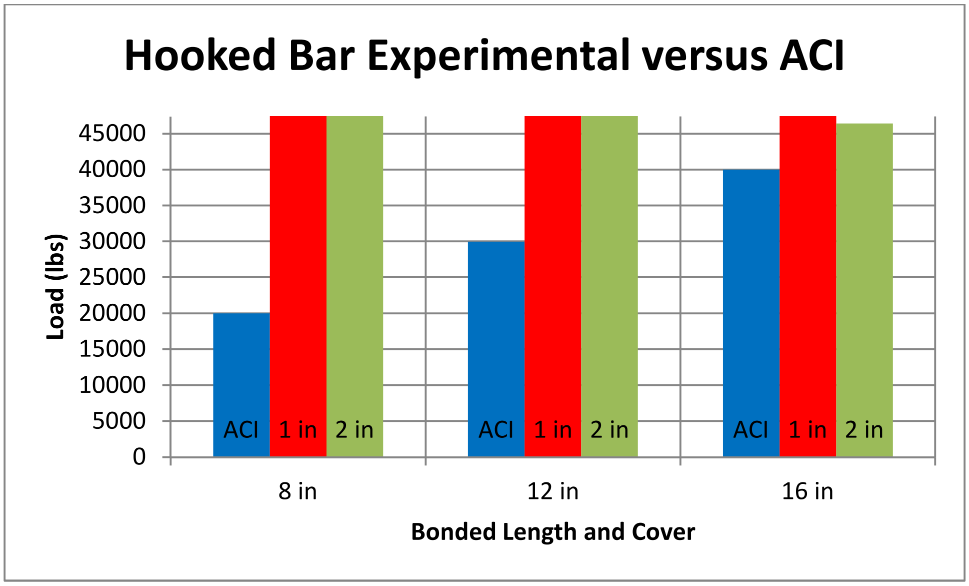


Figure 64 - Strength of Experimental Hooked Bars versus ACI Developed Bars.

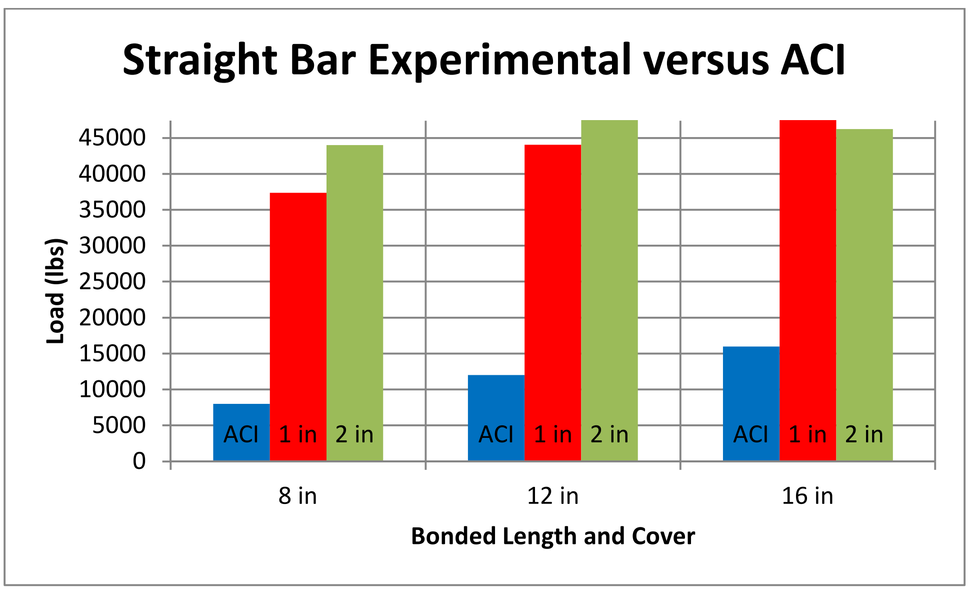


Figure 65 - Strength of Experimental Straight Bars versus ACI Developed Bars.

6.3 Effect of Variables on Stiffness

6.3.1 Hook Bar Stiffness Versus Straight Bar Stiffness

The hooked bar stiffness versus the straight bar stiffness can be seen in Figure 66 and Figure 67. The hooked bars are stiffer than the straight bars in every instance, except for H16.1 which is smaller than S16.1, seen in Figure 67.

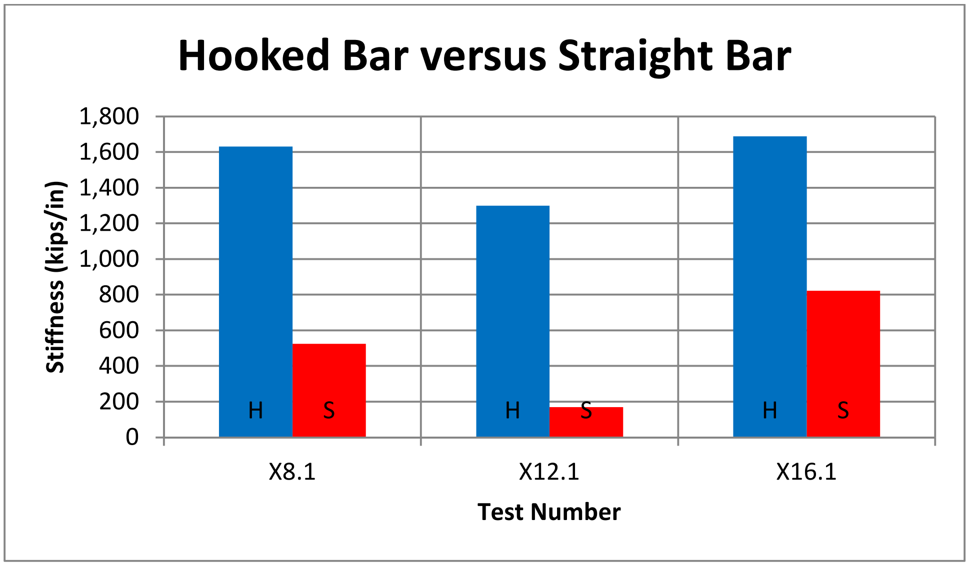


Figure 66 - Hooked Bar Stiffness versus Straight Bar Stiffness for 1" Cover.

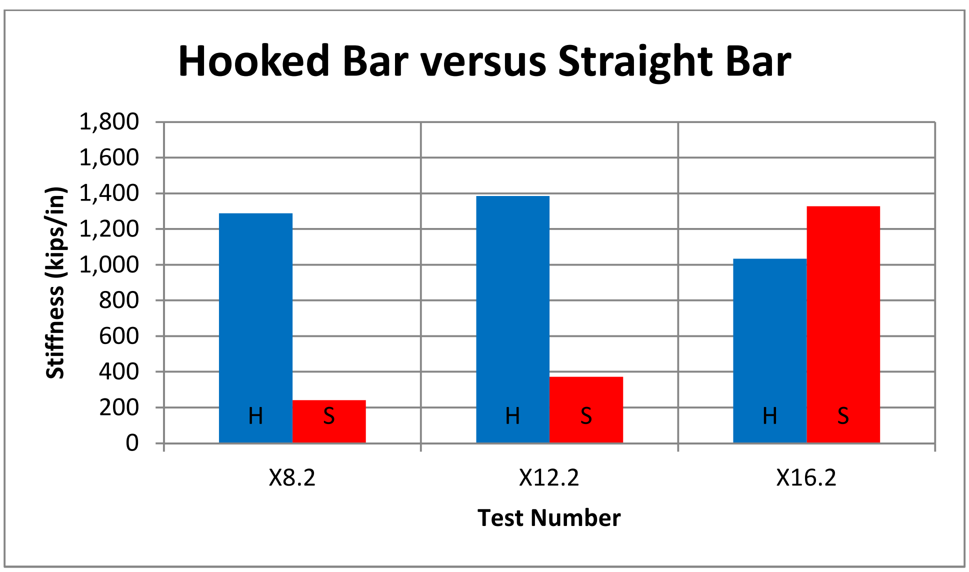


Figure 67 - Hooked Bar Stiffness versus Straight Bar Stiffness for 2" Cover.

6.3.2 Effect of Bonded Length on Stiffness

The effect of bonded length on stiffness can be seen in Figure 68 and Figure 69. No pattern appears to develop in the stiffness values.

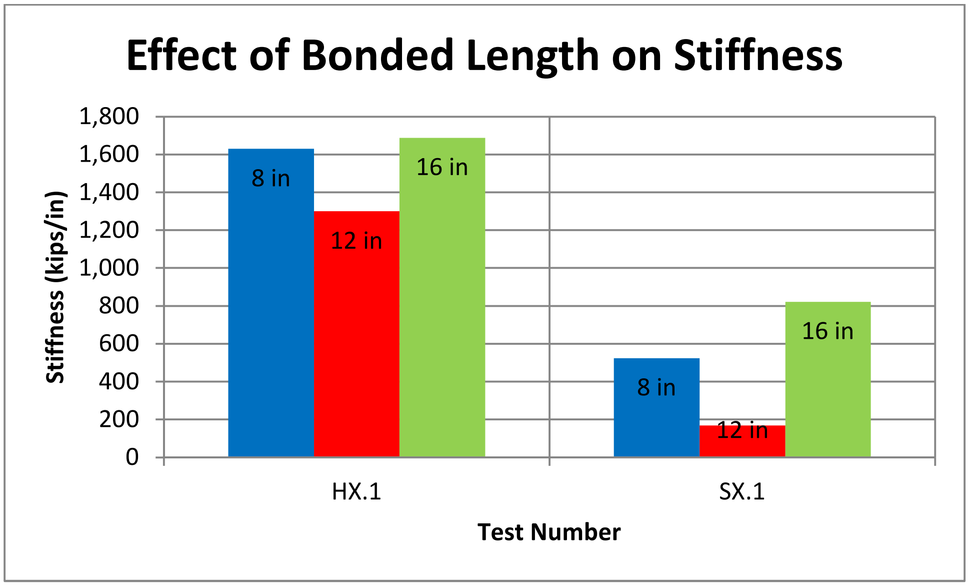


Figure 68 - Effect of Bonded Length on Stiffness for 1” Cover.

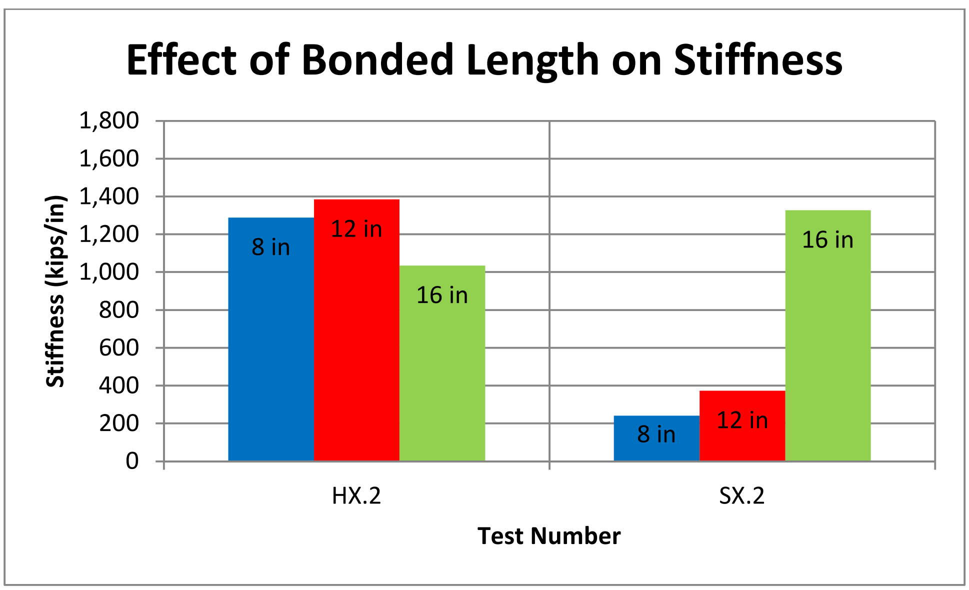


Figure 69 - Effect of Bonded Length on Stiffness for 2” Cover.

6.3.3 Effect of Cover on Stiffness

The effect of cover on stiffness can be seen in Figure 70, 71, and 72. The cover in these specimens did not seem to have a consistent effect on the stiffness.

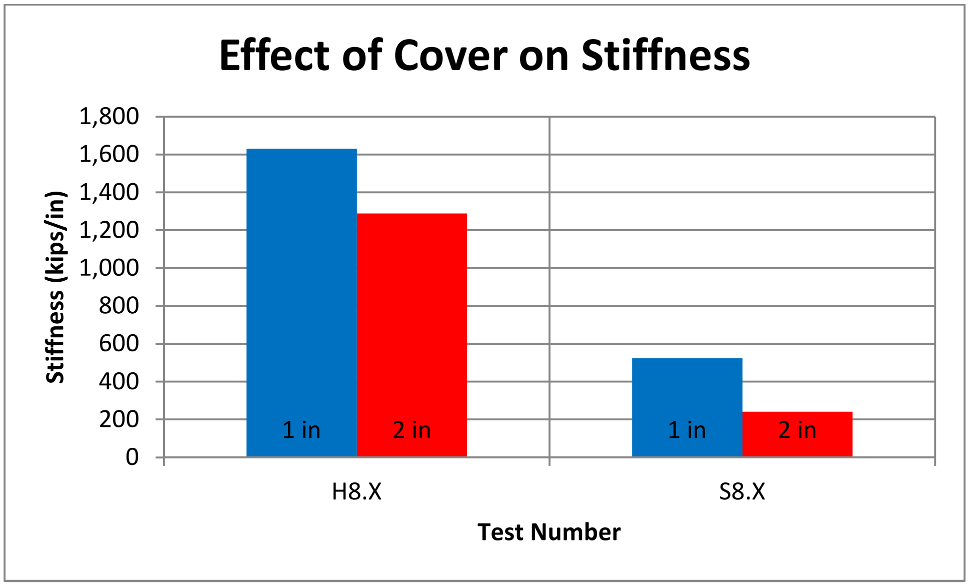


Figure 70 - Effect of Cover on Stiffness for 8" Bonded Length.

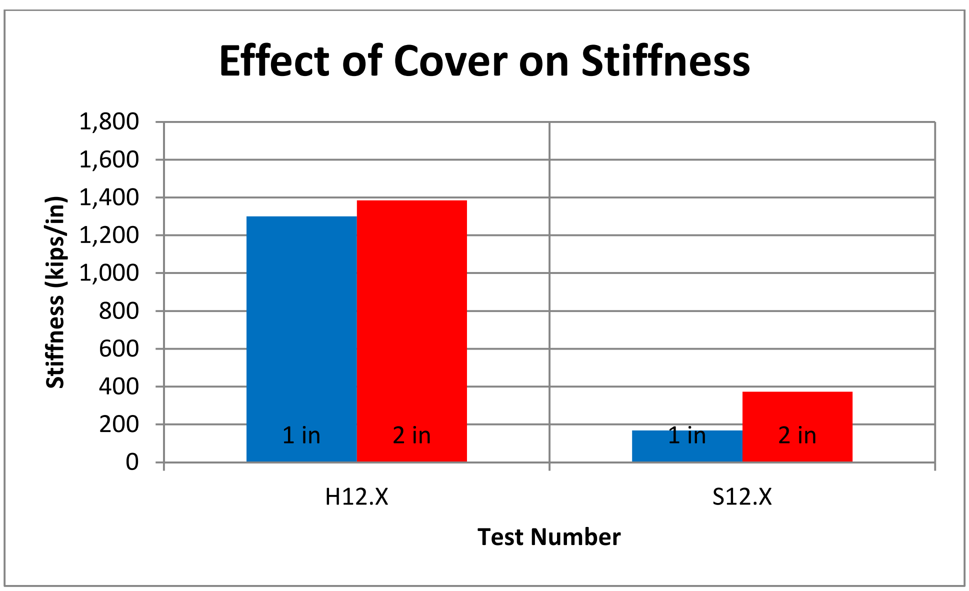


Figure 71 - Effect of Cover on Stiffness for 12" Bonded Length.

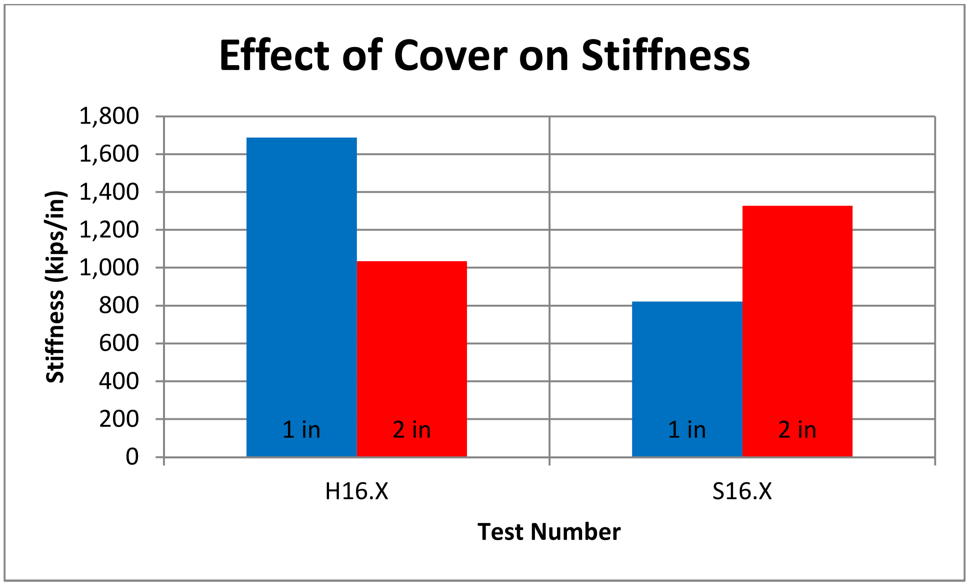


Figure 72 - Effect of Cover on Stiffness for 16" Bonded Length.

6.4 Effect of Variables on Load Distribution

6.4.1 Effect of Bond Length on Load Distribution

It is known that as bonded length and cover increase that the load carrying capability also increases. With the strain gauge measurements, just the load carried by the initial bonded length or just the load carried by the hook end, can be observed. The effect of the bonded length can be seen in Figure 73, separated by 1-inch cover and 2-inch cover. As the initial bonded length increases, the load carried by this portion increases. The greatest increase can be seen from 8-inch bonded length to 12-inch with 1 inch of cover (i.e. Test H8.1 to Test H12.1). With shorter bonded lengths, the hook takes the greatest portion of load.

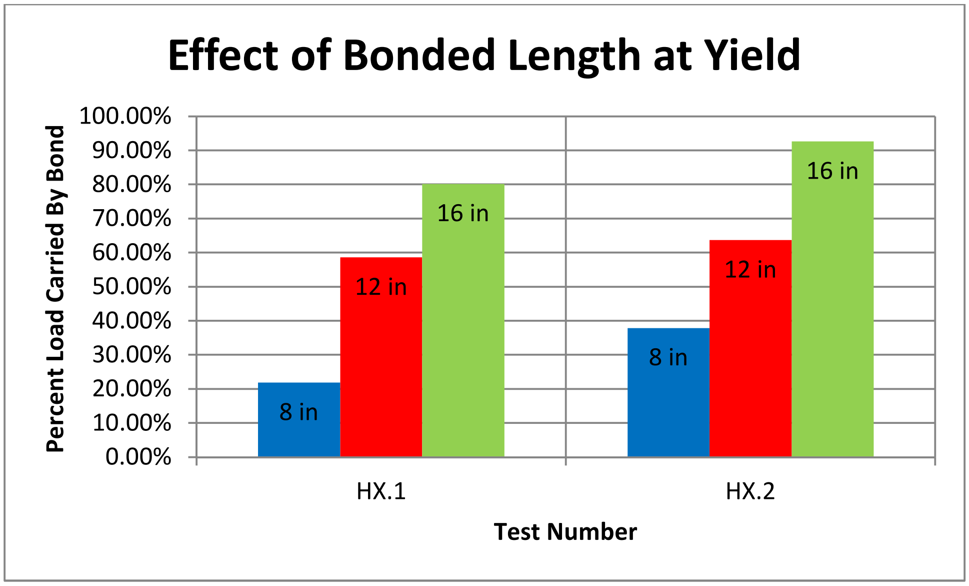


Figure 73 - Load Distribution Affected By Bonded Length at Yield.

The load carried by the bonded length or hook changes based on the applied load. Two additional figures were created to show the effect at 90% yield and 35 kips, seen in Figure 74 and 75. Test S8.1 failed at a load of 37,354 lbs; therefore, 35,000 lbs can also be used when comparing hooked bars to straight bars. For most of the specimens, the change in load carried by the bonded length is negligible.

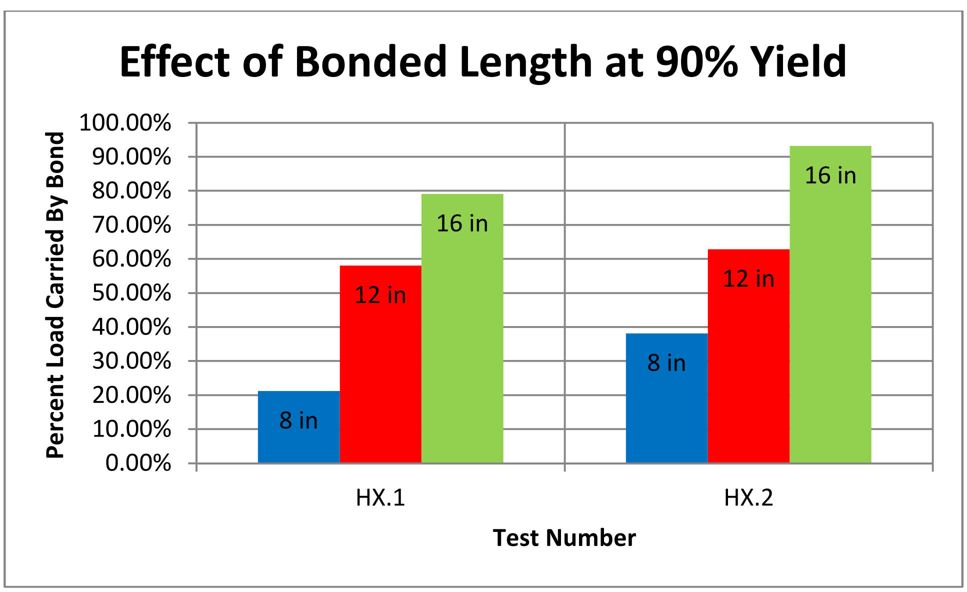


Figure 74 - Load Distribution Affected By Bonded Length at 90% Yield.

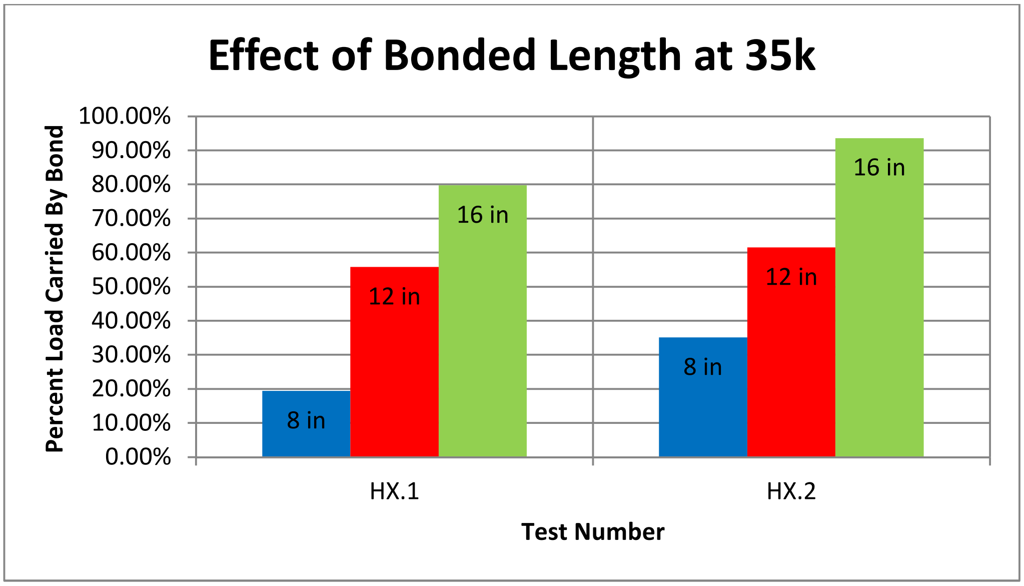


Figure 75 - Load Distribution Affected By Bonded Length at 35k.

6.4.2 Effect of Cover on Load Distribution

Much like the increase in bonded length, the increase in cover allows the specimen to carry greater load. This increase can be seen in Figure 76. The figure is separated into the three separate bonded lengths: 8-inch, 12-inch, and 16-inch. In the shorter bonded length, the hook takes the greatest portion of the load. With the added cover, the bonded length starts to take more of this load. In the longer bonded lengths, the increase in percentage of load carried by the bond is less noticeable. The increase of bonded length has a much greater effect on the magnitude of increase in percentage of load carried by the bonded length (see Figure 73 compared to Figure 76).

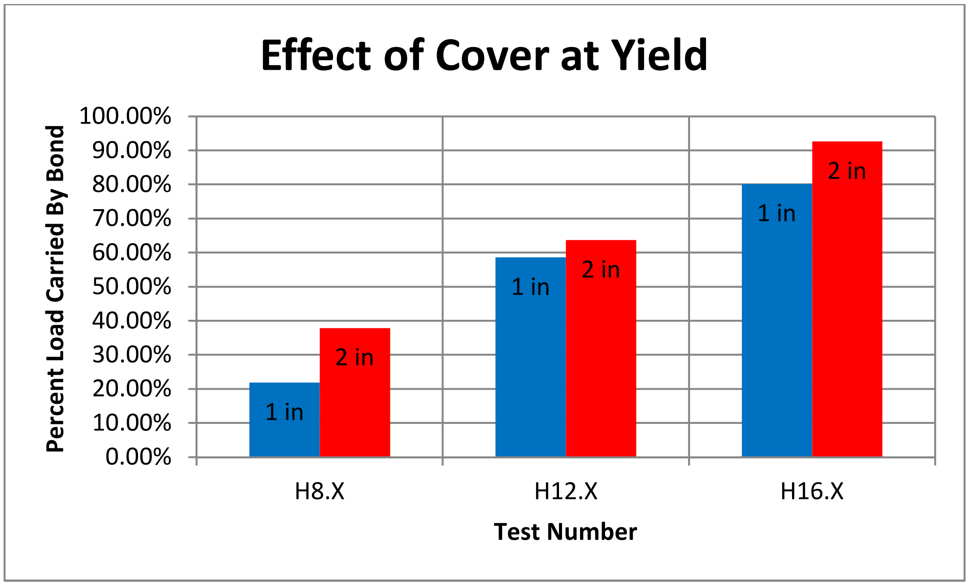


Figure 76 - Load Distribution Affected By Cover at Yield.

Much like the effect of bonded length, it is worthwhile to compare the load distribution between the hook and bonded length at different loads. The effect of cover can be seen at 90% yield and 35 kips in Figure 77 and 78. In every specimen, an increase in cover increases the percentage of load carried by the bond; however, the increase in bond length has a greater effect on this increase.

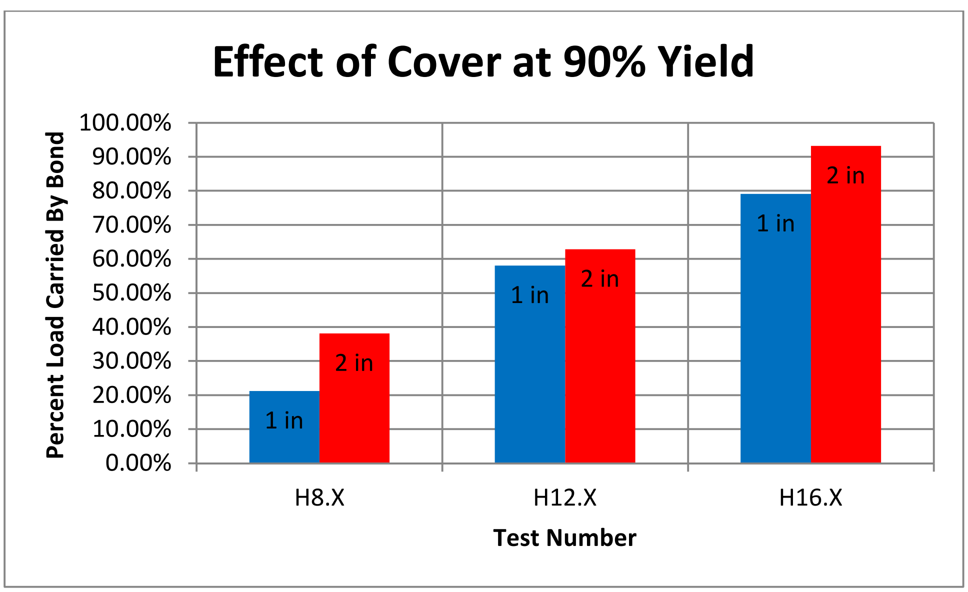


Figure 77 - Load Distribution Affected By Cover at 90% Yield.

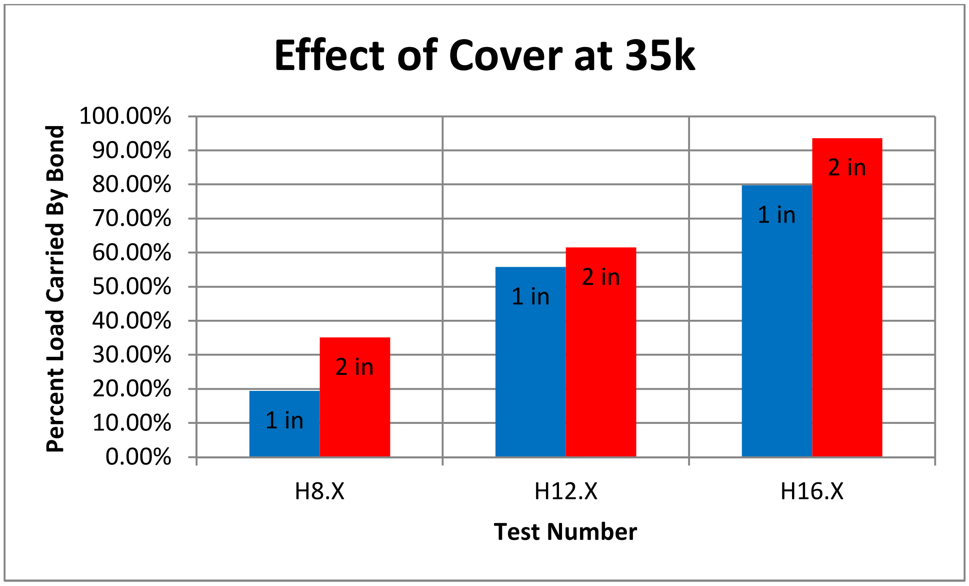


Figure 78 - Load Distribution Affected By Cover at 35k.

6.5 Hooked Bars Versus Headed Bars

During the testing for this report, Blau did concurrent testing of headed rebar [3]. It is useful to compare the behavior of headed bars and hooked bars. Blau tested headed bars with 8 or 16 inches of bond length with 1 or 2 inches of cover. He also varied the size of the head itself. Blau's test results can be seen in Table 10. The minimum failure load was 45.5 kips; therefore, 45 kips will be used to compare the bars. Blau used three head sizes for each bond length and cover variable. Each of the 8- or 16-inch bonded length specimens in this report are compared to three of Blau's specimens.

Table 10 - Headed Bar Specimen Test Data [3].

Specimen	Failure Mode	Failure Load (lbs)	Head Contribution at: ** Failure Load (%)	90% Failure Load (%)	45,000 pounds (%)	Contribution Switch (%) †	Stiffness (lbs/in)	Straight Bar Failure Load (lbs)	Vs. Straight Bar ‡
9-16-1	Yield	52,661	12	7	7	N/A	755,787	55,469	D
9-8-1	Blowout	47,852	94	79	87	6	1,427,452	37,354	I
6-16-1	Blowout	52,393	49	17	17	N/A	1,325,479	55,469	D
6-8-1	Blowout	51,123	85	72	79	3	1,135,804	37,354	I
3.5-16-1	Yield	53,223	15	8	8	N/A	1,036,177	55,469	D
3.5-8-1	Blowout	45,605	83	61	78	33	322,155	37,354	I
9-16-2	Yield	46,729	4	4	4	N/A	1,316,505	46,680	I ‡‡
9-8-2	Yield	54,883	69	57	63	7	674,357	43,994	I
6-16-2	Yield	45,459	3	3	2	N/A	1,110,272	46,680	D
6-8-2	Yield	45,557	63	56	60	8	784,875	43,994	I
3.5-16-2	Yield	45,557	4	4	4	N/A	1,012,538	46,680	D
3.5-8-2*	Yield	53,223	62	54	59	7	1,492,959	43,994	I

* Specimen experienced an abrupt removal of the tensile load applied to the headed bar which may have caused shock loading effects (see section 4.6 for further explanation).

** Values are the percentage of the total load on the headed bar that was resisted by the head at the given load. 45,000 pounds was used as a comparison point because it was the highest load all specimens reached.

† The Contribution Switch is the percentage of the failure load of the headed bar where the head began resisting more of the load than the bond. As such, this does not apply to the specimens where the bond resisted most of the total load for the entire test.

‡ The failure load for the specimen was compared to the failure load of a bar tested by Bolda [6] with the same bond length and clear cover. "D" indicates that the addition of the head decreased the failure load of the bar, while "I" indicates that the addition of the head increased the failure load of the bar.

‡‡ This increase is so small, that it may in fact be due to the irregularities inherent of concrete and if a duplicate specimen was tested, could very well result in a decrease which would fit the pattern.

Blau's testing returned similar results to the findings in this report. The effects of bonded length at 45 kips with 1- and 2-inch cover are shown in Figure 79 and Figure 80, respectively. While the area of the head seemed to have an effect, the percentage of load carried by the bonded length was similar for the headed bars. At shorter bonded length, Blau concludes that a larger head area increases the percentage of load carried by the head [3]. This effect is especially apparent in Test 9-8-1 compared to Test 6-8-1 and Test 3.5-8-1. In the 16-inch bonded length with 1-inch cover, the pattern of load distribution to the head is less apparent. The 2-inch cover specimens have more similar and consistent comparability. In all instances, the hook seems to behave most similar to the headed bars with $6A_b$ (i.e. Tests 6-X-X).

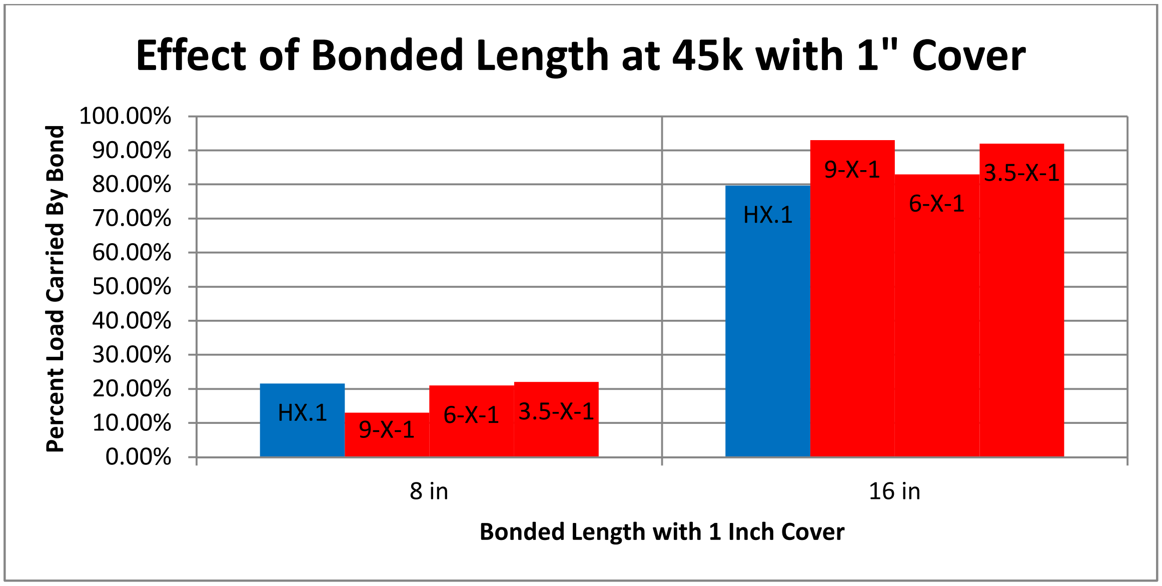


Figure 79 - Hooked Bar versus Headed Bar Varying Bonded Length with 1" Cover.

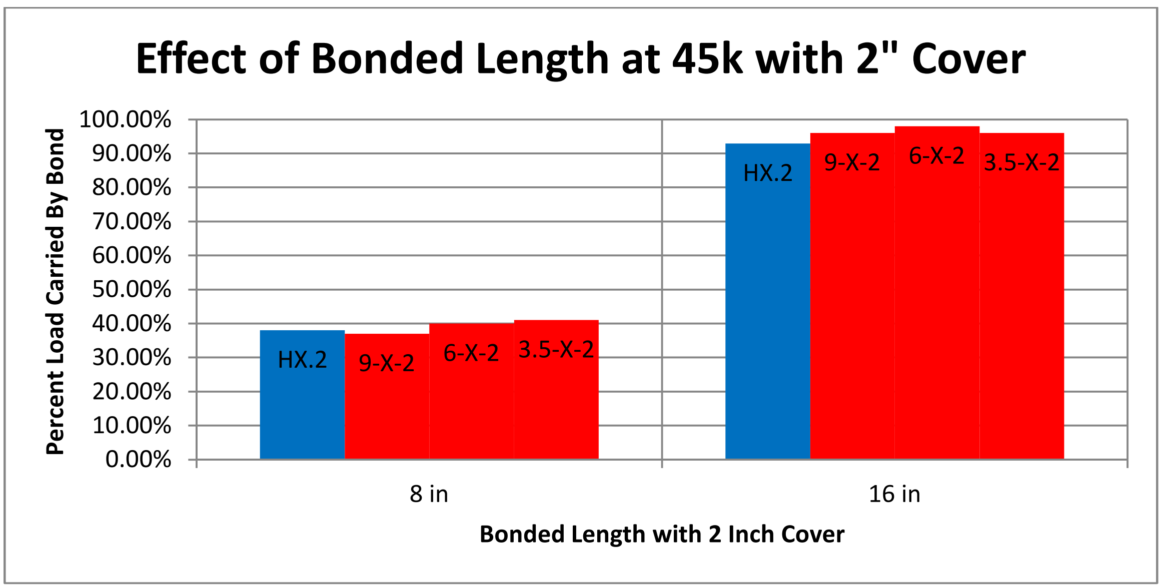


Figure 80 - Hooked Bar versus Headed Bar Varying Bonded Length with 2" Cover.

The effect of cover on the specimens with 8-inch bonded length and 16-inch bonded length are shown in Figure 81 and Figure 82, respectively. Comparing the specimens with 8-inch bonded length, the increase in cover has a smaller effect on the percentage of load carried by the bond than the bond length increase. The percentage carried by the bonded length increases less than 20% due to the increase of cover in all specimens, whereas, the increase in bonded length increases the percent of load carried by bond by at least 55% in all specimens.

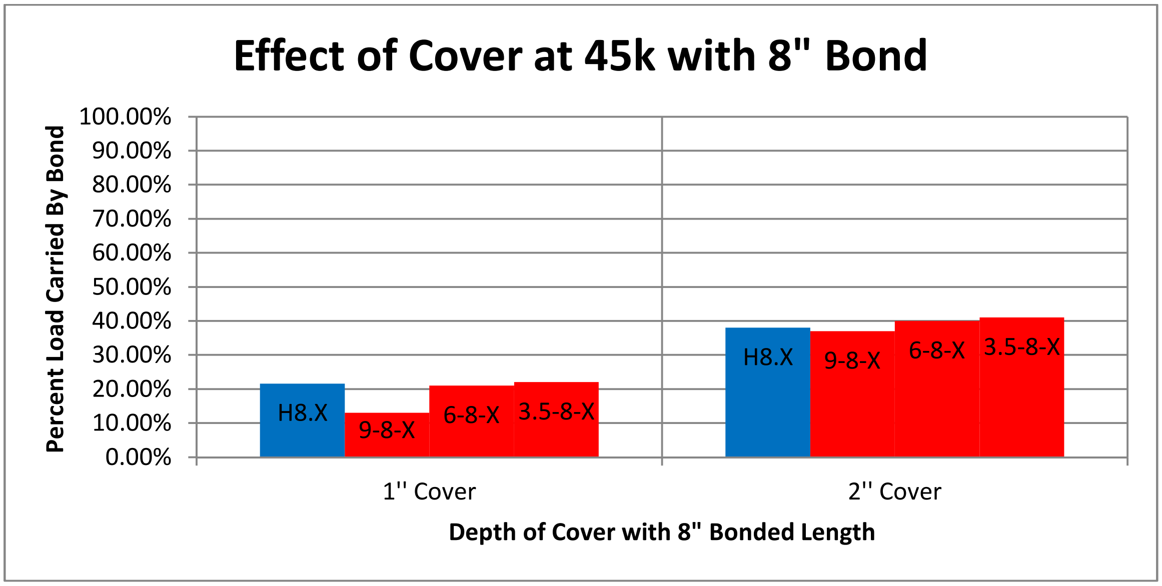


Figure 81 - Hooked Bar versus Headed Bar Varying Cover with 8” Bonded Length.

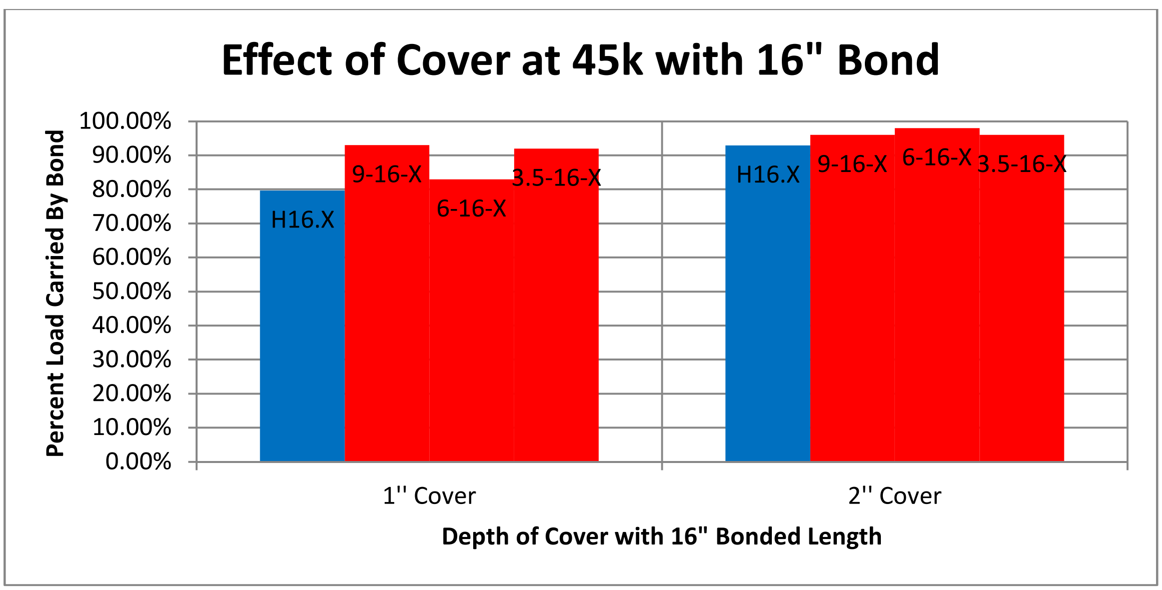


Figure 82 - Hooked Bar versus Headed Bar Varying Cover with 16” Bonded Length.

6.6 Comparing Test Results to Literature Review Data

Table 11 lists the results obtained in this investigation and Table 12 lists the results from the articles reviewed in Section 1.3 in a comparable form. Many differences in the data need to be highlighted. The stiffness values obtained in this capstone report were calculated using the end slip and a trendline drawn in Microsoft Excel®. The data in Table 12 were largely derived from the results tables in Section 1.3. The slip values from the literature review are lead slip values as designated in the test results tables.

In Jirsa and Minor, the maximum stress and the stress at 0.01 inches of slip were given [1]. The maximum load was derived from the area of the bar and the maximum stress. The stiffness was derived from the area of the bar and the stress at 0.01 inches of slip. In Jirsa and Marques, the values were derived in much the same manner, except the stress was listed at 0.005 inches, 0.016 inches, and 0.05 inches of slip with stresses for each. The slip at 0.016 inches was chosen to find the stiffness since this is the limit for concrete crack width by ACI code [4].

Table 11 - Test Results.

Test Number	Rebar #	Configuration	Bond Length	Cover	Failure Mode	Max Load (lbs)	Max Stress (psi)	Stiffness (k/in)
H8.1	#8	Hook	8 in	1 in	Plastic†	55,127	69,781	1630
H8.2	#8	Hook	8 in	2 in	Plastic†	55,225	69,905	1288
H12.1	#8	Hook	12 in	1 in	Plastic†	55,225	69,905	1300
H12.2	#8	Hook	12 in	2 in	Plastic†	54,492	68,977	1385
H16.1	#8	Hook	16 in	1 in	Plastic†	55,371	70,090	1688
H16.2	#8	Hook	16 in	2 in	Yield†	46,387	58,717	1034
S8.1	#8	Straight	8 in	1 in	Splitting	37,354	47,283	524
S8.2	#8	Straight	8 in	2 in	Splitting	43,994	55,689	241
S12.1	#8	Straight	12 in	1 in	Splitting	44,043	55,751	169
S12.2	#8	Straight	12 in	2 in	Yield†	47,656	60,324	373
S16.1	#8	Straight	16 in	1 in	Plastic†	55,469	70,214	822
S16.2	#8	Straight	16 in	2 in	Yield†	46,240	58,532	1327

Table 12 - Comparable Literature Review Test Results [3, 4, 5].

Tester	Rebar #	Configuration	Bond Length	Cover	Failure Mode	Max Load (lbs)	Max Stress (psi)	Stiffness (k/in)
Jirsa April 1975	#7	Hook - 1.7db*	4.3 in	NF**	Fracture	34,800	58,000	1260
Jirsa April 1975	#7	Hook - 1.7db*	4.3 in	NF**	Fracture	38,400	64,000	1380
Jirsa April 1975	#7	Hook - 2.3db*	4.3 in	NF**	Fracture	34,200	57,000	2040
Jirsa April 1975	#7	Hook - 2.3db*	4.3 in	NF**	Fracture	39,600	66,000	1800
Jirsa April 1975	#7	Straight	4.3 in	NF**	Fracture	37,800	63,000	1980
Jirsa April 1975	#7	Straight	4.3 in	NF**	Fracture	37,800	63,000	2580
Jirsa April 1975	#7	Hook - 2.3db*	6.4 in	NF**	Fracture	40,200	67,000	1260
Jirsa April 1975	#7	Hook - 2.3db*	6.4 in	NF**	Fracture	36,600	61,000	1200
Jirsa April 1975	#7	Hook - 3.4db*	6.4 in	NF**	Fracture	40,800	68,000	1140
Jirsa April 1975	#7	Hook - 3.4db*	6.4 in	NF**	Pullout	36,600	61,000	1020
Jirsa April 1975	#7	Straight	6.4 in	NF**	Fracture	44,400	74,000	2280
Jirsa April 1975	#7	Straight	6.4 in	NF**	Fracture	44,400	74,000	2640
Jirsa May 1975	#7	Hook	6.5 in	NF**	Spalling	37,800	63,000	1163
Jirsa April 1975	#7	Hook - 1.7db*	8.5 in	NF**	Fracture	39,000	65,000	1020
Jirsa April 1975	#7	Hook - 1.7db*	8.5 in	NF**	Terminated	37,800	63,000	900
Jirsa April 1975	#7	Hook - 2.3db*	8.5 in	NF**	Fracture	40,800	68,000	1380
Jirsa April 1975	#7	Hook - 2.3db*	8.5 in	NF**	Terminated	37,800	63,000	1800
Jirsa April 1975	#7	Hook - 5.7db*	8.5 in	NF**	Fracture	37,800	63,000	3480
Jirsa April 1975	#7	Hook - 5.7db*	8.5 in	NF**	Terminated†	55,800	93,000	3300
Jirsa May 1975	#7	Hook	9.5 in	NF**	Spalling	54,600	91,000	2063
Jirsa May 1975	#7	Hook	9.5 in	NF**	Spalling	60,000	100,000	2288
Jirsa May 1975	#7	Hook	9.5 in	NF**	Spalling	58,200	97,000	1950
Jirsa May 1975	#7	Hook	9.5 in	NF**	Spalling	59,400	99,000	1950
Jirsa May 1975	#7	Hook	9.5 in	NF**	Spalling	57,000	95,000	1725
Jirsa May 1975	#7	Hook	9.5 in	NF**	Spalling	62,400	104,000	2438
Jirsa May 1975	#7	Hook	9.5 in	NF**	Spalling	58,800	98,000	2363
Jirsa May 1975	#7	Hook	9.5 in	NF**	Spalling	44,400	74,000	2025
Soroushian May-June 1988	#8	Hook	0.0 in	NF**	Terminated	60,000	75,949	-
Soroushian May-June 1988	#8	Hook	0.0 in	NF**	Terminated	65,000	82,278	-
Delany	#8	Straight	8.0 in	1.0 in	Splitting	28,467	36,034	138
Delany	#8	Straight	8.0 in	2.0 in	Splitting	46,119	58,378	362
Delany	#8	Straight	12.0 in	1.0 in	Splitting	44,519	56,353	274
Delany	#8	Straight	12.0 in	2.0 in	Yield†	54,834	69,410	409
Delany	#8	Straight	16.0 in	1.0 in	Splitting	51,184	64,790	382
Delany	#8	Straight	16.0 in	2.0 in	Yield†	58,105	73,551	554
Jirsa April 1975	#9	Hook - 2.7db*	8.3 in	NF**	Fracture	53,000	53,000	1000
Jirsa April 1975	#9	Hook - 2.7db*	8.3 in	NF**	Fracture	57,000	57,000	1100
Jirsa April 1975	#9	Hook - 4.0db*	8.3 in	NF**	Pullout	43,000	43,000	1200
Jirsa April 1975	#9	Hook - 4.0db*	8.3 in	NF**	Terminated	-	-	3200
Jirsa April 1975	#9	Straight	8.3 in	NF**	Pullout	58,000	58,000	3300
Jirsa April 1975	#9	Straight	8.3 in	NF**	Terminated	-	-	2300

* bend radius designated for non ACI-conforming bends

** Non-factor - Cover is aqeduate to create pullout or concrete spalling instead of splitting failure

Concrete Failure Unless Otherwise Noted

† Steel failure

The tables contain two different categories of failure mode: concrete failure and steel failure. Steel failure is largely represented by test termination. Many tests in this capstone report were terminated when the steel stress reached the yield of 60 ksi and/or is loaded into the plastic range. The concrete failure is represented by pullout, splitting, or concrete fracture.

Taking all of these sources of variability into consideration, the data should only be compared within its test program. Comparing specific results from this capstone report to values obtained by Jirsa and Minor, for example, will not provide useful conclusions. However, generally comparing the data between test programs shows that the data obtained in this capstone report are similar to the data obtained from the literature review. This result provides some validity to the data collected for this capstone report.

Jirsa and Minor observed that slip increased when the angle of the bend increased (i.e. from 90° to 180°), as well as when the radius of the bend decreased [1]. The most slip was observed at the bend. This is an interesting fact to note since end slip in this report was measured off of the bend. Jirsa and Marques observed that slip increased as the bonded length decreased [4]. In this report, the hooks experienced comparable slip throughout the whole test. The straight bar slip had a much greater deviation from the consistent hook slip. Some straight bar specimens experienced less slip than the hook specimens and some straight bar specimens had a larger slip. Jirsa and Marques also noted that when cover was reduced, the stress and slip both decreased. The investigation in this capstone report led to the observation that cover reduction decreased the maximum stress achieved in the bar, as seen in Test S8.1 and Test S8.2. However, the cover-slip relationship was not observed in this report.

Chapter 7 – Conclusions

7.1 Conclusions

To observe the hook bar development behavior under tension, the cover and bond length were varied. All of the hooked bars experienced a steel failure. This result means that the addition of the hook adds enough strength to prevent concrete failure when compared to the straight rebar with similar bond length and cover. The straight rebar experienced steel failure in the 16-inch bond length with both 1-inch and 2-inch cover (i.e. Test S16.1 and Test S16.2) and the 12-inch bond length with 2-inch cover (i.e. Test S12.2). With bond lengths less than 12 inches and minimal cover, the addition of the hook adds enough strength for the steel to reach yield. The hooked bar stiffness was larger than the straight bar stiffness in every specimen, except for the straight bar specimen with 16 inches of bonded length and 2 inches of cover.

An interesting trend is the effect of development length and cover on load distribution between hook and bond. As the bond length increased, the bond took a greater portion of the load. At shorter bond lengths, the hook takes the greatest portion of the load. An increase in cover increased the load carried by the bond in all cases. This effect was greater at shorter bond lengths, since the hook carries the greater portion of the load. This behavior is similar to that of the headed bars tested by Blau [3].

7.2 Recommendations and Further Work

It is suggested in further work to continue to include a load cell, slip measurement, and strain gauges to allow for comparison of maximum loading, load distribution, and stiffness. The method for measuring lead and end slip might be improved. The lead slip in this capstone report was erratic or failed to record due to the LVDT slipping off the angle. The use of two LVDTs per desired measurement point might prevent failed data recording. The Jirsa and Minor method of casting a wire in the concrete encased in a tube seems to be a more elegant solution if it is not disturbed during casting [1]. Perhaps a combination of both measurement systems can be employed to provide the best data. It is also suggested that slip be measured in multiple locations along the bar since the slip might not be uniform throughout the bar or throughout the loading cycle.

The bulk of research conducted on hooks concentrates on a pullout failure. Further research and data will be required to make any statements regarding splitting-controlled hook configurations. The data obtained in this capstone report are not sufficient to create a model that can be applied to the code.

References

[1] Jirsa, James O. and John Minor. April 1975. "Behavior of Bent Bar Anchorages." *ACI Journal* Vol. 72(4), pp. 141-149. [PDF]. Copy Received from Dr. Richard DeVries, Milwaukee School of Engineering.

[2] Delany, Heather. 2009. "The Load-Deflection Behavior of Straight Deformed Bars in Concrete." Master's thesis, Milwaukee School of Engineering.

[3] Blau, Andrew M. June 2010. "Head and Bond Contributions to Anchorage of a Headed Reinforcing Bar." Master's thesis, Milwaukee School of Engineering.

[4] Jirsa, James O. and Jose L.G. Marques. May 1975. "A Study of Hooked Bar Anchorages in Beam-Column Joints." *ACI Journal* Vol. 72(5), pp. 198-209. [PDF]. Copy Received from Dr. Richard DeVries, Milwaukee School of Engineering.

[5] Soroushian, Parviz, Kienuwa Obaseki, Mohamad Nagi, and Maximo C. Rojas. May-June 1988. "Pullout Behavior of Hooked Bars in Exterior Beam-Column Connections." *ACI Structural Journal* Vol. 85(3), pp. 269-273. [PDF]. Copy Received from Dr. Richard DeVries, Milwaukee School of Engineering.

[6] Orangun, C.O., J.O. Jirsa, and J.E. Breen. March 1977. "A Reevaluation of Test Data on Development Length and Splices." *ACI Journal* Vol. 74(3), pp. 114-122. [PDF]. Copy Received from Dr. Richard DeVries, Milwaukee School of Engineering.

Structural Engineering

Capstone Report Approval Form

Master of Science in Structural Engineering –MSST

Milwaukee School of Engineering

This capstone report, titled "Load Distribution and Load-Deflection Behavior of Hooked Reinforcing Bars Loaded in Tension," submitted by the student, Jacob R. Bolda, has been approved by the following committee:

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