THE PORT AUTHORITY OF NY & NJ

TRANSMITTAL
Engineering Department

To: **NYC Deartment of Buildings**

Date: **18 June 2007**

Attention: **Gus Sirakis, P.E., Technical Affairs Division**

Subject: **WTC - 97 ksi Rebar for Freedom Tower**

☒ *Herewith*

☐ *Under Separate Cover*

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REMARKS:

Final Version of the report "BOND TESTS OF HIGH STRENGTH THREADED BARS", rev. May 2007 as per your request

Sent by: Saroj Bhol

Bhol, Saroj

From: Gus Sirakis [ConstadinoS@bb.nyc.gov]

Sent: Wednesday, May 02, 2007 2:10 PM

To: Bhol, Saroj

Cc: ahmad.rahimian@wspcs.com; felix@stressteel.com; Skghosh@aol.com; Fatma Amer; Dan Eschenasy

Subject: RE: Freedom Tower: 97 ksi Steel

Saroj,

The Department would like to see the complete final version of the report from NC State (expected date of May 2007) that Dr. Ghosh mentions below regarding the 97 ksi steel.

Thank you,

Gus Sirakis
Project Engineer – NYC DOB
T: (212) 566-3810
constadinos@buildings.nyc.gov

From: Skghosh@aol.com [mailto:Skghosh@aol.com]
Sent: Tuesday, May 01, 2007 4:40 PM
To: Gus Sirakis; DanE@bb.nyc.gov
Cc: sbhol@panynj.gov; ahmad.rahimian@wspcs.com; felix@stressteel.com
Subject: Re: Freedom Tower: 97 ksi Steel

Dear Gus and Dan:

In regards to the report IS-06-16 "Bond Tests of High Strength SAS Threaded Bars", NCState is in the process of issuing a final version that will be dated May 2007. The attached table is from that report.

The difference between the numbers in the attached table and the corresponding numbers in the September 2006 draft is due almost entirely to one reason. The latest version calculates u sub aci using field-measured concrete cover for all splice beams. The September draft calculated u sub aci using the design cover. It was discovered after issuing the September draft that the as-built concrete cover in the beams varied from the design cover by 0.5 in. to 1 in. Since concrete cover is a primary factor controlling bond strength, the results for the splice beams were recalculated using the measured as-built cover in lieu of the design cover.

It should be noted that the 1.25 factor in Eq. 2 of AC 237 was put in there by me as an additional safety measure. Many would question whether this is strictly required by ACI 318. As should be clear from the attached table, this enhanced criterion was failed to be met in only five of the sixteen cases tested. It should be noted, however, that since both of the top bars were spliced at the same location in each test specimen, the splice length used, according to ACI 318, should have been 1.3 times the development length. The 1.3 factor was not used in the design and fabrication of the test specimens. This additional factor, if used, would doubtless have taken care of the "shortfalls" observed in the five cases. Thus I feel quite comfortable about the test results. You really need not feel any qualms about allowing lap splices with the Stressteel bars.

If I can clarify anything else, please do not hesitate to get un touch with me.

Thank you.

S. K. Ghosh

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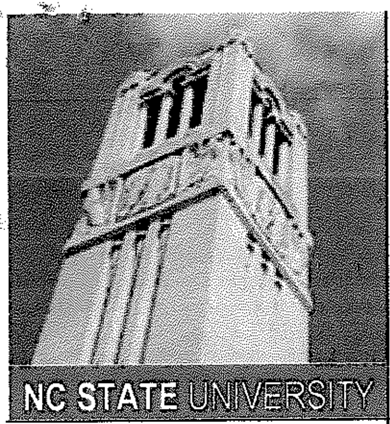

Constructed Facilities Laboratory
Department of Civil, Construction, and Environmental Engineering

Technical Report
IS-06-16

BOND TESTS OF HIGH STRENGTH THREADED BARS

Prepared by:

Dr. Sami Rizkalla, *Laboratory Director*
Mr. Lee Nelson, *Laboratory Manager*
Mr. Greg Lucier, *Research Engineer*

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rev. May 2007

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IAS

TL-252

Technical Report

Bond Tests of High Strength SAS Threaded Bars

Prepared by

James Lee Nelson III
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Dr. Sami Rizkalla
Principal Investigator

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Research Engineer

Submitted to

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Fairfield, NJ 07004

NCSU-CFL Report No. IS-06-16

Revised May, 2007

Constructed Facilities Laboratory
Department of Civil, Construction, and Environmental Engineering
North Carolina State University
Raleigh, NC 27695

Table of Contents

INTRODUCTION

This document presents the results measured from a series of reinforced concrete beam end specimens and splice beams which were tested at the North Carolina State University Constructed Facilities Laboratory. The tests were conducted to evaluate the bond of SAS high-strength threaded bars to concrete. The tested bars are the product of SAS Stressteel of Fairfield, NJ, and the tests were performed according to AC 237 *Acceptance Criteria for Concrete Threaded Reinforcing Bars Formed from High-Strength Steel.*

REFERENCED DOCUMENTS

- *ASTM A944-05 – Standard Test Method for Comparing Bond Strength of Steel Reinforcing Bars to Concrete Using Beam-End Specimens*, 2005, American Society for Testing and Materials, West Conshohocken, PA.
- *ACI 318-05 – Building Code Requirements for Structural Concrete,* 2005, American Concrete Institute, Farmington Hills, MI.
- *ICC-ES AC237 – Acceptance Criteria for Concrete Threaded Reinforcing Bars Formed from High-Strength Steel,* November 2003, International Code Council Evaluation Service, Inc., Whittier, CA.
- *ICC-ES AC85 – Acceptance Criteria for Test Reports, 2003,* International Code Council Evaluation Service, Inc., Whittier, CA.

SAMPLING PROCEDURES

A total of four different bar sizes were tested in this program. Table 1 summarizes the nominal dimensions of the tested bars. All bars have a specified nominal yield stress of 97 ksi (670 N/mm^2), and are threaded over their entire length. The bars used in this testing program were shipped from a production plant in Germany, and were accompanied by an Affidavit from the product manufacturer certifying that the products to be tested were representative of the standard manufactured product to be covered in the evaluation report.

Table 1 – Nominal Bar Properties

Bar Size	Diameter	Yield Stress	Area
	in (mm)	ksi (N/mm^2)	in^2 (mm^2)
No. 20	2.50 (63.5)	97 (670)	4.91 (3167)
No. 14	1.69 (43.0)	97 (670)	2.27 (1466)
No. 9	1.10 (28.0)	97 (670)	0.96 (616)
No. 6	0.71 (18.0)	97 (670)	0.39 (250)

BEAM END SPECIMENS

Section *4.1.1* of AC237 requires that beam-end specimens be tested in accordance with ASTM A944 *Standard Test Method for Comparing Bond Strength of Steel Reinforcing Bars to Concrete Using Beam-End Specimen.* AC 237 requires that a total of three ASTM A944 beam end tests be performed on all bar diameters using concrete with compressive strength of 6,000 psi and 12,000 psi . Table 2 summarizes the number of ASTM A944 beam end specimens as required by AC237.

Table 2 – Summary of Beam End Specimens

Bar Size	Concrete Strength (ksi)	Number of Tests
No. 20	6.0	3
	12.0	3
No. 14	6.0	3
	12.0	3
No. 9	6.0	3
	12.0	3
No. 6	6.0	3
	12.0	3

DEVIATIONS FROM ASTM A944 STANDARD

Section 1.2 of ASTM A944 limits the scope of the standard to bars of size No. 3 to No. 11. Two of the bars in this testing program, No. 14 and No. 20, are outside the specified range. Through a series of pilot tests, it was determined that the standard dimensions and reinforcing, as outlined in section 5.1 and as shown in Figure 2 of ASTM A944, are not appropriate for No. 20 and No. 14 bars. The standard specimen size is too small with respect to the size of the bars. With the approval of ICC the specimen dimensions were increased, and a minimum amount of transverse reinforcing was added to appropriately accommodate the large diameter bars. Illustrations of the dimensions and reinforcing which were used for these specimens are shown in Appendix A. The specimens are 40" wide by 44" tall by 84" long. No. 20 and No. 14 bars are cast in the center of the specimen with a 10 in. bond length. PVC conduits were used to debond the bar from the surrounding concrete outside of the bonded area. No. 3 grade 60 stirrups were placed on 5.5 in. centers for the entire length of the specimen to provide minimum confinement to the test bar.

TEST SETUP FOR BEAM END SPECIMENS

The test setup follows the requirements of ASTM A944 with some modifications made to accommodate the large size specimens for the No. 14 and No. 20 bars. The specimens were placed on a steel platform on the laboratory strong floor. A pressure calibrated 300 ton hydraulic jack and electric pump were used to load the bars. For the No. 6 and No. 9 bars, a calibrated load cell was used to measure the applied load. The non-loading end of the specimen was tied to the laboratory strong floor using a steel beam and threaded post-tensioning bars which passed through the laboratory strong floor and were anchored in the basement. For the No. 14 and No. 20 bars, two 60-ton jacks attached to a hand pump were used to adjust the tie-down force while the test was taking place. Adjusting the tie-down force was necessary to prevent the large specimens from rotating under high loads. A potentiometer was used to monitor the rotation of the specimens for the No. 14 and No. 20 specimens. Potentiometers were also used to monitor the movement of the bar with respect to the front and back surfaces of the concrete in accordance with the Standard. Figure 1 shows a photograph of the test setup for the No. 14 and No. 20 bars and Figure 2 shows a photograph of the test setup for the No. 6 and No. 9 bars.

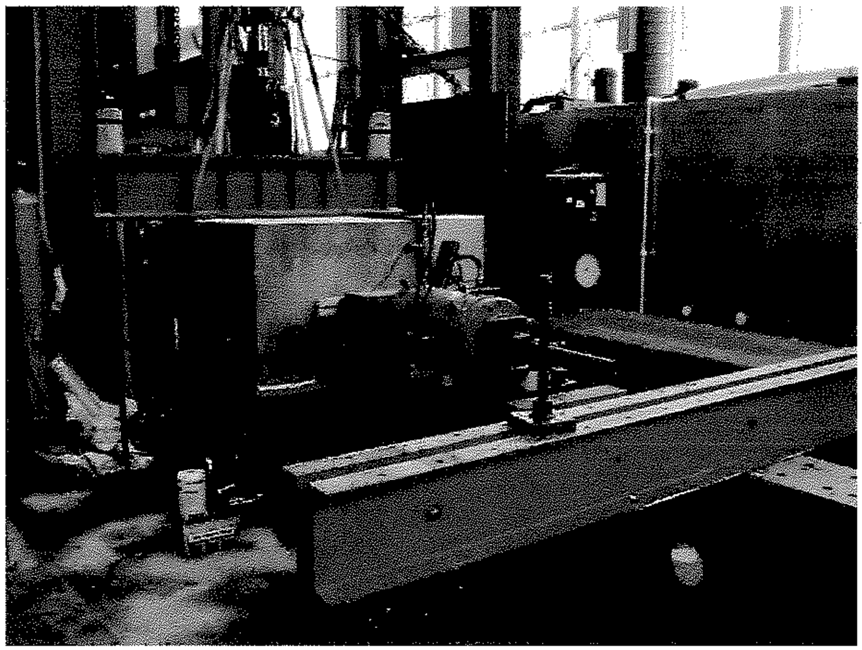


Figure 1 – Photograph of Test Setup for No. 14 and No. 20 Bars

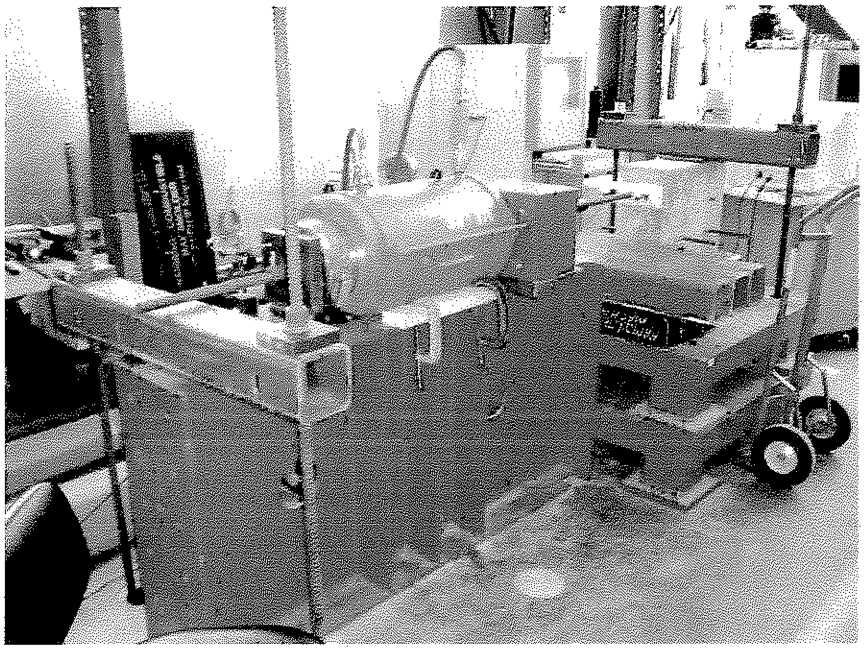


Figure 2 – Photograph of Test Setup for No. 6 and No. 9 Bars

BEAM END TEST RESULTS

All instrumentation was connected to an electronic data acquisition system which continuously recorded and displayed data at a rate of one point per second. All specimens were loaded incrementally to failure. In accordance with section 3.1.2 of AC237 the bond stress achieved by the test must be greater than or equal to the bond stress as required by ACI 318-05 ($u_{test} \geq u_{aci}$), eq(1). The bond stresses required by AC237 are calculated as shown in Equation 1. The terms used in Equation 1 are defined by AC237. The results of all tests are summarized in Table 3.

$$u_{test} \geq u_{aci}$$

$$\frac{P_{\max}}{\pi d_b l_{bond}} \geq \frac{1.25 f_y d_b}{4 l_{d,aci}} \qquad \text{Eq. (1)}$$

Table 3 – Results of Beam End Specimens

Bar Size	d_b	$f'_{c\ specified}$	$f'_{c\ measured}$	l_{bond}	$l_{d,aci}$	Maximum Applied Load			u_{test}			u_{aci}
						Specimen 1	Specimen 2	Specimen 3	Specimen 1	Specimen 2	Specimen 3	
	(in)	(ksi)	(ksi)	(in)	(in)	(kips)	(kips)	(kips)	(psi)	(psi)	(psi)	(psi)
No. 20	2.5	6.0	7.4	10.0	109.9	317	300	298	4038	3822	3796	690
	2.5	12.0	10.4	10.0	92.7	329	334	331	4038	3822	3796	690
No. 14	1.69	6.0	5.3	10.0	87.8	202	147	158	3807	2770	2977	583
	1.69	12.0	10.6	10.0	62.1	161	170	172	3807	3807	3807	583
No. 9	1.1	6.0	6.0	5.0	57.4	40.8	39.1	35.6	2362	2264	2061	581
	1.1	12.0	14.2	5.0	37.3	57.7	55.8	64.6	3341	3231	3741	894
No. 6	0.71	6.0	6.0	5.0	37.0	40.1	38.6	38.5	3341	3341	3341	894
	0.71	12.0	14.2	5.0	24.1	39.6	36.9	36.8	3553	3310	3301	893

Note: $l_{d,aci}$ is based on measured concrete strengths

BEAM END FINDINGS

In examining the results for the beam-end tests, it is clear that each case satisfies the requirements of Equation 1. Thus, all of the ASTM A944 beam-end tests passed the requirements of AC237.

SPLICE SPECIMENS

Section 4.1.1 and Table 2 of AC237 require that a total of eight splice beams be tested for each of the selected bar sizes of No. 9 and No. 20. Each bar size is required to be tested using two concrete compressive strengths (6ksi and 12 ksi), and three different transverse reinforcing ratios (none, minimum, and twice minimum). Two splice specimens with minimum transverse reinforcement were tested for each bar size and concrete strength. One specimen was tested for each of the other transverse reinforcement conditions for a total of 16 specimens. This approach deviates slightly from AC237. AC237 requires the total of 16 specimens, but in lieu of 2 specimens reinforced with minimum transverse reinforcement, two specimens reinforced with no transverse reinforcement are required. Table 4 summarizes the tested splice beams.

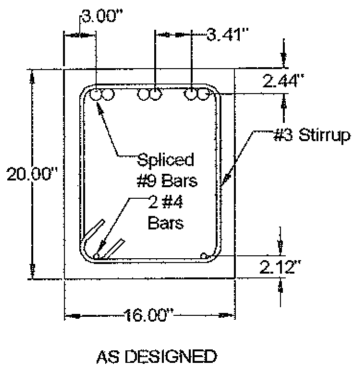
Table 4 – Summary of Splice Beam Specimens

Bar Size	Specimen Length (ft)	Concrete Strength (ksi)	Transverse Reinforcement	No. of Specimens	Splice Length (in)
No. 9	22	6000	none	1	64
			min	2	60
			2xmin	1	56
		12000	none	1	46
			min	2	43
			2xmin	1	40
No. 20	48	6000	none	1	235
			min	2	207
			2xmin	1	185
		12000	none	1	166
			min	2	146
			2xmin	1	131

SPLICE SPECIMEN DESIGN

For all splice specimens, the splice length was designed according to Section 12.2.3 of ACI 318. Calculations are shown in Appendix C. A minimum cover of 1.5 in. was used for all splice specimens in accordance with section 7.7 of ACI 318. The stirrup spacing in the constant moment region of the specimens varied according to Table 2 of AC237, which references section 7.10.5 of ACI 318. The stirrup spacing outside of the constant moment region was conservatively designed to prevent shear failure. Appendix B contains complete drawings for all splice specimens. Appendix E shows the splice length calculation for each of the specimens.

The splice specimens for #9 bars were 22 feet long and had a rectangular cross section of 16in. x 20in. Three #9 bars were used in each beam, with each of those bars spliced at midspan. Number 3 stirrups were used as transverse reinforcing, and two longitudinal #4 bars were placed in the compression region of the beam to minimize cracking during



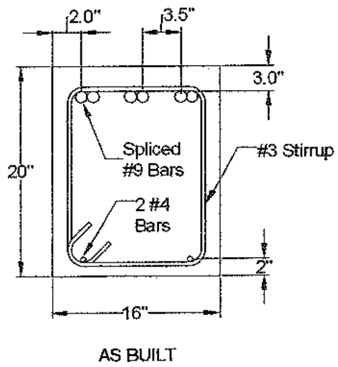
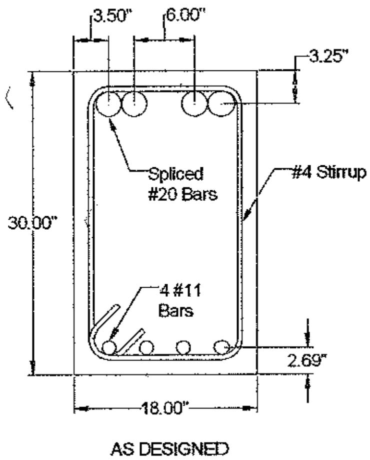


Figure 3 – Cross Section of No. 9 Splice Beam Specimens



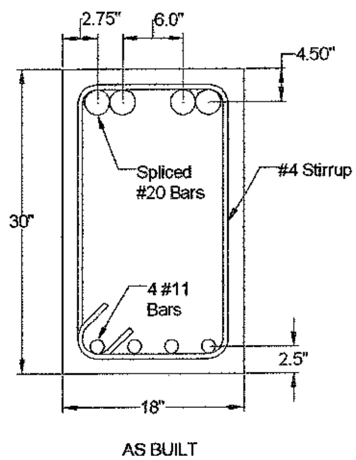


Figure 4 – Cross Section of No. 20 Splice Specimens

Figure 5 –Example of As-Constructed Concrete Covers (#9 on left, #20 side cover on right)

INSTRUMENTATION AND TEST SETUP FOR SPLICE SPECIMENS

For all beams, electrical resistance strain gauges were placed on the top of the steel bars approximately 1in. from splice length to monitor the strains developed in the bars. In addition, PI gauges were mounted on the compression face of the specimen to monitor strains in the compression zone. Five string potentiometers were attached to the bottom face of the specimen at the location of the supports, at quarter points, and at the center of the beam to monitor deflections. The core test setup involved placing the #9 specimens on two 60-ton calibrated hydraulic jacks located at the quarter-spans of each beam. Four 60-ton jacks were used to create the higher loads required when testing #20 specimens. Two steel plates and sandwiching a piece of 3in thick neoprene rubber were placed between the bottom of the #9 beams and the top of each jack. For the #20 beams, steel rollers were used in place of the neoprene to maintain stability at the higher loads. Two steel cross-beams were used to tie the ends of each specimen to the testing floor. A steel plate was placed on a leveled pad of non-shrink grout at the end of each specimen, directly underneath the tie-down beams. Calibrated load cells were placed on top of the steel plates and underneath the tie down beams. Figure 6 shows a photograph of a typical test setup for the #20 specimens, and Figures 7 and 8 show illustrations of the test setups used for all No. 9 and No. 20 specimens respectively.

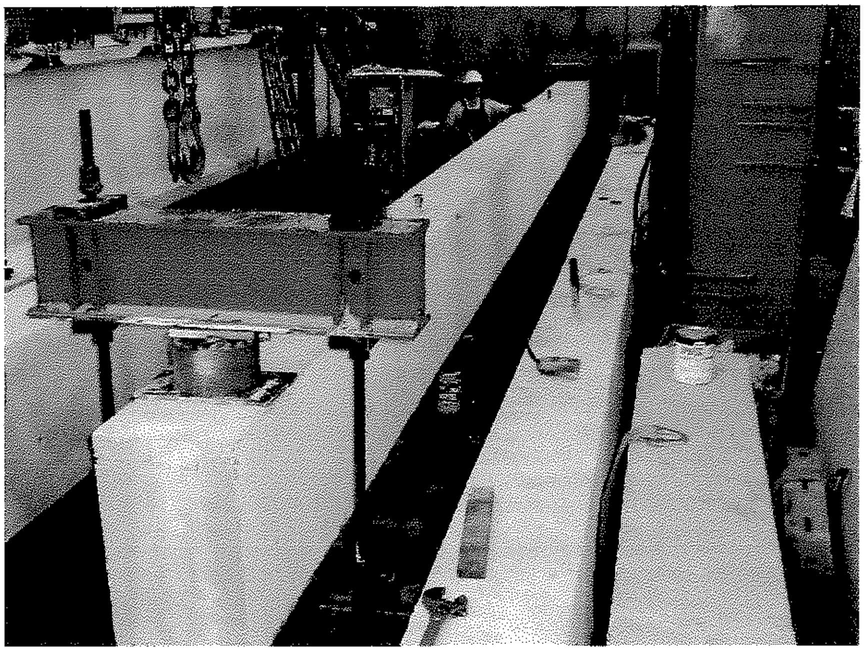


Figure 6 – Typical Test Setup for Splice Specimens

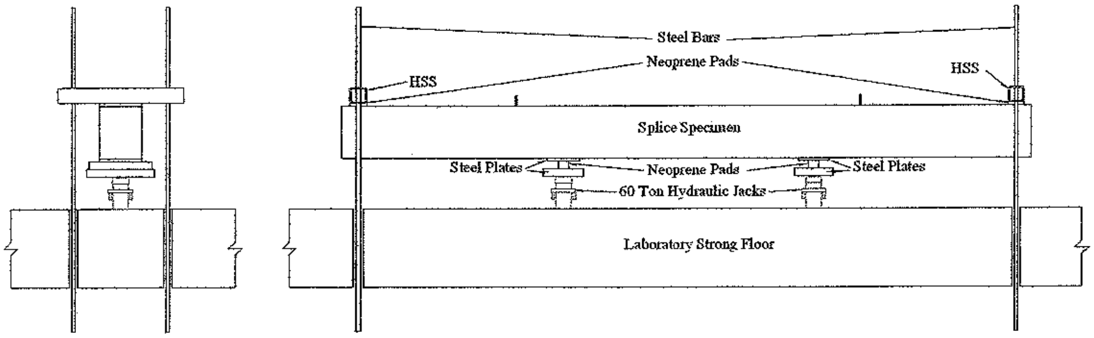


Figure 7 – Illustration of Test Setup for No. 9 Splice Specimens

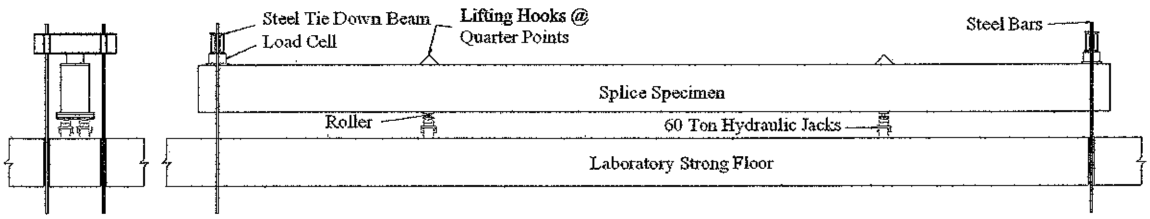


Figure 8 – Illustration of Test Setup for No. 20 Splice Specimens

SPLICE SPECIMEN RESULTS

In accordance with section 3.1.2 of AC237, the bond stress achieved by the test must be greater than or equal to 125% of the bond stress as required by ACI 318-05. The bond stresses required by AC237 are calculated as shown in Equation 2. The terms used in Equation 2 are defined by AC237. It should be noted that the post-test data gathering included measuring the concrete compressive strength for each splice beam, and measuring the as-built concrete cover, based on the discussion above. Both the design and the analysis of all splice lengths included the ACI-specified factor of 1.3 for bars which are top-cast. The ACI requirement to use a factor of 1.3 for Class-B sections was not considered in either the design or the analysis of the beams.

Results of the splice beam testing are summarized in Table 5. The tested and ACI-specified bond stresses, as specified in Equation (2) below, are given in the last two columns of the Table. A typical splice failure is shown in Figure 9. Appendix C outlines the calculation of strains due to dead weight of a beam. Appendix D provides a test summary sheet for each of the tests performed. Appendix E provides the calculations which were used to determine the splice lengths for initial design of the splice beams, and Appendix F gives example calculations for determination of the ACI-specified splice lengths (l_{daci}) using actual concrete cover and actual concrete compressive strengths.

$$u_{test} \geq u_{aci}$$

Eq. (2)

$$\frac{f_s d_b}{4 l_s} \geq \frac{1.25 f_y d_b}{4 l_{d,aci}}$$

Notes: $l_{d,aci}$ is based on actual concrete strengths and constructed dimensions. Thus, it may deviate from the design splice length.

u_{aci} is determined as 1.25% of the development bond stress required by ACI318-05 chapter 12 for lap splices.

Figure 9 – Typical Splice Failure

Table 5 – Summary of Splice Specimen Results

Bar Size	Specimen Length (ft)	Specified Concrete Strength (psi)	Meaured Concrete Strength (psi)	Transverse Reinforcement	Actual Splice (l_s) (in)	ACI Splice (l_{daci}) (in)	Measured Steel Stress (ksi)	u_{test} (psi)	u_{aci} (psi)
No. 9 db = 1.125"	22	6000	6300	none	64	75	105	461	452
			6300	min	60	69	100	469	494
			6300	min	60	69	105	492	494
			6300	2xmin	56	64	99	497	535
		12000	9400	none	46	62	110	673	552
			10100	min	43	55	111	726	625
			10100	min	43	55	113	739	625
			9400	2xmin	40	52	112	788	654
No. 20 db = 2.5"	48	6000	6000	none	235	277	88	234	273
			6000	min	207	239	109	329	317
			7700	min	207	211	108	326	359
			8400	2xmin	185	177	112	378	428
		12000	11300	none	166	215	94	354	353
			11100	min	146	185	105	449	410
			10300	min	146	185	105	449	410
			10100	2xmin	131	162	107	510	467

SPLICE SPECIMEN FINDINGS

Table 6 – Summary of Splice Specimen Findings

Bar Size	Specimen Length (ft)	Specified Concrete Strength (psi)	Meaured Concrete Strength (psi)	Transverse Reinforcement	Maximum Steel Stress (ksi)	ICC Criteria Equation 2 (% of u_{aci})	Equation 3 (% of U_{aci})
No. 9	22	6000	6300	none	105	102%	128%
			6300	min	100	95%	119%
			6300	min	105	100%	125%
			6300	2xmin	99	93%	116%
		12000	9400	none	110	122%	152%
			10100	min	111	116%	145%
			10100	min	113	118%	148%
			9400	2xmin	112	120%	151%
No. 20	48	6000	6000	none*	88	86%	107%
			6000	min*	109	104%	130%
			7700	min	108	91%	113%
			8400	2xmin	112	88%	111%
		12000	11300	none	94	100%	125%
			11100	min	105	110%	137%
			10300	min	105	110%	137%
			10100	2xmin	107	109%	137%

*These two beams are replacements. Results from the two originals are not included due to errors in fabrication and casting.

Table 6 summarizes the findings of the testing, and provides the ratio of $u_{measured}$ to u_{aci} in the second to last column. This comparison is based on Equation (2), and indicates that all 8 splice beams (4 #9 and 4 #20) cast with high-strength concrete (12,000 psi specified) passed the ICC criteria. In addition, two of the splice beams tested using #9 bars and lower-strength concrete (6,000 psi specified) also passed the ICC criteria. The remaining two splice beams using #9 bars did not pass the ICC criteria, but they reached 95% and 93% of u_{aci}. Finally, one of the of the four #20 splice beams cast with 6,000 psi (specified) concrete passed the ICC acceptance criteria. The three remaining beams reached 86%, 91%, and 88% of the ICC criteria.

Test results indicate that all but two of the total 16 tests developed the full specified yield stress of 97ksi in the SAS steel bar. In addition, all tests developed bar stresses exceeding those predicted by ACI-318-05. This finding is reflected in the final column of Table 6 using Equation 3. Note that Equation 3 is not a requirement of AC237. Rather, it follows ACI-318-05 for predicting splice lengths to obtain the full specified yield strength of a bar, not 125% of the specified yield strength.

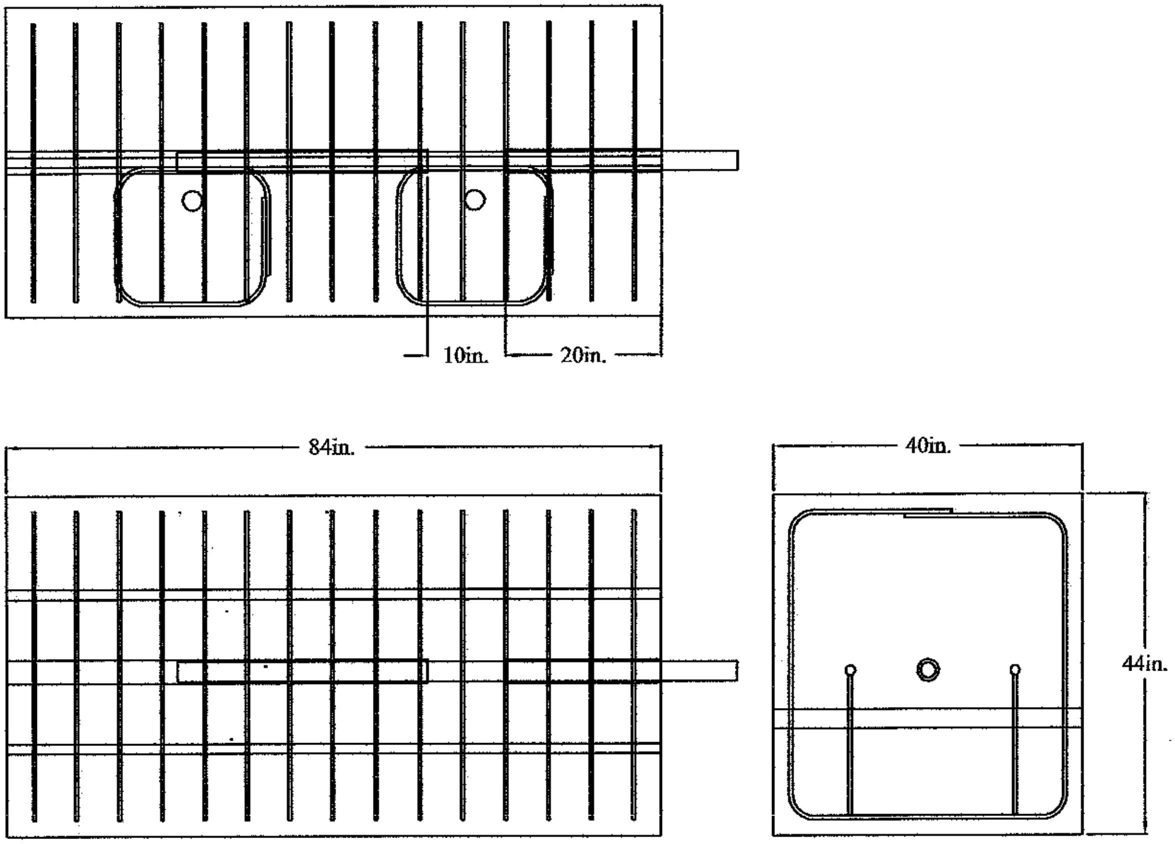
$$u_{test} \geq U_{aci}$$

$$\frac{f_s d_b}{4l_s} \geq \frac{f_y d_b}{4l_{d,aci}} \qquad \text{Eq. (3)}$$

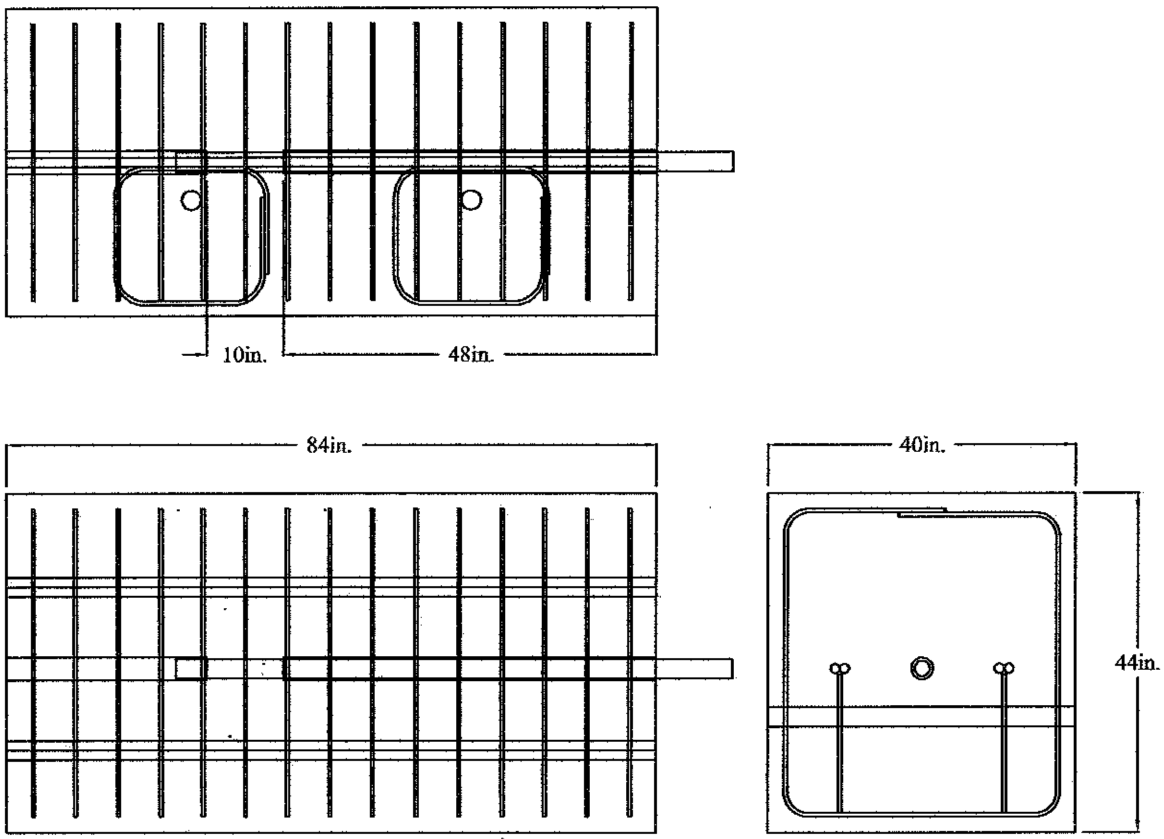
In summary, 11 of 16 splice specimens passed the ICC criteria given in Equation 2. Of the 5 beams which did not pass the criteria, all reached at least 86% of the requirement. It is further noted that all sixteen beams in the testing program developed stresses exceeding those predicted by ACI-318-05, as shown by Equation 3.

Appendix A

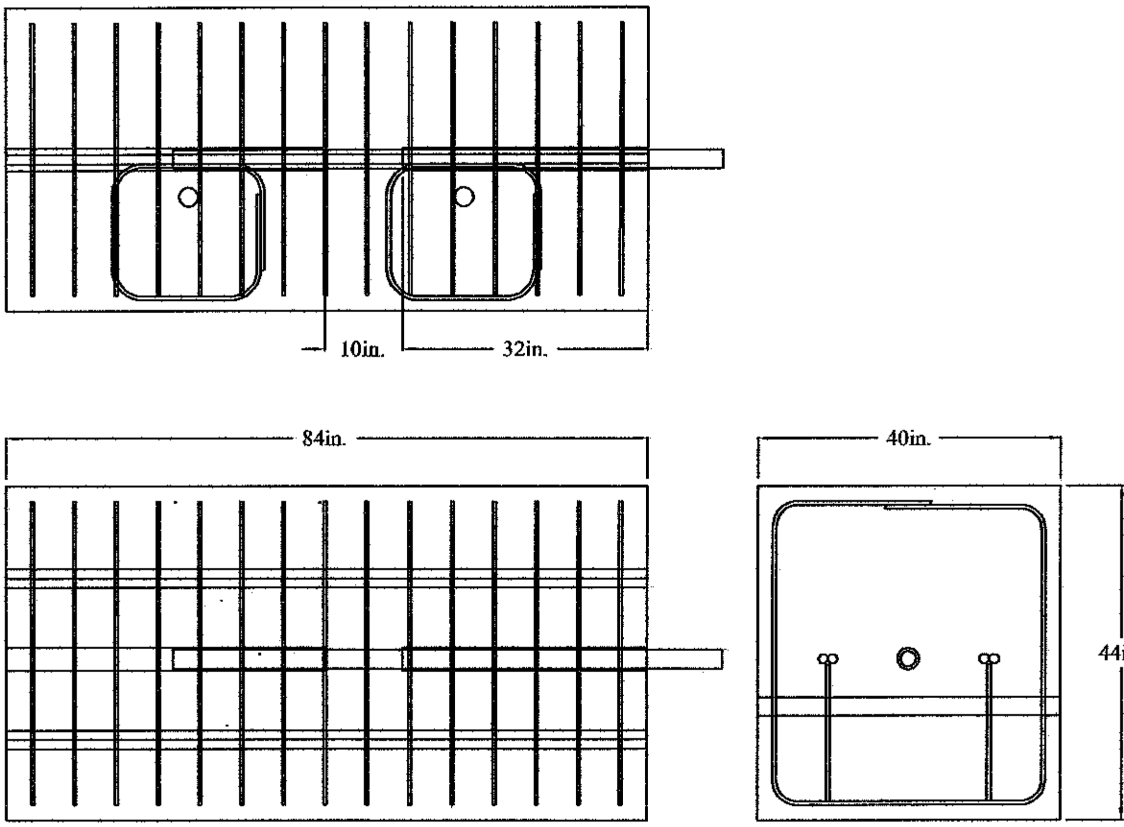
Drawings of Beam End Specimens



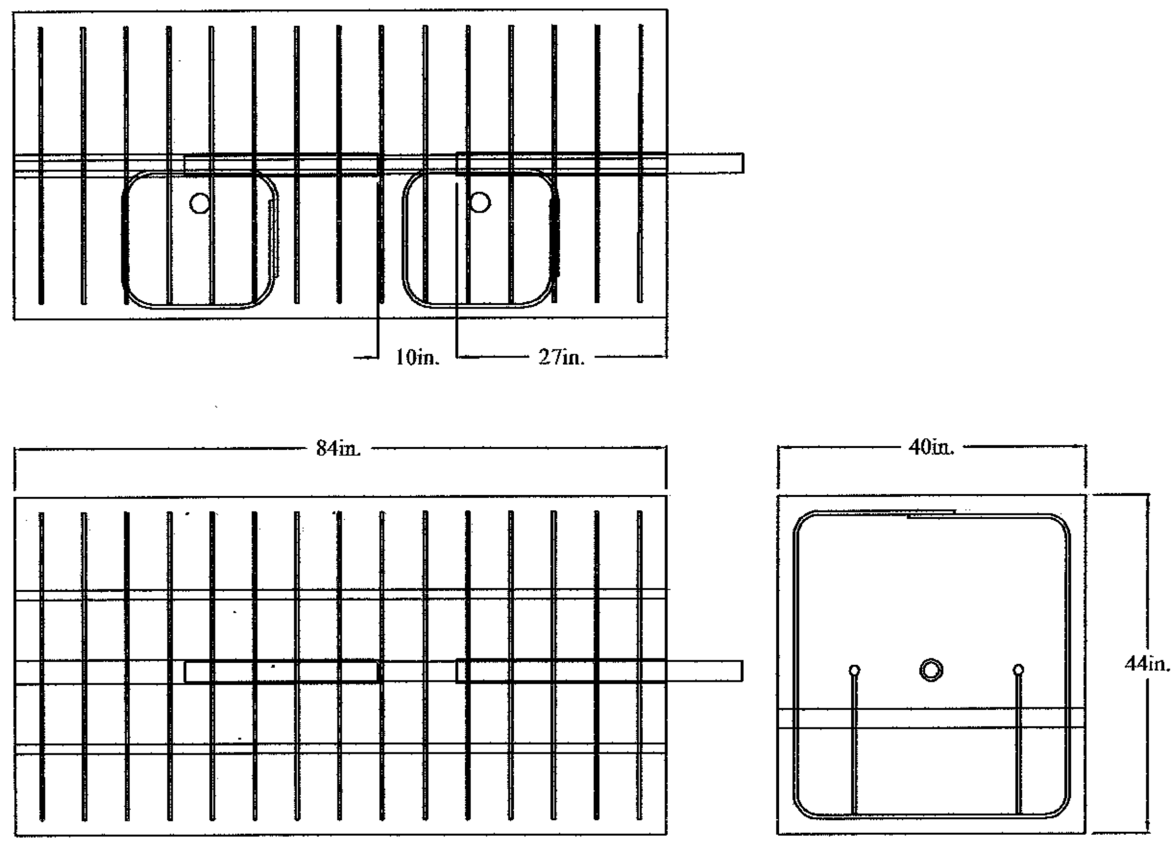
No. 14 Bar in 12,000psi concrete



No. 20 Bar in 6,000psi concrete



No. 20 Bar in 12,000psi concrete

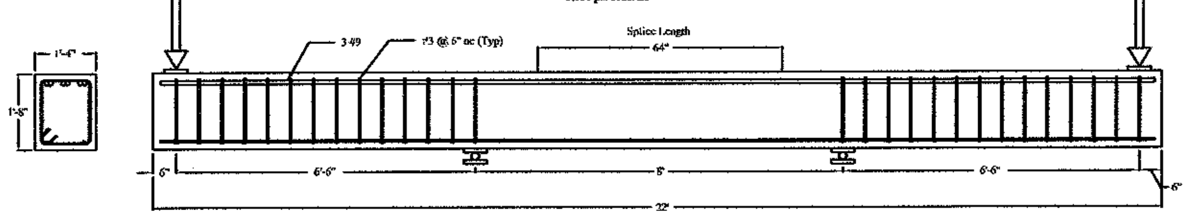


No. 14 Bar in 6,000psi concrete

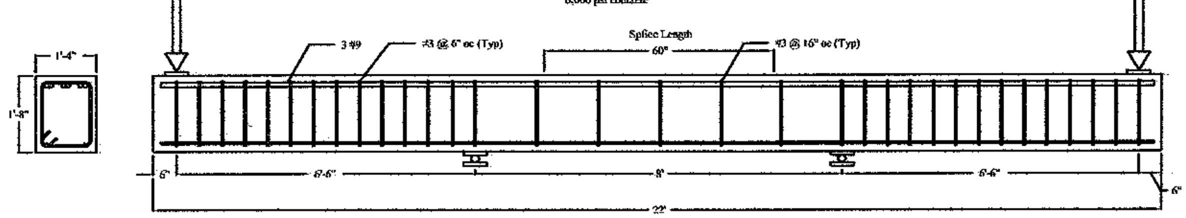
Appendix B

Drawings of Splice Specimens

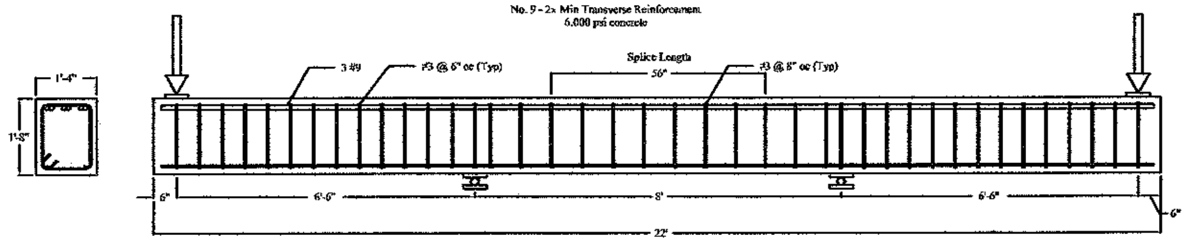
No. 9 - No Transverse Reinforcement
6,000 psi concrete

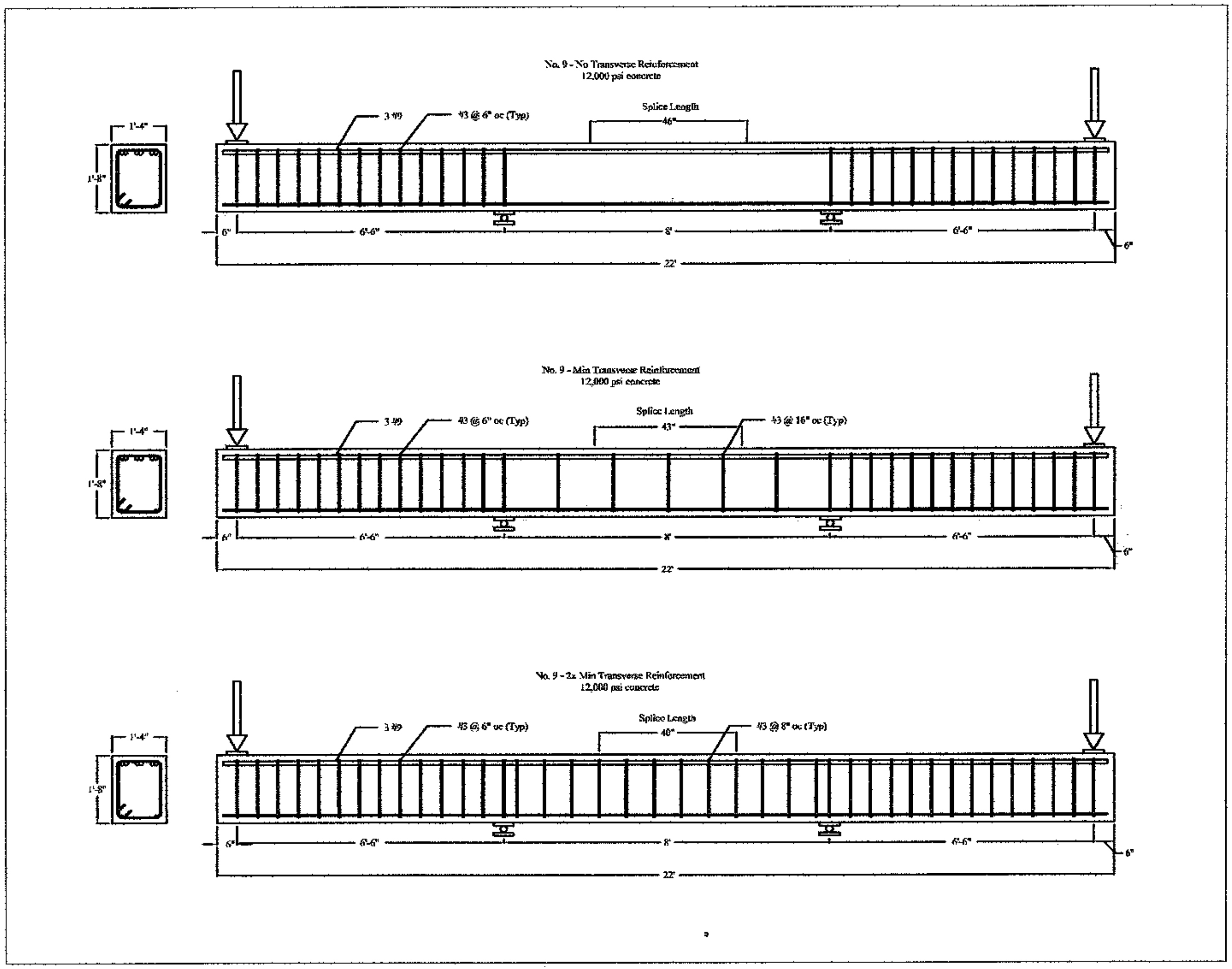


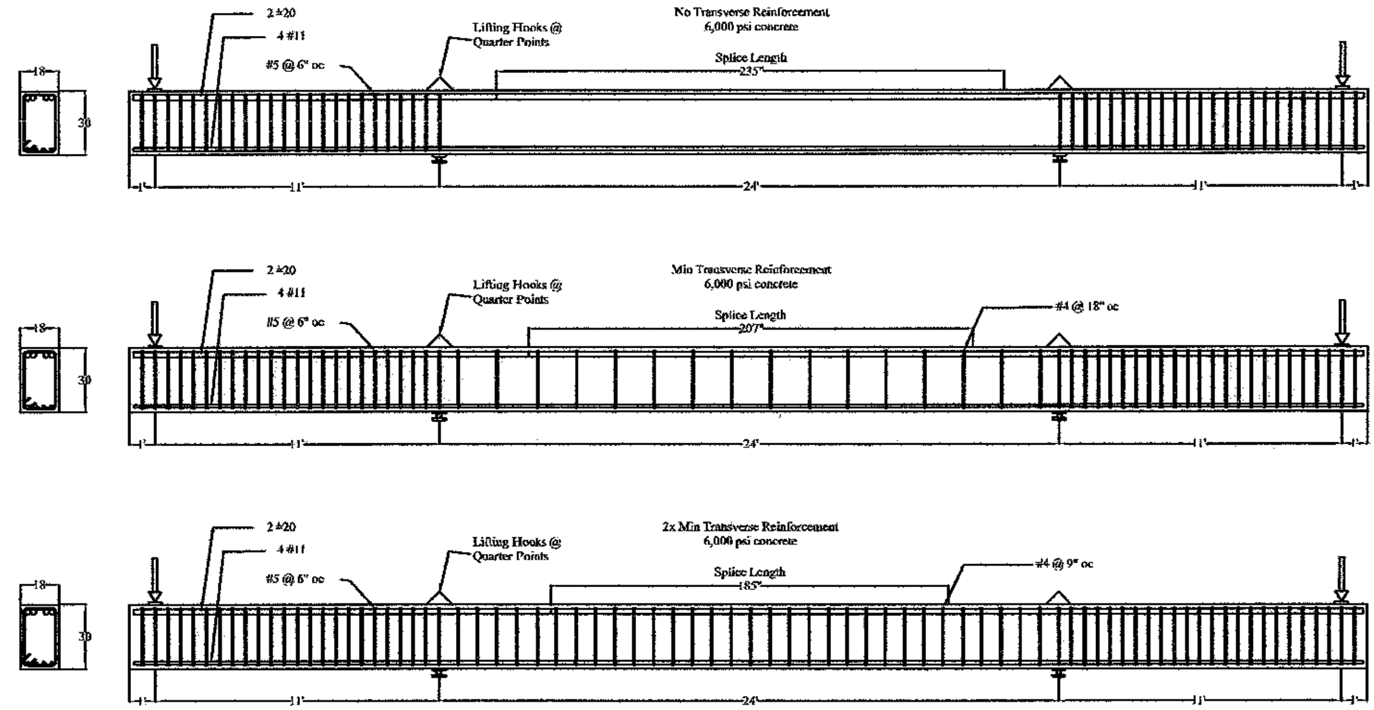
No. 9 - Min Transverse Reinforcement
6,000 psi concrete



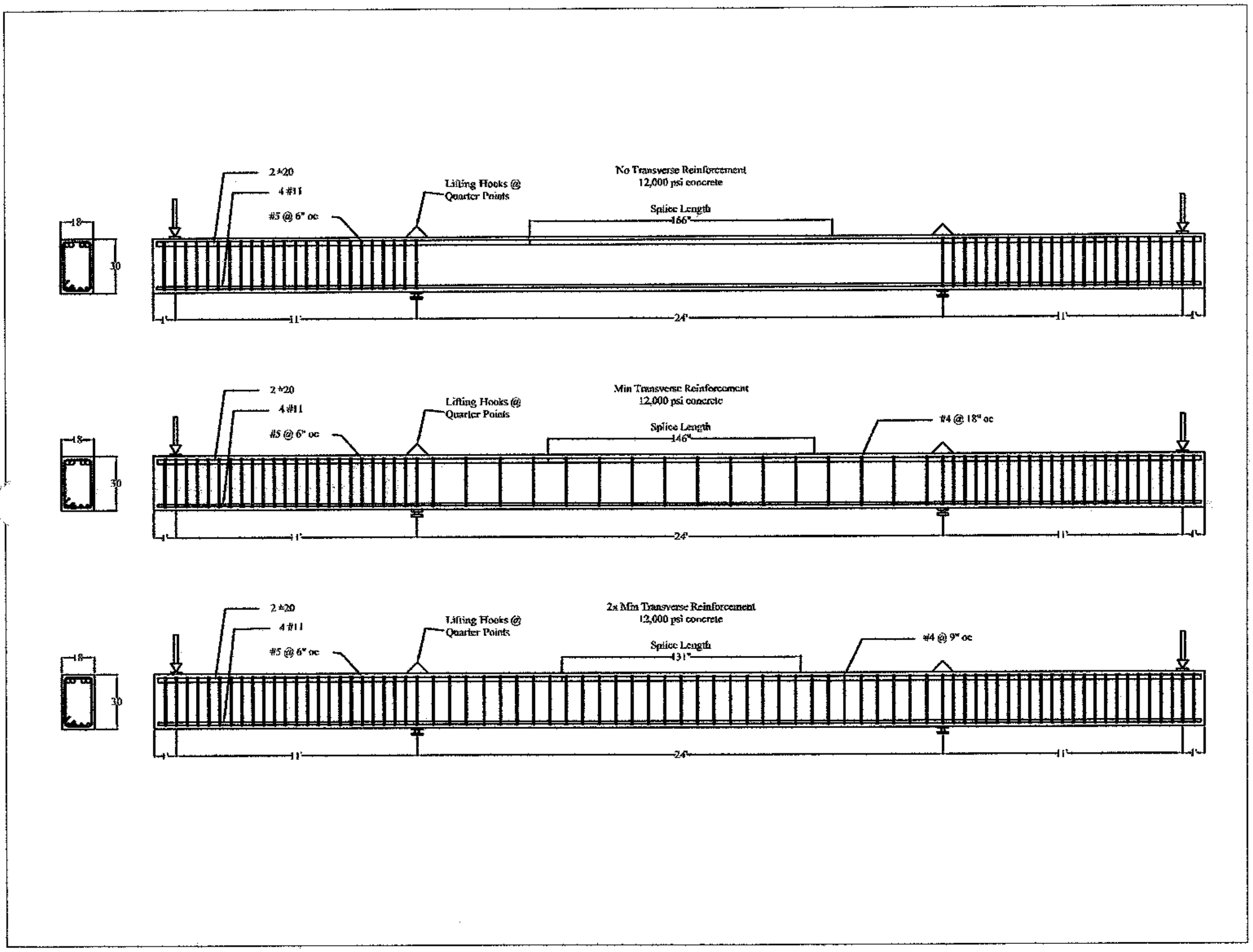
No. 9 - 2x Min Transverse Reinforcement
6,000 psi concrete




No. 9 - No Transverse Reinforcement
12,000 psi concrete
Splice Length
46"
3 #9
#3 @ 6" oc (Typ)
1'-4"
1'-8"
6"
6'-6"
8'
6'-6"
6"
22'
No. 9 - Min Transverse Reinforcement
12,000 psi concrete
Splice Length
43"
3 #9
#3 @ 6" oc (Typ)
#3 @ 16" oc (Typ)
1'-4"
1'-8"
6"
6'-6"
8'
6'-6"
6"
22'
No. 9 - 2x Min Transverse Reinforcement
12,000 psi concrete
Splice Length
40"
3 #9
#3 @ 6" oc (Typ)
#3 @ 8" oc (Typ)
1'-4"
1'-8"
6"
6'-6"
8'
6'-6"
6"
22'



No Transverse Reinforcement
6,000 psi concrete
2 #20
4 #11
#5 @ 6" oc
Lifting Hooks @ Quarter Points
Splice Length
235"
18
30
1'
11'
24'
11'
1'
Min Transverse Reinforcement
6,000 psi concrete
2 #20
4 #11
#5 @ 6" oc
Lifting Hooks @ Quarter Points
Splice Length
207"
#4 @ 18" oc
18
30
1'
11'
24'
11'
1'
2x Min Transverse Reinforcement
6,000 psi concrete
2 #20
4 #11
#5 @ 6" oc
Lifting Hooks @ Quarter Points
Splice Length
185"
#4 @ 9" oc
18
30
1'
11'
24'
11'
1'


No Transverse Reinforcement
12,000 psi concrete
2 #20
4 #11
#5 @ 6" oc
Lifting Hooks @ Quarter Points
Splice Length
166"
18
30
1'
11'
24'
11'
1'
Min Transverse Reinforcement
12,000 psi concrete
2 #20
4 #11
#5 @ 6" oc
Lifting Hooks @ Quarter Points
Splice Length
146"
#4 @ 18" oc
18
30
1'
11'
24'
11'
1'
2x Min Transverse Reinforcement
12,000 psi concrete
2 #20
4 #11
#5 @ 6" oc
Lifting Hooks @ Quarter Points
Splice Length
131"
#4 @ 9" oc
18
30
1'
11'
24'
11'
1'

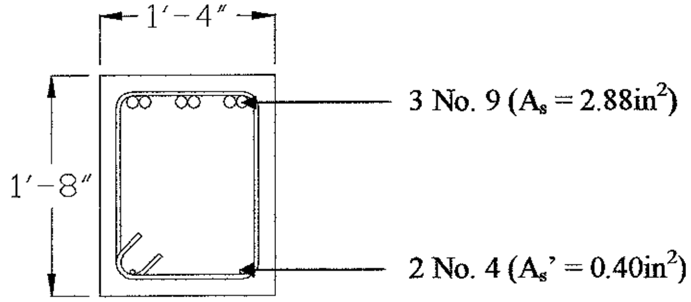
Appendix C

Calculation of Dead Weight Strains

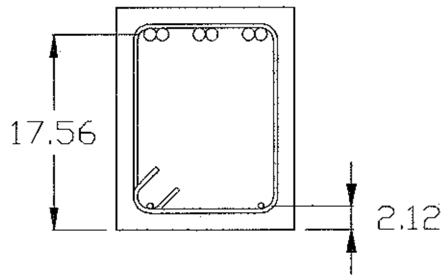
Example Calculation of Strain Due to Dead Load

Calculation of transformed section properties for the uncracked section:

Steel Areas:



Steel Locations:



d = 17.56in
d' = 2.12in

Calculate the modular ratio:

$$E_c = 57{,}000\sqrt{f_c{}'} = 57{,}000\sqrt{6000} = 4.415E6$$

$$n = \frac{E_s}{E_c} = \frac{29E6}{4.415E6} = 6.57$$

Calculate the transformed areas for the two layers of steel:

Compression Steel: $(6.57-1)0.40 = 2.23\text{ in}^2$

Tension Steel: $(6.57-1)2.88 = 16.04\text{ in}^2$

Locate the centroid of the transformed section:

Part	Area (in^2)	y (in)	Ay (in^3)
Concrete	320.00	10.00	3200.00
Tension Steel	16.04	17.56	281.66
Compression Steel	2.23	2.12	4.73
	338.27		3486.39

$$\bar{y}_{comp} = \frac{3486.39}{338.27} = 10.31\,\text{in}$$

Calculate the transformed moment of inertia:

Part	Area (in^2)	$\bar{y}$ (in)	$I_{own\ axis}$ (in^4)	$A\bar{y}^2$ (in^4)
Concrete	320.00	-0.31	10667	30.75
Tension Steel	16.04	7.25	---	843.10
Compression Steel	2.23	-8.19	---	149.58
			$I_{gt} = 11690\ in^4$	

Calculation of strains due to dead weight:

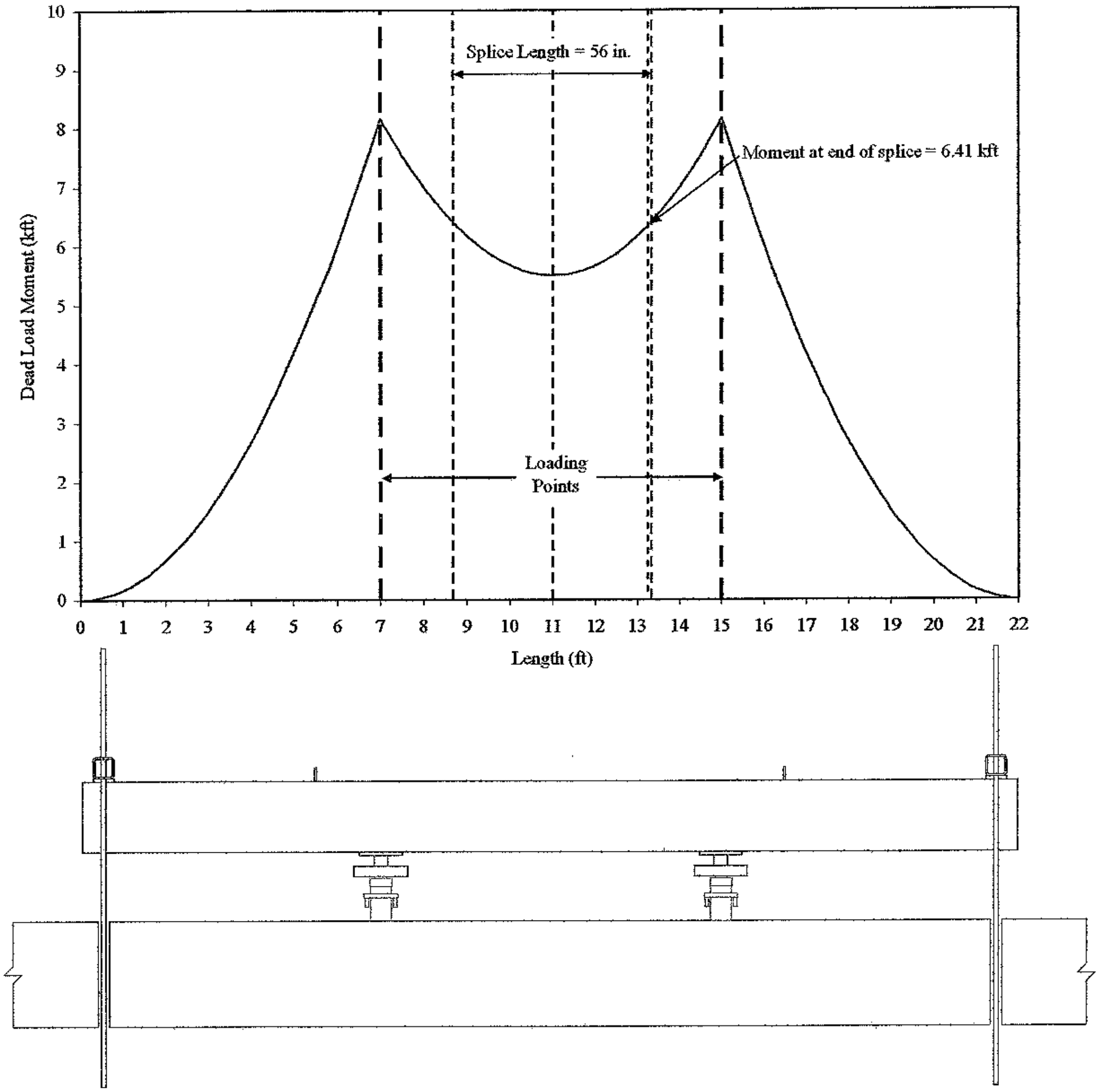
Determine load due to dead weight:

Total beam volume = (16/12)ft x (20/12)ft x 22ft = 48.89ft^3

Total beam weight = (48.89ft^3)(150lbs/ft^3) = 7333.3lbs

w = 7333.3lbs / 22ft = 333.3lbs/ft

Example determination of moment due to dead weight (for a 56" splice):



Splice length vs. moment due to dead weight for all specimens:

Splice Length (in)	Moment (kft)
56	6.41
60	6.54
64	6.68
28	5.73
30	5.76
32	5.80

Example Strain Calculation (for a 56" splice):

$$\sigma_s = \frac{My}{I} = \frac{(6.41 \text{ kft})(12000 \text{ lbin/1 kft})(17.56 \text{ in})}{11690 \text{ in}^4} = 115.5\text{psi}$$

$$\varepsilon_s = (115.5 \text{ psi})/(4.415E6 \text{ psi}) = 26 \ \mu\text{S}$$

Strain Values for all Specimens:

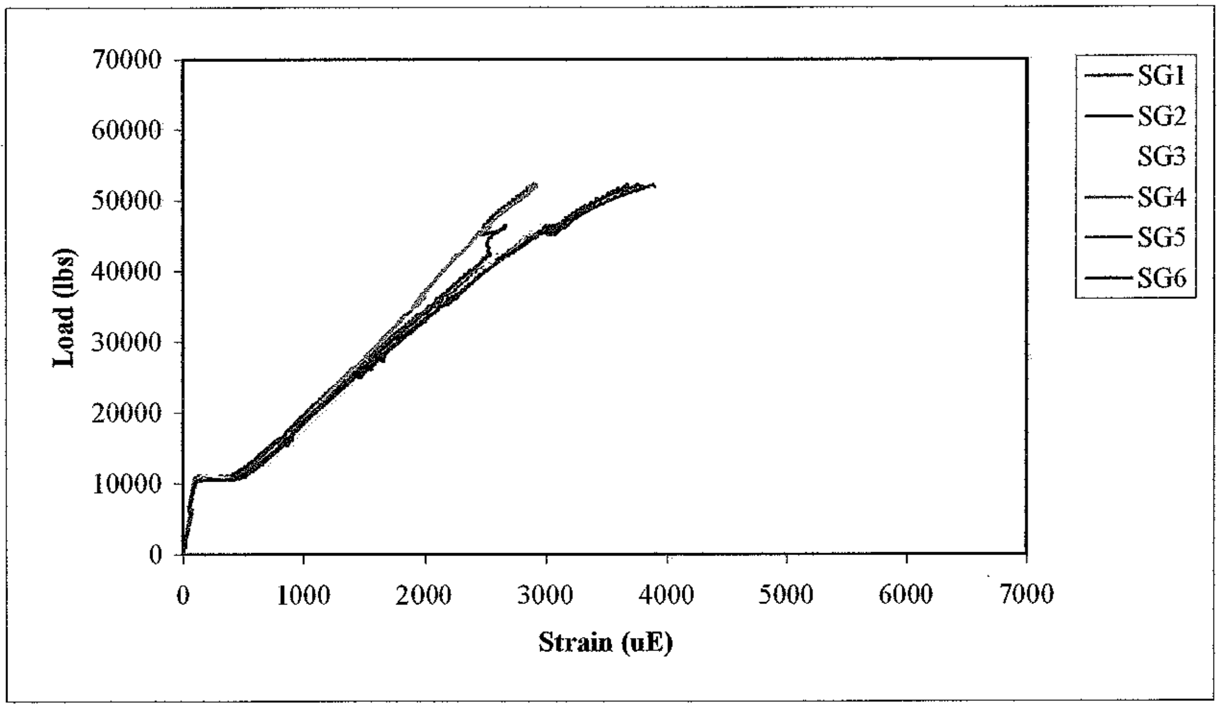
Bar Size	Specimen Length (ft)	Concrete Strength (ksi)	Transverse Reinforcement	Dead Weight Strain (uE)
No. 9	22	6000	none	25
			min	25
			2xmin	24
		12000	none	17
			min	17
			2xmin	17
No. 20	48	6000	none	37
			min	29
			2xmin	12
		12000	none	14
			min	11
			2xmin	11

Appendix D

Test Summary Sheets for Splice Specimens

Splice Specimen Test Summary Sheet

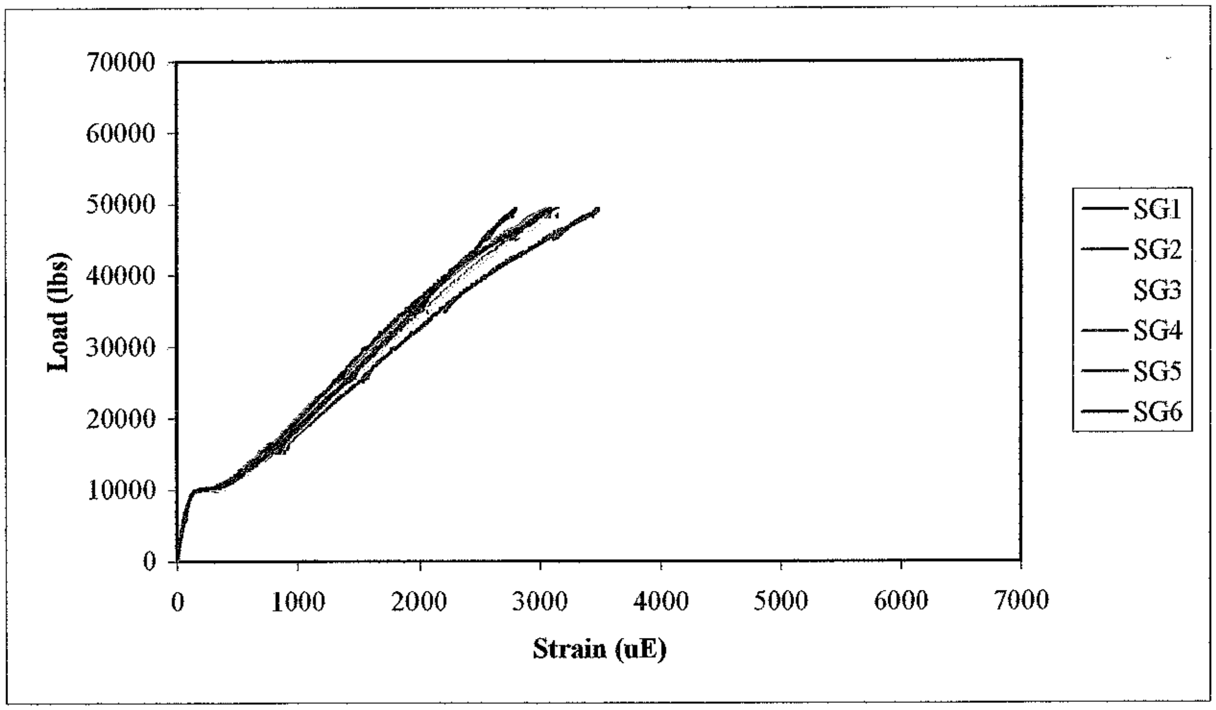
Specimen Identification:	SAS_No9_6000_none_full
Date Tested:	12/7/2005
Bar Size:	No. 9
Specified Concrete Strength:	6.0 ksi
Measured Concrete Strength:	6.3 ksi
Transverse Reinforcement:	none
Splice Length:	64 in (Full Splice Length)
Failure Load:	52.4 kips
Max Measured Steel Strain at Failure due to Applied Load:	3886 uE
Additional Strain due to Dead Load:	25 uE
Total Strain:	3911 uE
Maximum Stress in Bar:	105ksi
Specified Yield Strength:	97 ksi
Failure Mode:	Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

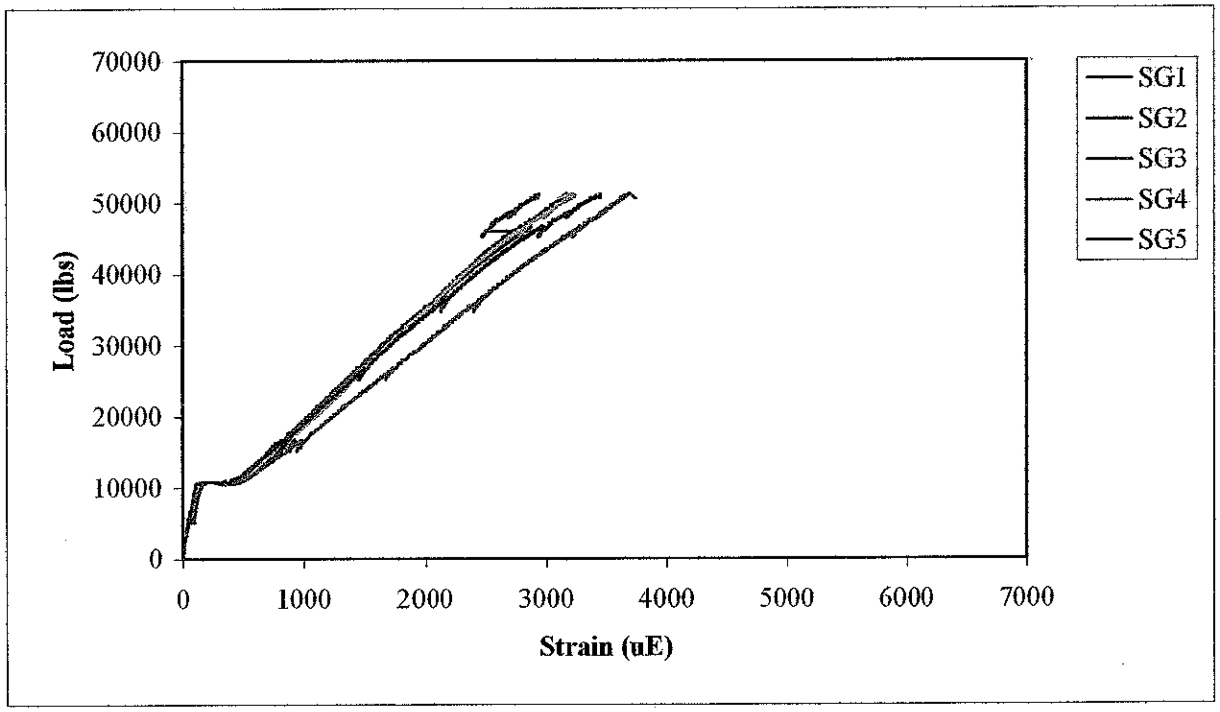
Specimen Identification:	SAS_No9_6000_min_full_#1
Date Tested:	12/16/2005
Bar Size:	No. 9
Specified Concrete Strength:	6.0 ksi
Measured Concrete Strength:	6.3 ksi
Transverse Reinforcement:	minimum (#3 @ 16" oc)
Splice Length:	60 in (Full Splice Length)
Failure Load:	49.4 kips
Max Measured Steel Strain at Failure due to Applied Load:	3430 uE
Additional Strain due to Dead Load:	25 uE
Total Strain:	3455 uE
Maximum Stress in Bar:	100 ksi
Specified Yield Strength:	97 ksi
Failure Mode:	Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

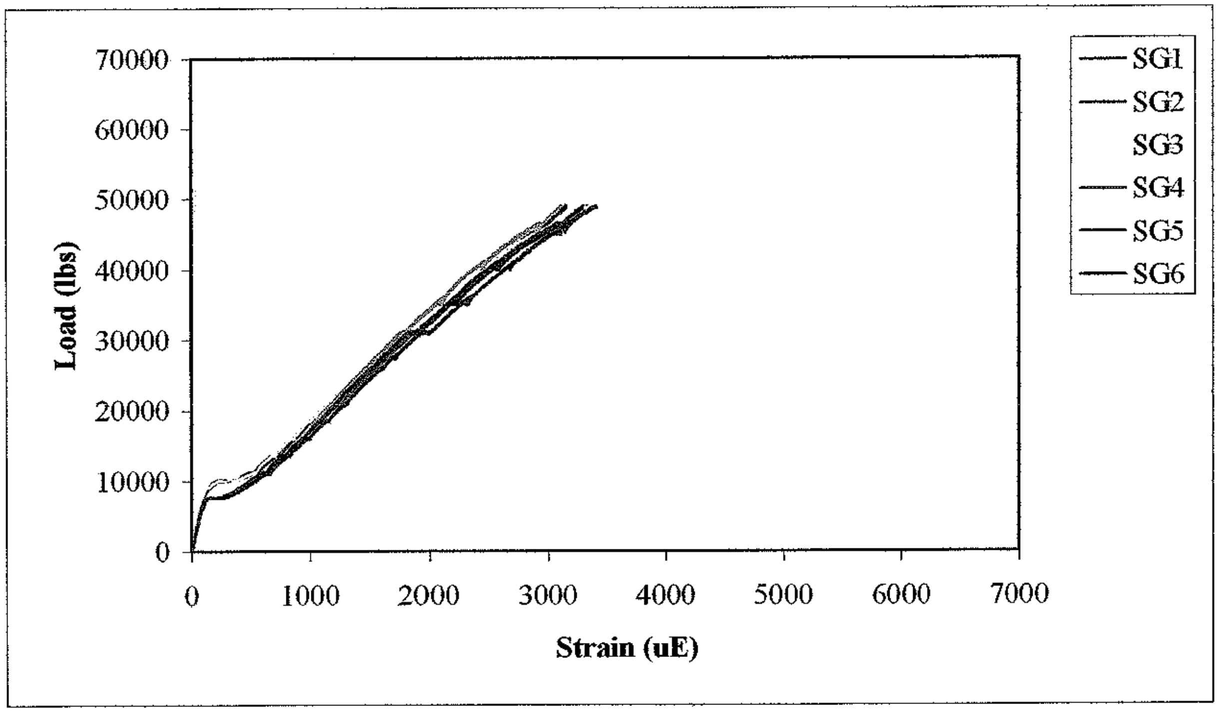
Specimen Identification:	SAS_No9_6000_min_full_#2
Date Tested:	12/17/2005
Bar Size:	No. 9
Specified Concrete Strength:	6.0 ksi
Measured Concrete Strength:	6.3 ksi
Transverse Reinforcement:	minimum (#3 @ 16" oc)
Splice Length:	60 in (Full Splice Length)
Failure Load:	51.3 kips
Max Measured Steel Strain at Failure due to Applied Load:	3687 uE
Additional Strain due to Dead Load:	25 uE
Total Strain:	3712 uE
Maximum Stress in Bar:	105 ksi
Specified Yield Strength:	97 ksi
Failure Mode:	Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

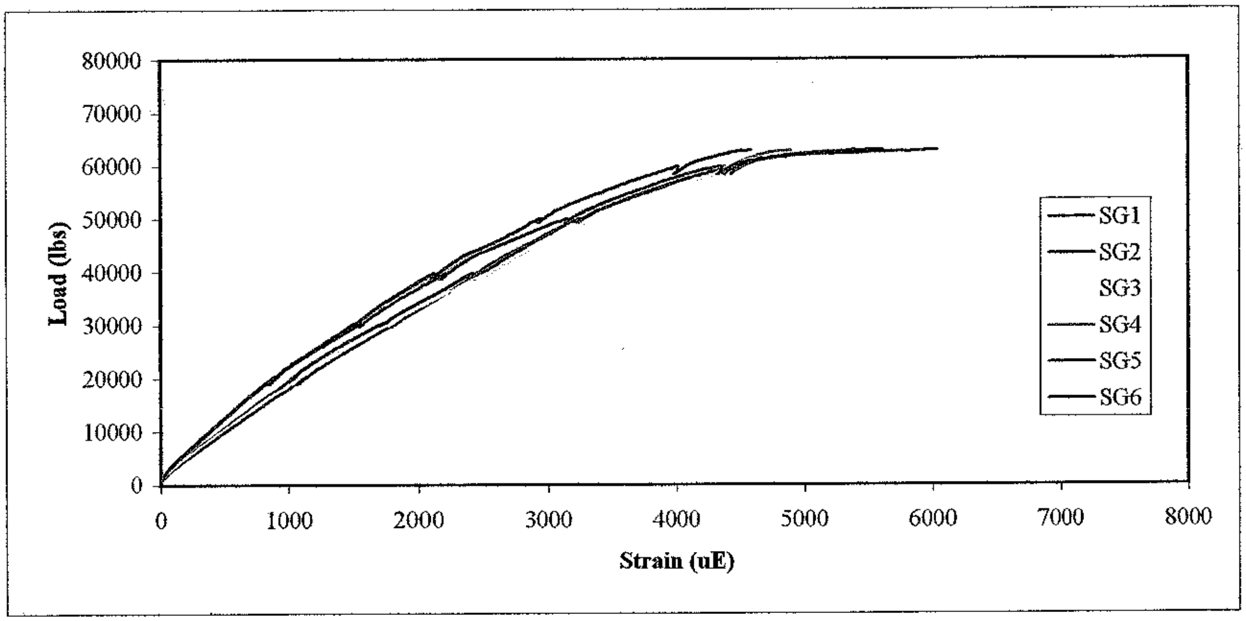
Specimen Identification:	SAS_No9_6000_2x_full
Date Tested:	12/1/2005
Bar Size:	No. 9
Specified Concrete Strength:	6.0 ksi
Measured Concrete Strength:	6.3 ksi
Transverse Reinforcement:	2 x minimum (#3 @ 8" oc)
Splice Length:	56 in (Full Splice Length)
Failure Load:	49.2 kips
Measured Steel Strain at Failure due to Applied Load:	3402 uE
Additional Strain due to Dead Load:	24 uE
Total Strain:	3426 uE
Maximum Stress in Bar:	99.0 ksi
Specified Yield Stress:	97 ksi
Failure Mode:	Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

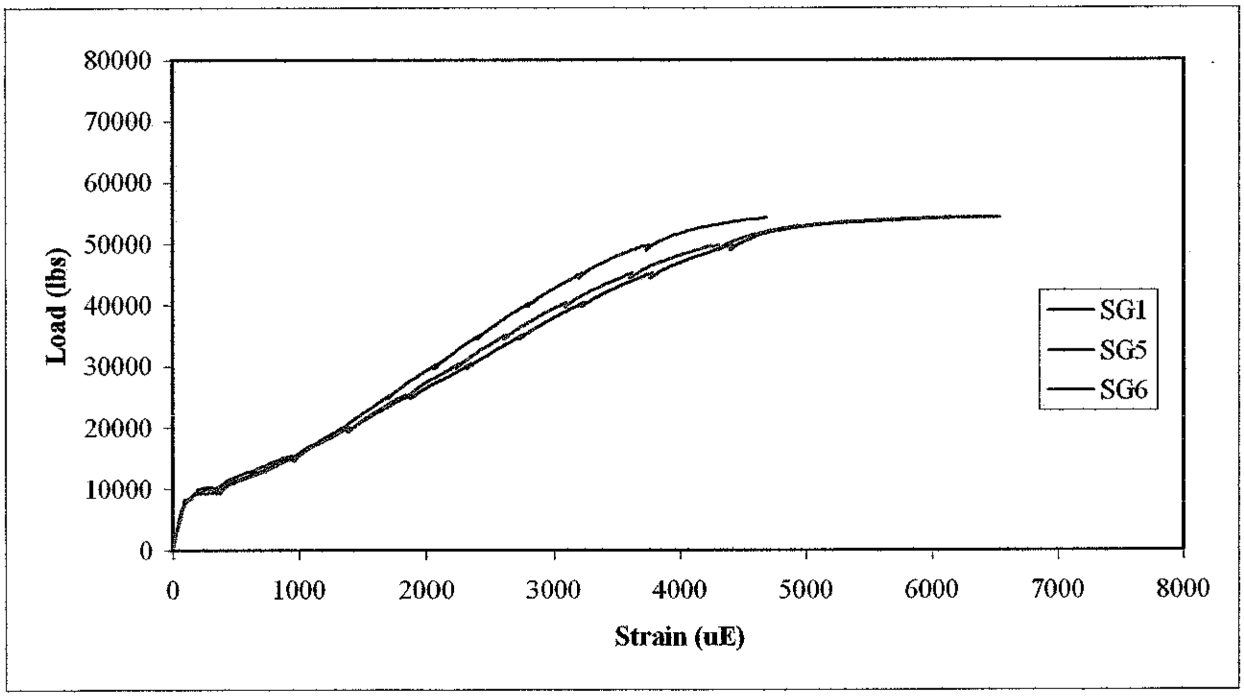
Specimen Identification:	SAS_No9_12000_none
Date Tested:	6/30/2006
Bar Size:	No. 9
Specified Concrete Strength:	12.0 ksi
Measured Concrete Strength:	9.4 ksi
Transverse Reinforcement:	none
Splice Length:	46.0 in (Full Splice Length)
Failure Load:	62.9 kips
Max Measured Steel Strain at Failure due to Applied Load:	6,354 uE
Additional Strain due to Dead Load:	17 uE
Total Strain:	6,036 uE
Maximum Stress in Bar:	110 ksi
Specified Yield Strength:	97 ksi
Failure Mode:	Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

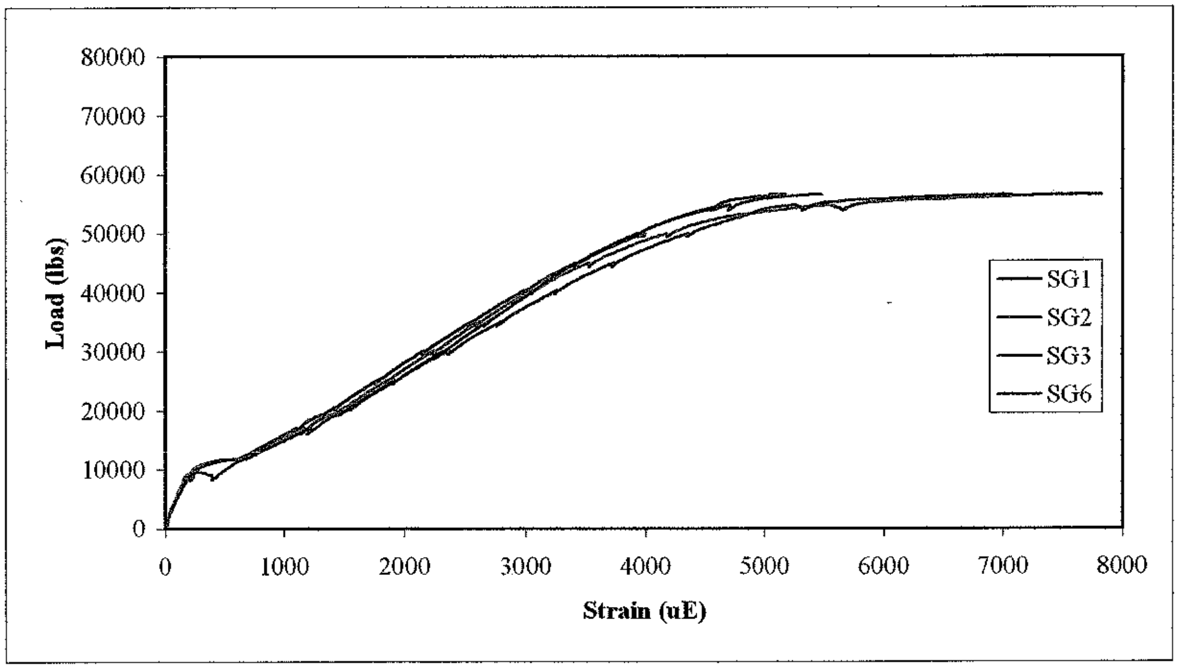
Specimen Identification:	SAS_No9_12000_min#1
Date Tested:	8/1/2006
Bar Size:	No. 9
Specified Concrete Strength:	12.0 ksi
Measured Concrete Strength:	10.1 ksi
Transverse Reinforcement:	minimum (#3@16")
Splice Length:	43.0 in (Full Splice Length)
Failure Load:	54.3 kips
Max Measured Steel Strain at Failure due to Applied Load:	6885 uE
Additional Strain due to Dead Load:	17 uE
Total Strain:	6902 uE
Maximum Stress in Bar:	111 ksi
Specified Yield Strength:	97 ksi
Failure Mode:	Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

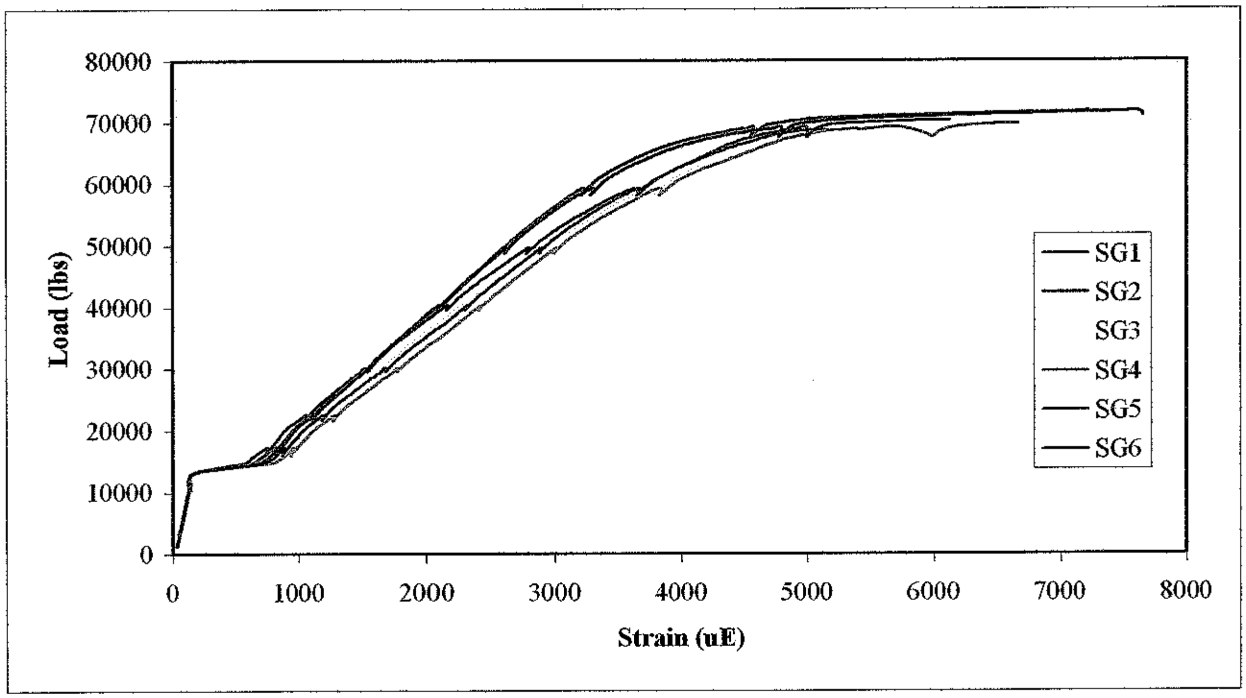
Specimen Identification:		SAS_No9_12000_min#2
Date Tested:		8/1/2006
Bar Size:		No. 9
Specified Concrete Strength:		12.0 ksi
Measured Concrete Strength:		10.1 ksi
Transverse Reinforcement:		minimum (#3@16")
Splice Length:		43.0 in (Full Splice Length)
Failure Load:		56.6 kips
Max Measured Steel Strain at Failure due to Applied Load:		7820 uE
Additional Strain due to Dead Load:		17 uE
Total Strain:		7837 uE
Maximum Stress in Bar:		113 ksi
Specified Yield Strength:		97 ksi
Failure Mode:		Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

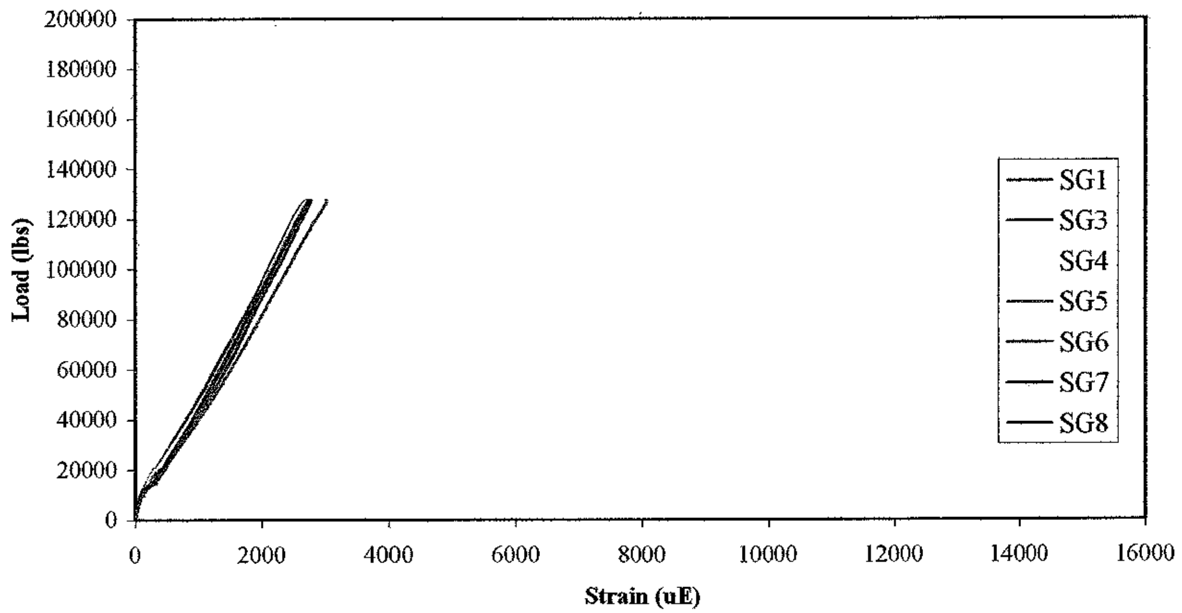
Specimen Identification:	SAS_No9_12000_2xmin
Date Tested:	7/1/2006
Bar Size:	No. 9
Specified Concrete Strength:	12.0 ksi
Measured Concrete Strength:	9.4 ksi
Transverse Reinforcement:	2 x minimum (#3 @ 8" oc)
Splice Length:	40.0 in (Full Splice Length)
Failure Load:	73.7 kips
Max Measured Steel Strain at Failure due to Applied Load:	7,649 uE
Additional Strain due to Dead Load:	17 uE
Total Strain:	7,666 uE
Maximum Stress in Bar:	112 ksi
Specified Yield Strength:	97 ksi
Failure Mode:	Compression Zone Crushing



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

Specimen Identification:	SAS_No20_6000_none_r
Date Tested:	3/23/2007
Bar Size:	No. 20
Specified Concrete Strength:	6.0 ksi
Measured Concrete Strength:	6.0 ksi
Transverse Reinforcement:	none
Splice Length:	235.0 in (Full Splice Length)
Failure Load:	127.4 kips
Max Measured Steel Strain at Failure due to Applied Load:	3019 uE
Additional Strain due to Dead Load:	37 uE
Total Strain:	3085 uE
Maximum Stress in Bar:	88 ksi
Specified Yield Strength:	97 ksi
Failure Mode:	Side Splitting



Strain in the Steel at the End of the Splice

transportation. Figure 3 illustrates the cross-section of the #9 splice beams. For the #9 splice specimens using concrete compressive strength of 6 ksi, the bars were spliced with the flat faces of the bars touching each other. For the #9 splice beams using concrete compressive strength of 12 ksi, the deformations of the bars were touching.

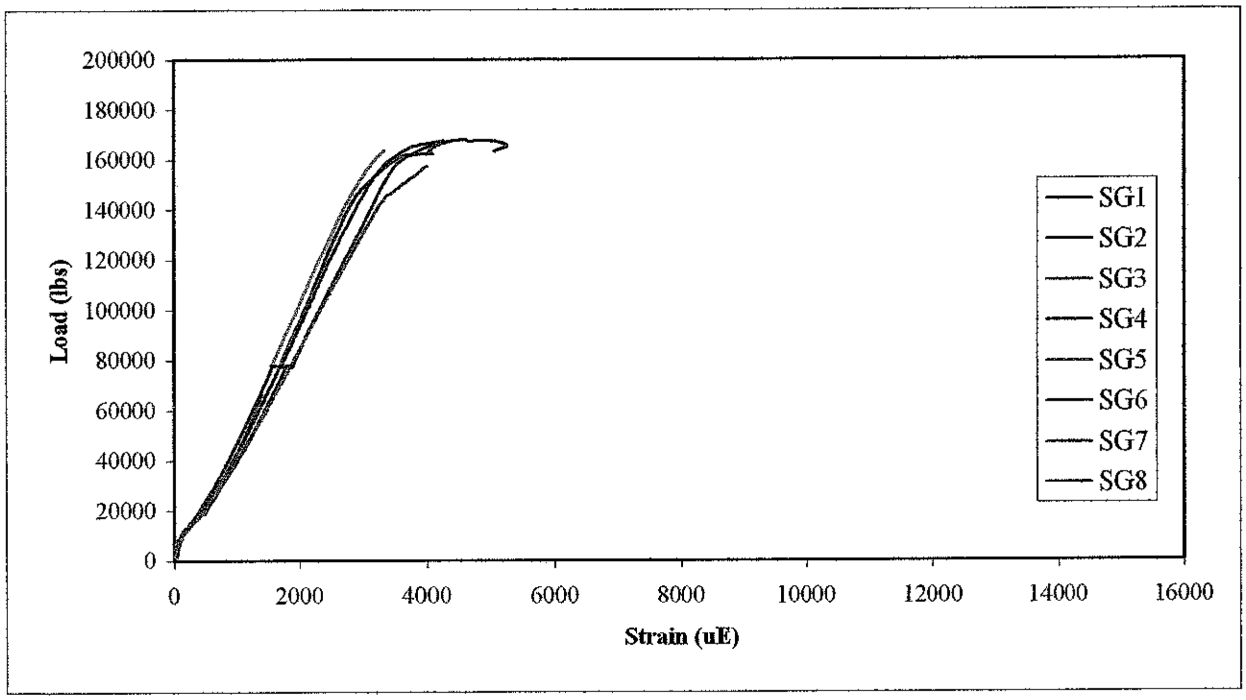
The splice beams for the #20 bars were 48ft. long with a rectangular cross section of 18in. x 30in. Two #20 bars were spliced at the center of the beam. Number 4 and #5 stirrups were used as transverse reinforcing. The stirrups in the constant moment region of the beam were #4's. The stirrups outside of the constant moment region were #5's. Four #11 bars were placed in the compression region of the beam to minimize cracking during transportation and handling. Figure 4 illustrates the cross-section of the #20 splice specimens. For all #20 specimens, the bars were spliced with the bar deformations facing one another. For specimens with minimum or twice the minimum transverse reinforcement, the ties closest to each end of the splice were adjusted to ensure that a tie fell within 1in of the end of the splice.

It is important to note that two cross-sections are shown for each beam size. The first is the cross-section as designed. The measurements of the constructed beams, however, did not exactly match the specified designed measurements. Since relatively small differences in concrete cover can have a dramatic effect on the calculated splice length, the field measured covers are presented in an as-built drawing given next to the design drawing. All beams were observed to be constructed with top covers greater than intended, and side covers less than intended. The magnitudes of these differences were very consistent among beams of a given size. It is postulated that these differences are due to expected construction and material tolerances, and to the way in which the beams were fabricated. Since the stirrups themselves were used to hold the spliced bars at the top of the forms, any variations in stirrup size from the design size directly changed the location of the splice with respect to the cross-section. If stirrups were delivered ½" shorter and ½" wider than anticipated (within the ½" tolerance typically expected for bent reinforcing bars), bar placement would be significantly influenced, as shown in the "As Built" detail within Figure 3 and Figure 4.

In addition to fabrication tolerances, the weight of the stirrups and spliced-bars tended to pull the reinforcing cages down in the forms as the concrete was vibrated, especially in the case of #20 bars, leading to significant increase in top cover. Furthermore, (prior to casting) the vertical legs of the stirrups also had the tendency to bow outward under the weight of the spliced bars (especially the #20 bars). This deflection under the self weight of the bars also tended to reduce side cover and to increase top cover. Finally, post-testing observation indicated that the spliced bars were tied tightly into the bends of the stirrups from the sides. While this detail is difficult to reflect in the Figures, the inner radius of the stirrup had the tendency to pull the spliced bars outwards and downwards as they were tied. It is assumed that a combination of the issues presented above resulted in the discrepancies between design and construction seen in the Figure 3 and Figure 4. The photographs shown in Figure 5 clearly show the increased top cover and decreased side cover for a #9 specimen and a #20 specimen. These differences were typical for all beams tested in this program. Arrows in the corresponding Figure highlight locations where the cover differs from the original design values.

Splice Specimen Test Summary Sheet

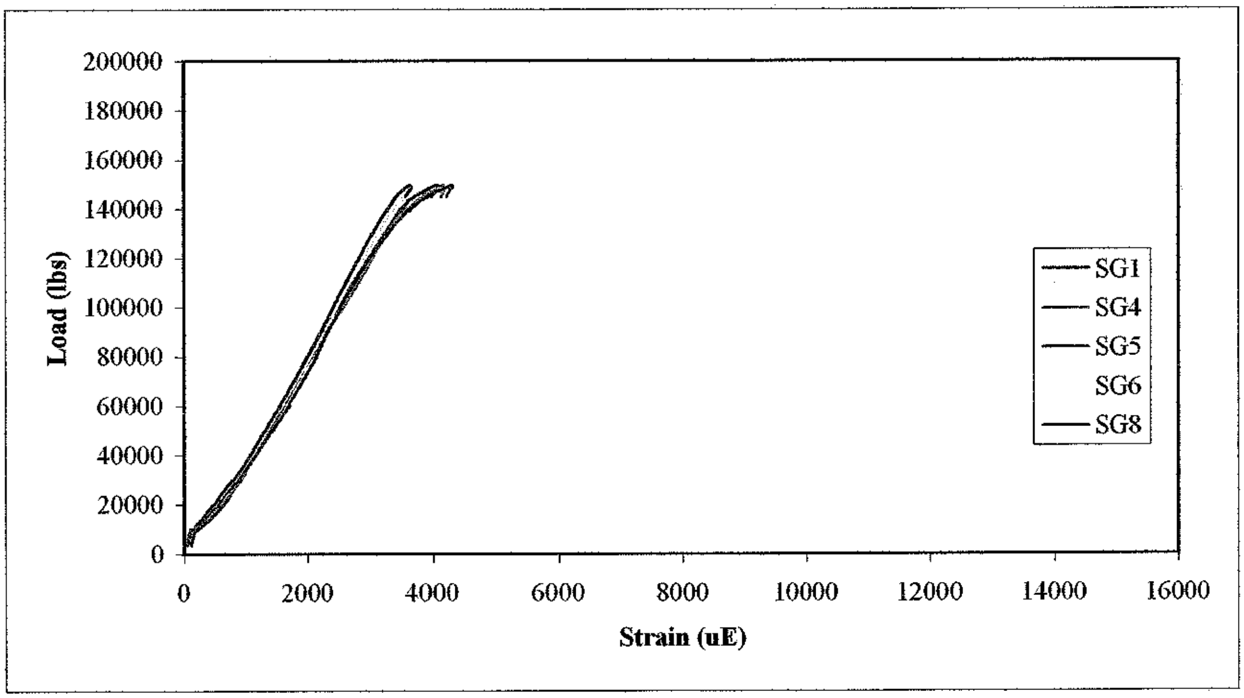
Specimen Identification:	SAS_No20_6000_min_r
Date Tested:	3/20/2007
Bar Size:	No. 20
Specified Concrete Strength:	6.0 ksi
Measured Concrete Strength:	6.0 ksi
Transverse Reinforcement:	minimum (#4@18")
Splice Length:	207.0 in (Full Splice Length)
Failure Load:	167.9 kips
Max Measured Steel Strain at Failure due to Applied Load:	5241 uE
Additional Strain due to Dead Load:	29 uE
Total Strain:	5270 uE
Maximum Stress in Bar:	109 ksi
Specified Yield Strength:	97 ksi
Failure Mode:	Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

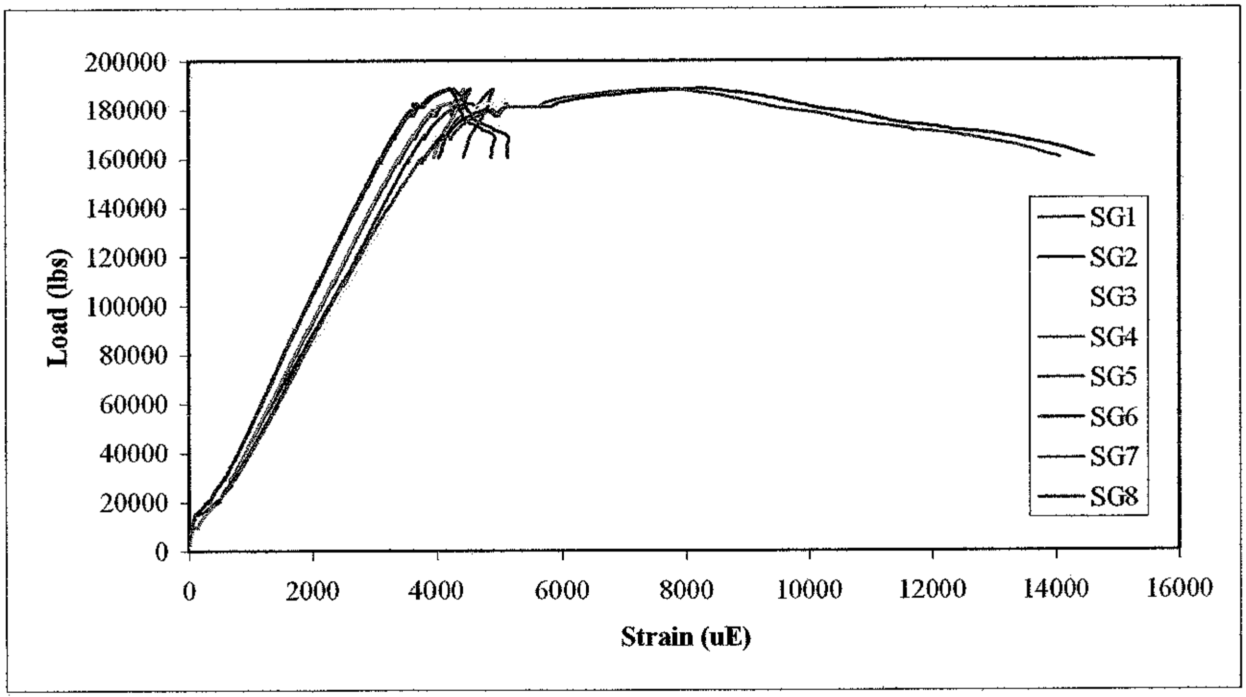
Specimen Identification:	SAS_No20_6000_min
Date Tested:	7/31/2006
Bar Size:	No. 20
Specified Concrete Strength:	6.0 ksi
Measured Concrete Strength:	7.7 ksi
Transverse Reinforcement:	minimum (#4@18")
Splice Length:	207.0 in (Full Splice Length)
Failure Load:	149.6 kips
Max Measured Steel Strain at Failure due to Applied Load:	4315 uE
Additional Strain due to Dead Load:	30 uE
Total Strain:	4345 uE
Maximum Stress in Bar:	108 ksi
Specified Yield Strength:	97 ksi
Failure Mode:	Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

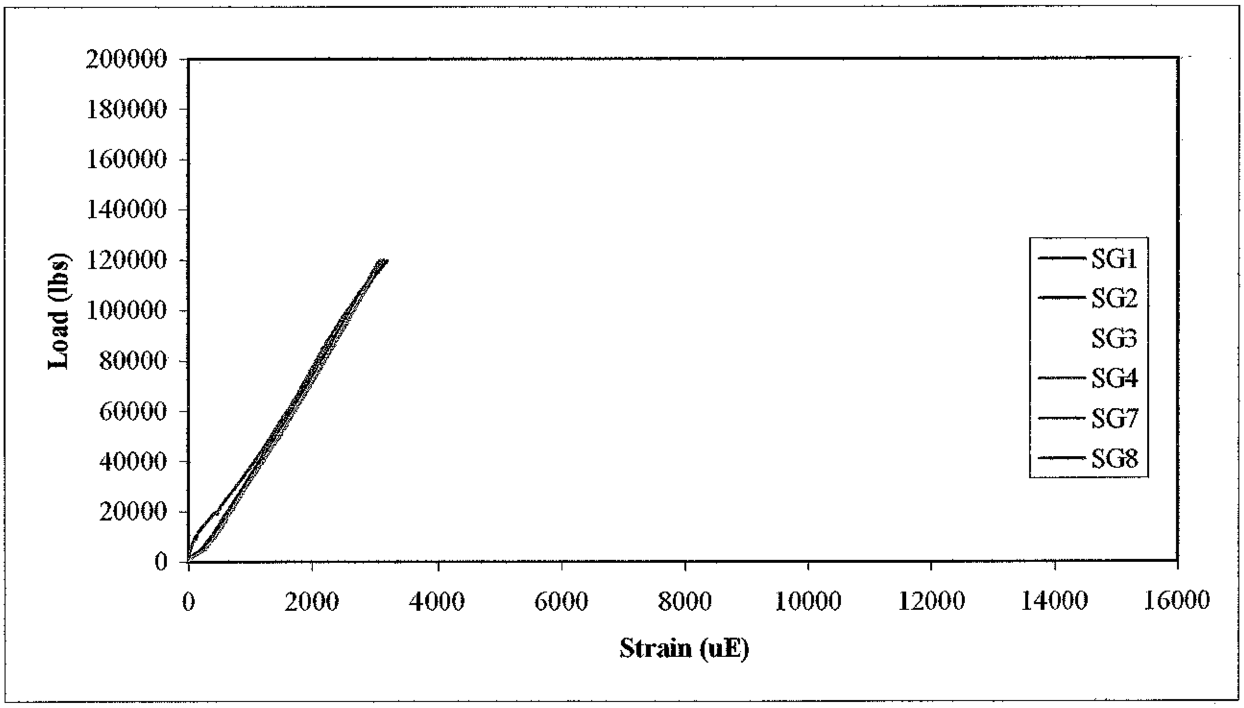
Specimen Identification:	SAS_No20_6000_2xmin
Date Tested:	4/13/2006
Bar Size:	No. 20
Specified Concrete Strength:	6.0 ksi
Measured Concrete Strength:	8.4 ksi
Transverse Reinforcement:	2 x minimum (#4 @ 9" oc)
Splice Length:	92.5 in (Full Splice Length)
Failure Load:	188.6 kips
Max Measured Steel Strain at Failure due to Applied Load:	14,613 uE
Additional Strain due to Dead Load:	12 uE
Total Strain:	14,625 uE
Maximum Stress in Bar:	112 ksi
Specified Yield Strength:	97 ksi
Failure Mode:	Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

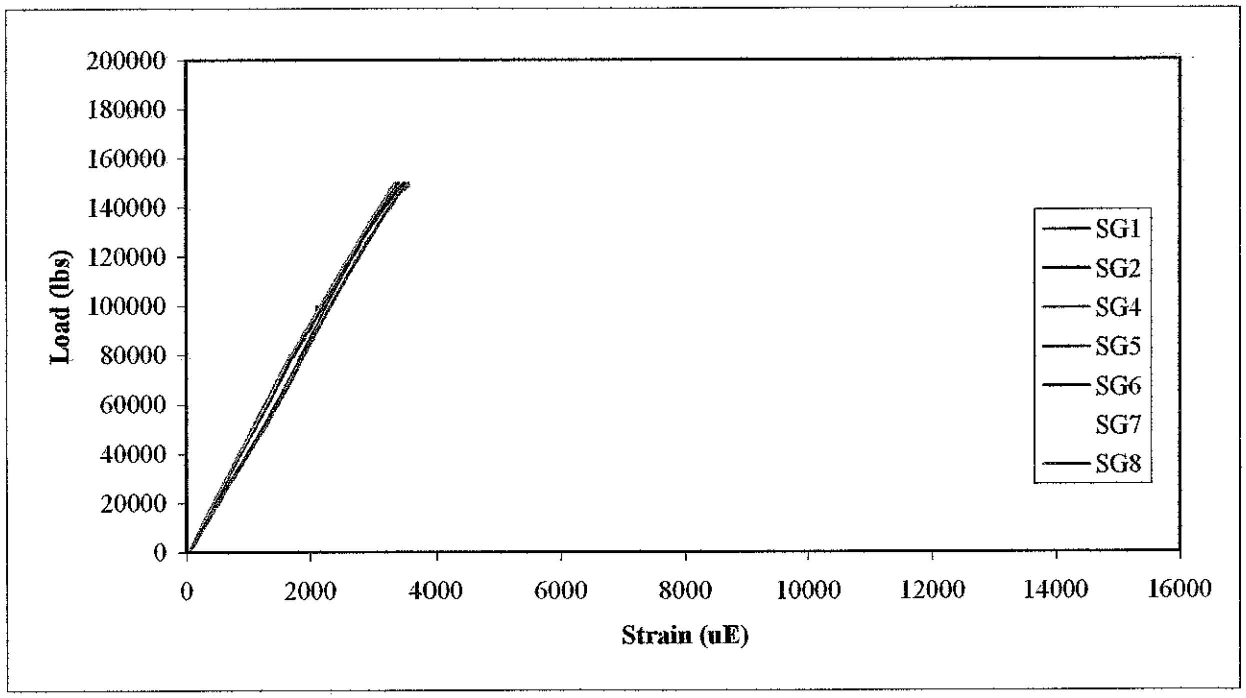
Specimen Identification:		SAS_No20_12000_none
Date Tested:		7/25/2006
Bar Size:		No. 20
Specified Concrete Strength:		12.0 ksi
Measured Concrete Strength:		11.3 ksi
Transverse Reinforcement:		none
Splice Length:		166.0 in (Full Splice Length)
Failure Load:		120.1 kips
Max Measured Steel Strain at Failure due to Applied Load:		3214 uE
Additional Strain due to Dead Load:		14 uE
Total Strain:		3228 uE
Maximum Stress in Bar:		94 ksi
Specified Yield Strength:		97 ksi
Failure Mode:		Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

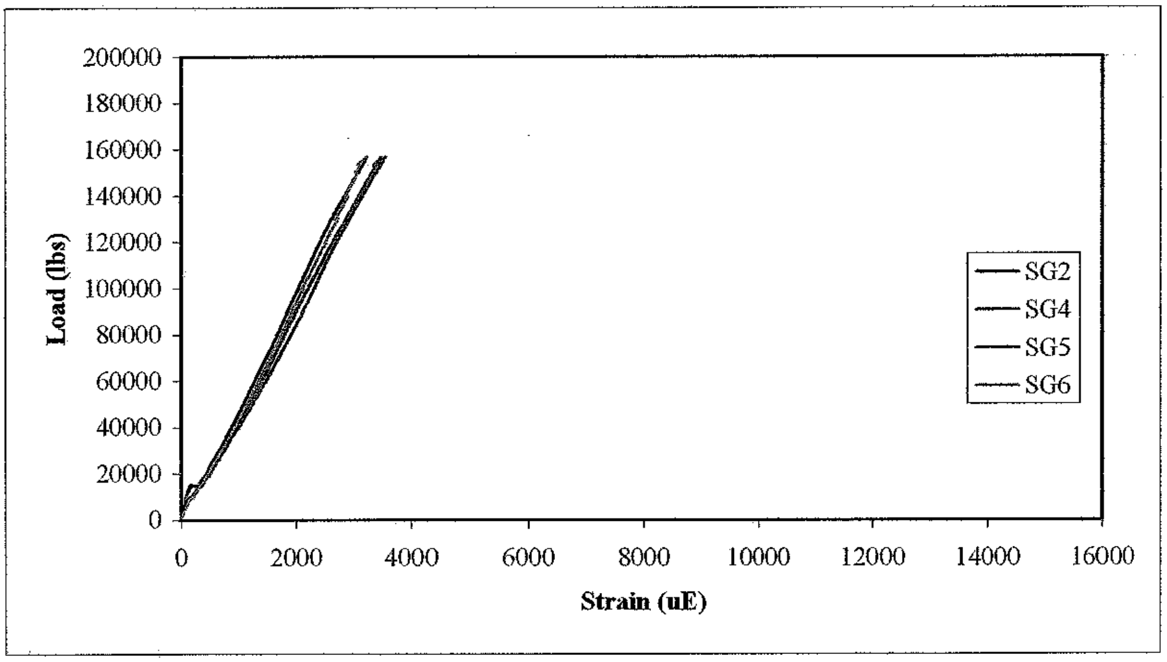
Specimen Identification:		SAS_No20_12000_min #1
Date Tested:		7/26/2006
Bar Size:		No. 20
Specified Concrete Strength:		12.0 ksi
Measured Concrete Strength:		11.1 ksi
Transverse Reinforcement:		minimum (#4 @18")
Splice Length:		146.0 in (Full Splice Length)
Failure Load:		149.9 kips
Max Measured Steel Strain at Failure due to Applied Load:		3579 uE
Additional Strain due to Dead Load:		11 uE
Total Strain:		3590 uE
Maximum Stress in Bar:		105 ksi
Specified Yield Strength:		97 ksi
Failure Mode:		Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

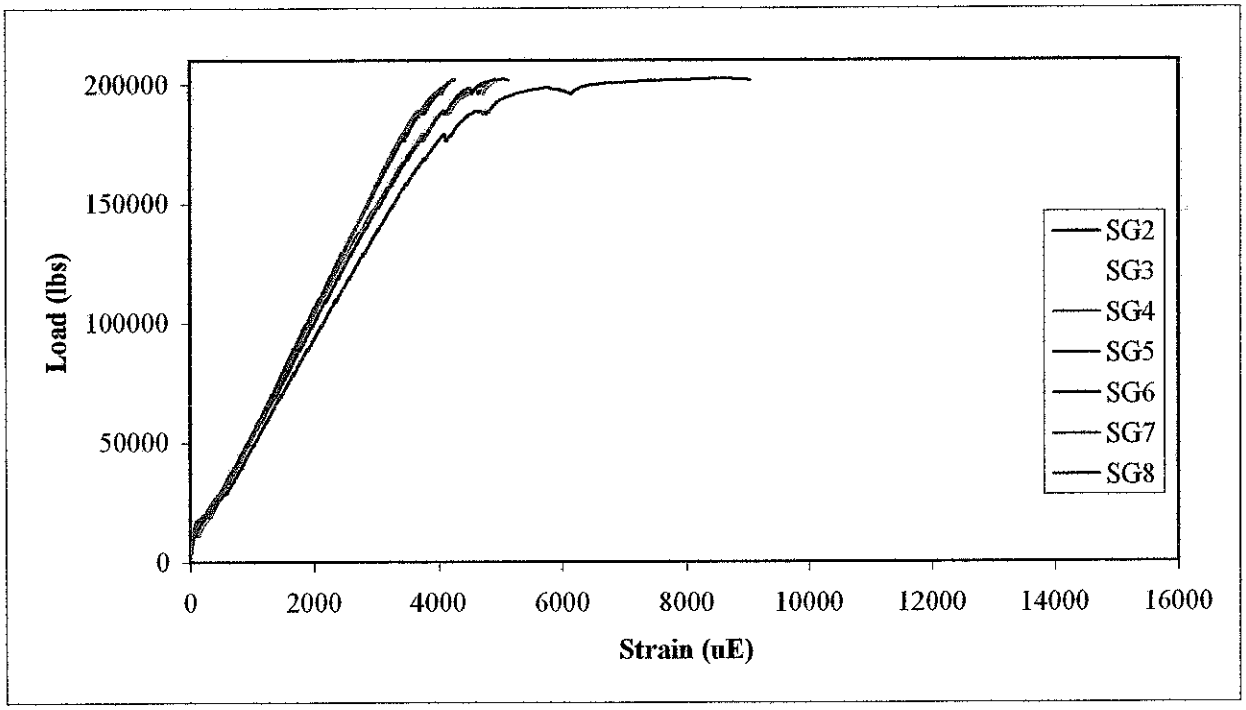
Specimen Identification:	SAS_No20_12000_min #2
Date Tested:	7/27/2006
Bar Size:	No. 20
Specified Concrete Strength:	12.0 ksi
Measured Concrete Strength:	10.3 ksi
Transverse Reinforcement:	minimum (#4 @18")
Splice Length:	146.0 in (Full Splice Length)
Failure Load:	156.9 kips
Max Measured Steel Strain at Failure due to Applied Load:	3554 uE
Additional Strain due to Dead Load:	11 uE
Total Strain:	3565 uE
Maximum Stress in Bar:	105 ksi
Specified Yield Strength:	97 ksi
Failure Mode:	Side Splitting



Strain in the Steel at the End of the Splice

Splice Specimen Test Summary Sheet

Specimen Identification:	SAS_No20_12000_2xmin
Date Tested:	4/17/2006
Bar Size:	No. 20
Specified Concrete Strength:	12.0 ksi
Measured Concrete Strength:	10.1 ksi
Transverse Reinforcement:	2 x minimum (#4 @ 9" oc)
Splice Length:	65.5 in (Half Splice Length)
Failure Load:	202.2 kips
Max Measured Steel Strain at Failure due to Applied Load:	9006 uE
Additional Strain due to Dead Load:	11 uE
Total Strain:	9017 uE
Maximum Stress in Bar:	107 ksi
Specified Yield Strength:	97 ksi
Failure Mode:	Side Splitting



Strain in the Steel at the End of the Splice

Appendix E

Calculation of l_{daci} for Splice Specimens Using Design Values

Development Length Calculations for No. 9 Bars

$$\ell_d = \left(\frac{3}{40} \frac{f_y}{\sqrt{f_c'}} \frac{\alpha\beta\gamma\lambda}{\left(\frac{c+K_{tr}}{d_b} \right)} \right) d_b$$

f'_c (psi)	Transverse Reinforcement	f_y (psi)	$\alpha\beta\gamma\lambda$	c (in)	K_{tr}	d_b (in)	*$(c+K_{tr})/d_b$	l_d (in)	**$1.3*l_d$ (in)	splice length (in)
6000	none	97000	1.0	2.4	0.00	1.125	2.13	49.5	64.4	64
6000	min	97000	1.0	2.4	0.18	1.125	2.30	46.0	59.8	60
6000	2 x min	97000	1.0	2.4	0.37	1.125	2.46	42.9	55.8	56
12000	none	97000	1.0	2.4	0.00	1.125	2.13	35.0	45.5	46
12000	min	97000	1.0	2.4	0.18	1.125	2.30	32.5	42.3	43
12000	2 x min	97000	1.0	2.4	0.37	1.125	2.46	30.4	39.5	40

* $(c+K_{tr})/d_b < 2.5$

** Assuming a class B splice ($f_s/f_y > 0.5$)

f'_c (psi)	Transverse Reinforcement	A_{tr} (in)	f_{yt} (psi)	s (in)	n	K_{tr}
6000	none					0.00
6000	min	0.22	60000	16	3	0.18
6000	2 x min	0.22	60000	8	3	0.37
12000	none					0.00
12000	min	0.22	60000	16	3	0.18
12000	2 x min	0.22	60000	8	3	0.37

$$K_{tr} = \frac{A_{tr} f_{yt}}{1500sn}$$

Development Length Calculations for No. 20 Bars

$$\ell_d = \left(\frac{3}{40} \frac{f_y}{\sqrt{f_c'}} \frac{\alpha\beta\gamma\lambda}{\left(\frac{c+K_{tr}}{d_b} \right)} \right) d_b$$

f'c (psi)	Transverse Reinforcement	f_y (psi)	$\alpha\beta\gamma\lambda$	c (in)	K_{tr}	d_b (in)	*$(c+K_{tr})/d_b$	l_d (in)	**$1.3*l_d$ (in)	splice length (in)	splice length (ft-in)
6000	none	97000	1.0	3.25	0.00	2.5	1.30	180.6	234.8	235	19 - 7
6000	min	97000	1.0	3.25	0.44	2.5	1.47	159.2	207.0	207	17 - 3
6000	2 x min	97000	1.0	3.25	0.87	2.5	1.65	142.4	185.1	185	15 - 5
12000	none	97000	1.0	3.25	0.00	2.5	1.30	127.7	166.0	166	13 - 10
12000	min	97000	1.0	3.25	0.44	2.5	1.47	112.6	146.4	146	12 - 2
12000	2 x min	97000	1.0	3.25	0.87	2.5	1.65	100.7	130.9	131	10 - 11

* $(c+K_{tr})/d_b < 2.5$

** Assuming a class B splice ($f_s/f_y > 0.5$)

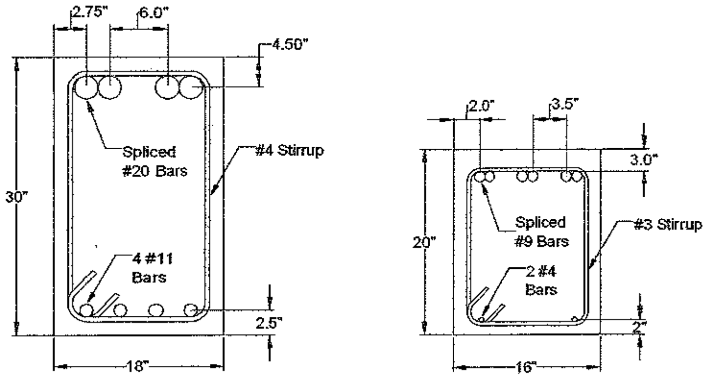
f'c (psi)	Transverse Reinforcement	A_{tr} (in)	f_{yt} (psi)	s (in)	n	K_{tr}
6000	none					0.00
6000	min	0.39	60000	18	2	0.44
6000	2 x min	0.39	60000	9	2	0.87
12000	none					0.00
12000	min	0.39	60000	18	2	0.44
12000	2 x min	0.39	60000	9	2	0.87

$$K_{tr} = \frac{A_{tr} f_{yt}}{1500sn}$$

Appendix F

Calculation of l_{daci} for Splice Specimens Using Measured Values

Example Calculations – Determining l_{daci}



Cross-Sections with As-Built Dimensions for #20 and #9 Splice Specimens

l_{daci} is calculated according to Section 12.2.3 of ACI-318:

For deformed bars and wires: $$\ell_d = \left(\frac{3}{40} \frac{f_y}{\sqrt{f'_c}} \frac{\alpha\beta\gamma\lambda}{\left(\frac{c+K_{tr}}{d_b} \right)} \right) d_b$$

Where: $$K_{tr} = \frac{A_{tr} f_{yt}}{1500sn}$$

Given:

l_{daci} = ACI-specified tensile development length.

f_y = Yield stress of spliced steel in psi.

f'_c = Compressive strength of concrete in psi limited to 10,000.

$\alpha\beta\gamma\lambda$ = Factors for location, coatings, size, and concrete weight. For the topcast, uncoated bars tested, the product of these factors = 1.3

d_b = Bar diameter in inches.

c = The smallest of side cover (to center of bar), cover over bar (to center of bar), or one-half center-to-center spacing of spliced bars.

K_{tr} = A factor representing the contribution of any confining reinforcement across potential splitting planes.

A_{tr} = Area of transverse reinforcement across a splitting plane.

f_{yt} = The yield stress of transverse reinforcement.

s = Maximum center to center spacing of transverse reinforcement within development length

n = The number of spliced bars in a single splice plane.

Determination of l_{daci} for #9 bars using actual concrete strengths:

f'c (psi)	Transverse Reinforcement	f_y (psi)	$\alpha\beta\gamma\lambda$	c (in)	Atr (in)	fyt (psi)	s (in)	n	K_{tr}	l_{daci} (in)
6300	none	97000	1.3	2.0					0.00	75
6300	min 1	97000	1.3	2.0	0.22	60000	16	3	0.18	69
6300	min 2	97000	1.3	2.0	0.22	60000	16	3	0.18	69
6300	2 x min	97000	1.3	2.0	0.22	60000	8	3	0.37	64
9400	none	97000	1.3	2.0					0.00	62
10100	min 1	97000	1.3	2.0	0.22	60000	16	3	0.18	55
10100	min 2	97000	1.3	2.0	0.22	60000	16	3	0.18	55
9400	2 x min	97000	1.3	2.0	0.22	60000	8	3	0.37	52

NOTE: d_b = 1.125"

Determination of l_{daci} for #20 bars using actual concrete strengths:

f'c (psi)	Transverse Reinforcement	f_y (psi)	$\alpha\beta\gamma\lambda$	c (in)	Atr (in)	fyt (psi)	s (in)	n	K_{tr}	l_d (in)
6000	none 2	97000	1.3	2.75					0.00	277
6000	min	97000	1.3	2.75	0.40	60000	9	2	0.44	239
7700	min 2	97000	1.3	2.75	0.40	60000	18	2	0.44	211
8400	2 x min	97000	1.3	2.75	0.40	60000	9	2	0.89	177
11300	none	97000	1.3	2.75					0.00	215
11100	min 1	97000	1.3	2.75	0.40	60000	18	2	0.44	185
10300	min 2	97000	1.3	2.75	0.40	60000	18	2	0.44	185
10100	2 x min	97000	1.3	2.75	0.40	60000	9	2	0.89	162

NOTE: d_b = 2.5"