

Appendix F

Shear Specimens

F.1 Introduction

Specimen design, details, instrumentation, testing procedure, and material properties of nine shear specimens consisting of five rectangular beams (SR1-5) and four AASHTO Type I girders (SP1-4) are presented. The first four rectangular beams as well as the four Type I girders incorporate both #3 A1035 and #4 A615 stirrups in their design for comparison purposes; the last rectangular beam (SR5) was designed and constructed with only #3 A1035 stirrups. A summary of all measured and visual data are also provided in this appendix.

F.2 Specimen Design

All of the shear specimens, except for the last rectangular beam (SR5) and the last Type I girder (SP4), were designed to produce equal forces in the #3 A1035 and #4 A615 stirrups based on the Sectional Design Model as stated in the *AASHTO LRFD Bridge Design Specifications* (Section 5.8.3). Specimen SR5 was fabricated similar to SR1 except that the entire beam contained only #3 A1035 stirrups. Specimen SP4 was designed with an imbalance in the stirrup forces such that failure would be precipitated on the side reinforced with A1035 stirrups. Moreover, two of the rectangular beams (SR2 and SR3) had their stirrup spacing controlled by the maximum allowed spacing of transverse reinforcement as stipulated in Section 5.8.2.7 of the *AASHTO LRFD Bridge Design Specification*. The design equations are presented below.

Sectional Design Model:

$$V_n = V_c + V_s$$

in which:

$$V_c = 0.0316\beta\sqrt{f'_c}b_vd_v$$
$$V_s = \frac{A_v f_y d_v (\cot\theta + \cot\alpha) \sin\alpha}{s}$$

where:

f'_c = concrete compressive strength (ksi)

b_v = effective web width taken as the minimum web width within the depth d_v (in.)

d_v = effective shear depth taken as the distance between the resultants of the tensile and compressive forces due to flexure (in.)

s = spacing of stirrups (in.)

A_v = area of shear reinforcement within a distance s (in.²)

f_y = yield strength of shear reinforcement (ksi)

α = angle of inclination of transverse reinforcement ($^{\circ}$)

β = factor indicating ability of diagonally cracked concrete to transmit tension

θ = angle of inclination of diagonal compressive stresses ($^{\circ}$)

and:

$$\beta = \frac{4.8}{(1 + 750\epsilon_s)} \text{ or } 4.8 \text{ if } \epsilon_s \leq 0$$

$$\theta = 29 + 3500\epsilon_s \text{ or } 29 \text{ if } \epsilon_s \leq 0$$

in which:

$$\epsilon_s = \frac{\frac{|M_u|}{d_v} + V_u - A_{ps}f_{po}}{E_s A_s + E_p A_{ps}}$$

where:

M_u = applied moment, not to be taken less than $V_u d_v$ (kip-in.)

V_u = applied shear force (kip)

A_{ps} = area of prestressing steel on the flexural tension side of the member (in.²)

A_s = area of nonprestressed steel on the flexural tension side of the member (in.²)

$f_{po} = 0.7 f_{pu}$ (ksi)

f_{pu} = ultimate strength of prestressing steel (ksi)

E_p = modulus of elasticity of prestressing steel (ksi)

E_s = modulus of elasticity of nonprestressed steel (ksi)

Maximum Spacing of Transverse Reinforcement:

If $v_u \leq 0.125 f_c'$ then $s_{\max} = 0.8 d_v \leq 24.0$ in.

If $v_u \geq 0.125 f_c'$ then $s_{\max} = 0.4 d_v \leq 12.0$ in.

where:

v_u = shear stress (ksi)

$$v_u = \frac{|V_u|}{b_v d_v}$$

The above equations address only the shear capacities of the specimens. The flexural capacities of the shear specimens were amplified in order to induce shearing failure. The longitudinal steel in the rectangular beams consisted of #8 A1035; six bars were used in specimens SR1 and SR5 while five bars were used in specimens SR2, SR3, and SR4. The Type I girders contained 0.6"-diameter, Low-Relaxation prestressing strands as the flexural reinforcement. For each girder, twelve strands were placed in the bottom bulb of the cross section and two strands in the top bulb. Two #6 A615 mild-steel bars were also placed in the top bulb of each girder. The variables used in the design calculations are summarized in Table F1.

Table F1 Design Variables
(a) Rectangular Beams

Variable	Specimen				
	SR1	SR2	SR3	SR4	SR5
L (ft) - Overall Length	13.75	13.75	26	26	13.75
a (ft) - Shear Span	5.5	5.5	5	5	5.5
f'_c (ksi) - Concrete Strength	10	10	10	10	15
b_v (in) - Beam Width	12	12	12	12	12
h (in) - Beam Height	24	24	24	24	24
d_v (in) - Effective Shear Depth	17.3	17.3	17.3	17.3	17.3
s (in) - Stirrup Spacing (#3 A1035)	8.5	13	13	8.5	8.5
s (in) - Stirrup Spacing (#4 A615)	9.5	13	13	9.5	N/A
A_v (in ²) - Area of Two Legs of Stirrup (#3 A1035)	0.22	0.22	0.22	0.22	0.22
A_v (in ²) - Area of Two Legs of Stirrup (#4 A615)	0.4	0.4	0.4	0.4	N/A
f_y (ksi) - Yield Strength of Stirrups (#3 A1035)	100	100	100	100	100
f_y (ksi) - Yield Strength of Stirrups (#4 A615)	60	60	60	60	N/A
α (°) - Angle of Inclination of Stirrups	90	90	90	90	90
A_s (in ²) - Area of Longitudinal Steel (#8 A1035)	4.74	3.95	3.95	3.95	4.74
E_s (ksi) - Modulus of Elasticity of Longitudinal Steel	29000	29000	29000	29000	29000
Side Cover to Stirrups (in)	1.5	1.5	1.5	1.5	1.5
Bottom Cover to Stirrups (in)	1.5	1.5	1.5	1.5	1.5

Table F1 (cont.) Design Variables

(b) AASHTO Type I Girders

Variable	Specimen			
	SP1	SP2	SP3	SP4
Cross-Section	AASHTO Type I Girder w/Slab			
Slab Width (in)	48	48	48	48
Slab Height (in)	7	7	7	7
L (ft) - Overall Length	30	30	30	30
a (ft) - Shear Span	7.75	7.75	7.75	7.75
f'_c (ksi) - Concrete Strength (Girder)	10	10	10	10
f'_c (ksi) - Concrete Strength (Slab)	5	5	5	5
b_v (in) - Effective Web Width	6	6	6	6
d_v (in) - Effective Shear Depth	30.51	30.51	30.51	30.51
s (in) - Stirrup Spacing (#3 A1035)	7.5	22	10	18
s (in) - Stirrup Spacing (#4 A615)	8	24	11	16
A_v (in ²) - Area of Two Legs of Stirrup (#3 A1035)	0.22	0.22	0.22	0.22
A_v (in ²) - Area of Two Legs of Stirrup (#4 A615)	0.4	0.4	0.4	0.4
f_y (ksi) - Yield Strength of Stirrups (#3 A1035)	100	100	100	100
f_y (ksi) - Yield Strength of Stirrups (#4 A615)	60	60	60	60
α (°) - Angle of Inclination of Stirrups	90	90	90	90
A_{ps} (in ²) - Area of Prestressing Steel (0.6" Strand)	2.604	2.604	2.604	2.604
A_s (in ²) - Area of Non-Prestressed Steel (#6 A615)	1.32	1.32	1.32	1.32
f_{pu} (ksi) - Ultimate Strength of Prestressing Steel	270	270	270	270
f_{po} (ksi) - 'Locked-In' Stress in Prestressing Steel	189	189	189	189
E_p (ksi) - Modulus of Elasticity of Prestressing Steel	28500	28500	28500	28500
E_s (ksi) - Modulus of Elasticity of Non-Prestressed Steel	29000	29000	29000	29000

F.3 Specimen Details

Figures F1 through F5 illustrate the elevation and cross section views of the rectangular beams. Note that specimens SR3 and SR4 were tested in two stages. The side reinforced with A615 in SR3 and the side of SR4 using A1035 stirrups were tested first. In the second stage, the specimens were rotated to allow testing of the other half. Figures F6 through F9 show the elevation details of the Type I girders. The cross-sectional and stirrup details are shown in Figures F10 through F12. The as-built dimensions of all the shear specimens are summarized in Table F2.

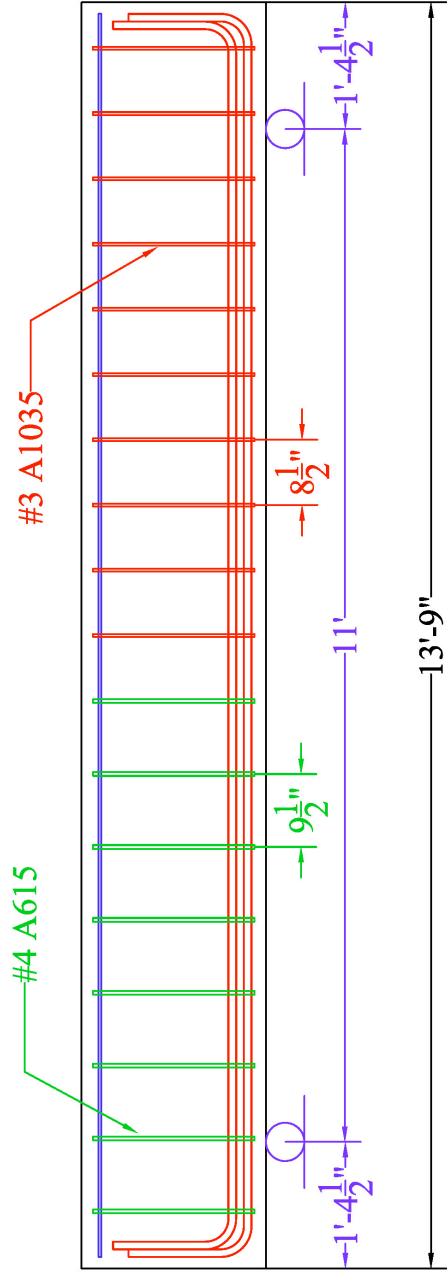


Figure F1 Elevation and Cross-Section Details for Specimen SR1

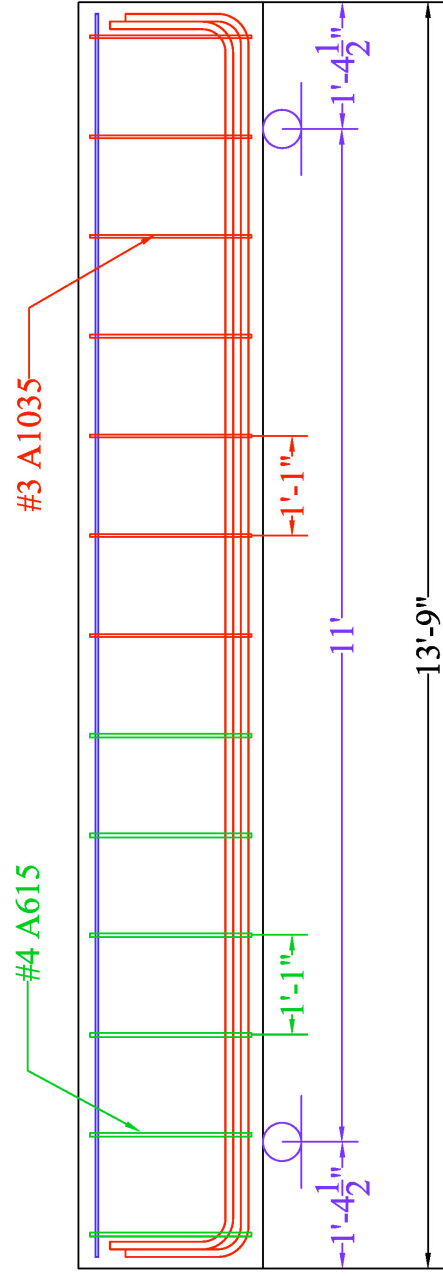


Figure F2 Elevation and Cross-Section Details for Specimen SR2

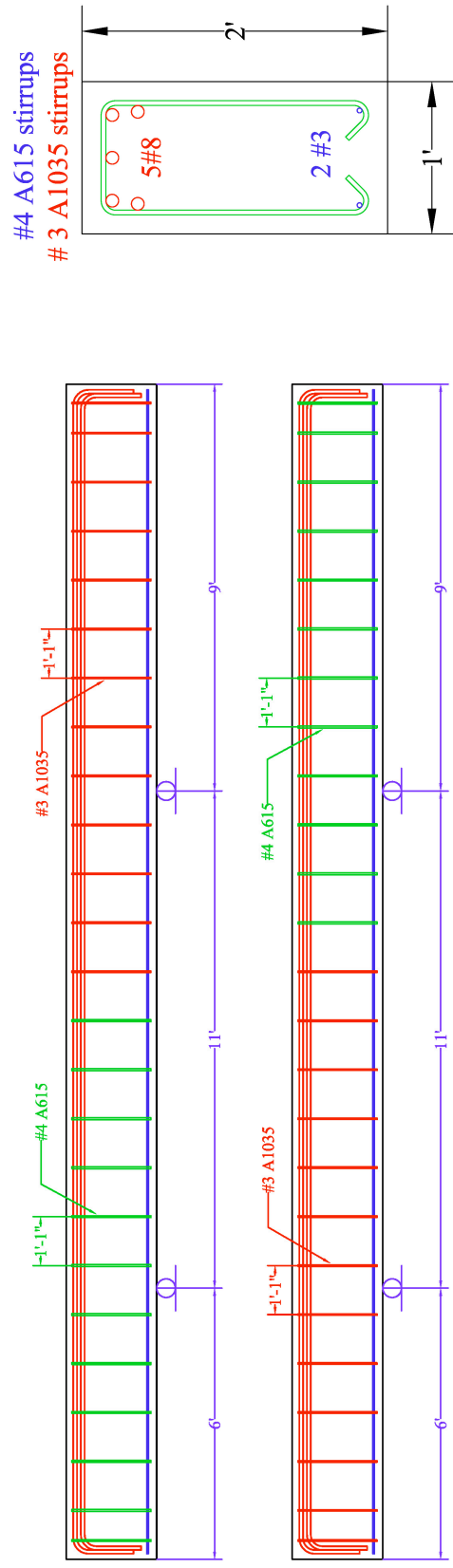


Figure F3 Elevation and Cross-Section Details for Specimen SR3

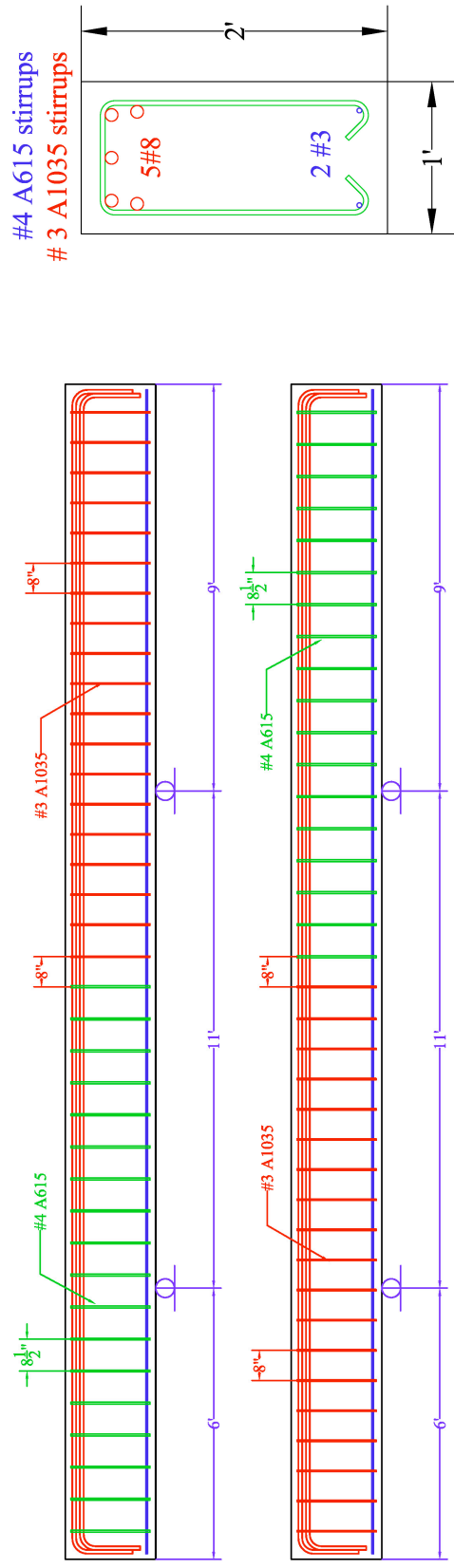


Figure F4 Elevation and Cross-Section Details for Specimen SR4

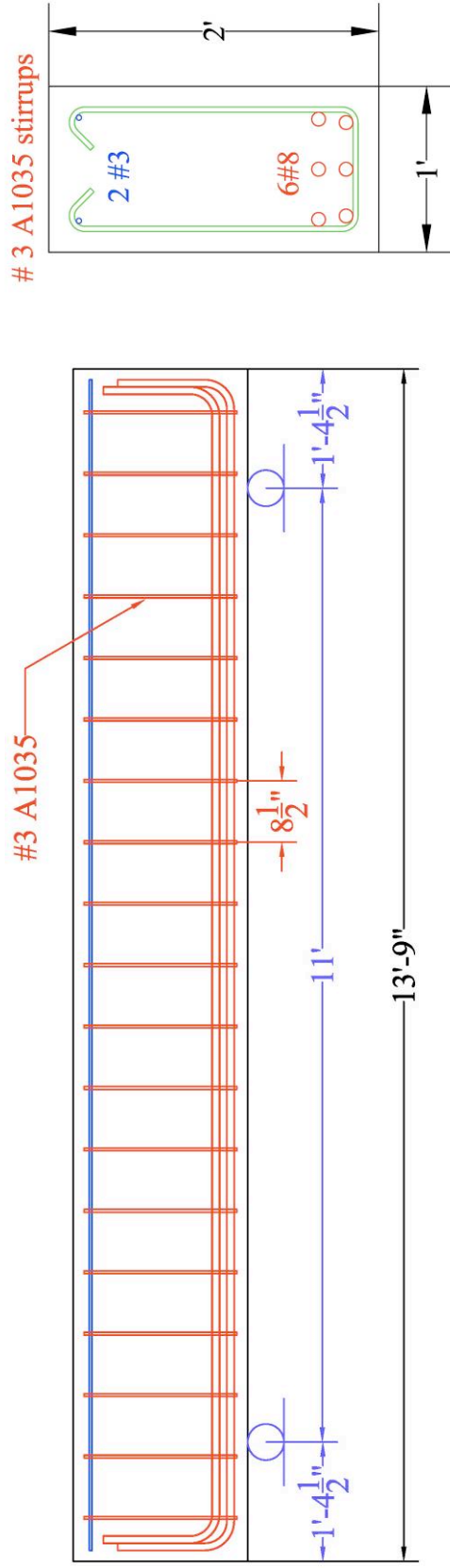


Figure F5 Elevation and Cross-Section Details for Specimen SR5

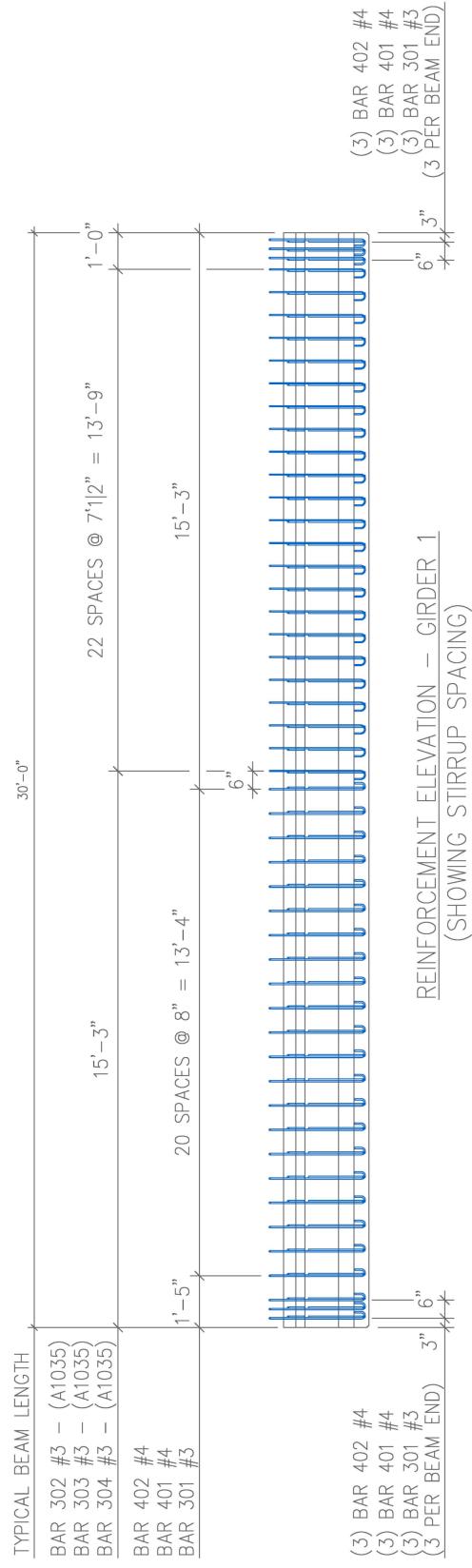


Figure F6 Elevation Details for Specimen SP1

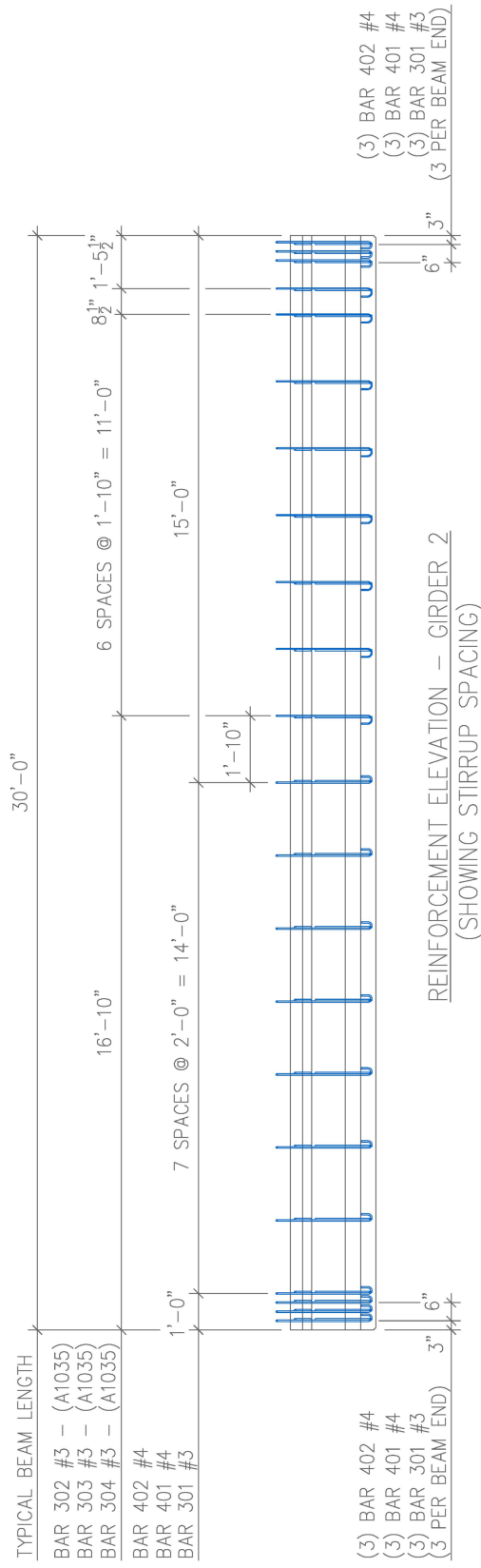


Figure F7 Elevation Details for Specimen SP2

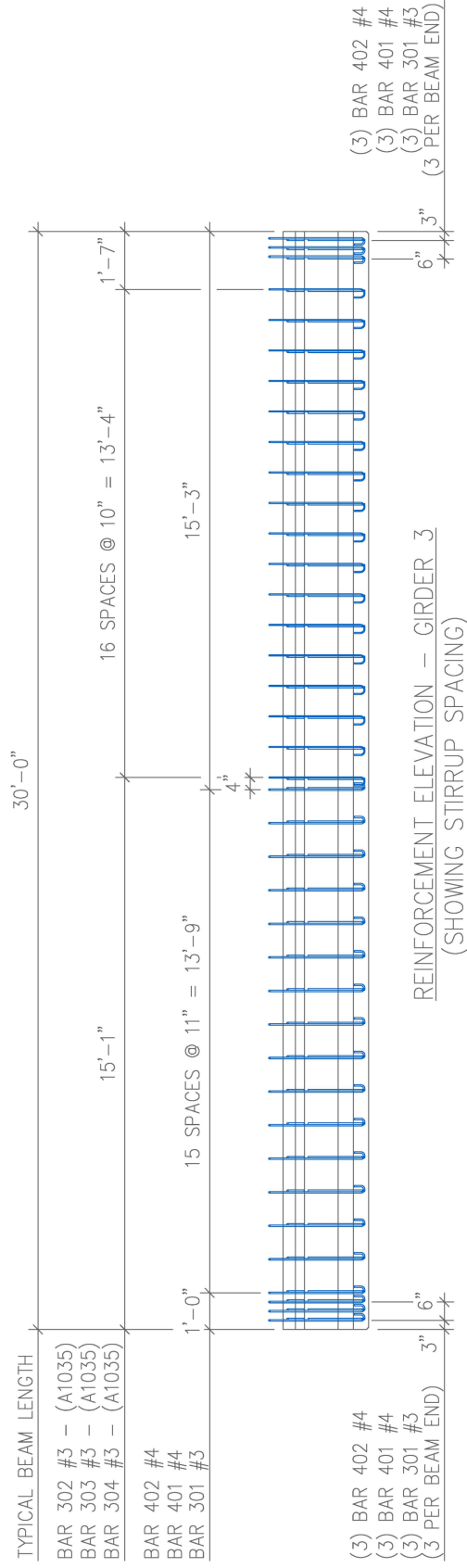


Figure F8 Elevation Details for Specimen SP3

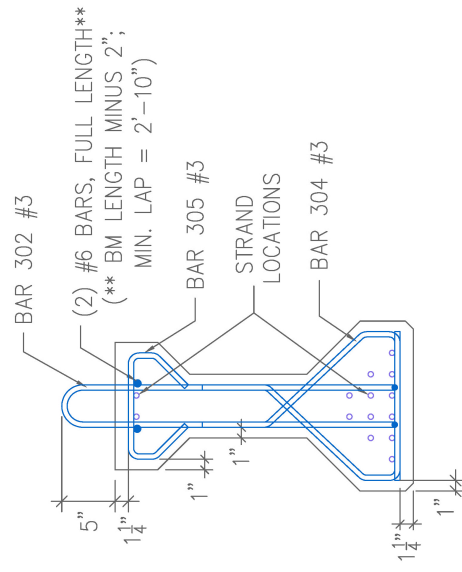
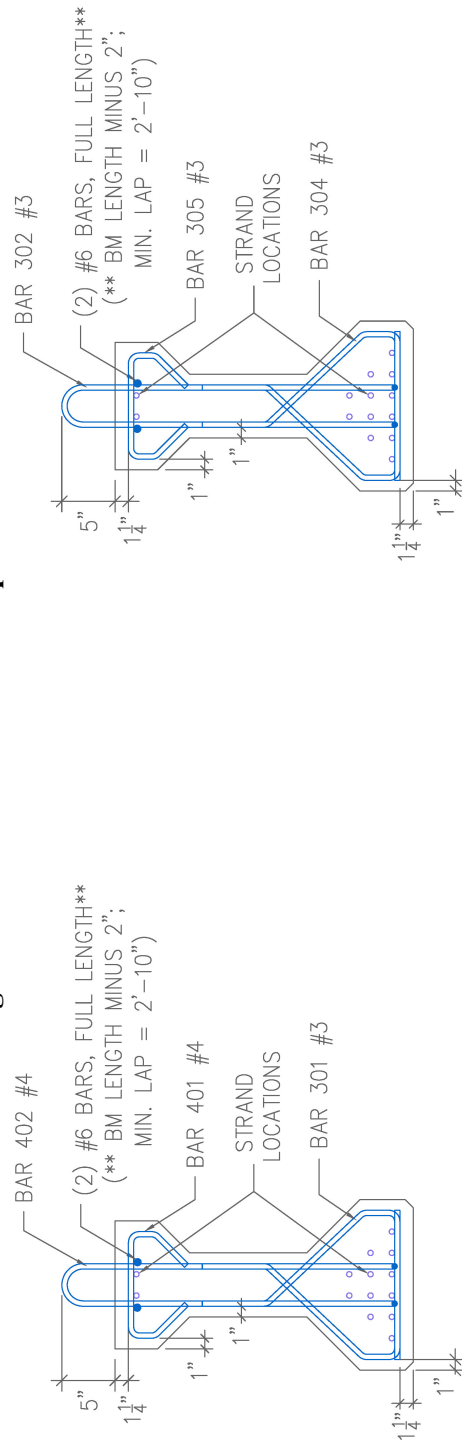
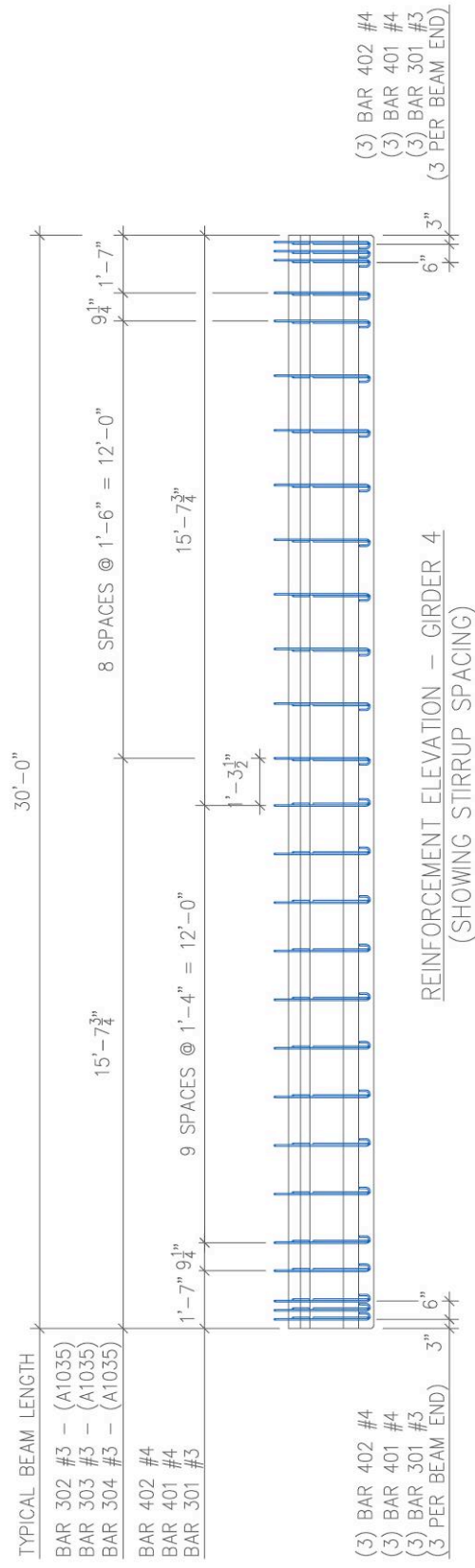


Figure F10 Stirrup Details for Type I Girders

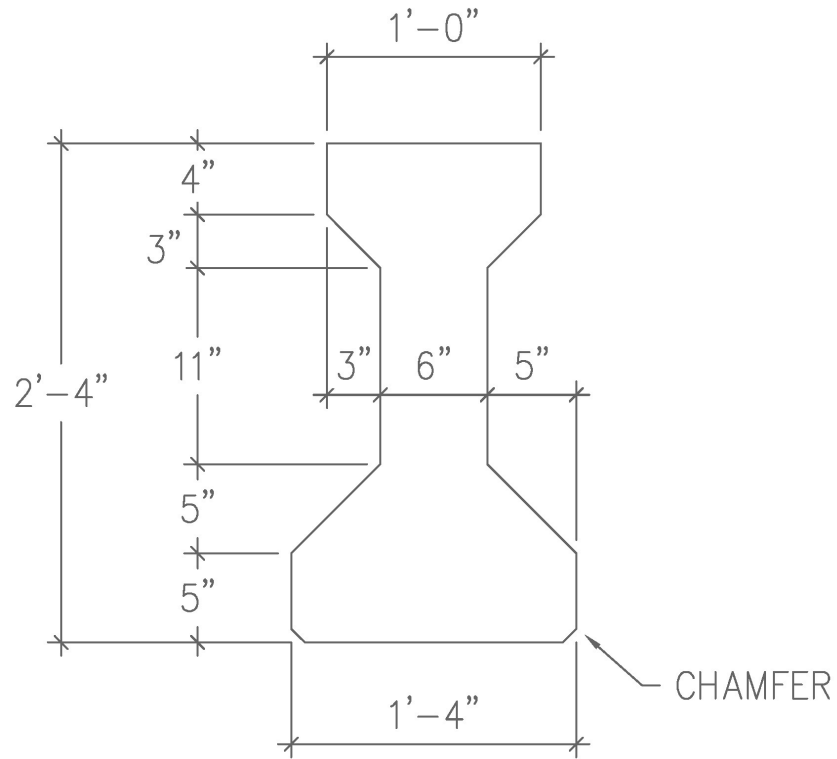


Figure F11 Nominal Dimensions for Type I Girders

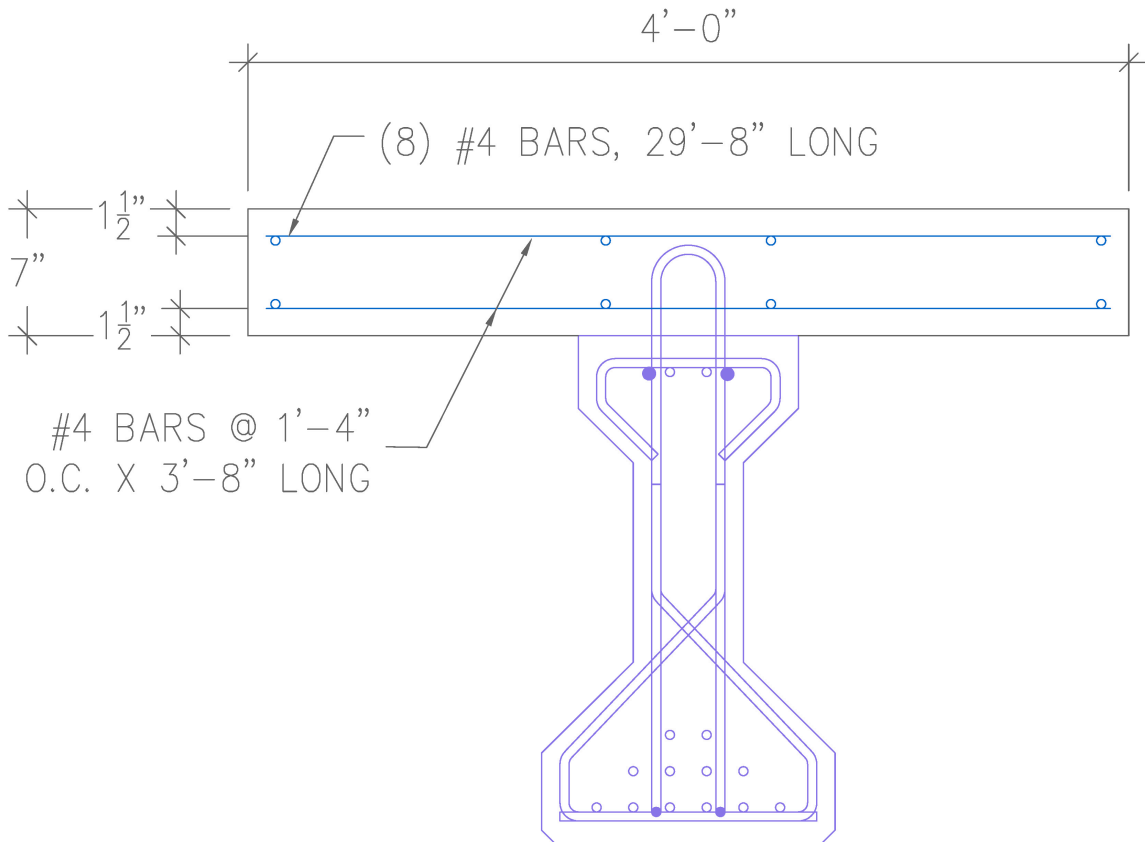
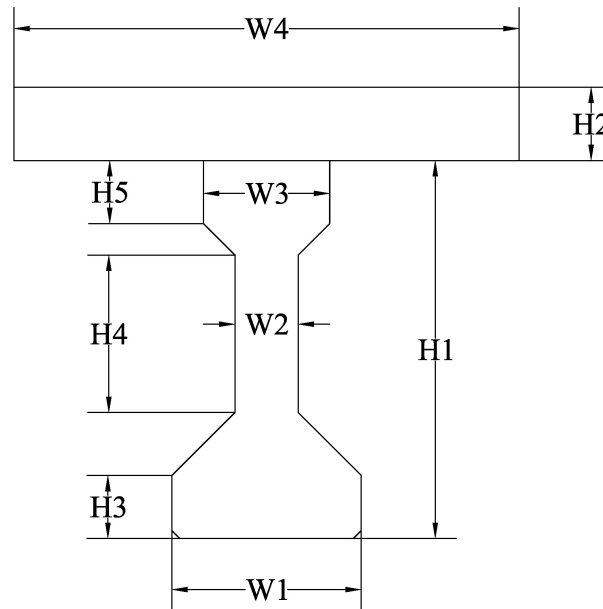


Figure F12 Typical Cross-Section Details for Type I Girders

Table F2 As-Built Dimensions
(a) Rectangular Beams

Specimen	Length	Width (in)	Depth (in)	Effective Depth (in)
SR1	13'-9"	12.38	24.08	21.67
SR2	13'-9"	12.13	23.98	21.57
SR3	26'-0"	12.25	24.08	3.74
SR4	26'-0"	12.25	24.05	3.55
SR5	13'-9"	11.95	24.08	21.08



(b) AASHTO Type I Girders

Specimen	H1 (in)	H2 (in)	H3 (in)	H4 (in)	H5 (in)	W1 (in)	W2 (in)	W3 (in)	W4 (in)
SP1	28.38	6.98	5.13	10.63	4.13	16.13	6.09	12.13	48.55
SP2	28.34	7.13	5.06	10.94	4.06	16.09	6.00	12.06	48.63
SP3	28.44	7.09	5.03	11.00	4.22	16.06	6.03	12.19	48.83
SP4	28.38	7.06	5.13	10.81	4.25	17.00	6.50	12.19	48.03

F.4 Material Properties

F.4.1 Concrete Properties

Six different concrete mixes were used to fabricate the shear specimens. These mixes are summarized in Appendix A, Table A11. The first four rectangular beams were designed based on a compressive strength of 10 ksi while the last rectangular beam used 15 ksi concrete. Each of the Type I girders were designed with concrete strengths in the girder of 10 ksi while 5 ksi concrete was used in the slabs. Table F3 provides the compressive strengths of the concrete in each specimen at the time it was tested. Nearly all of the measured strengths were significantly

higher than the design strengths; however, having higher actual strengths than design strengths is a common occurrence in construction practices. The higher concrete strengths would certainly increase the shear capacities of the members but since the concrete plays a subordinate role to the transverse reinforcement the integrity of the tests is maintained. The actual concrete strengths of the specimens were to be used to calculate the expected capacities which will be presented later.

Table F3 Measured Concrete Compressive Strength*

Specimen	Strength (psi)
SR1	12,170
SR2	12,890
SR3	13,040
SR4	13,080
SR5+	16,880
SP1 (Girder)	11,930
SP1 (Slab)	7,220
SP2 (Girder)	12,380
SP2 (Slab)	9,970
SP3 (Girder)	13,070
SP3 (Slab)	10,080
SP4 (Girder)	10,530
SP4 (Slab)	6,280

* Strengths corresponding to when the specimens were tested.

+ The compressive strength was established based on cores taken from the ends of the specimen. The core strengths were corrected to obtain equivalent in-place strengths (Wight and MacGregor, 2009). The other strengths are based on 4"x8" cylinders that were 'field cured', i.e., these cylinders were kept near the specimens at the lab.

F.4.2 Reinforcing Steel Properties

The reinforcing bars used in the specimens consisted of both A1035 and A615 steel. All of the shear specimens except for SR5 used #3 A1035 stirrups in one half of the beams while the other half contained #4 A615 stirrups. The rectangular beams also contained #8 A1035 bars as longitudinal reinforcement. Table F4 provides an index of the reinforcing steel used to fabricate different specimens. The measured stress-strain diagrams are shown in Appendix A, Figures A1 and A3.

Table F4 Reinforcing Steel Index

ASTM Designation	Bar Size	Batch Number and Specimen Use		
A615	#4	<u>1</u> : SR1 to SR4	<u>3</u> : SP1 to SP3	<u>4</u> : SP4
A1035	#3	<u>1</u> : SR1 to SR5	<u>2</u> : SP4	<u>3</u> : SP1 to SP3*
A1035	#8	<u>1</u> : SR1 to SR4	<u>2</u> : SR5	

* There is no test data available for Batch 3 A1035 #3 bars. Samples were not provided.

F.5 Loading and Test Setup

Three different loading configurations were used to test the shear specimens. The shorter rectangular beams (SR1, SR2, and SR5) were simply supported and loaded in three-point bending. Figure F13 illustrates the loading and test setup. Specimens SR3 and SR4 were tested in two stages. In the case of specimen SR3, the region of the beam with A1035 stirrups was tested first, the specimen was rotated, and then the region with A615 stirrups was tested. The sequence of loading for specimen SR4 was reversed, i.e., the region of the beam with A615 stirrups was tested first followed by testing of the region reinforced with A1035 stirrups. A single actuator located 1 ft from the end of the beam was used to load the beam while the uplift reaction at the far end was resisted by a pair of C15x50 channels that were connected to the strong floor through a pair of high-strength threaded rods and universal joints. The setup for specimens SR3 and SR4 is shown in Figure F14. The Type I girders were simply supported but were loaded in four-point bending (two load points 11' apart). The test setup for the girders is displayed in Figure F15.

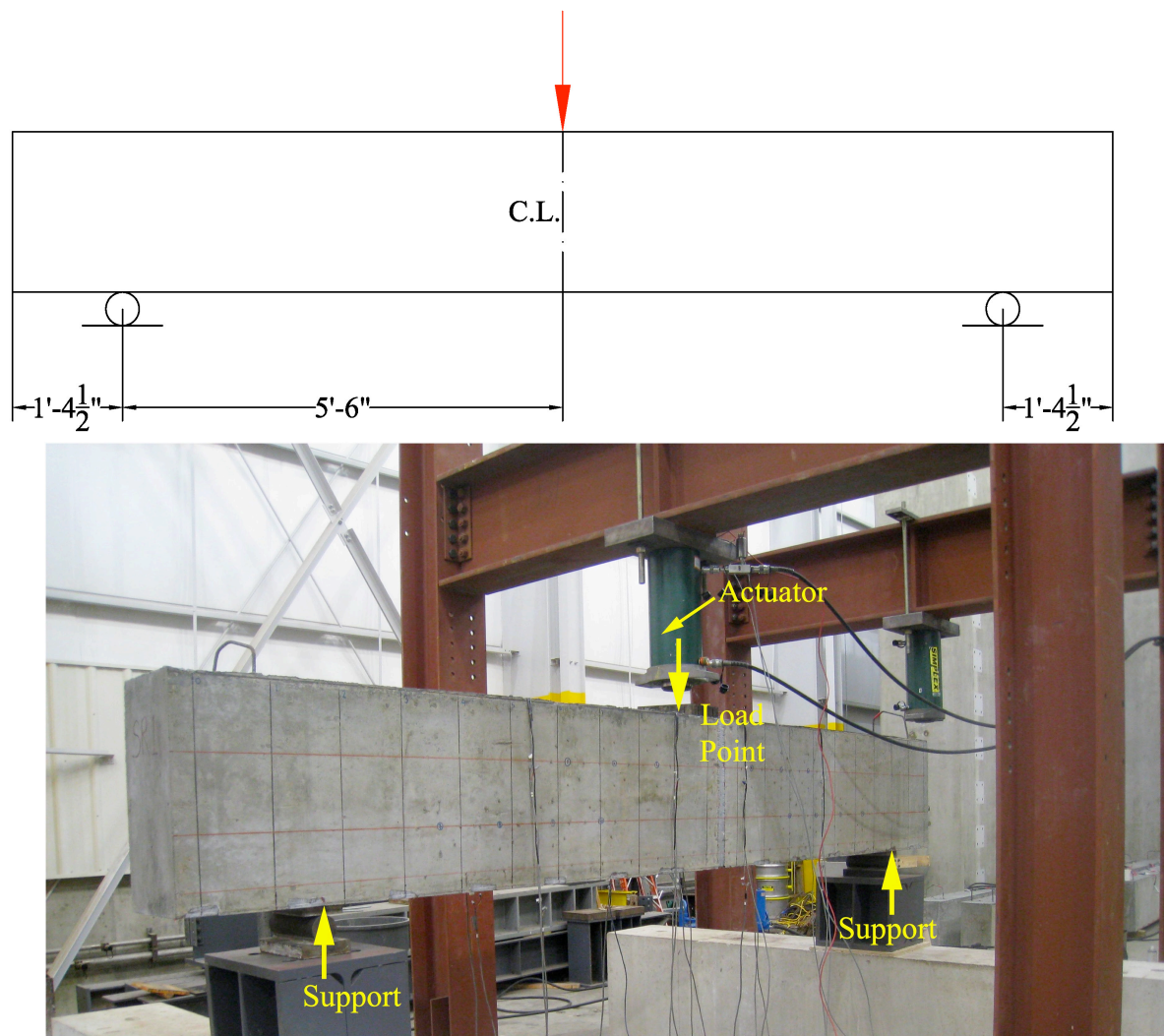


Figure F13 Loading and Test Setup for Specimens SR1, SR2, and SR5

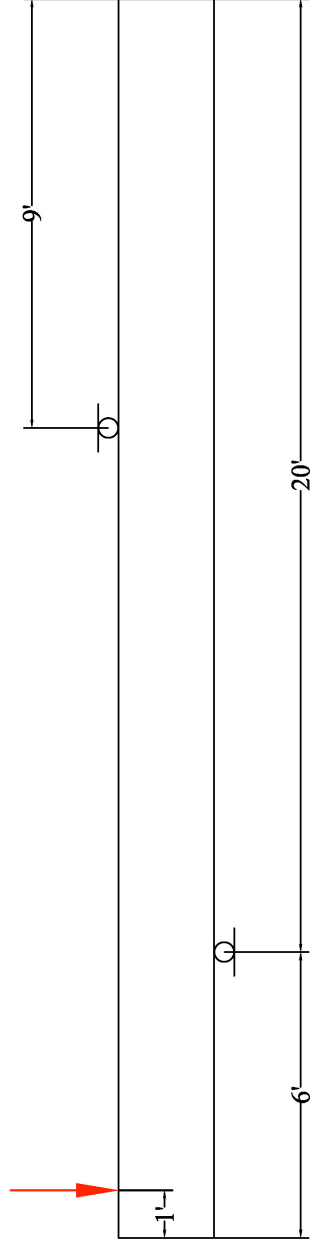


Figure F14 Loading and Test Setup for Specimens SR3 and SR4

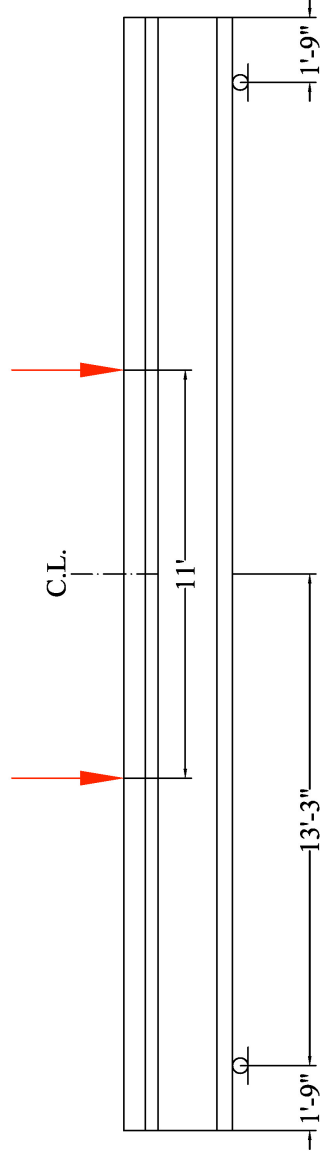
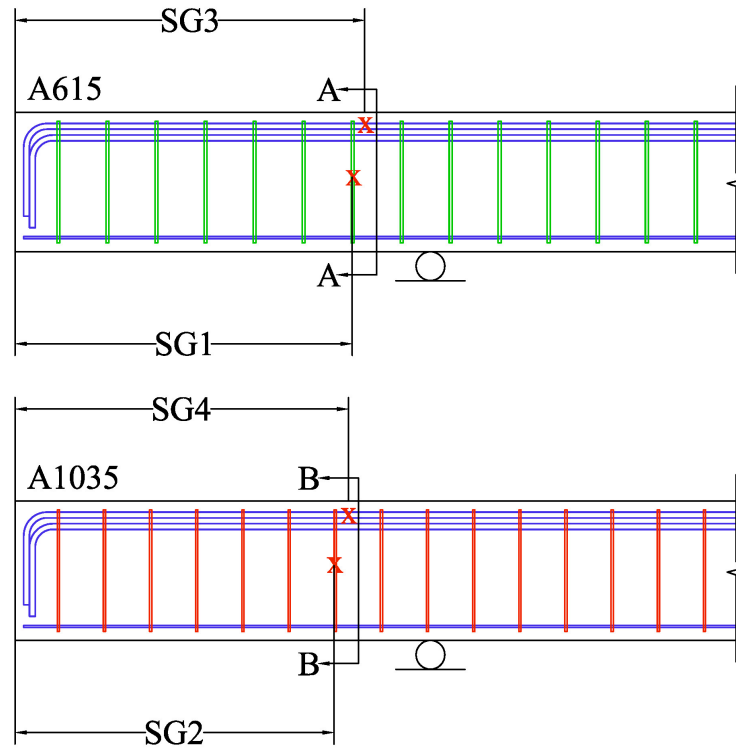


Figure F15 Loading and Test Setup for AASHTO Type I Girders

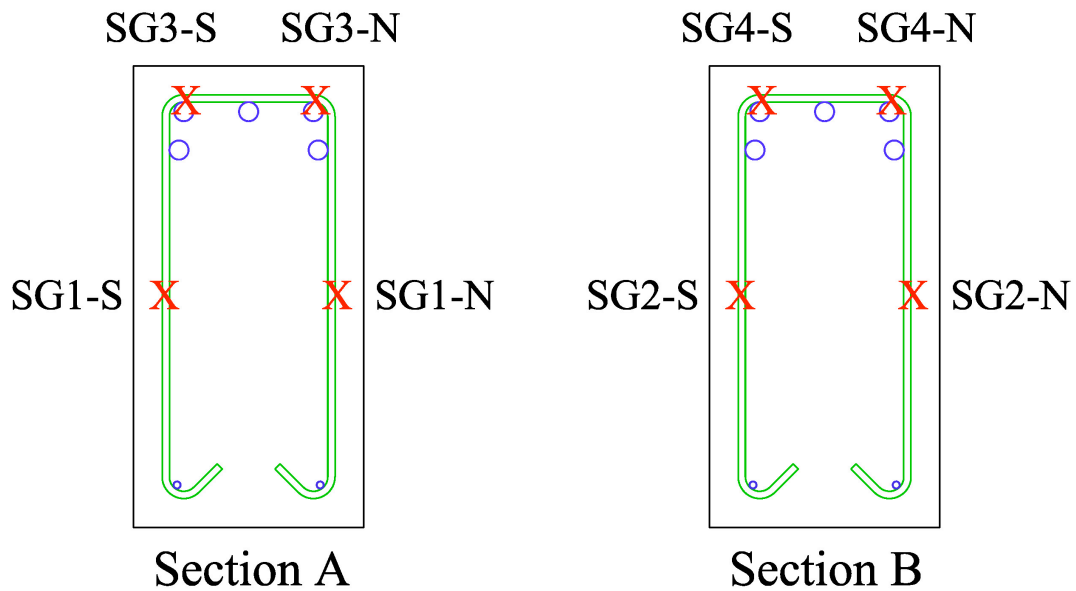
Strain gages were bonded to the steel reinforcement in the specimens in order to measure the tensile strain during the tests. Specimens SR1, SR2, and SR5 had eight gages located on the stirrups and eight gages located on the longitudinal steel corresponding to the stirrup strain gage locations. Specimens SR3 and SR4 contained half as many strain gages with four gages on the stirrups and four gages on the flexural reinforcement. The Type I girders contained eight strain gages installed on the stirrups in a similar fashion to beams SR1, SR2 and SR5. Furthermore, ten strain gages were bonded onto the bottom-most prestressing strands at the midspan and near the quarter points. For each specimen, a level of redundancy was provided at each strain gage location by installing one gage on the north side and one on the south side of the beams. This arrangement was intended to prevent loss of data in the event of a strain gage failure. Figure F16 depicts the location of various strain gages and Table F5 summarizes the distances to those locations.



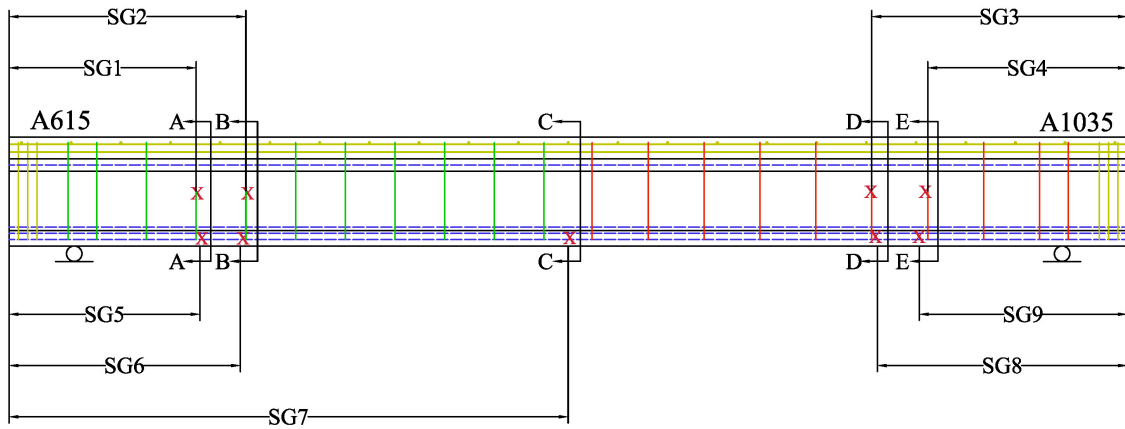
Figure F16 Strain Gage Locations



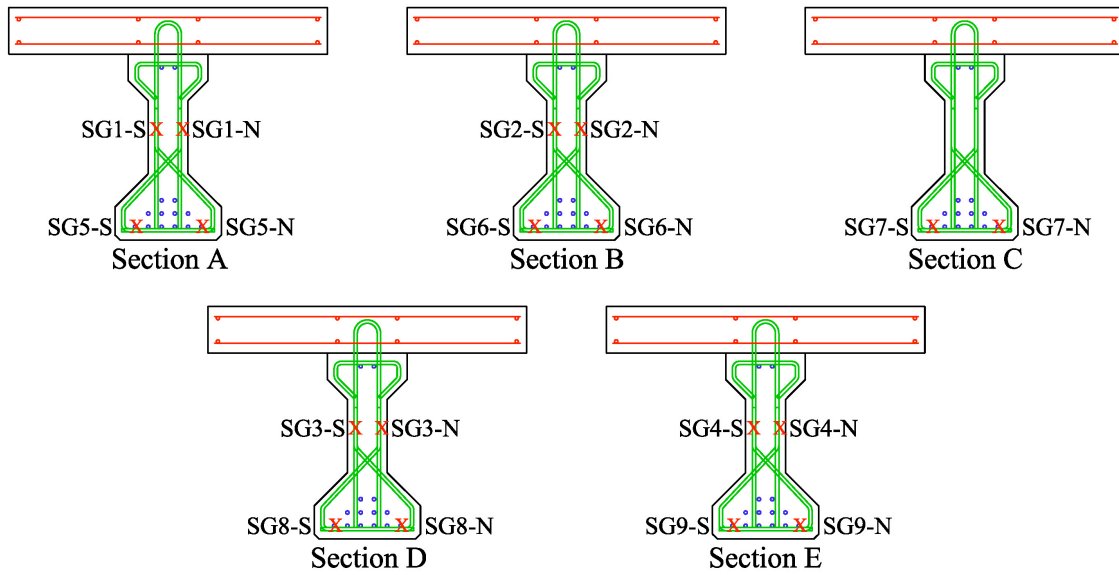
(c) Elevation View for Specimens SR3 and SR4



(d) Cross-Section View for Specimens SR3 and SR4
Figure F16 (cont.) Strain Gage Locations



(e) Elevation View for AASHTO Type I Girders



(f) Cross-Section View for AASHTO Type I Girders
Figure F16 (cont.) Strain Gage Locations

Table F5 Distances to Strain Gage Locations *
(a) Rectangular Beams

Strain Gage Label	Strain Gage Locations (in)				
	SR1	SR2	SR3	SR4	SR5
SG1-N	45.50	43.25	51.00	59.00	31.88
SG1-S	46.00	43.13	51.00	58.25	31.75
SG2-N	74.13	69.50	53.25	56.25	56.88
SG2-S	74.63	69.63	53.13	56.13	56.25
SG3-N	74.13	70.00	52.63	56.13	57.13
SG3-S	74.13	70.13	52.25	56.13	56.75
SG4-N	48.25	44.00	53.88	58.50	31.63
SG4-S	48.13	44.00	53.50	58.63	31.50
SG5-N	46.00	41.38	N/A	N/A	30.00
SG5-S	46.63	41.50	N/A	N/A	30.50
SG6-N	74.88	67.88	N/A	N/A	55.50
SG6-S	74.75	67.75	N/A	N/A	55.75
SG7-N	75.38	68.75	N/A	N/A	55.63
SG7-S	75.50	69.50	N/A	N/A	55.25
SG8-N	49.88	42.63	N/A	N/A	29.88
SG8-S	49.88	43.25	N/A	N/A	29.63

SG=Strain Gage; N,S=North, South

* Distances are measured from the concrete face of the corresponding end, i.e., strain gages located in the A615 half of a beam (West half for SR5) are measured from the A615 end whereas the gages in the A1035 half are measured from the A1035 end.

Table F5 (cont.) Distances to Strain Gage Locations *
(b) AASHTO Type I Girders

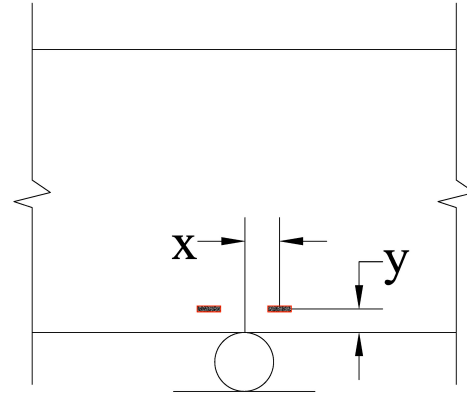
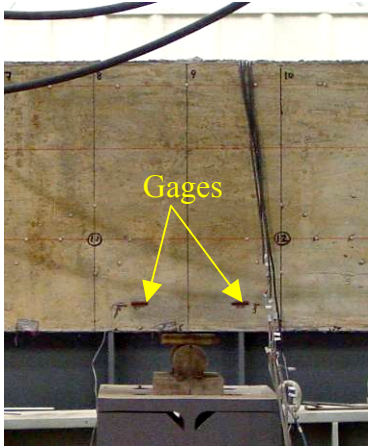
Strain Gage Label	Strain Gage Locations (in)			
	SP1	SP2	SP3	SP4
SG1-N	57.75	60.50	55.00	60.25
SG1-S	57.75	60.50	55.13	60.25
SG2-N	81.63	84.75	76.88	76.25
SG2-S	81.50	84.75	76.63	76.25
SG3-N	79.25	70.75	78.50	82.25
SG3-S	79.25	70.75	78.38	82.25
SG4-N	57.13	48.25	58.25	64.25
SG4-S	57.25	48.25	58.13	64.25
SG5-N	57.5	61.0	57.0	62.0
SG5-S	58.0	59.5	57.0	62.0
SG6-N	79.5	82.0	75.5	74.5
SG6-S	82.0	83.5	76.5	74.5
SG7-N+	180.0	180.0	180.0	180.0
SG7-S+	180.0	180.0	180.0	180.0
SG8-N	77.0	69.5	79.0	80.5
SG8-S	76.5	68.0	76.0	80.5
SG9-N	54.3	48.0	57.0	66.0
SG9-S	54.5	45.0	57.5	66.0

SG=Strain Gage; N,S=North, South

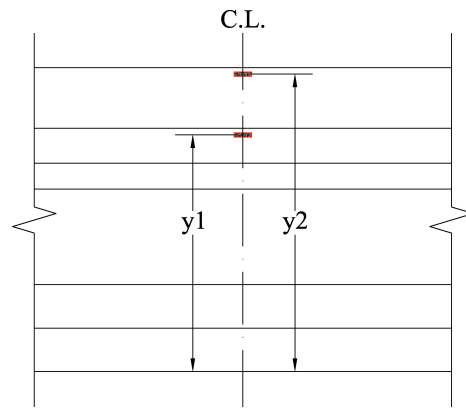
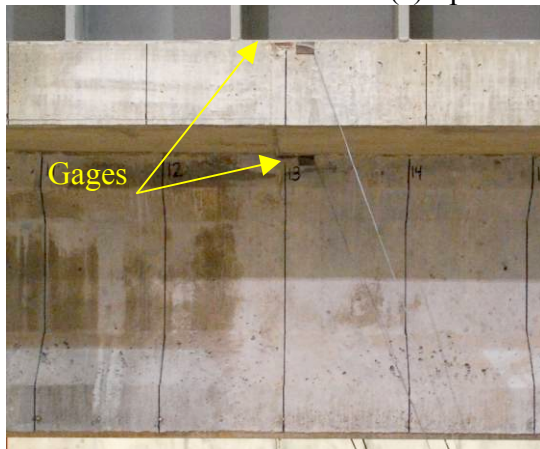
* Distances are measured from the concrete face of the corresponding end, i.e., strain gages located in the A615 half of a girder are measured from the A615 end whereas the gages in the A1035 half are measured from the A1035 end.

+ Distances represent theoretical location of mid-span as measured from the outer face of either end. Exact measurements were not recorded.

Surface gages were also mounted on certain specimens to measure the strain in the concrete. These gages were bonded when it was not exactly certain whether a particular specimen would fail in a shear or flexural manner. Due to the nature of their loading, specimens SR3 and SR4 contained surface gages, which were bonded to the face of the concrete near the first support. Two gages were used per specimen, both of which were bonded on the south face. Surface gages were also installed on the Type I girders at the mid-span of the specimens. Two gages were bonded near the top of the slab; one on the north face and one on the south face. Two gages were also placed near the top of the girder; again on both the north and south face. Figure F17 provides a visual depiction of the locations of the surface strain gages, and the distances to those gages are tabulated in Table F6.



(a) Specimens SR3 and SR4



(b) AASHTO Type I Girders
Figure F17 Surface Strain Gage Locations

Table F6 Distances to Surface Strain Gages

Dimension	Distance to Surface Gage (in)	
	SR3	SR4
x	4.5	4.5
y	2.5	2.5

Dimension	Distance to Surface Gage (in)							
	SP1		SP2		SP3		SP4	
	North	South	North	South	North	South	North	South
y1	27.63	27.63	27.97	27.97	27.32	27.32	27.25	27.63
y2	34.36	34.36	35.22	35.22	35.28	35.16	34.88	34.88

In addition to the strain gages, a wire potentiometer was used in order to measure deflections of the specimens. Since SR1, SR2, SR5, and the Type I girders were all simply supported, the wire potentiometer was positioned at the mid-span of the members. SR3 and SR4 were simply supported beams with an overhang; hence, their deflections were measured directly under the applied load. Figure F18 depicts the wire potentiometer which was attached to the soffit of the beams.



Figure F18 Instrumentation for Measuring Deflection

F.7 Experimental Results

F.7.1 Failure Mode

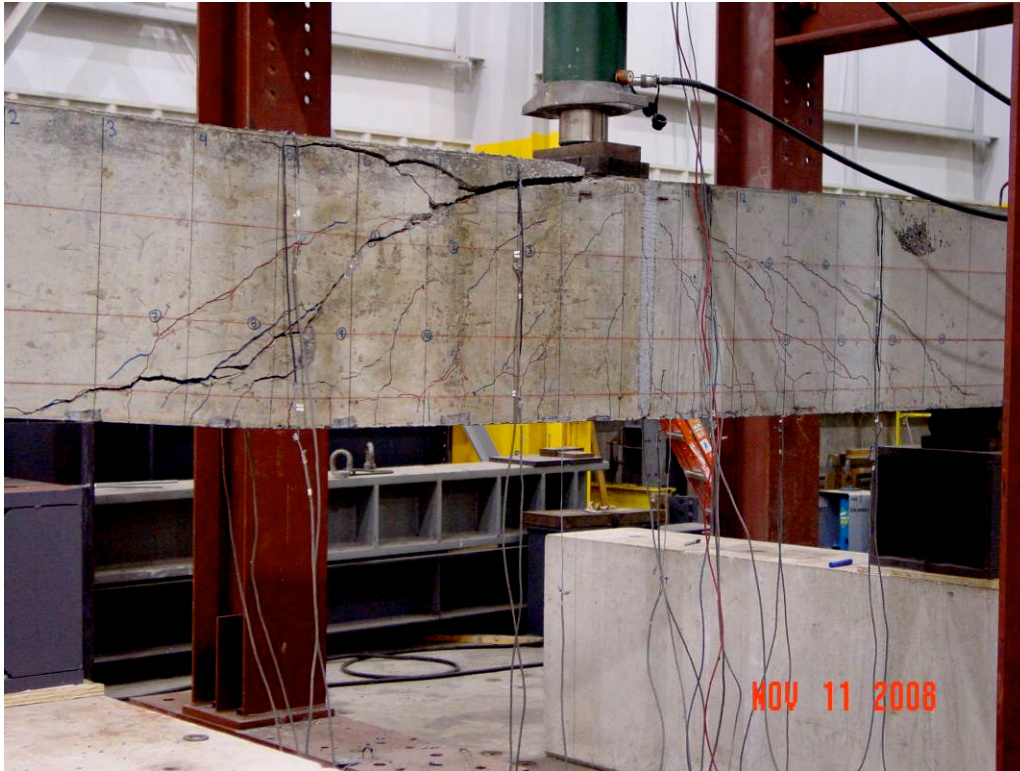
The observed failure mode provides an effective and simple means to evaluate and validate the performance of a test specimen, and to supplement the measured responses. For the shear specimens, the type of failure and its location (i.e., whether it occurred on the side reinforced with A615 stirrups or A1035 stirrups) are of particular importance. The first two rectangular beams (SR1 and SR2) exhibited shear failures and both beams failed on the A615 sides. SR1 had more of a shear-compression failure whereas SR2 had a shear-tension failure. Recall that specimens SR3 and SR4 were loaded in two stages. For SR3, the A1035 side was loaded first but not to failure; the A615 side exhibited a shear failure. For SR4, the A615 side was loaded first and again loading was stopped prior to failure. Subsequently, when the A1035 side was tested, the failure mode appeared to be flexural in nature although an argument could be made for a bearing failure. SR5 was the only shear specimen that did not fail because the hydraulic actuator reached its capacity of 300 kips before any type of failure could be induced to the specimen. However, towards the end of the test some concrete spalling was witnessed around the load point. Both Type I girders SP1 and SP3 failed in flexure. On the other hand, SP2 and SP4 failed quite dramatically as a result of shear. SP2 failed on the A615 side while SP4 failed on the A1035 side. Evidence of stirrup fracture was seen in both of those girders. Refer to Figures F19 through F27 for a pictorial representation of the failure modes.



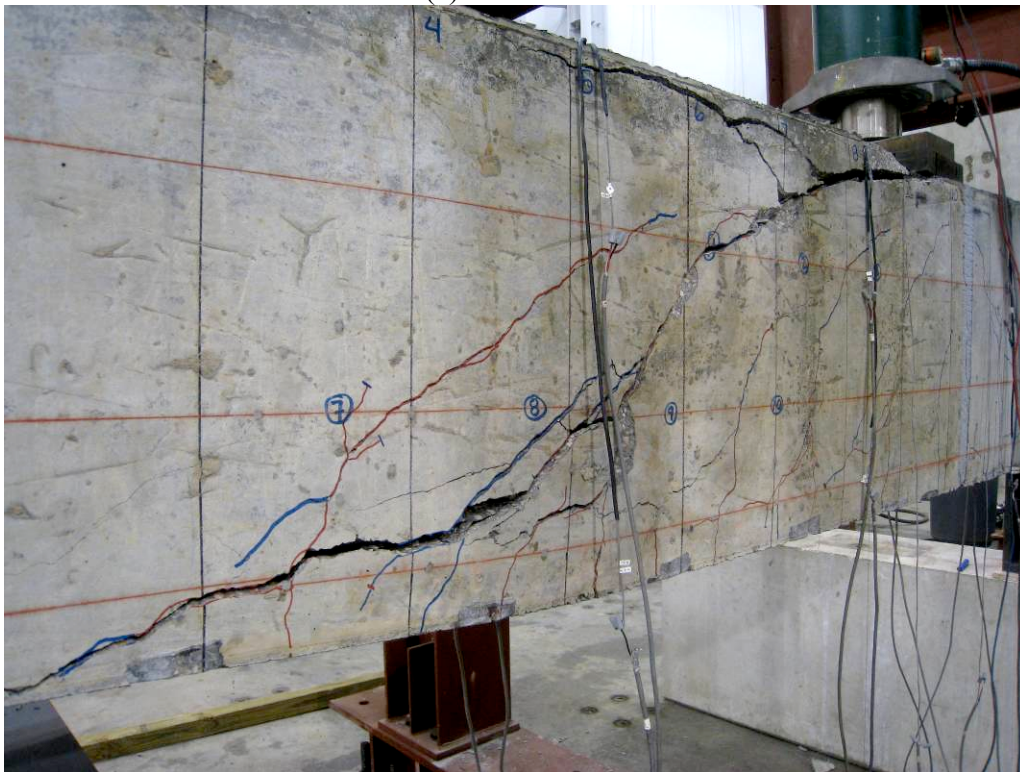
(a) Both Sides



(b) Close-Up of A615 Side
Figure F19 Failure Mode of SR1



(a) Both Sides



(b) Close-Up of A615 Side
Figure F20 Failure Mode of SR2



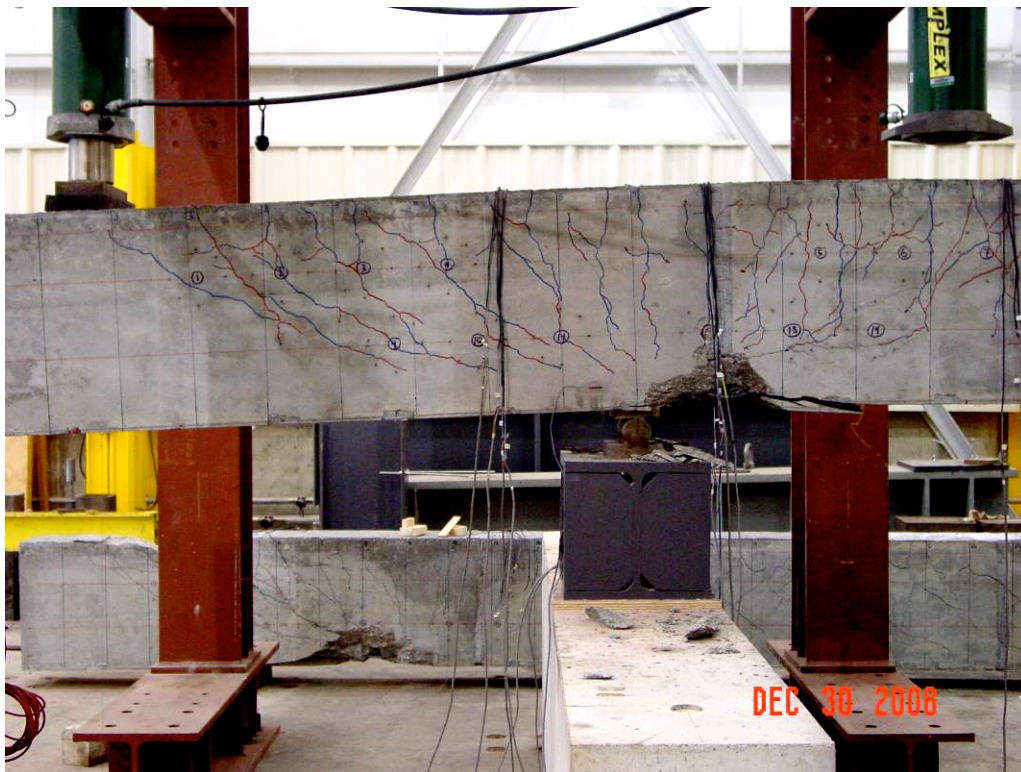
(a) A615 Side at Failure



(b) Close-Up of A615 Side



(c) A1035 Side at Maximum Load
Figure F21 Failure Mode of SR3



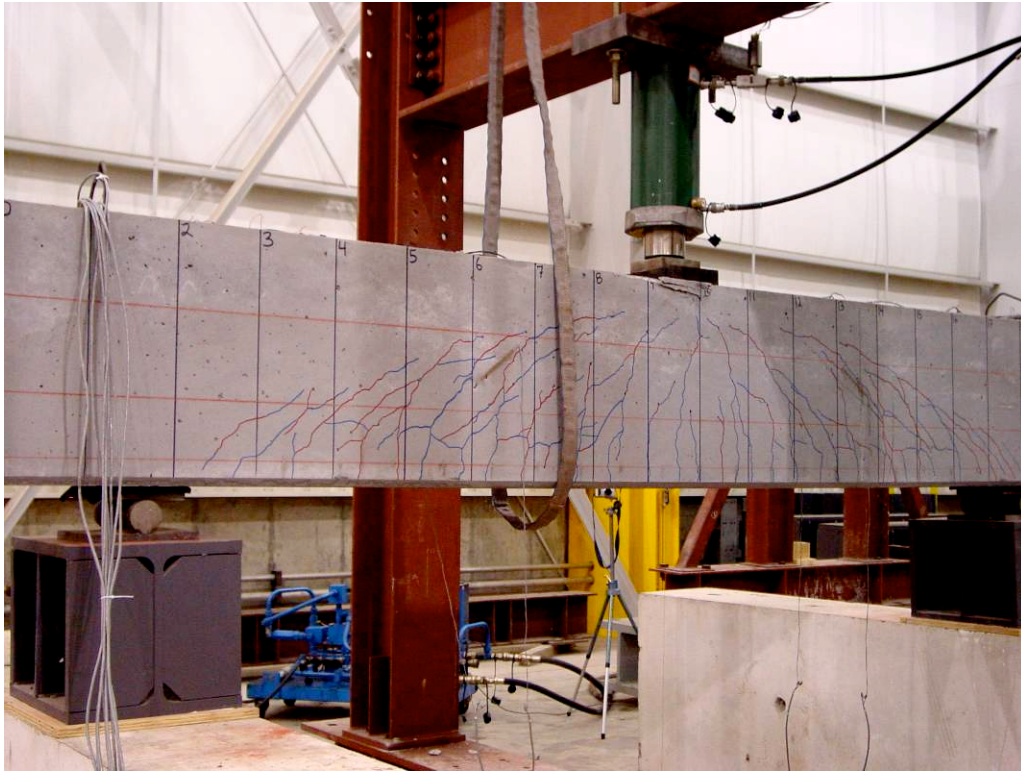
(a) A1035 Side at Failure



(b) Close-Up of A1035 Side



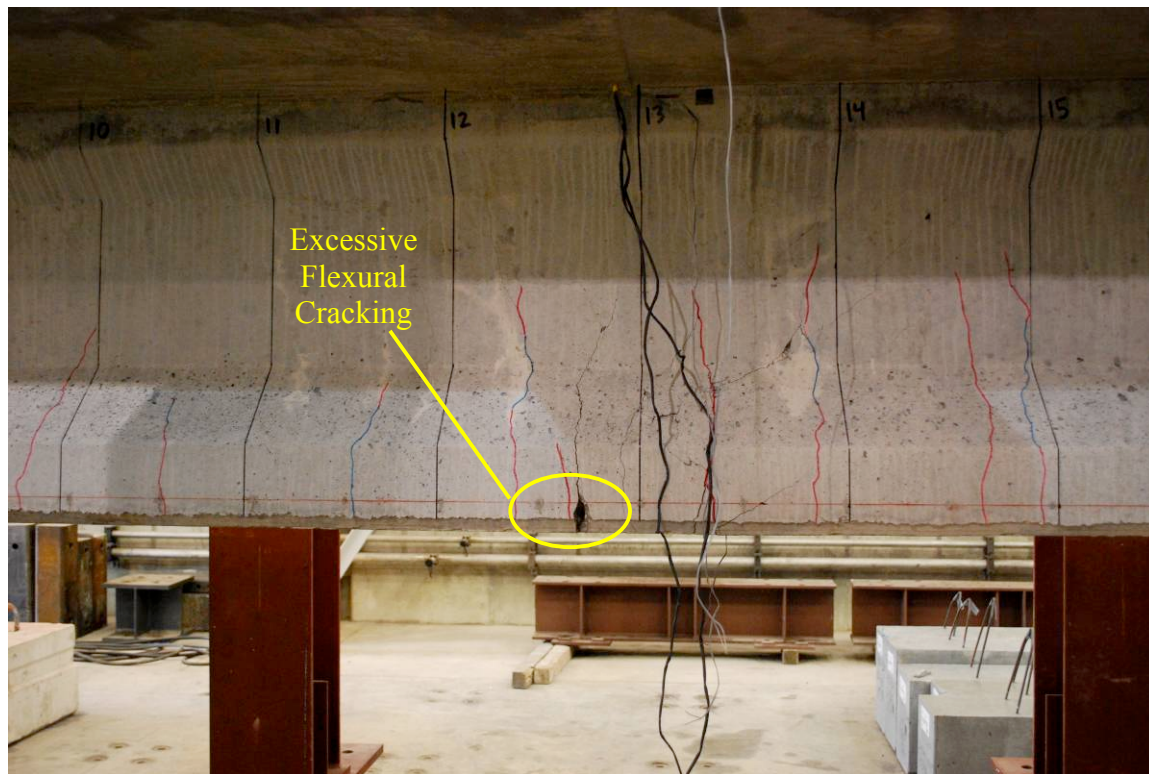
(c) A615 Side at Maximum Load
Figure F22 Failure Mode of SR4



(a) Overall View



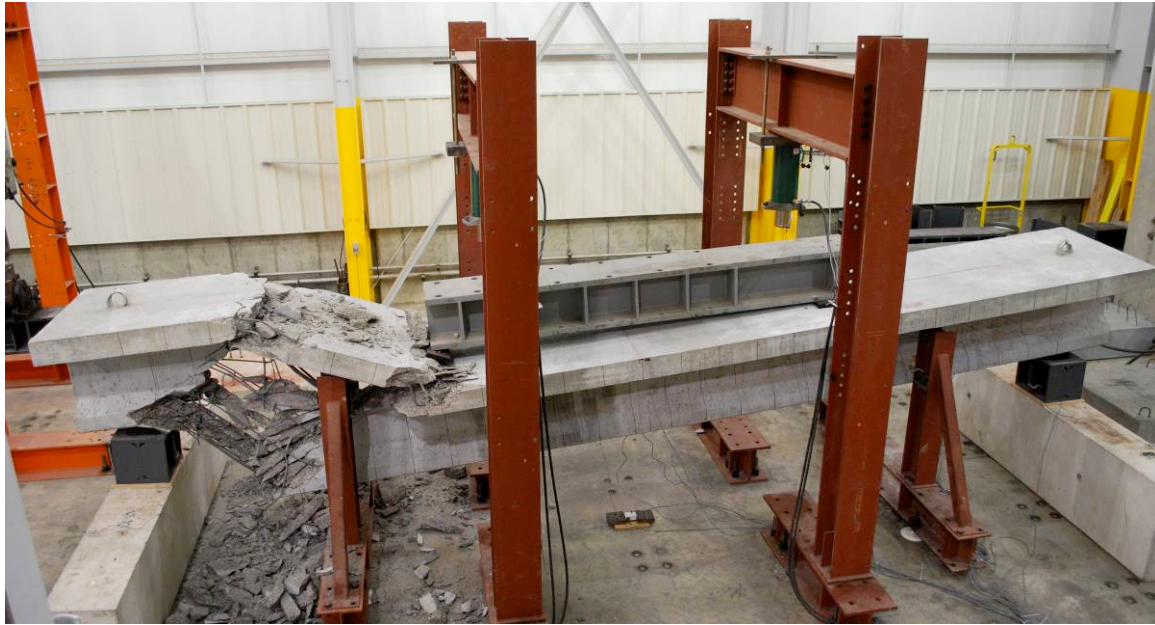
(b) Close-Up near Load Point
Figure F23 Maximum Load of SR5



(a) Close-Up of Mid-Span Cracking



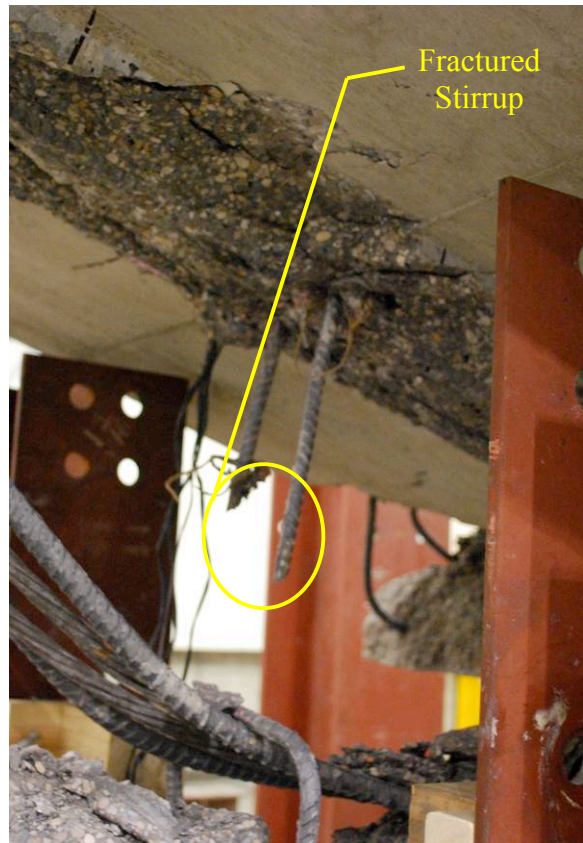
(b) Bottom View of Mid-Span Cracking
Figure F24 Failure Mode of SP1



(a) Both Sides

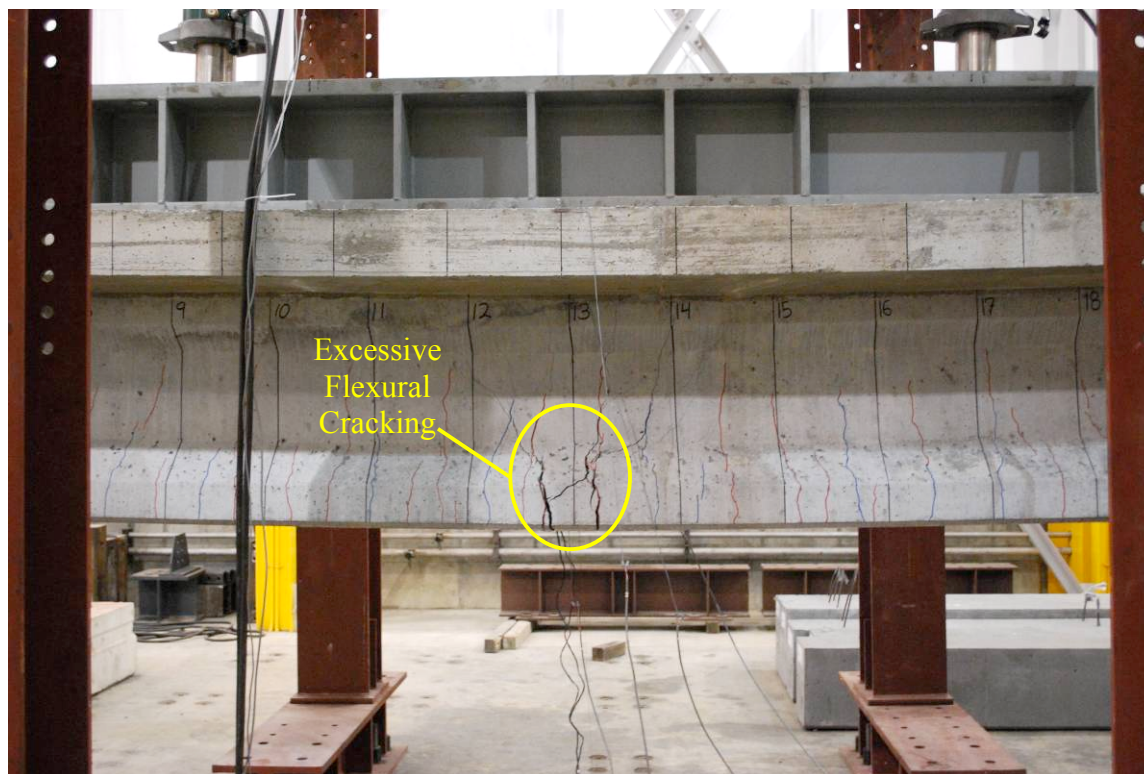


(b) Close-Up of A615 Side



(c) Fractured #4 A615 Stirrup

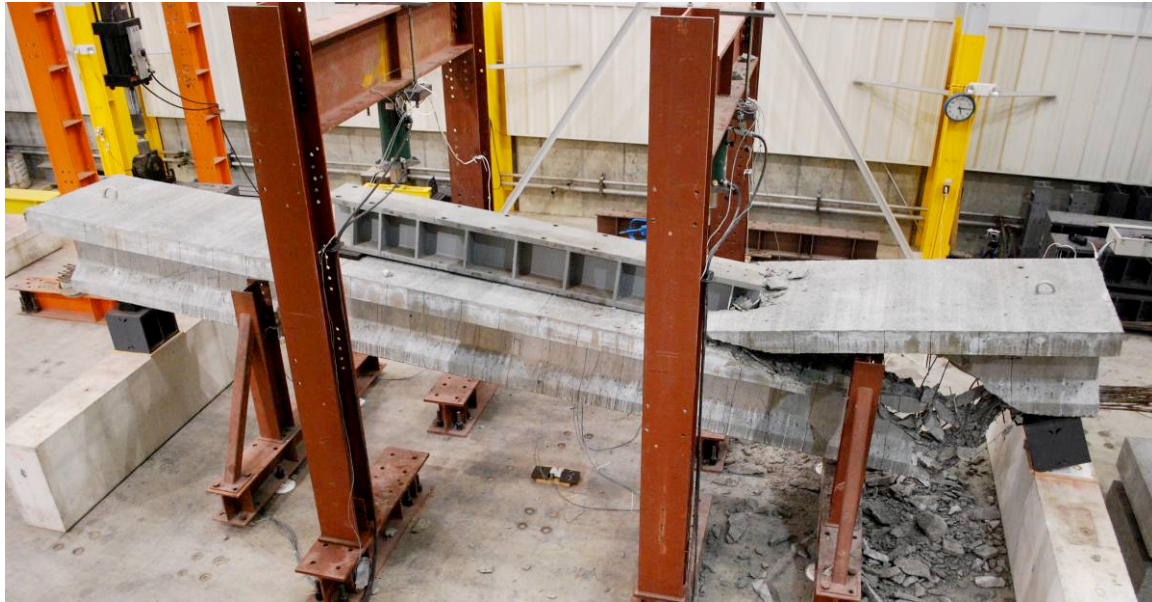
Figure F25 Failure Mode of SP2



(a) Close-Up of Mid-Span Cracking



(b) Bottom View of Mid-Span Cracking
Figure F26 Failure Mode of SP3



(a) Both Sides



(b) Close-Up of A1035 Side



(c) Fractured #3 A1035 Stirrup

Figure F27 Failure Mode of SP4

F.7.2 Load-Deflection Response

In addition to the measured load-deflection responses of the shear specimens, which can be found in Figures F29 through F37, the analytical load-deflection responses are plotted with the aid of a computer program, Response 2000 (Bentz, 2000), which is abbreviated as R2K. Also found in those figures are the expected capacities, as computed using AASHTO LRFD bridge design specifications with as-built properties. Response 2000 uses actual stress-strain relationships and other material properties, which are inputted manually, to model the expected behavior of the specimens. The measured material properties, which were obtained from sample testing and mill supplied stress-strain values for the 0.6-inch strands, were used in the models. Figure F28 illustrates the calibration of the Ramberg-Osgood function to fit the prestressing strand behavior. The exact parameters entered into the program, for all of the materials, can be found in Table F7. One setback of this program is that it cannot simultaneously model the entire span using both A615 and A1035 stirrups; hence, separate models were generated and analyzed in order to separately capture the response with A615 and A1035 stirrups. Additionally, due to the distinct loading arrangement of SR3 and SR4, Response 2000 could not be used to model these specimens. For each beam/stirrup type that was modeled, two cases were run by altering the value of the tension-stiffening factor. Theoretically a value of 1.0 should have worked, although using a value of 0.5 produced results that were closer to the experimental responses. It is also important to note that the #8 A1035 longitudinal bars in the rectangular beams were modeled as ‘tendons’ but with zero pre-strain; this technique allowed them to be modeled by the Ramberg-Osgood function. For the specimens cast with nominal 10-ksi concrete, the analytical load-deflections are close to their experimental counterparts. The analytical load-deflection for specimen SR5, which used nominal 15-ksi concrete, exhibits an appreciably stiffer response than what was measured. This difference is deemed to be because of overestimation of aggregate interlock in the matrix of 15-ksi concrete.

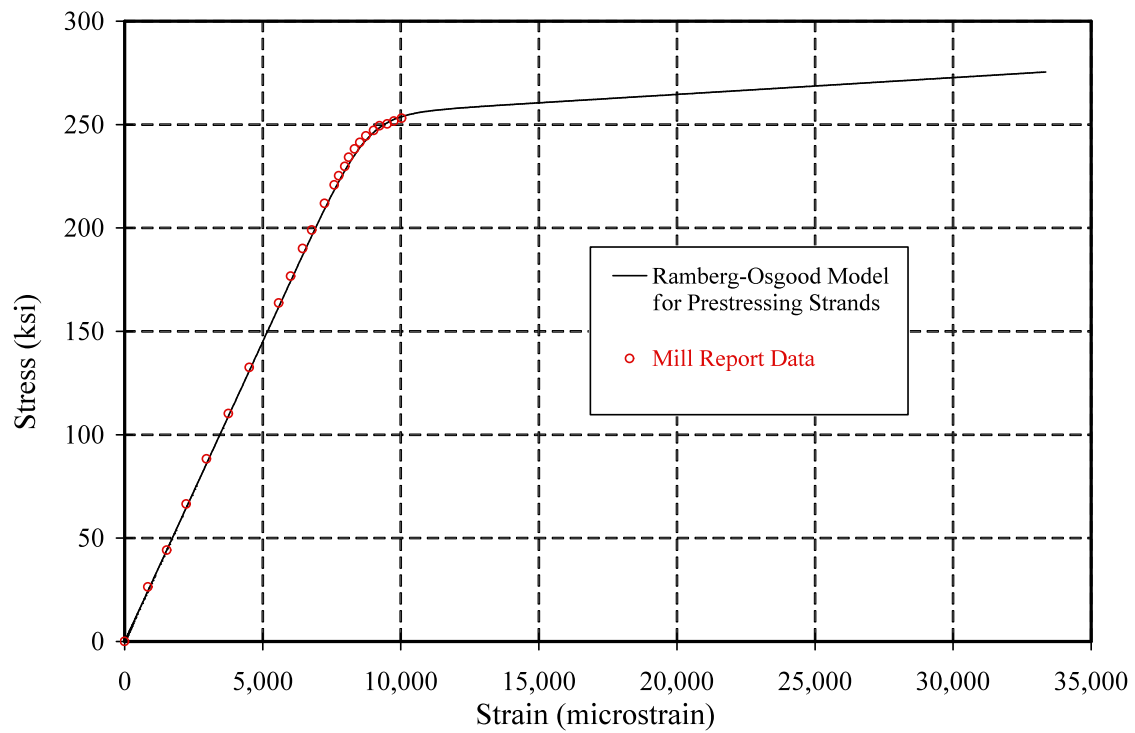


Figure F28 Calibration of Ramberg-Osgood Function for 0.6-inch Strands

Table F7 Response 2000 Parameters

	Parameter	SR1		SR2		SR5	
		Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Concrete Details	Cylinder Strength (psi)	12170		12890		16880	
	Tension Strength (psi)	Auto 384		Auto 393		Auto 438	
	Peak Strain (millistrain)	Auto 2.72		Auto 2.79		3.48	
	Aggregate Size (in)	0.4		0.4		0	
	Tension Stiff Factor	1	0.5	1	0.5	1	0.5
	Base Curve	PTC*		PTC		PTC	
	Comp. Softening	Vechio-Collins		Vechio-Collins		Vechio-Collins	
	Tension Stiffening	Bentz 1999		Bentz 1999		Bentz 1999	
Rebar Details (#4 A615 Stirrups)	Elastic Modulus (ksi)	29000		29000		N/A	
	Yield Strength (ksi)	62		62		N/A	
	e-Strain Hardening (millistrain)	2.1		2.1		N/A	
	Rupture Strain (millistrain)	70		70		N/A	
	Ultimate Strength (ksi)	99		99		N/A	
Rebar Details (#3 A1035 Stirrups)	Elastic Modulus (ksi)	29000		29000		29000	
	Yield Strength (ksi)	107		107		107	
	e-Strain Hardening (millistrain)	3.7		3.7		3.7	
	Rupture Strain (millistrain)	18		18		18	
	Ultimate Strength (ksi)	153		153		153	
Prestressing Steel Details (#8 A1035 Longitudinal)	Ramberg-Osgood A	0.055		0.055		0.0115	
	Ramberg-Osgood B	225		225		200	
	Ramberg-Osgood C	2.9		2.9		2.4	
	Elastic Modulus (ksi)	29000		29000		29000	
	Ultimate Strength (ksi)	157		157		157	
	Rupture Strain (millistrain)	60		60		60	

*Popovics/Thorenfeldt/Collins

Table F7 (cont.) Response 2000 Parameters

	Parameter	SP1		SP2		SP3		SP4	
		Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Concrete Details (Slab)	Cylinder Strength (psi)	7220		9970		10080		6280	
	Tension Strength (psi)	510		510		510		510	
	Peak Strain (millistrain)	Auto 2.24		Auto 2.52		Auto 2.53		Auto 2.15	
	Aggregate Size (in)	0.4		0.4		0.4		0.4	
	Tension Stiff Factor	1	0.5	1	0.5	1	0.5	1	0.5
	Base Curve	PTC*		PTC		PTC		PTC	
	Comp. Softening	Vechio-Collins		Vechio-Collins		Vechio-Collins		Vechio-Collins	
	Tension Stiffening	Bentz 1999		Bentz 1999		Bentz 1999		Bentz 1999	
Concrete Details (Girder)	Cylinder Strength (psi)	11930		12380		13070		10530	
	Tension Strength (psi)	656		656		656		656	
	Peak Strain (millistrain)	Auto 2.70		Auto 2.74		Auto 2.81		Auto 2.57	
	Aggregate Size (in)	0.4		0.4		0.4		0.4	
	Tension Stiff Factor	1	0.5	1	0.5	1	0.5	1	0.5
	Base Curve	PTC*		PTC*		PTC*		PTC*	
	Comp. Softening	Vechio-Collins		Vechio-Collins		Vechio-Collins		Vechio-Collins	
	Tension Stiffening	Bentz 1999		Bentz 1999		Bentz 1999		Bentz 1999	
Rebar Details (#4 A615 Stirrups)	Elastic Modulus (ksi)	29000		29000		29000		29000	
	Yield Strength (ksi)	88.3		88.3		88.3		90.0	
	e-Strain Hardening (millistrain)	15.3		15.3		15.3		15.3	
	Rupture Strain (millistrain)	70		70		70		70	
	Ultimate Strength (ksi)	105		105		105		105	
Rebar Details (#3 A1035 Stirrups)	Elastic Modulus (ksi)	29000		29000		29000		29000	
	Yield Strength (ksi)	114		114		114		114	
	e-Strain Hardening (millistrain)	3.9		3.9		3.9		3.9	
	Rupture Strain (millistrain)	29		29		29		29	
	Ultimate Strength (ksi)	162		162		162		162	
Rebar Details (#6 A615 Longitudinal)	Elastic Modulus (ksi)	29000		29000		29000		29000	
	Yield Strength (ksi)	88.3		88.3		88.3		90.0	
	e-Strain Hardening (millistrain)	15.3		15.3		15.3		15.3	
	Rupture Strain (millistrain)	70		70		70		70	
	Ultimate Strength (ksi)	105		105		105		105	
Prestressing Steel Details (0.6" Strands)	Ramberg-Osgood A	0.028		0.028		0.028		0.028	
	Ramberg-Osgood B	113.5		113.5		113.5		113.5	
	Ramberg-Osgood C	14		14		14		14	
	Elastic Modulus (ksi)	29000		29000		29000		29000	
	Ultimate Strength (ksi)	270		270		270		270	
	Rupture Strain (millistrain)	43		43		43		43	

*Popovics/Thorenfeldt/Collins

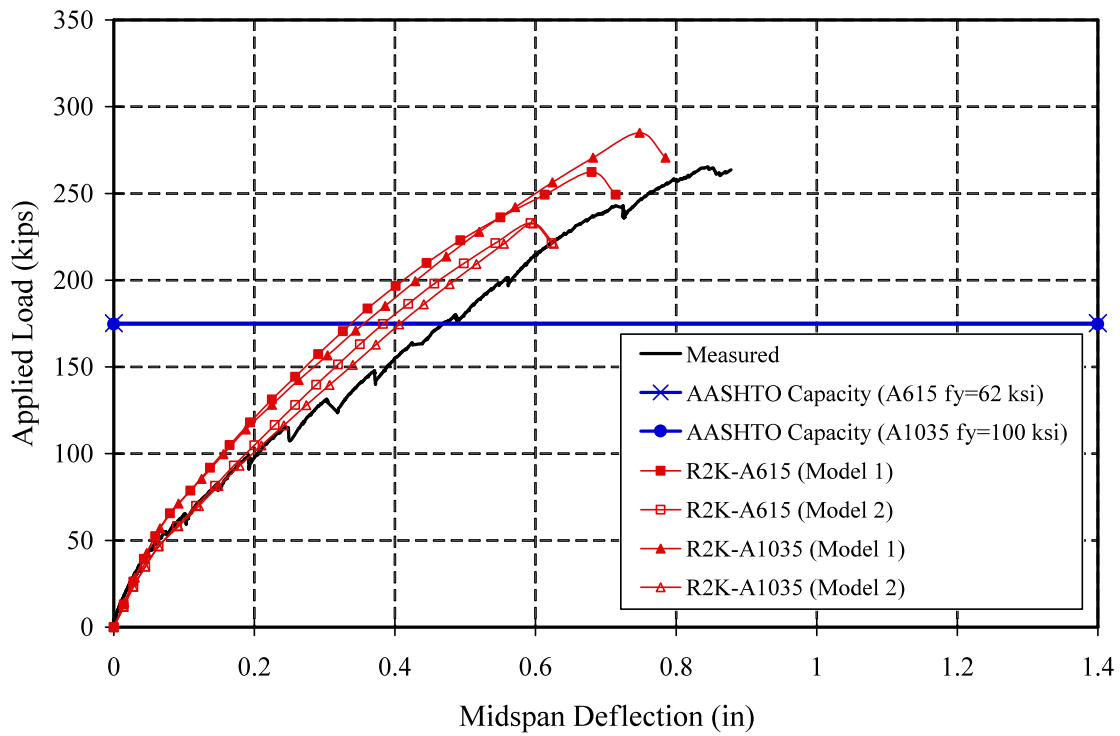


Figure F29 Load-Deflection Response of SR1

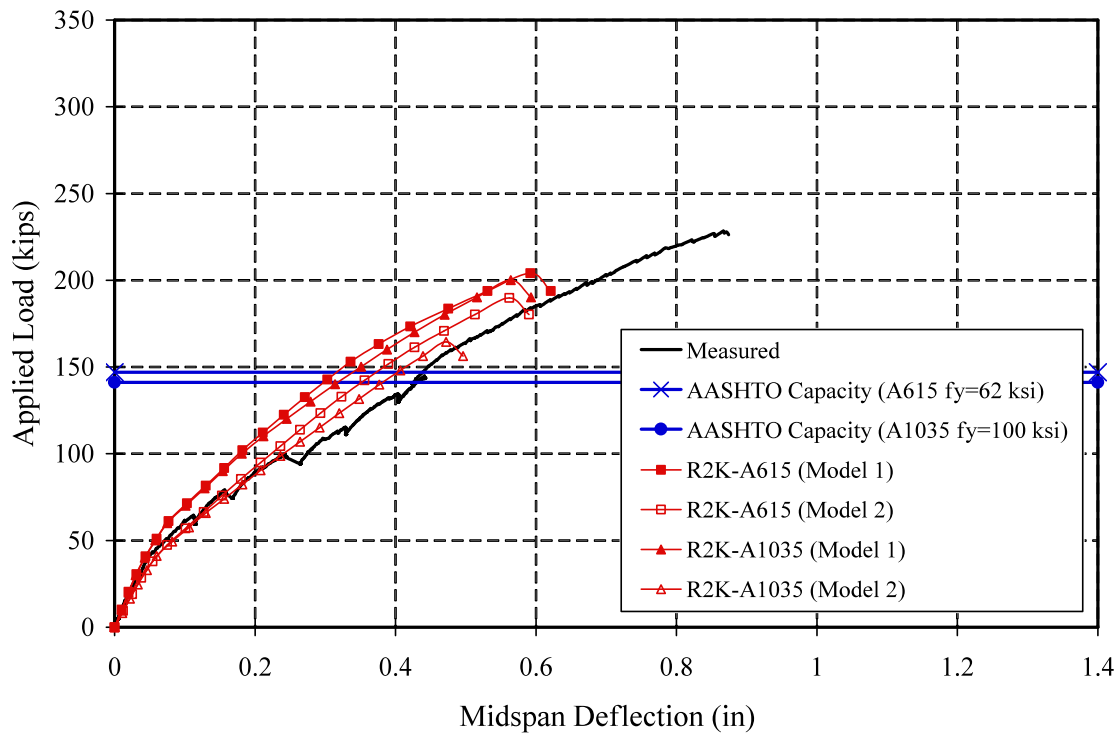


Figure F30 Load-Deflection Response of SR2

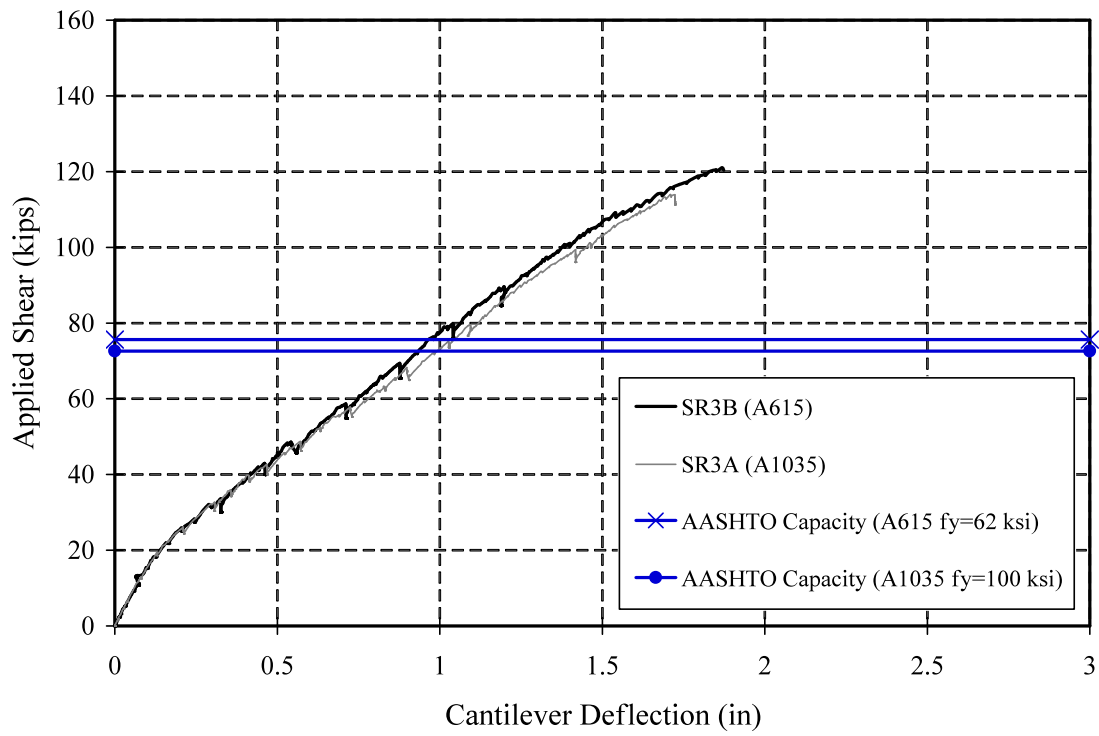


Figure F31 Load-Deflection Response of SR3

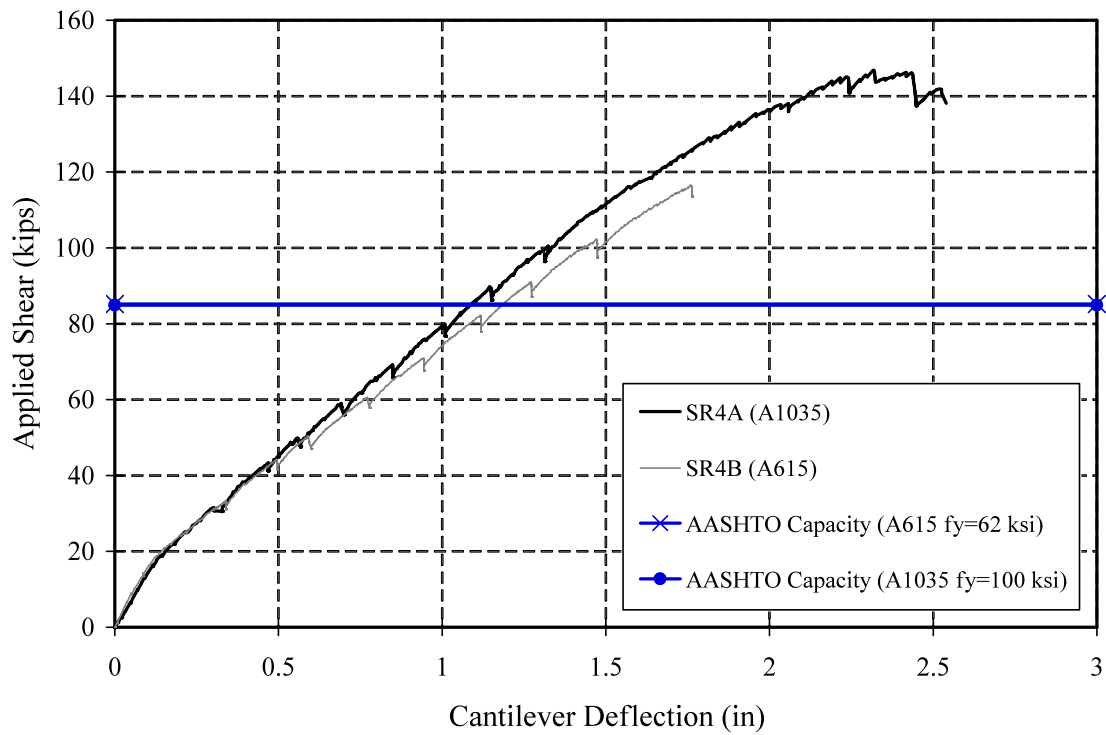


Figure F32 Load-Deflection Response of SR4

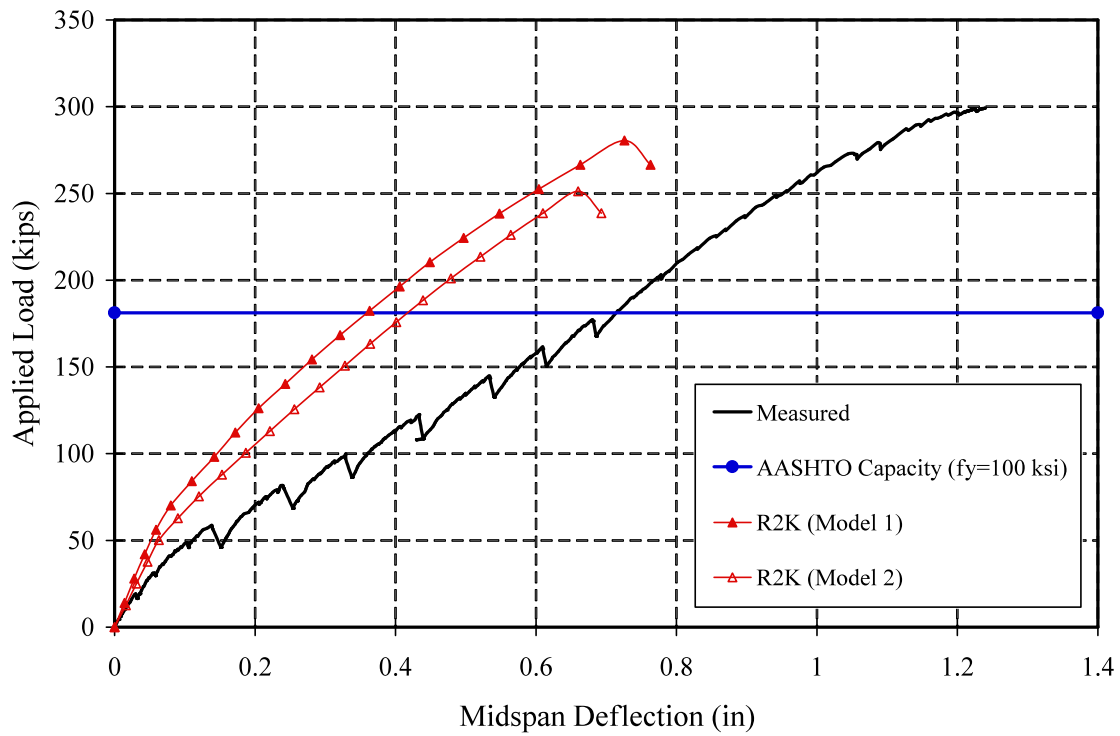


Figure F33 Load-Deflection Response of SR5

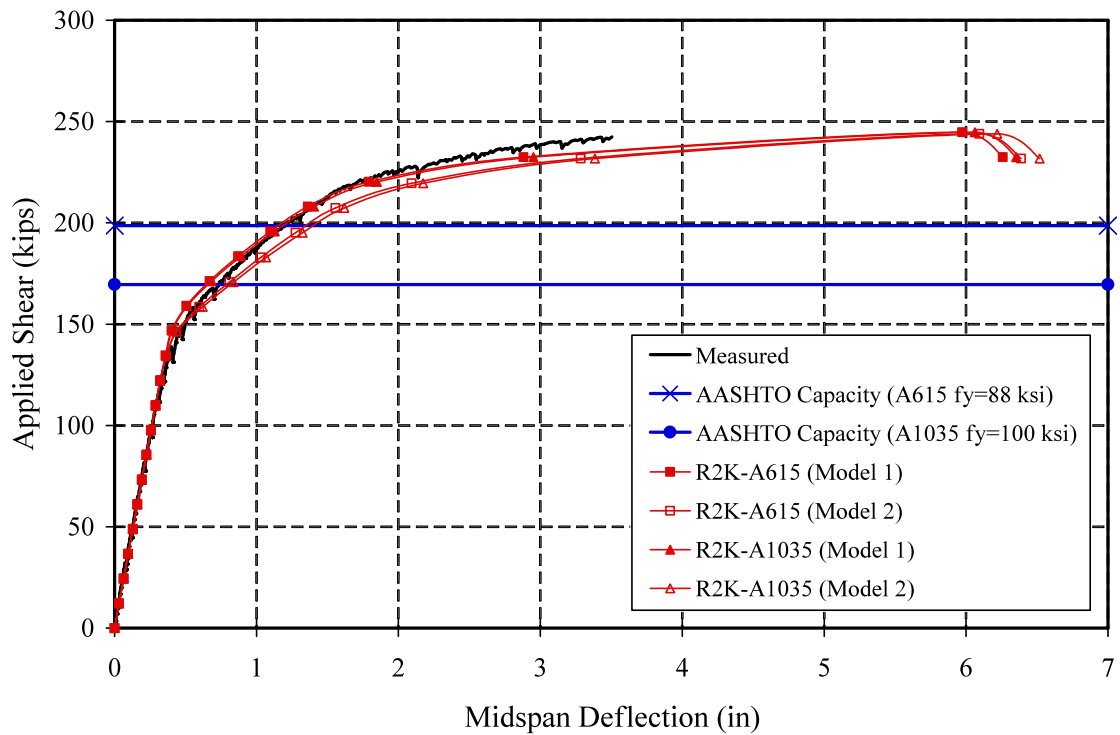


Figure F34 Load-Deflection Response of SP1

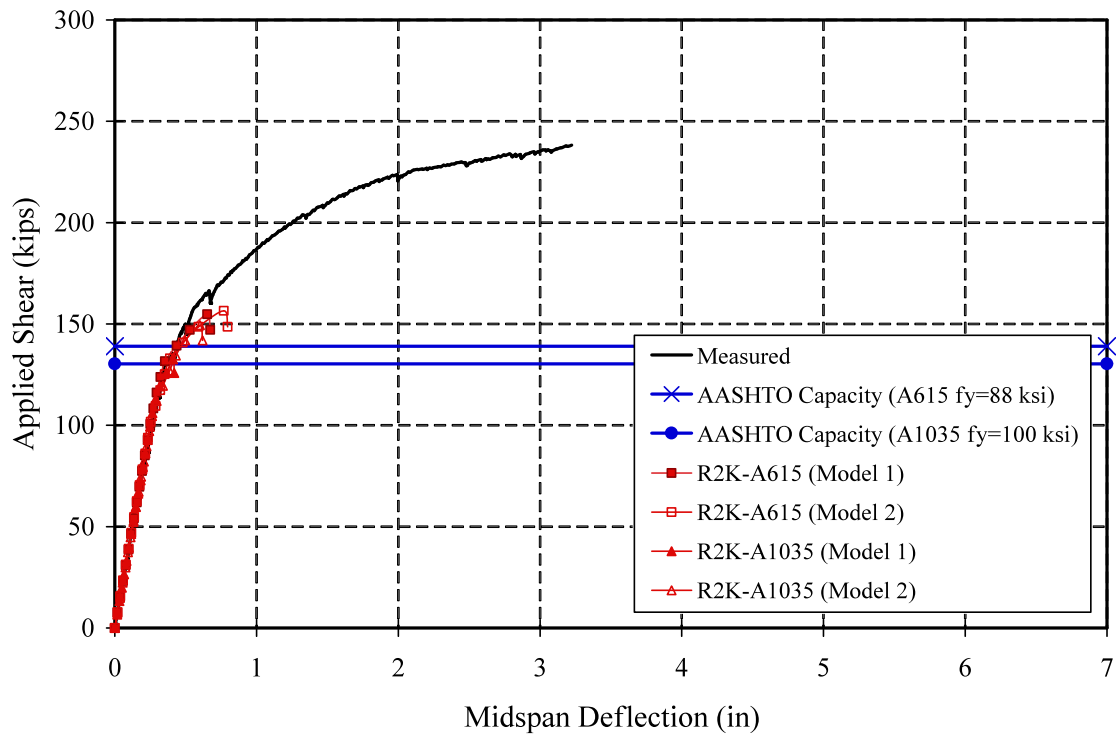


Figure F35 Load-Deflection Response of SP2

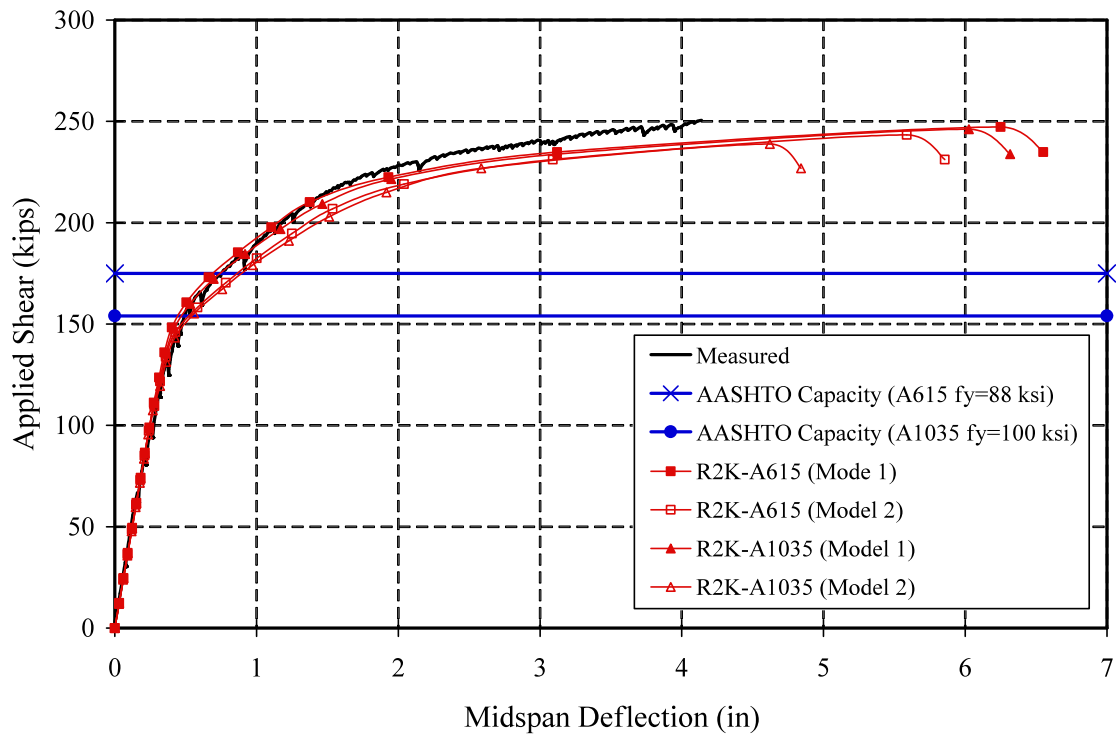


Figure F36 Load-Deflection Response of SP3

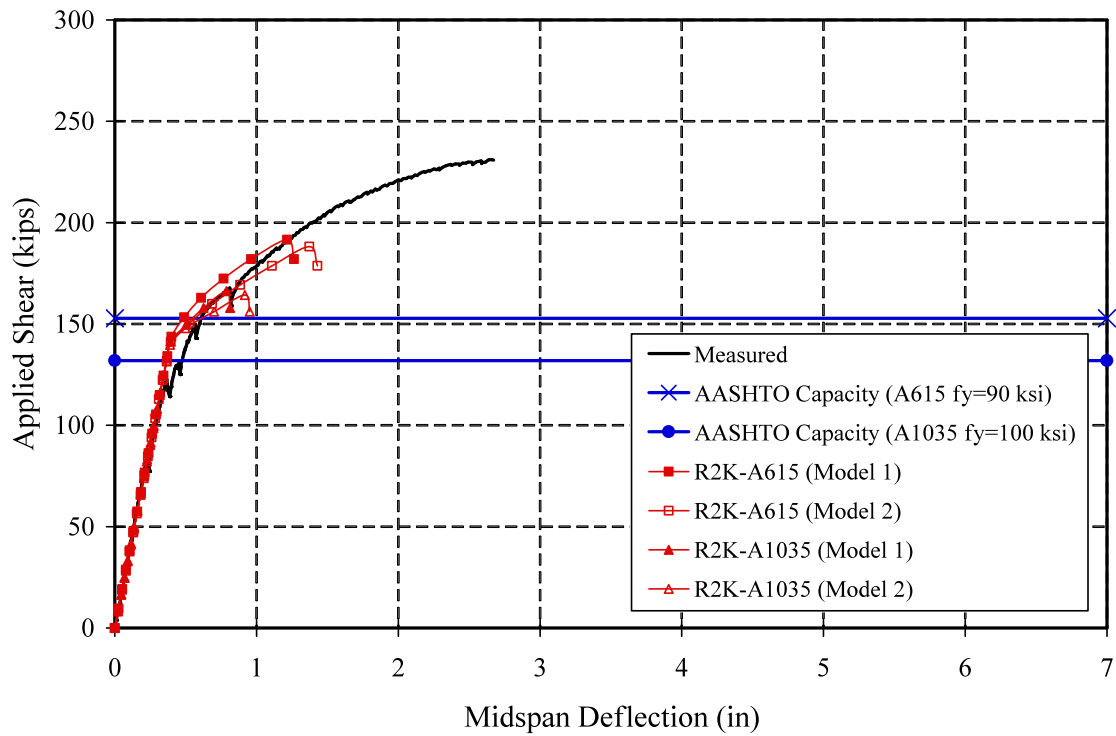
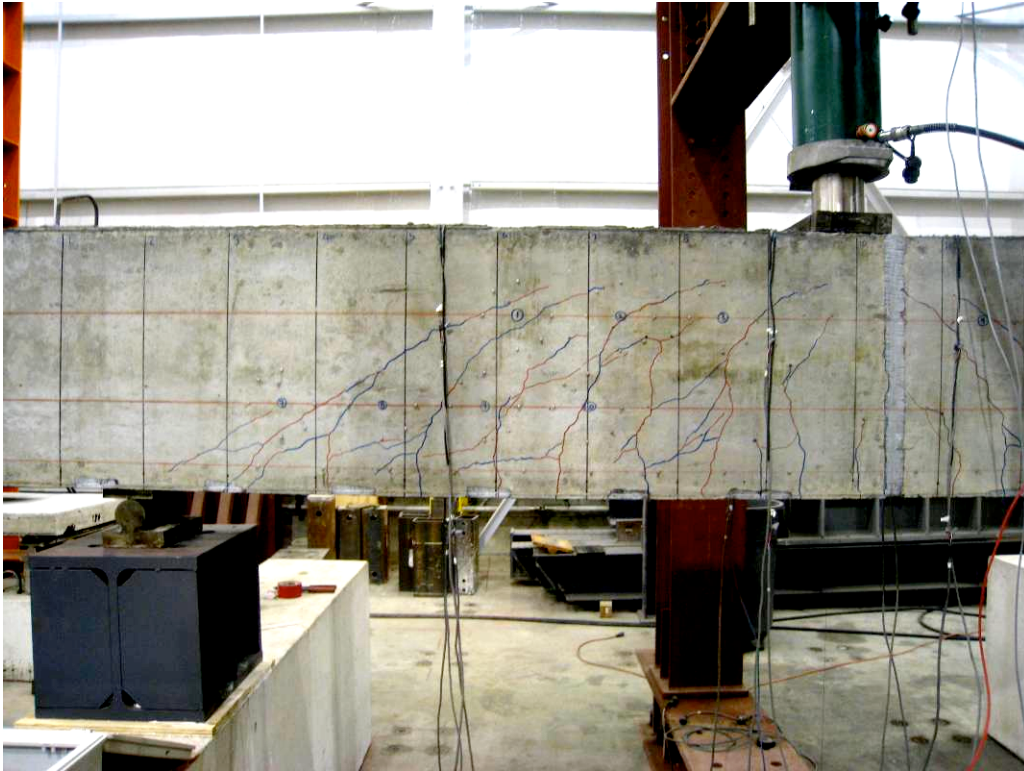


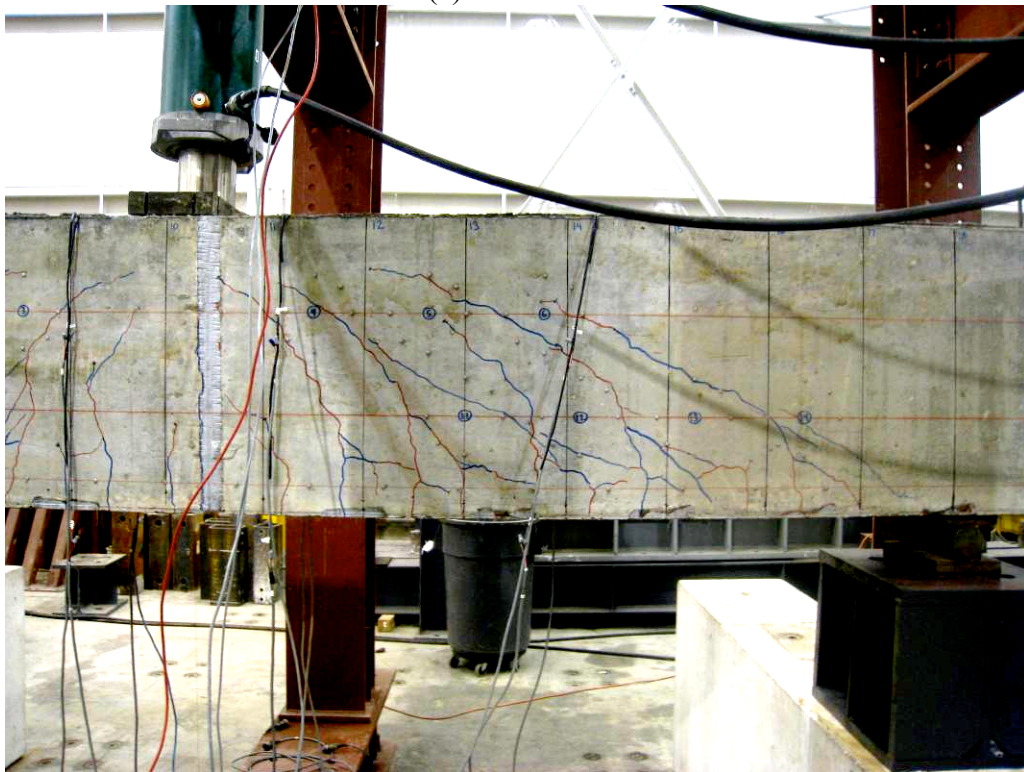
Figure F37 Load-Deflection Response of SP4

F.7.3 Crack Patterns & Crack Width

One of the serviceability concerns regarding the use of A1035 stirrups is crack propagation patterns and crack widths. Pictures were taken at various load increments to document the crack patterns found in the A615 and A1035 sides. For simplicity, the pictures shown in Figures F38 through F46 represent only the crack patterns at the load increment corresponding to the highest level of crack propagations for each specimen. In general, the load increments used in the following pictures coincide with the onset of yielding of the stirrups (100 ksi for the A1035 steel). Serviceability issues are relevant at lower stresses; however, the higher stresses used in Figures F38 through F46 allow for a better visual comparison of the crack patterns. For each of the following figures, the A615 side is presented first followed by the A1035 side (except SR5).

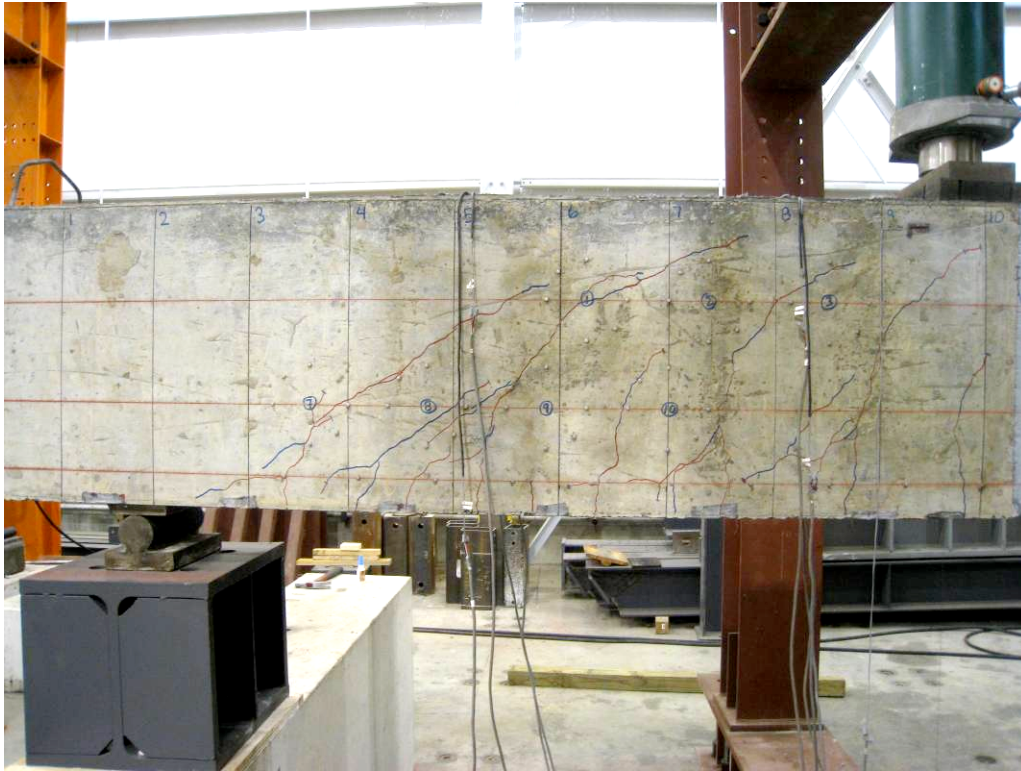


(a) A615 Side

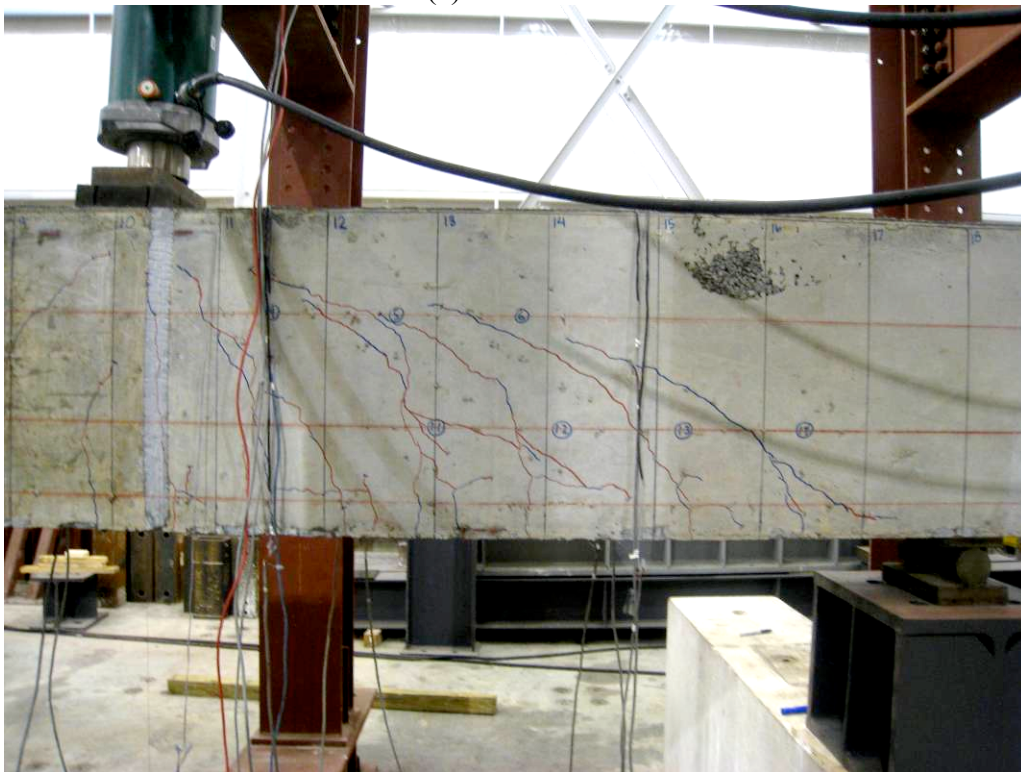


(b) A1035 Side

Figure F38 Crack Patterns of SR1



(a) A615 Side



(b) A1035 Side

Figure F39 Crack Patterns of SR2

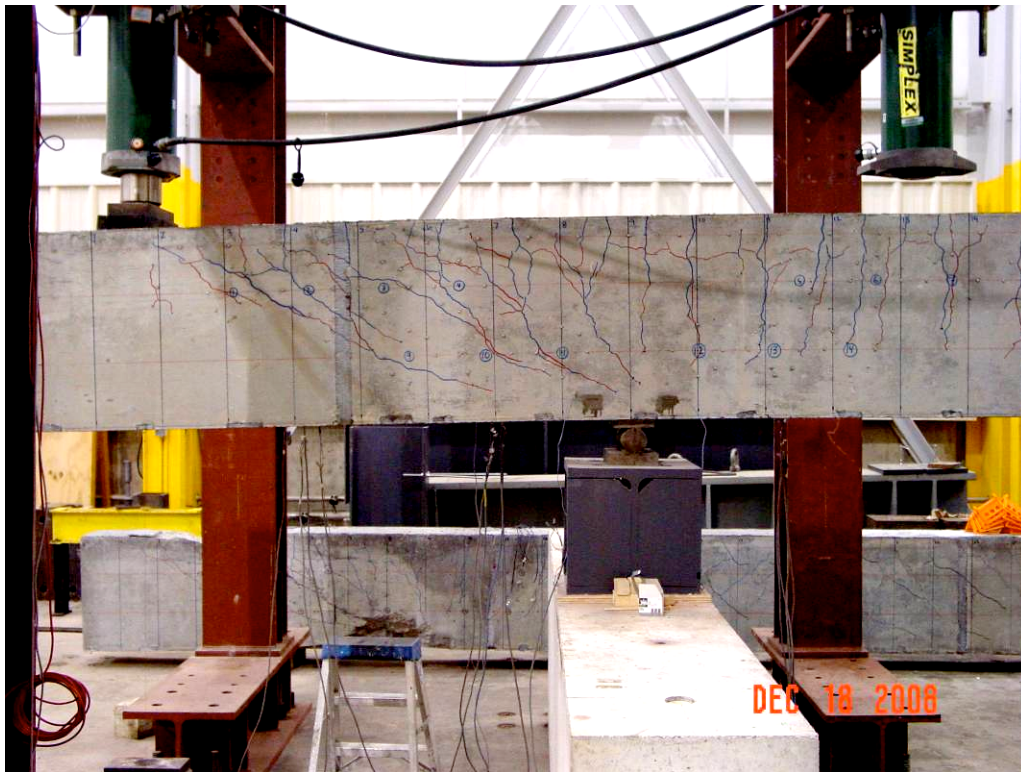


(a) A615 Side



(b) A1035 Side

Figure F40 Crack Patterns of SR3

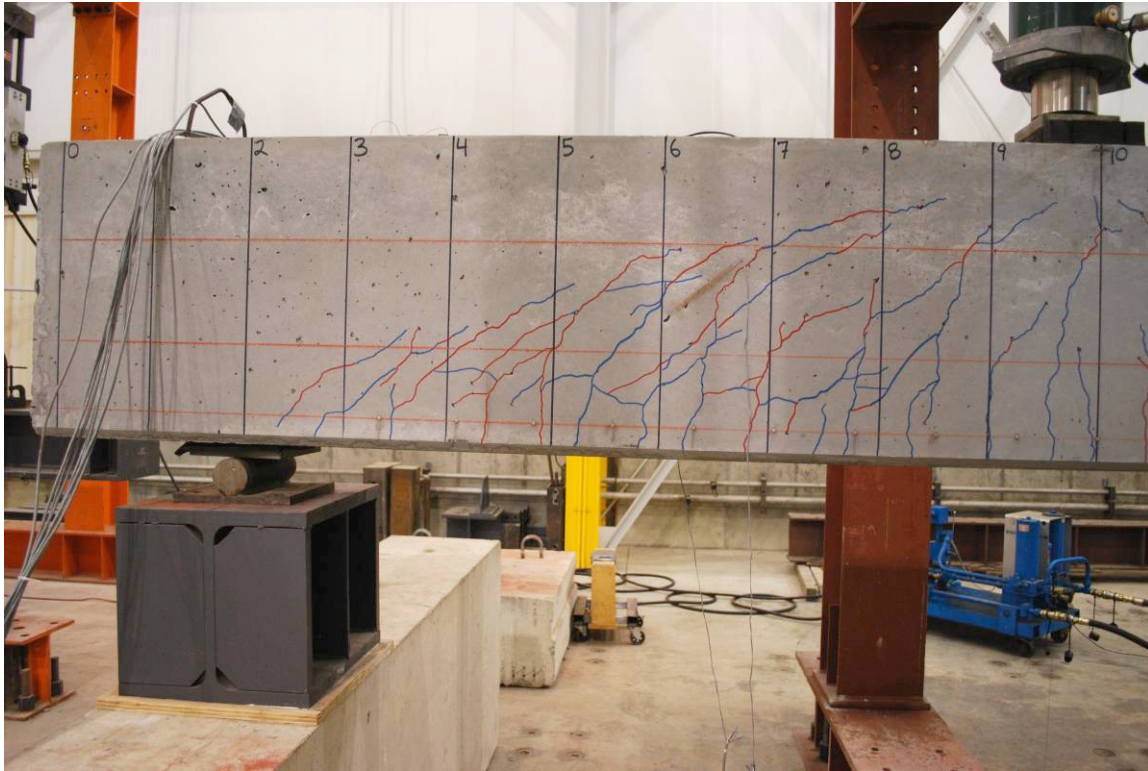


(a) A615 Side

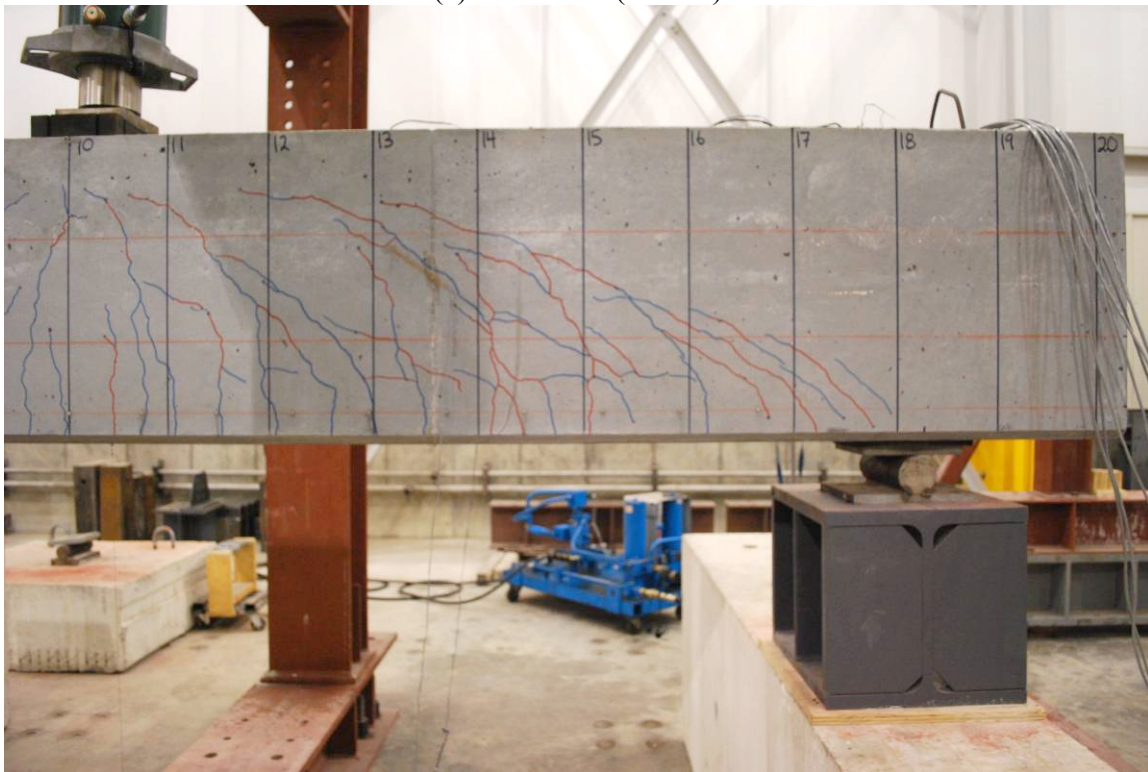


(b) A1035 Side

Figure F41 Crack Patterns of SR4



(a) West Side (A1035)



(b) East Side (A1035)

Figure F42 Crack Patterns of SR5



(a) A615 Side



(b) A1035 Side

Figure F43 Crack Patterns of SP1

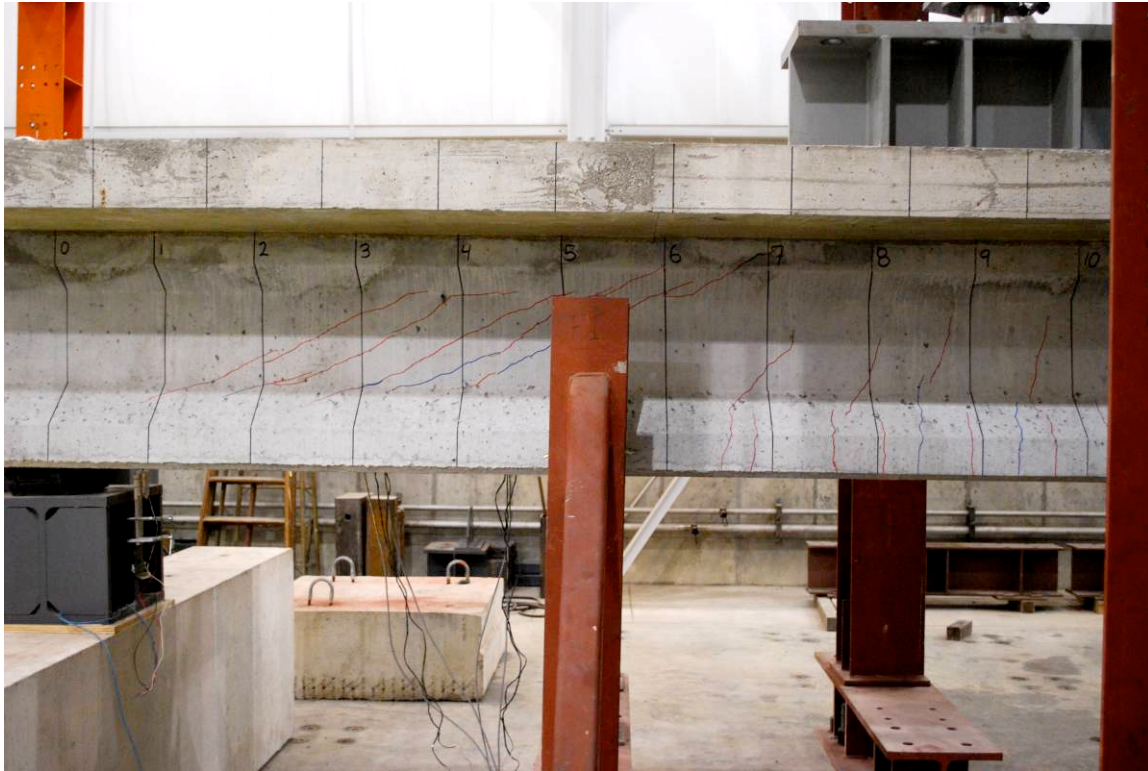


(a) A615 Side

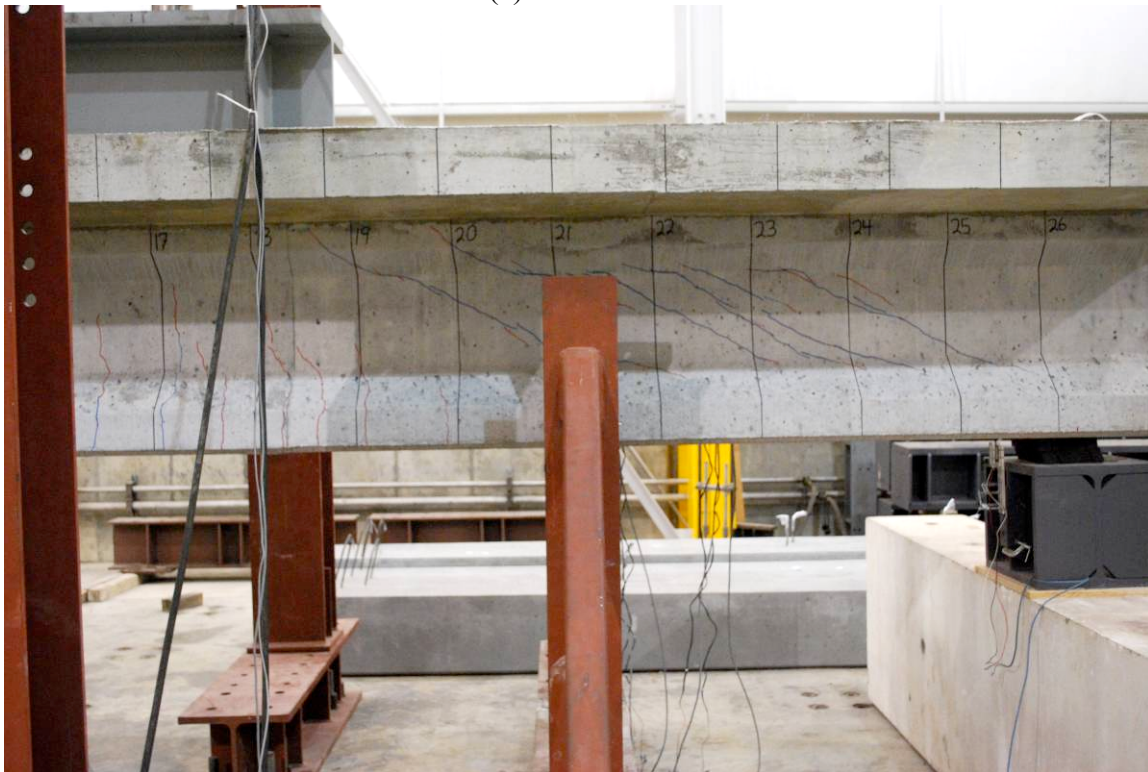


(b) A1035 Side

Figure F44 Crack Patterns of SP2



(a) A615 Side



(b) A1035 Side

Figure F45 Crack Patterns of SP3



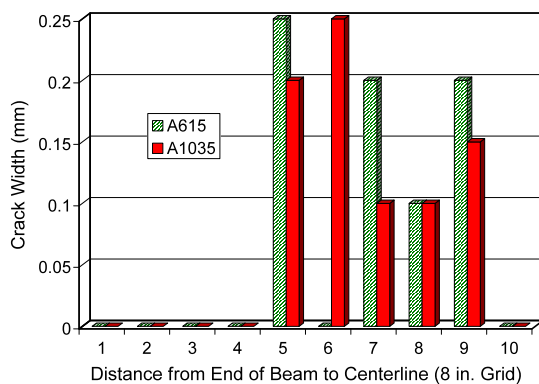
(a) A615 Side



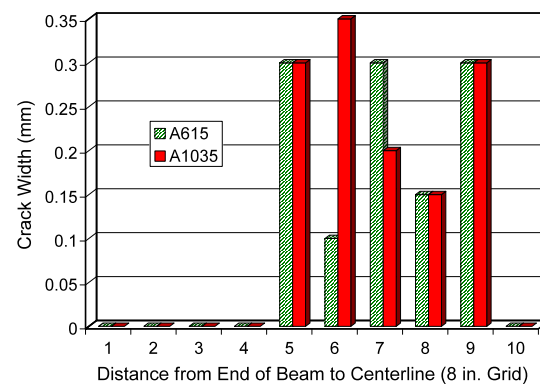
(b) A1035 Side

Figure F46 Crack Patterns of SP4

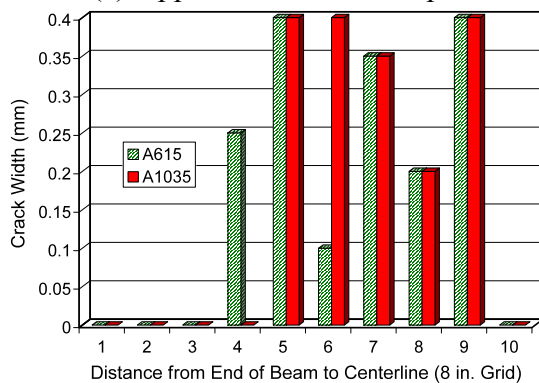
Measurements were also taken at various load increments to document the widths of the shear cracks. The crack widths (in millimeters) were measured by a plastic crack comparator. The results from the crack width measurements are plotted in Figures F47 thru F54. All of the specimens are shown except for SP1 since the observed shear cracks were too small to measure; recall that this specimen failed in flexure. The load increments in these plots are approximately based on 60% yield strength up to 100% yield strength of the stirrups. For each chart, the horizontal axis represents half of the length of a beam (SR1, SR2, SR5, and the Type I girders) or the length of the shear span (SR3 and SR4) divided into grid lengths. A615 and A1035 crack widths are superimposed on the same graph for side-by-side comparison with the maximum recorded crack width in a particular grid being shown. The charts for SR5 involve only the maximum crack widths (A1035) in their respective grids.



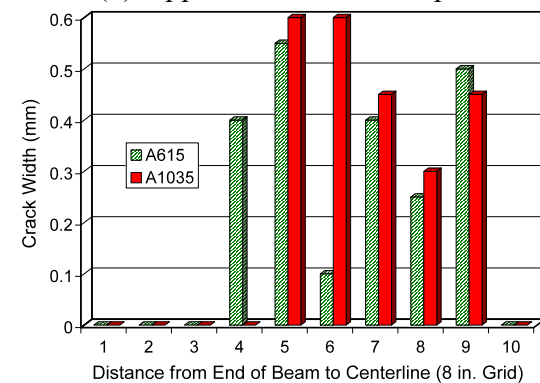
(a) Applied Load = 147 kips



(b) Applied Load = 163 kips

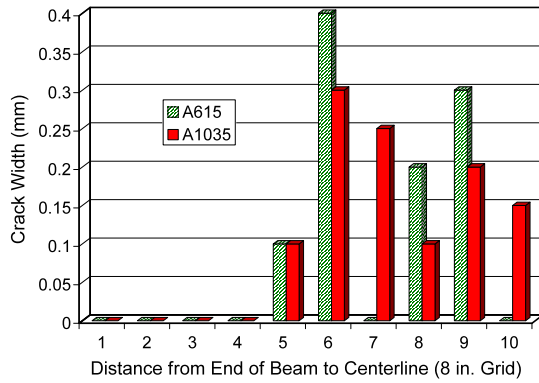


(c) Applied Load = 180 kips

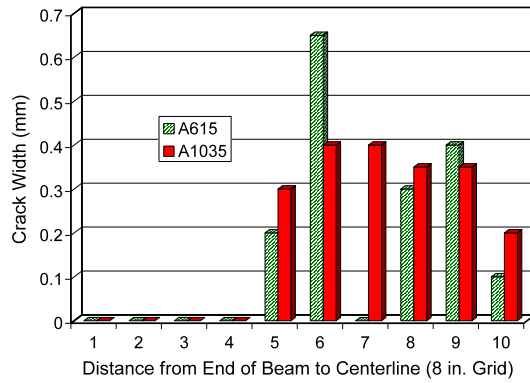


(d) Applied Load = 200 kips

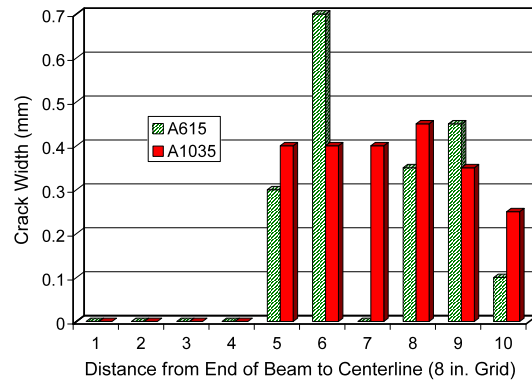
Figure F47 Shear Crack Widths for SR1



(a) Applied Load = 115 kips

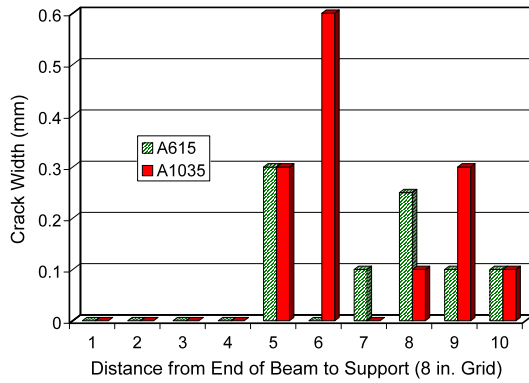


(b) Applied Load = 135 kips

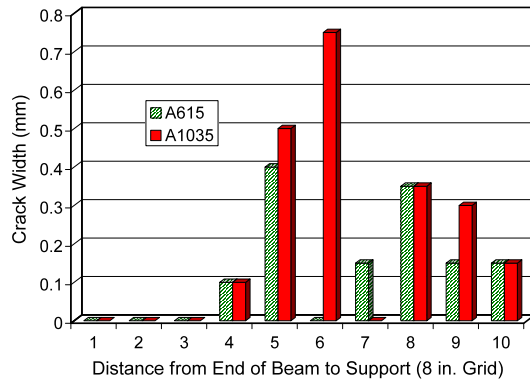


(c) Applied Load = 145 kips

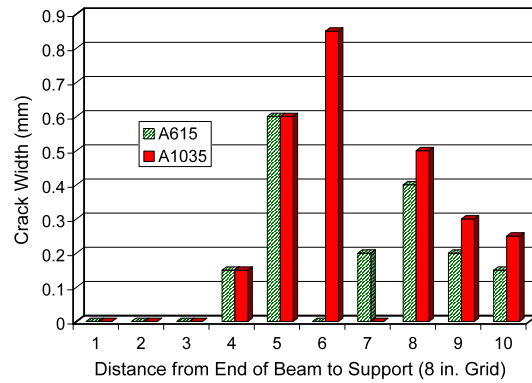
Figure F48 Shear Crack Widths for SR2



(a) Applied Shear = 60 kips

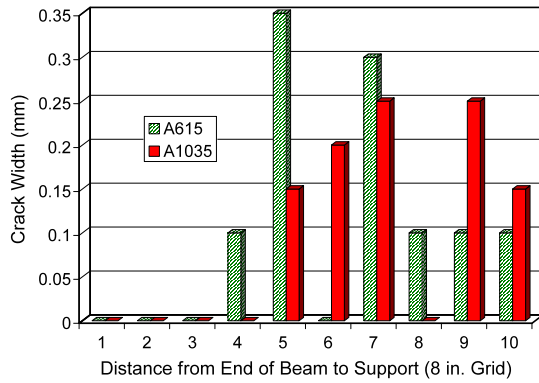


(b) Applied Shear = 71 kips

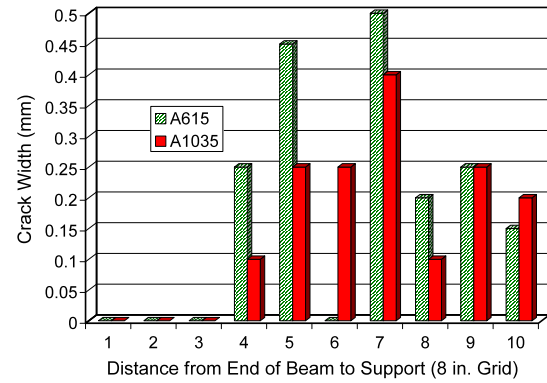


(c) Applied Shear = 81 kips

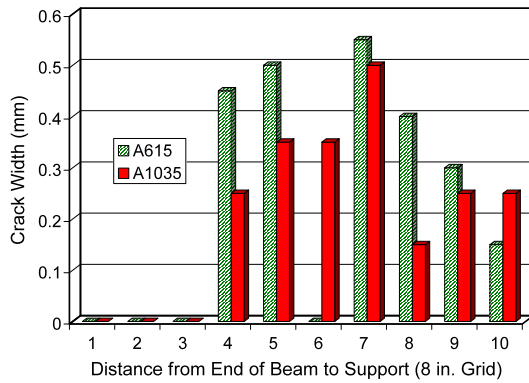
Figure F49 Shear Crack Widths for SR3



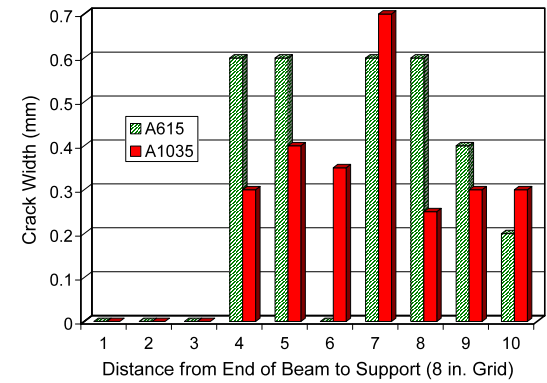
(a) Applied Shear = 61 kips



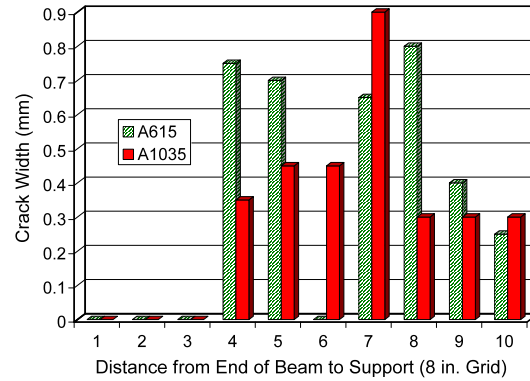
(b) Applied Shear = 71 kips



(c) Applied Shear = 82 kips

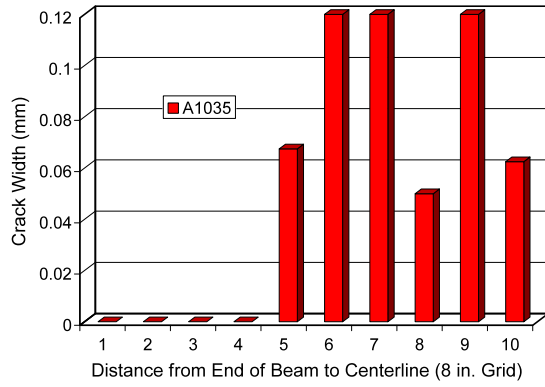


(d) Applied Shear = 92 kips

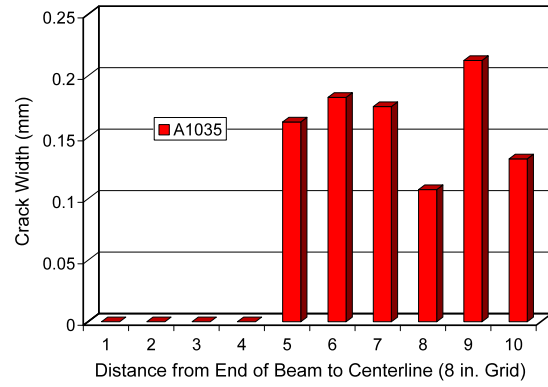


(e) Applied Shear = 102 kips

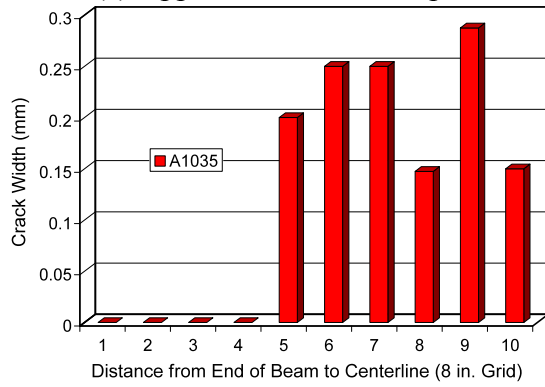
Figure F50 Shear Crack Widths for SR4



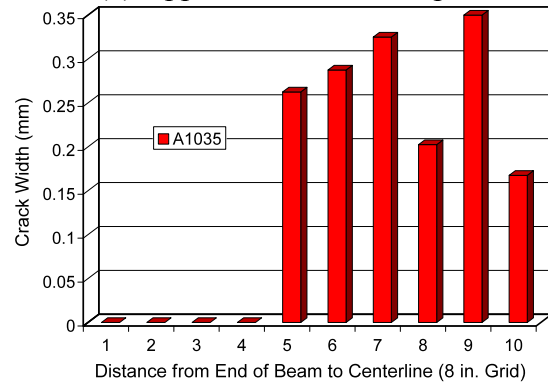
(a) Applied Load = 122 kips



(b) Applied Load = 145 kips

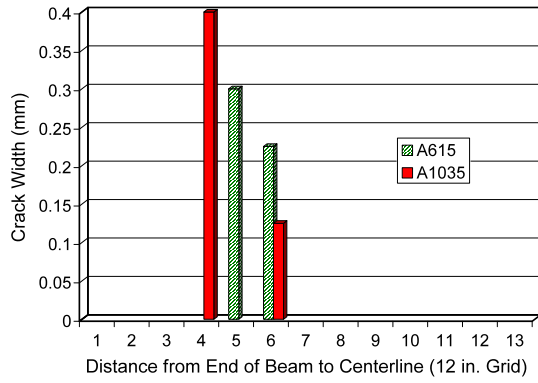


(c) Applied Load = 162 kips

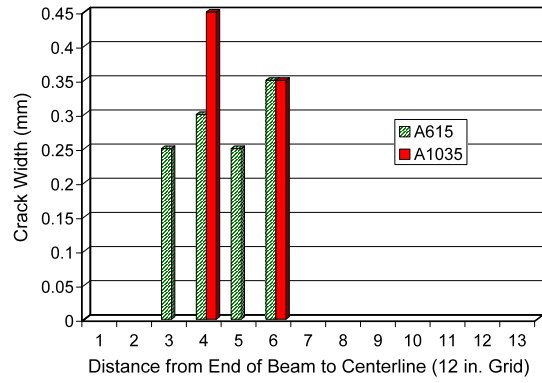


(d) Applied Load = 177 kips

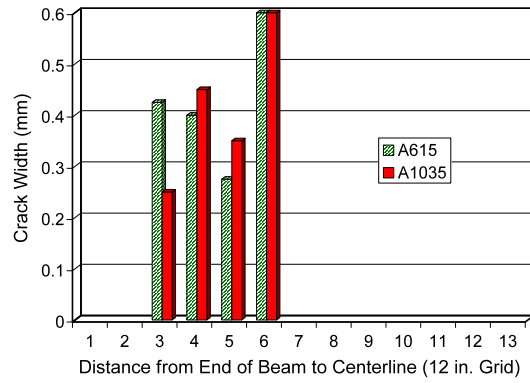
Figure F51 Shear Crack Widths for SR5



(a) Applied Shear = 130 kips

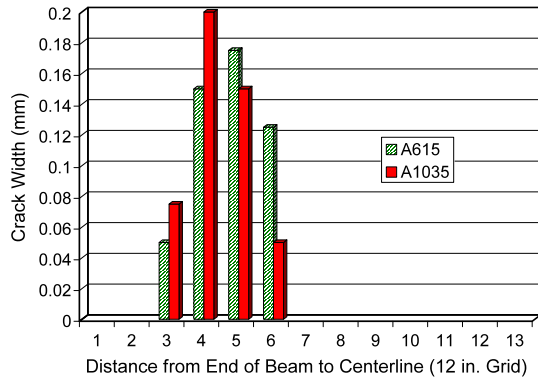


(b) Applied Shear = 148 kips

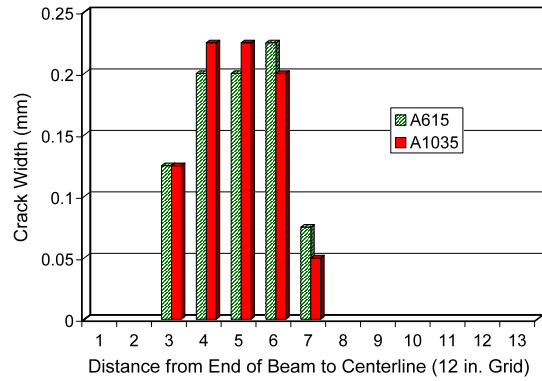


(c) Applied Shear = 162 kips

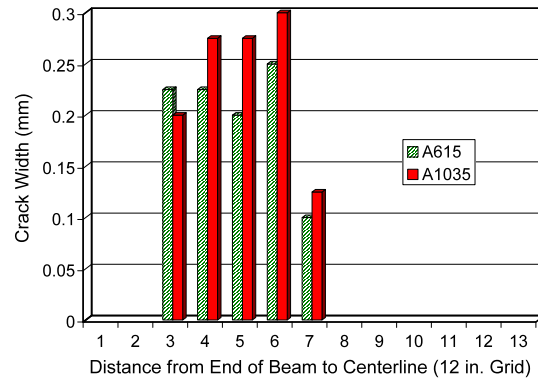
Figure F52 Shear Crack Widths for SP2



(a) Applied Shear = 145 kips

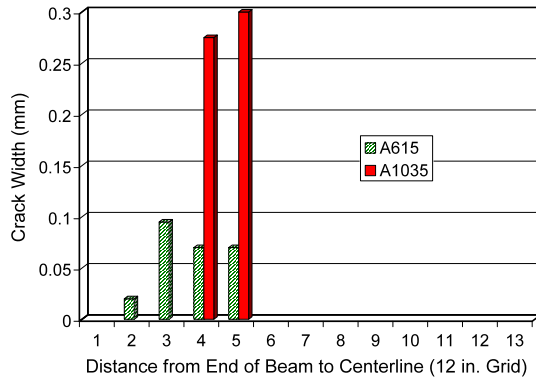


(b) Applied Shear = 165 kips

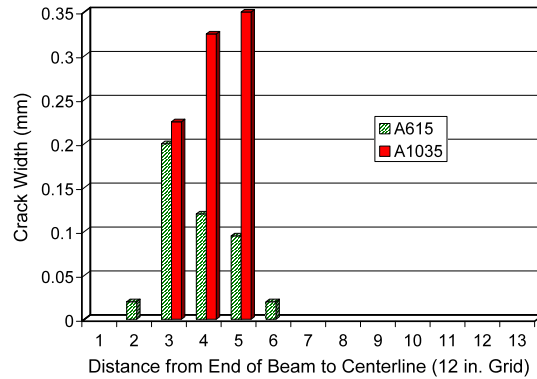


(c) Applied Shear = 184 kips

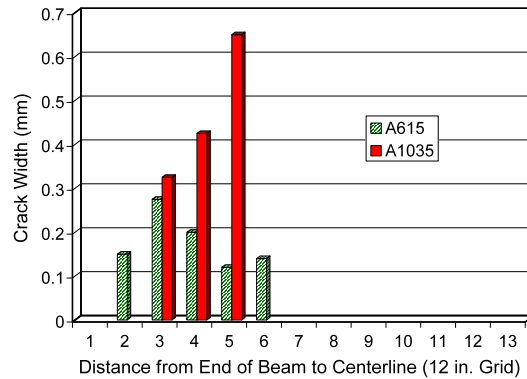
Figure F53 Shear Crack Widths for SP3



(a) Applied Shear = 131 kips



(b) Applied Shear = 150 kips

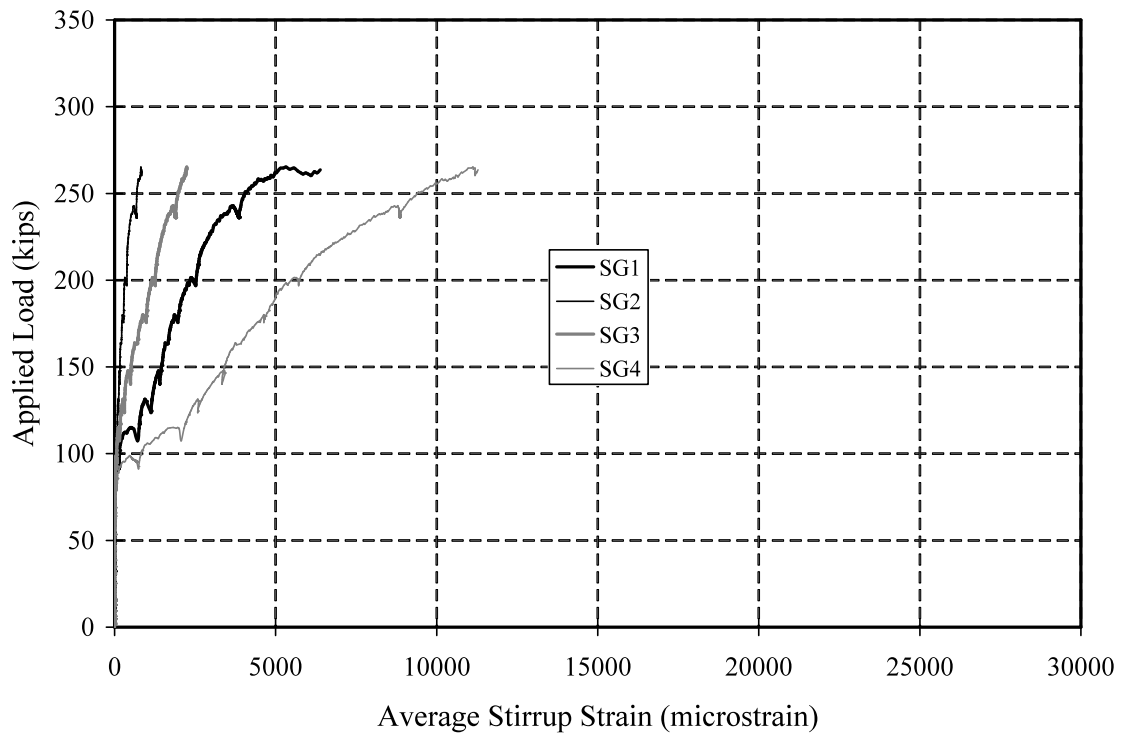


(c) Applied Shear = 168 kips

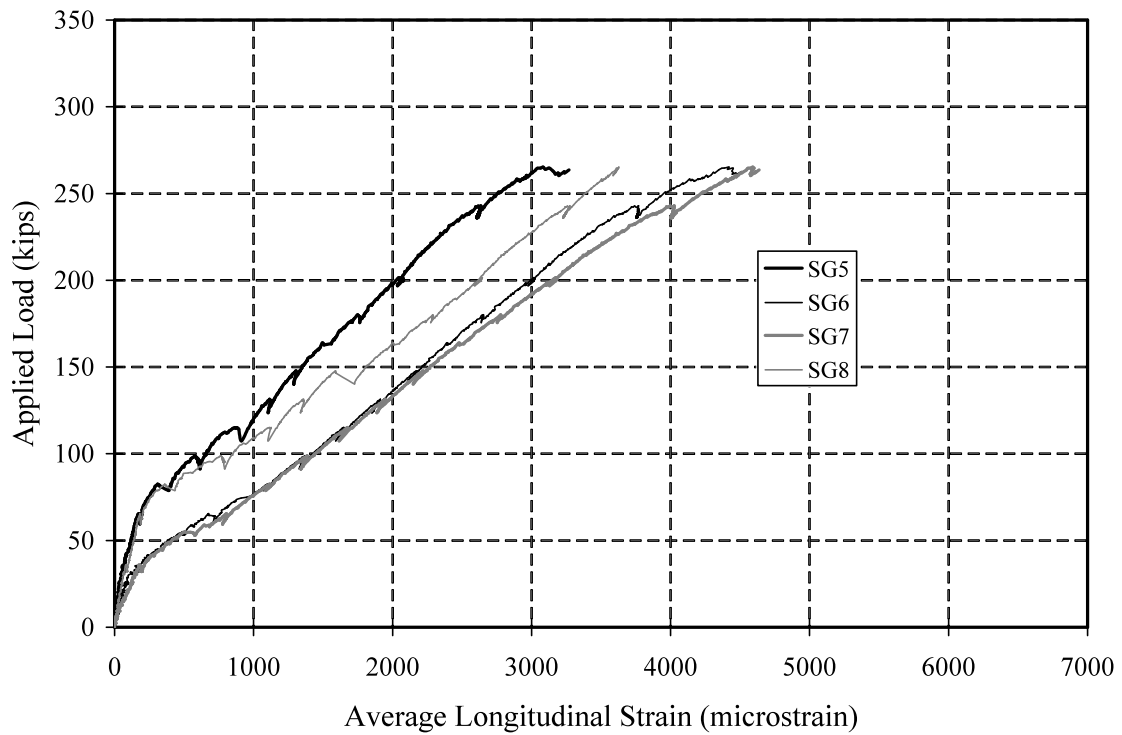
Figure F54 Shear Crack Widths for SP4

F.7.4 Load-Strain Behavior

The data from the strain gages are presented in Figures F55 through F63 as load versus strain plots. For specimens SR1, SR2 and SR5, there are six graphs per specimen. The first two graphs show the averaged strain values at each location (one for the stirrups and the other for the longitudinal bars). The remaining four graphs show the data from each strain gage subdivided by location (near support or near load point) and by stirrup strain or longitudinal strain. The data for each of specimens SR3 and SR4 are represented by five graphs. Again, the first two plots show average values at each location while the second two show each individual strain gage (still divided by stirrup and longitudinal steel). The fifth graph illustrates the concrete strain data as measured by the surface gages. The data for Type I girders are illustrated through eight graphs per specimen. The layout is similar to SR1, SR2, and SR5 with the addition of one graph for the mid-span longitudinal strain and another for concrete strain. For some specimens, certain strain gages did not survive the concrete pour and those are omitted from the results. Some of the strain gages exhibit excessive strain values; however, most of these large strain values can be traced to presence of cracks at or in the proximity of the location of these strain gages. Also note that the mid-span strand strain in SP4 is omitted due to failure of both of those strain gages.

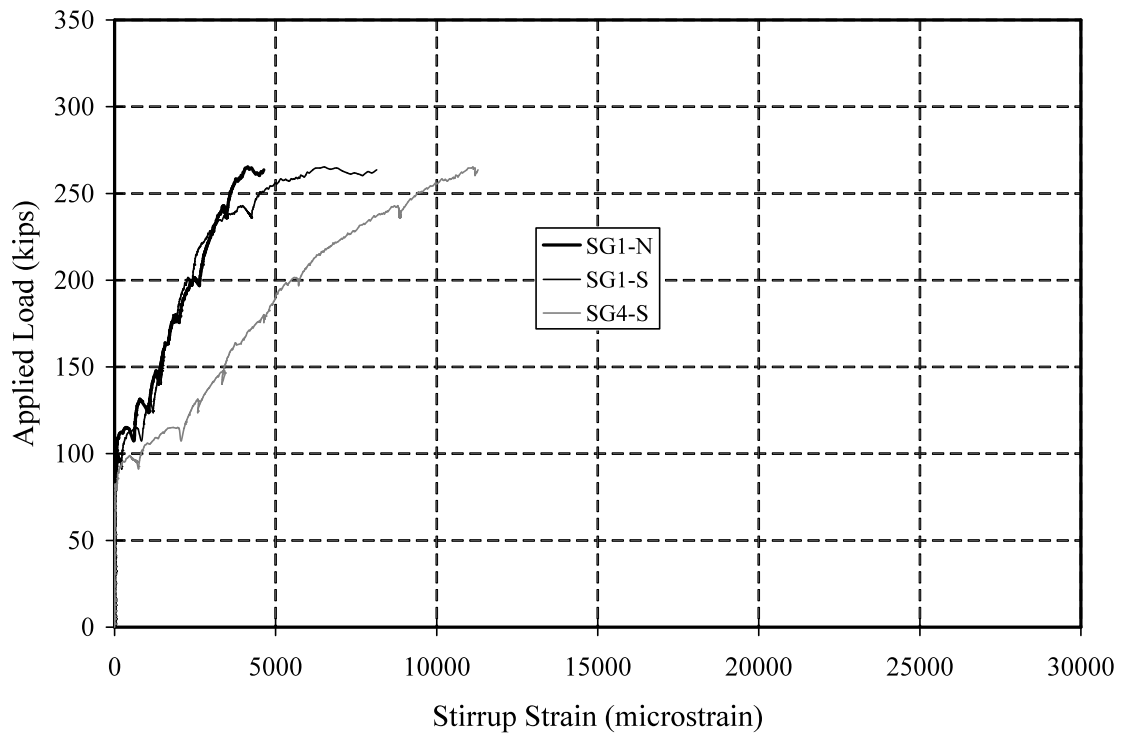


(a) Load vs. Average Stirrup Strain (All Locations)

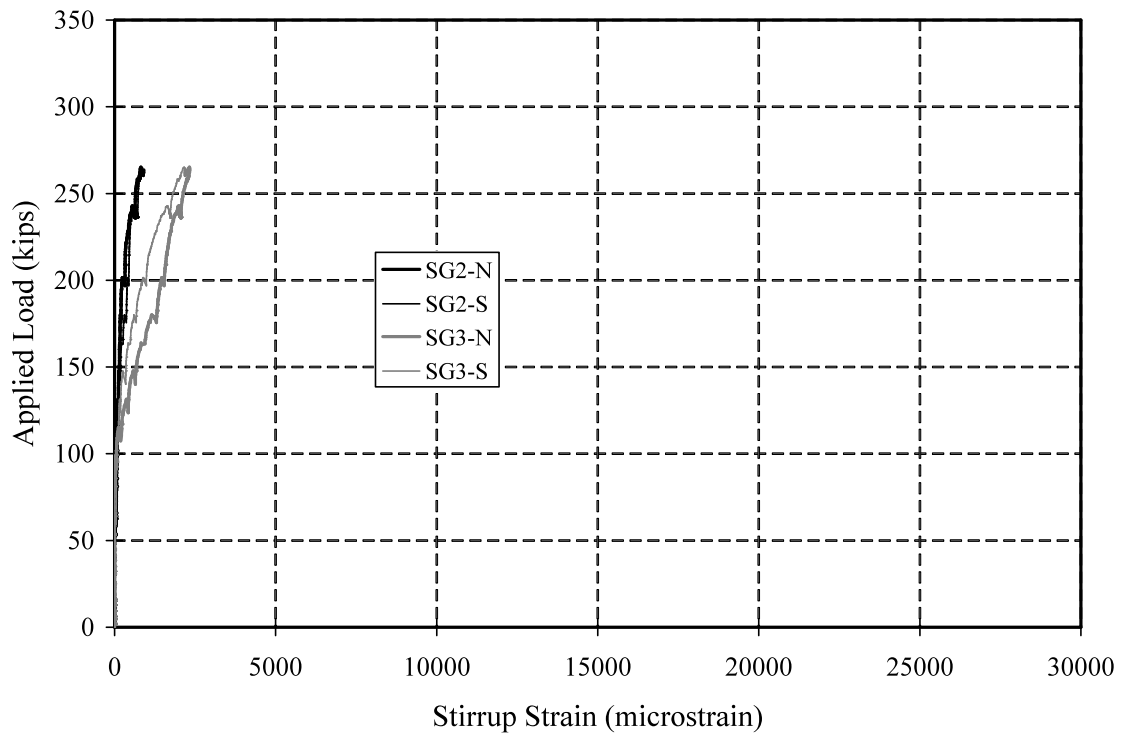


(b) Load vs. Average Longitudinal Strain (All Locations)

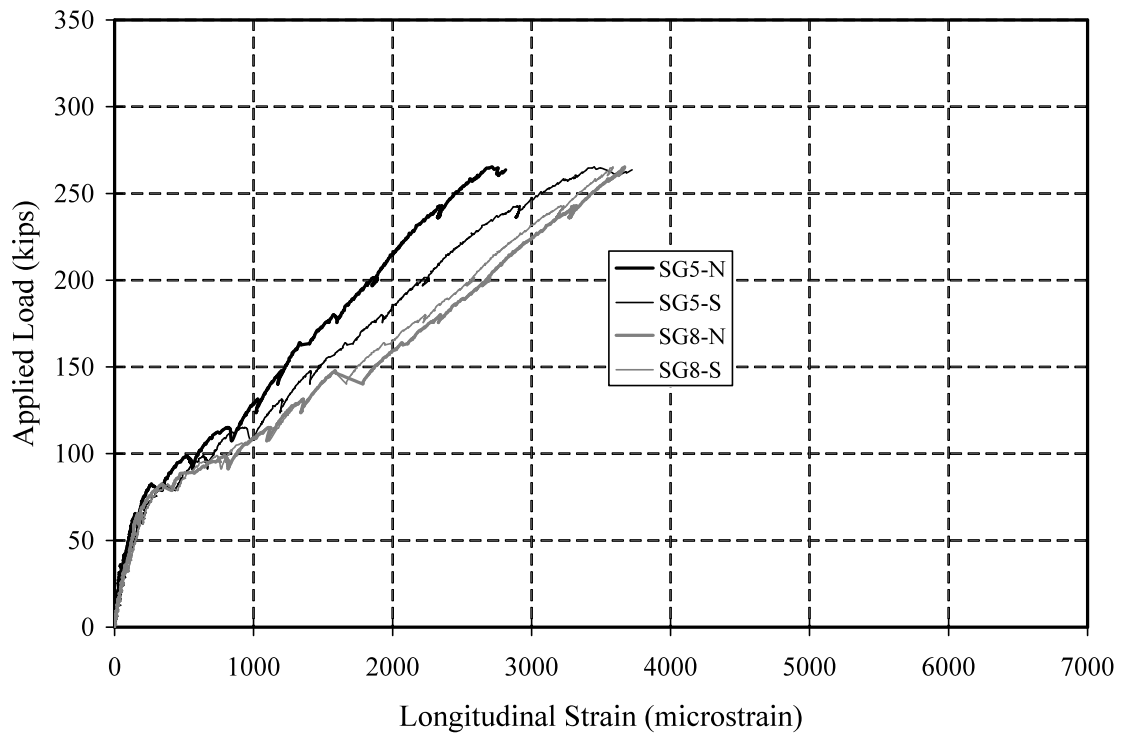
Figure F55 Strain Gage Data for SR1



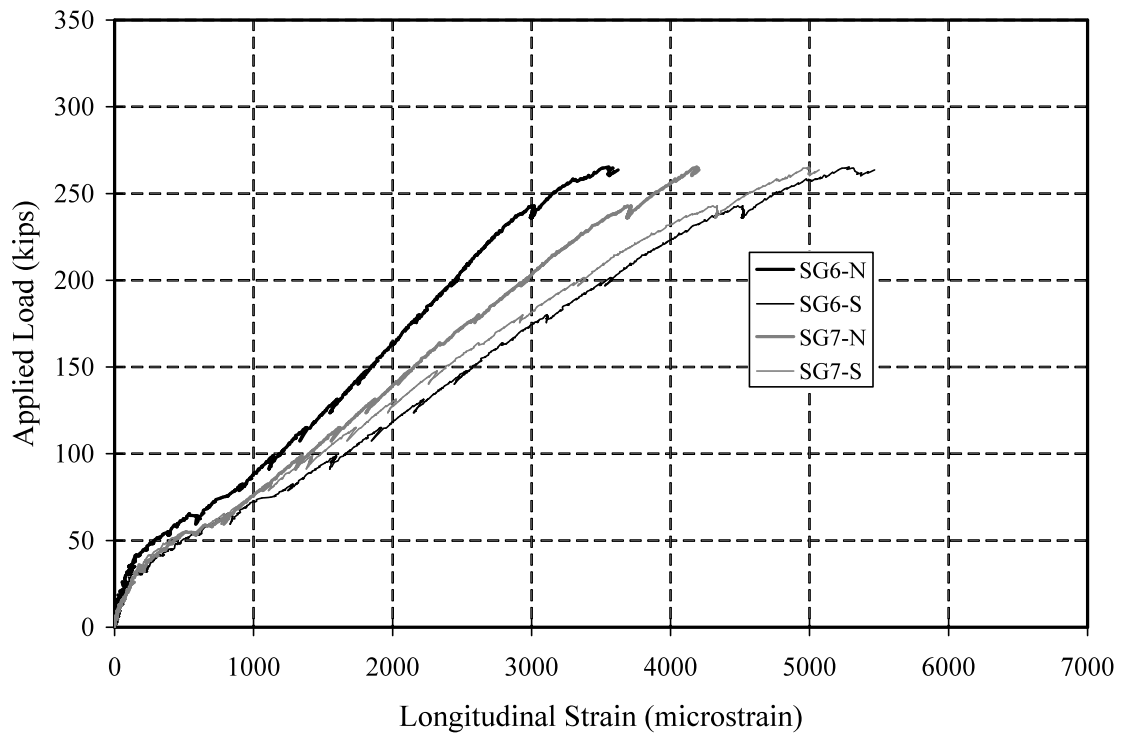
(c) Load vs. Stirrup Strain (Near Supports)



(d) Load vs. Stirrup Strain (Near Load Point)
Figure F55 (cont.) Strain Gage Data for SR1

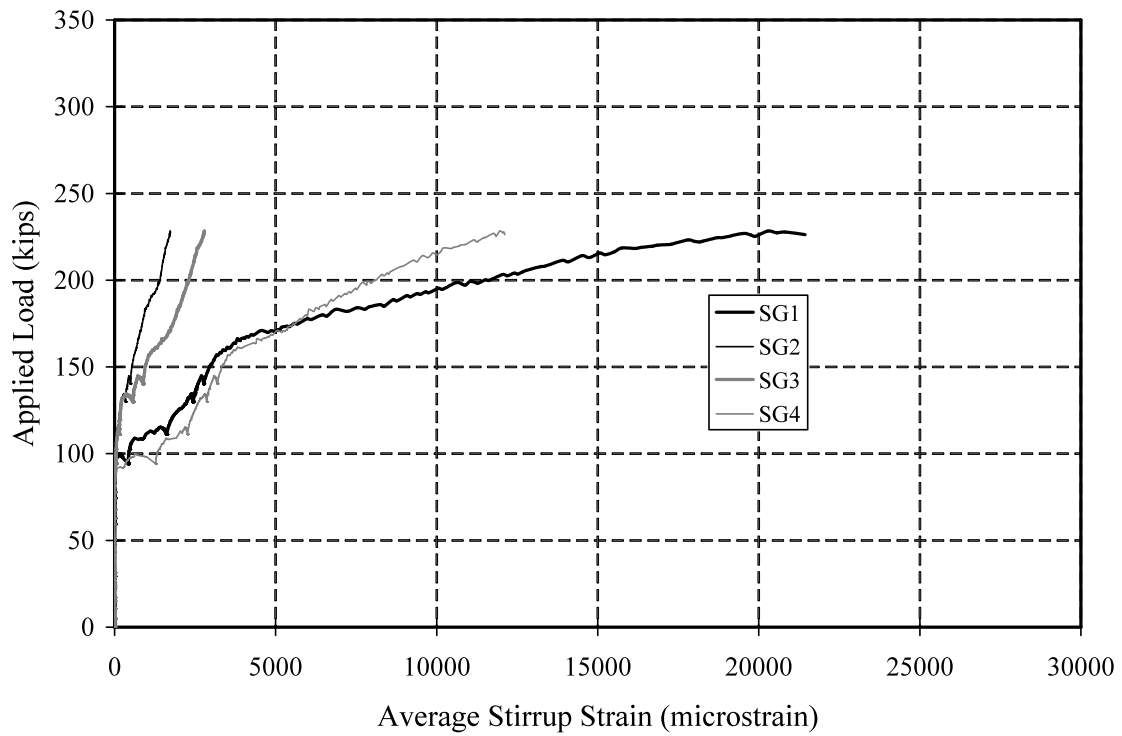


(e) Load vs. Longitudinal Strain (Near Supports)

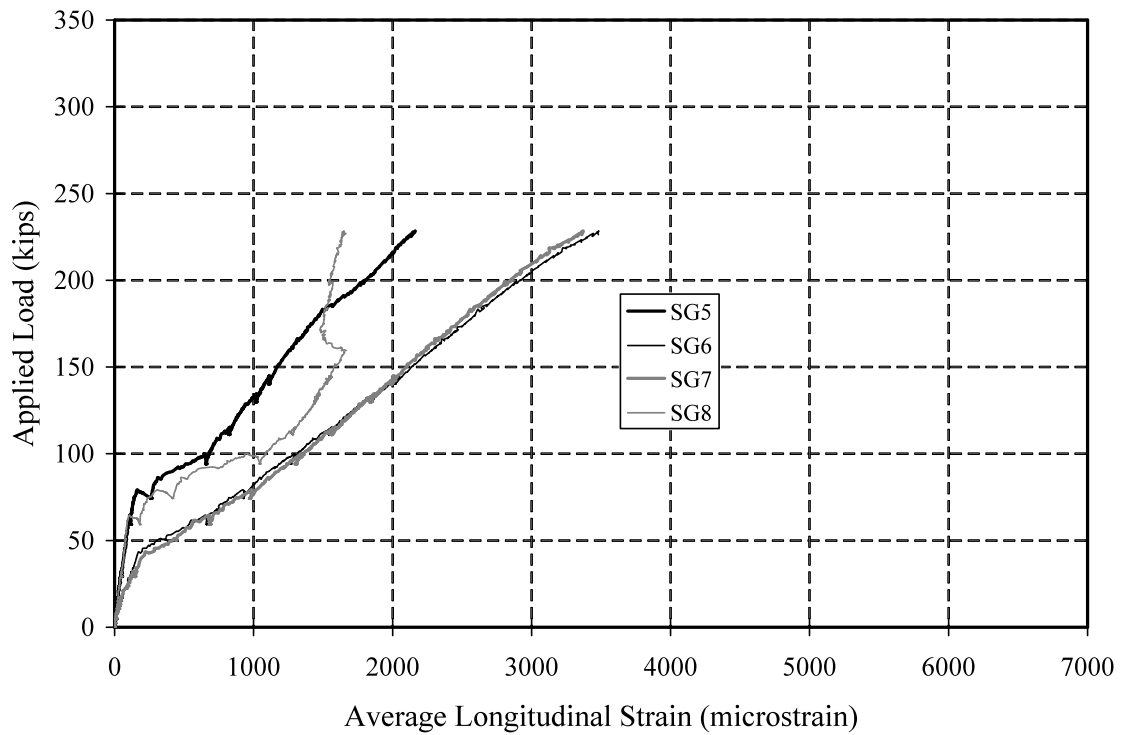


(f) Load vs. Longitudinal Strain (Near Load Point)

Figure F55 (cont.) Strain Gage Data for SR1

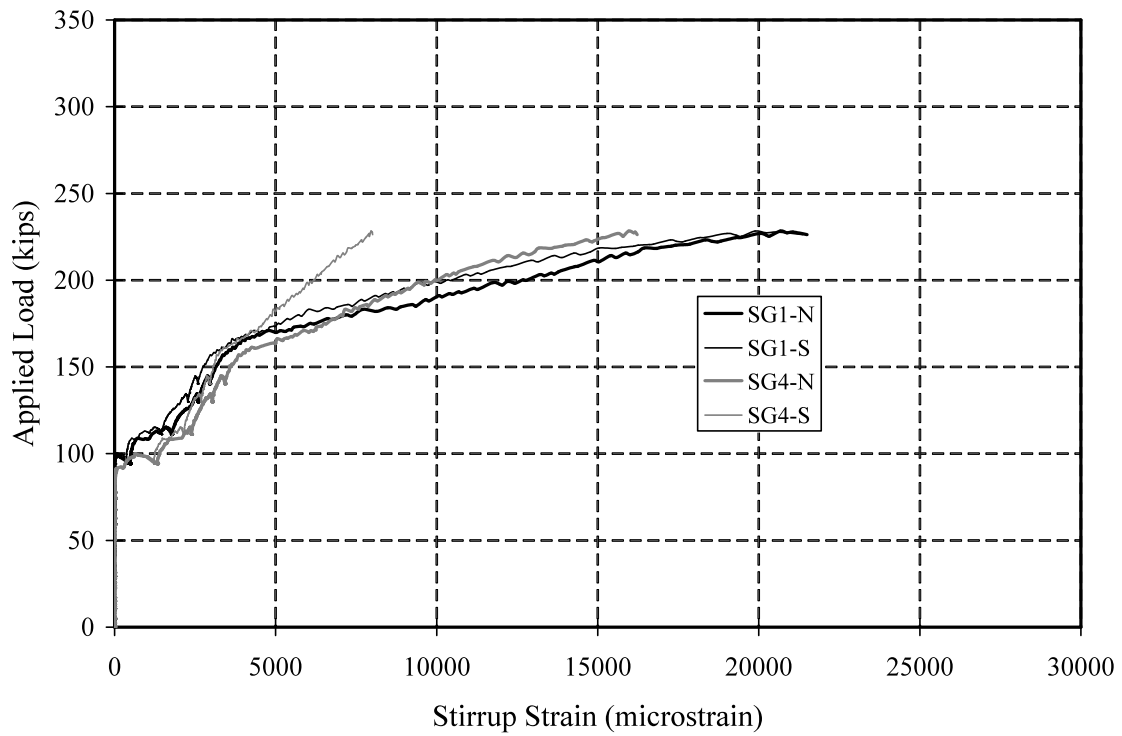


(a) Load vs. Average Stirrup Strain (All Locations)

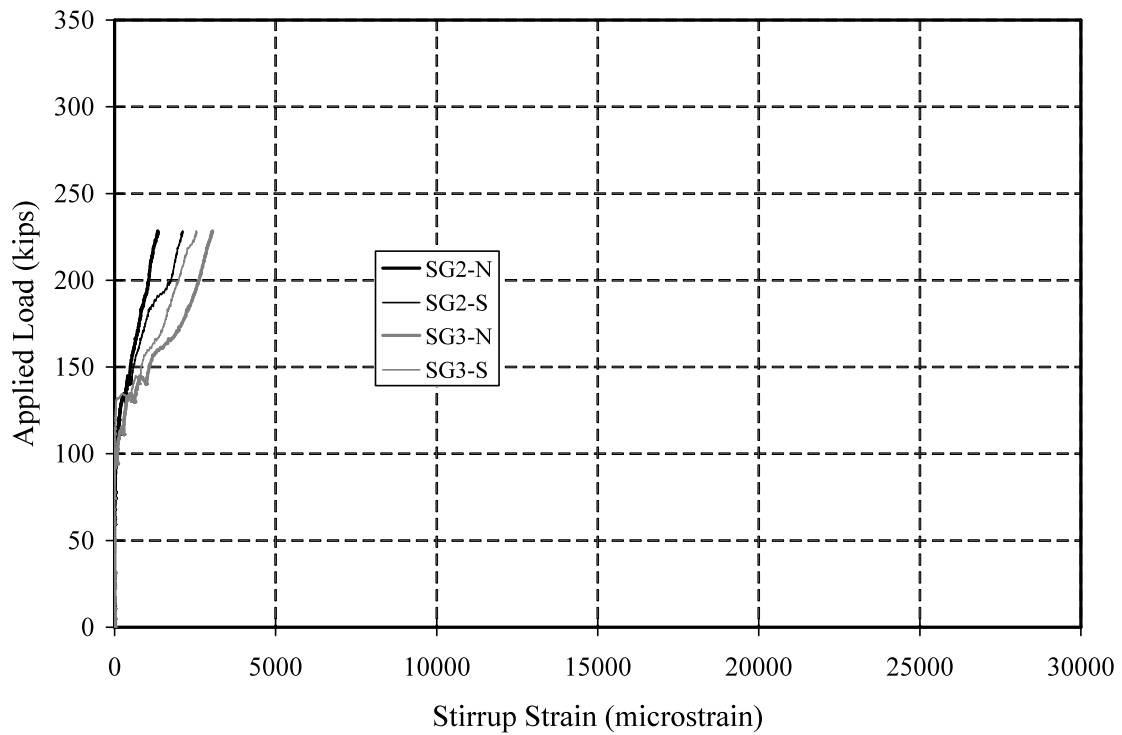


(b) Load vs. Average Longitudinal Strain (All Locations)

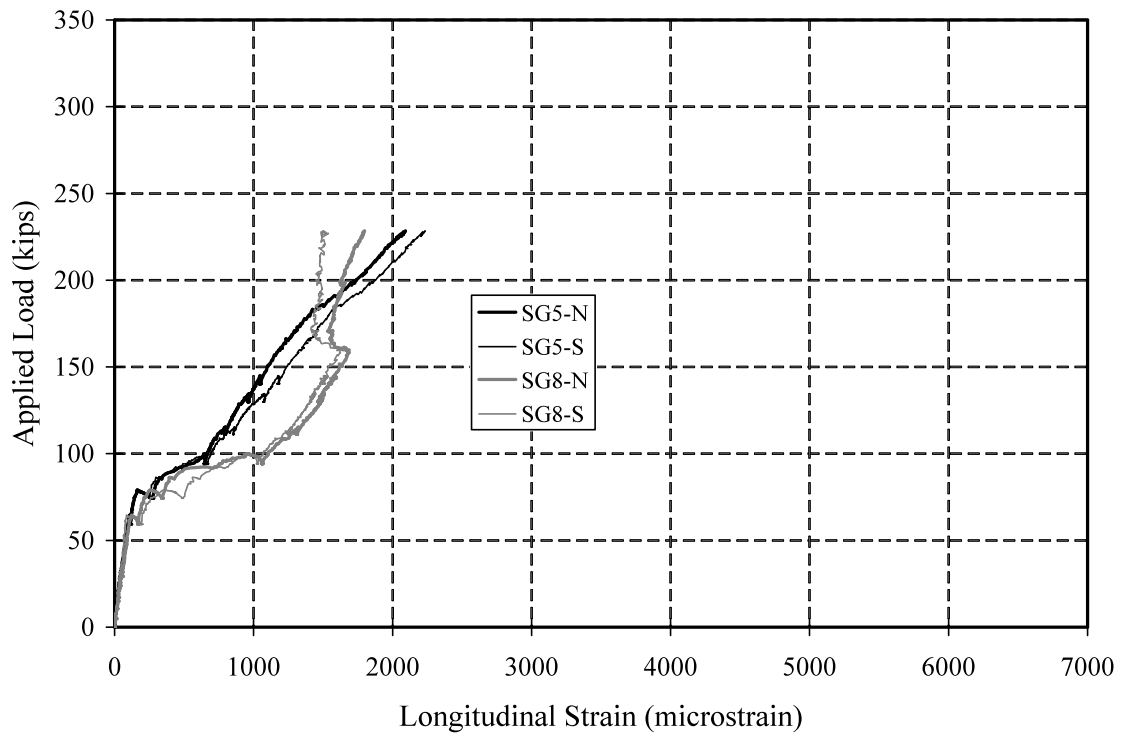
Figure F56 Strain Gage Data for SR2



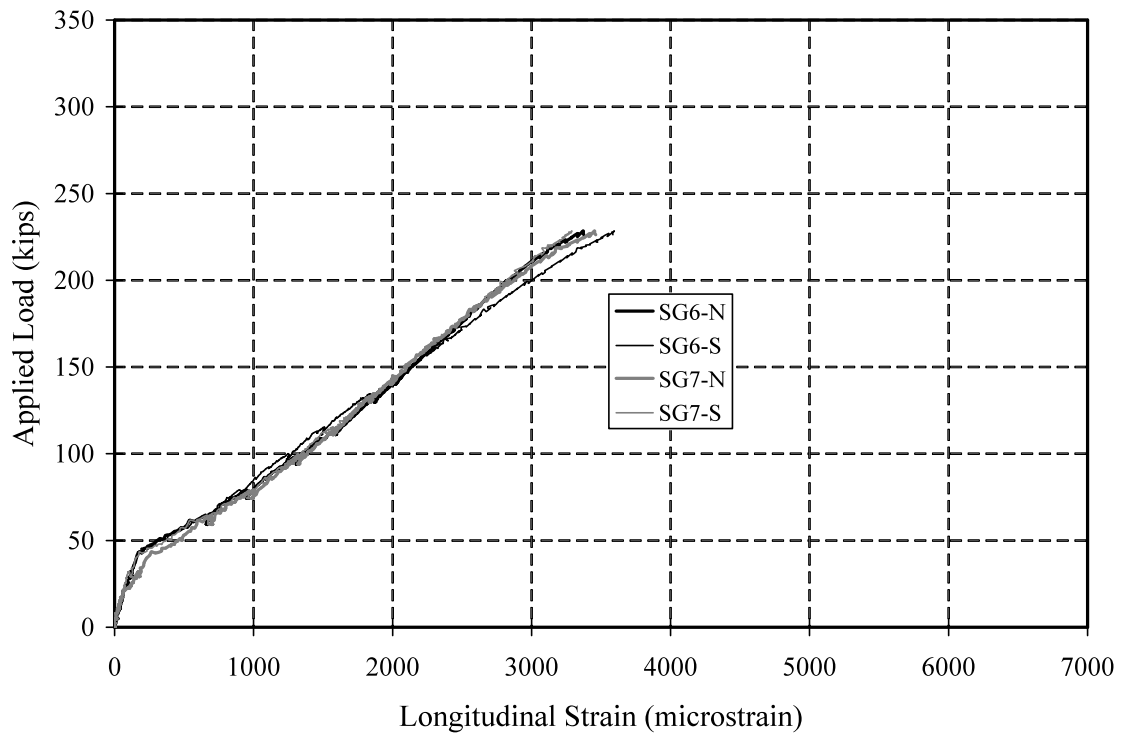
(c) Load vs. Stirrup Strain (Near Supports)



(d) Load vs. Stirrup Strain (Near Load Point)
Figure F56 (cont.) Strain Gage Data for SR2

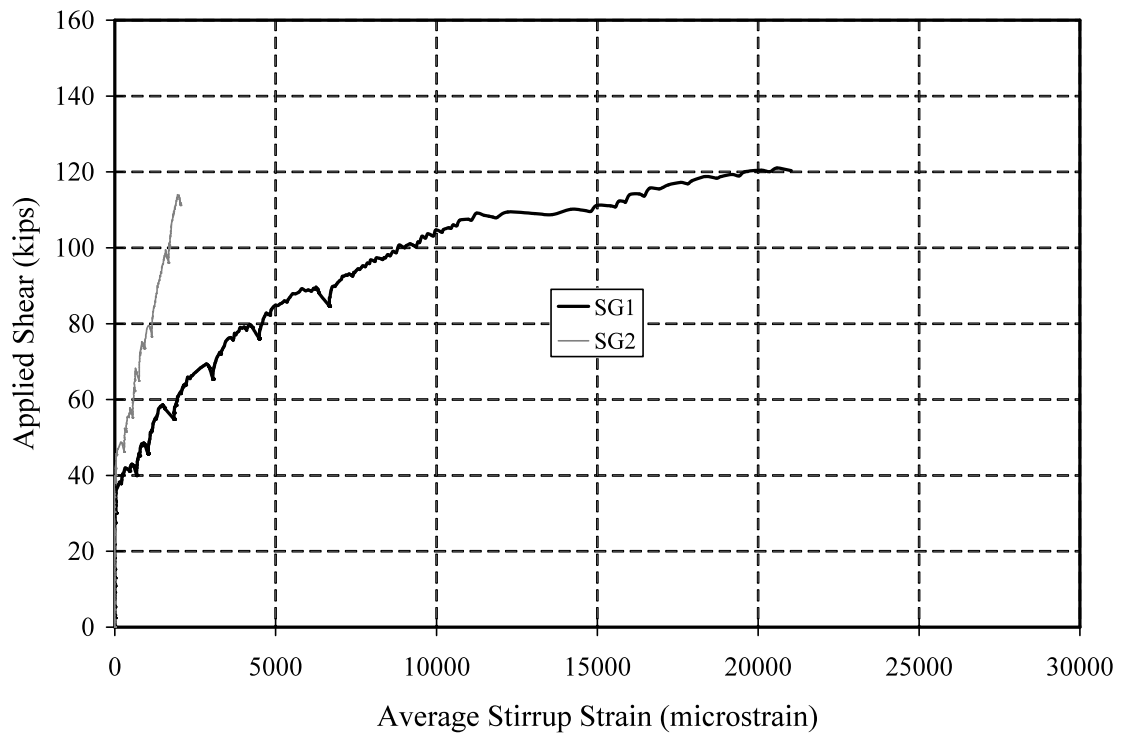


(e) Load vs. Longitudinal Strain (Near Supports)

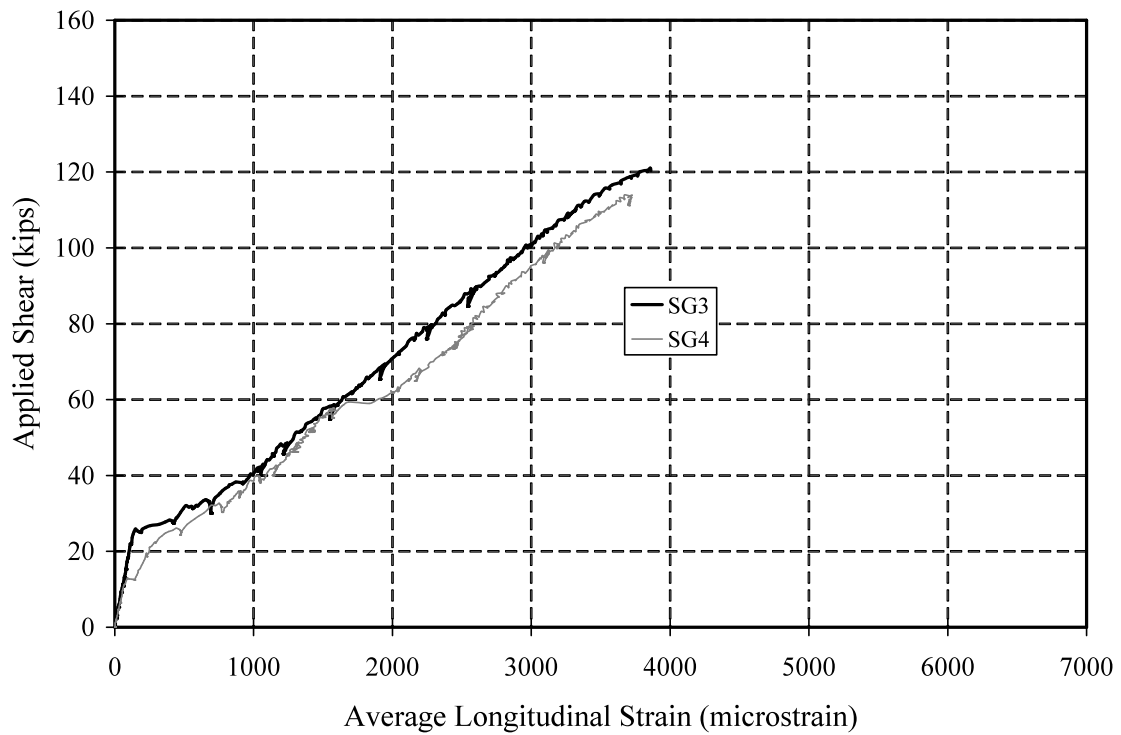


(f) Load vs. Longitudinal Strain (Near Load Point)

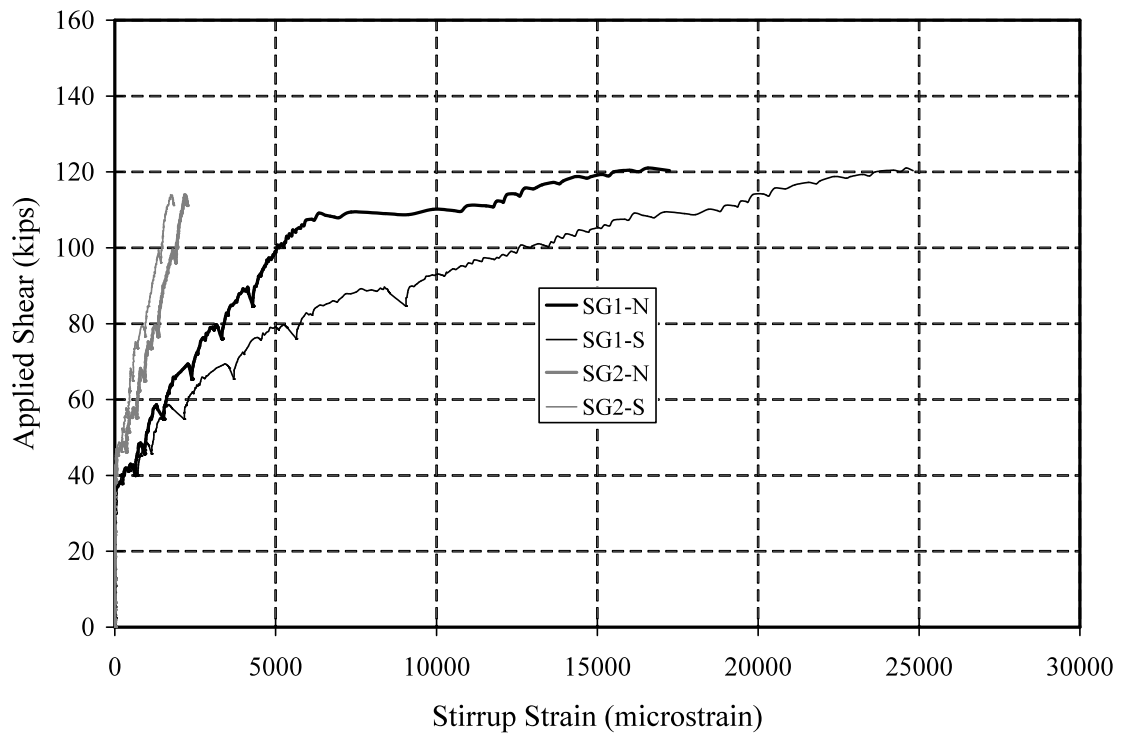
Figure F56 (cont.) Strain Gage Data for SR2



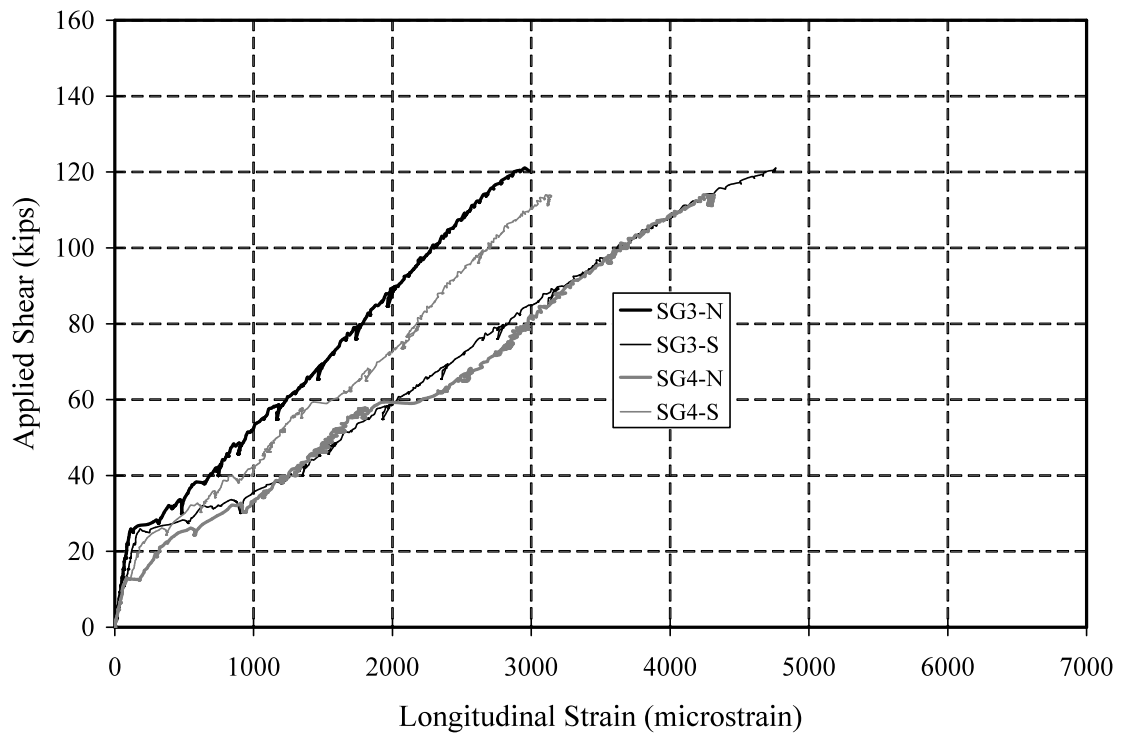
(a) Load vs. Average Stirrup Strain



(b) Load vs. Average Longitudinal Strain
Figure F57 Strain Gage Data for SR3

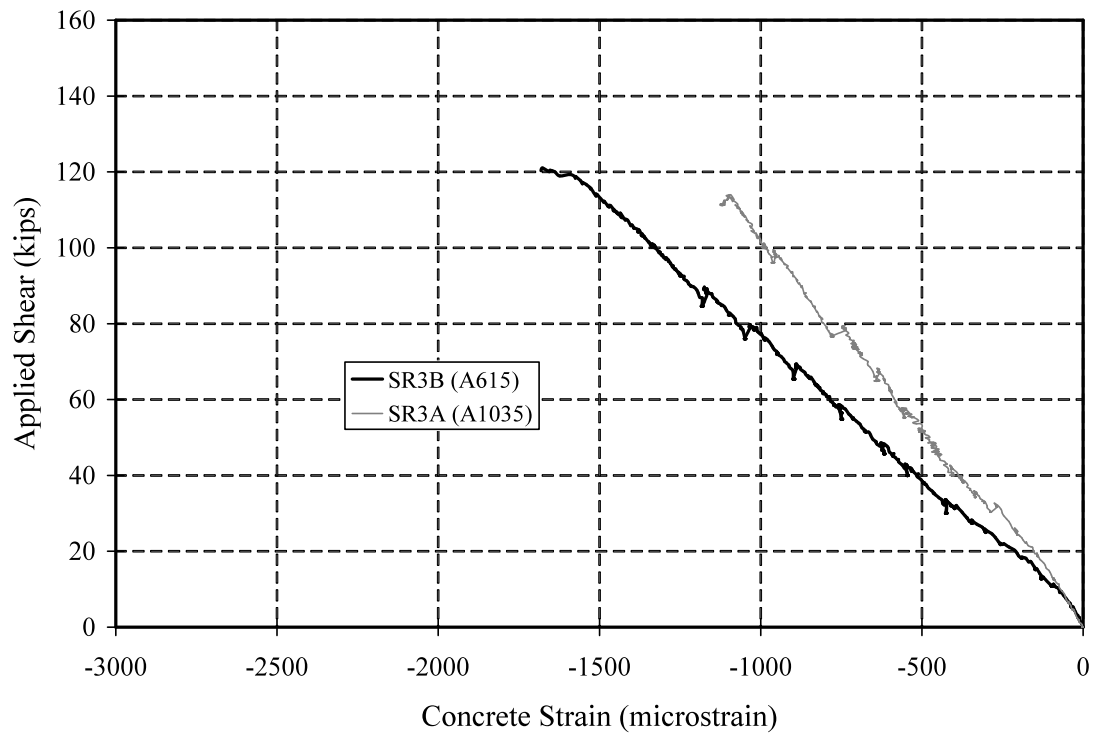


(c) Load vs. Stirrup Strain

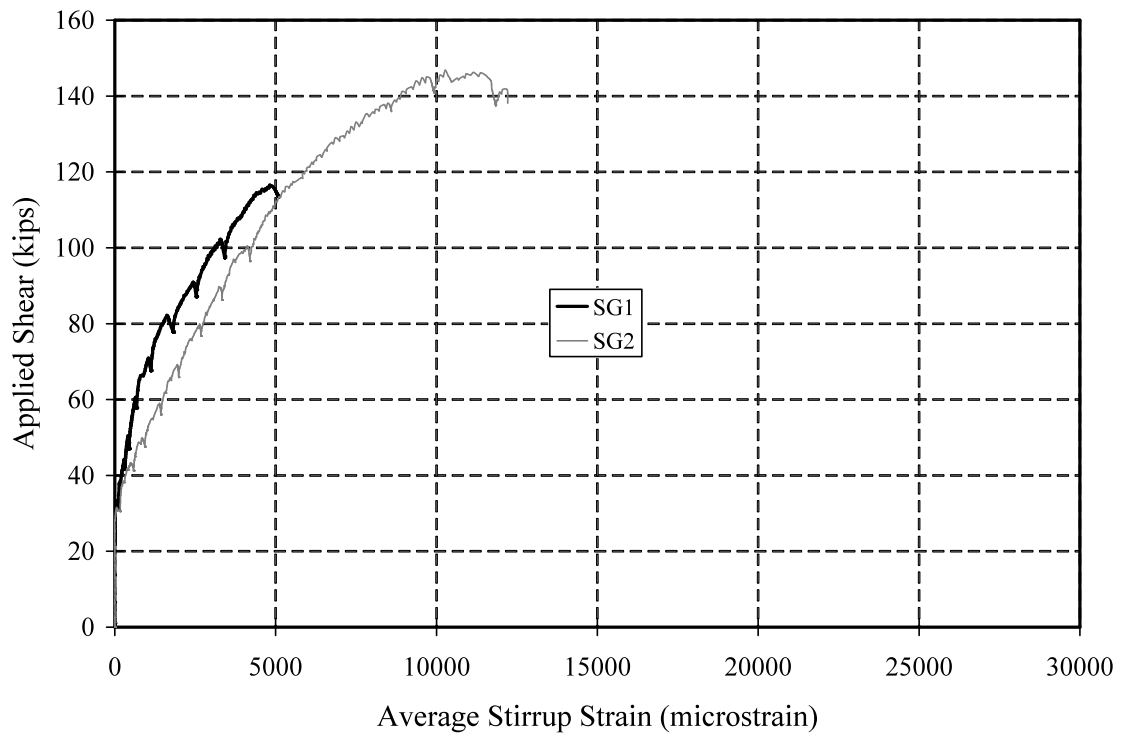


(d) Load vs. Longitudinal Strain

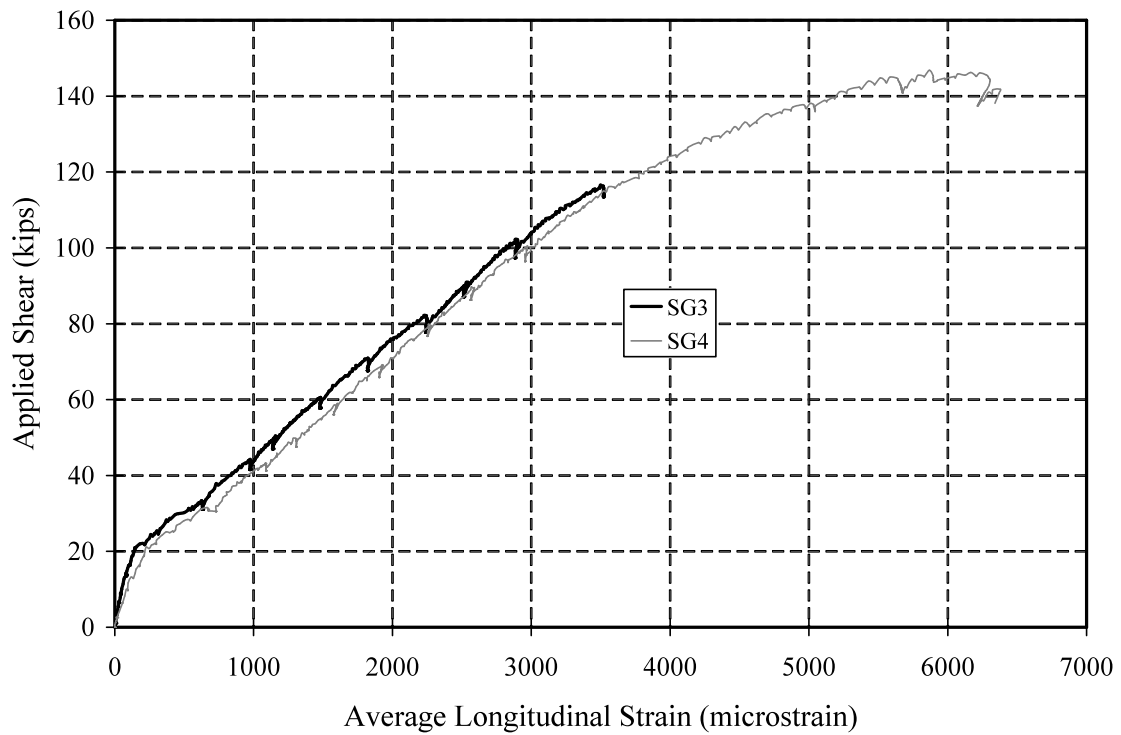
Figure F57 (cont.) Strain Gage Data for SR3



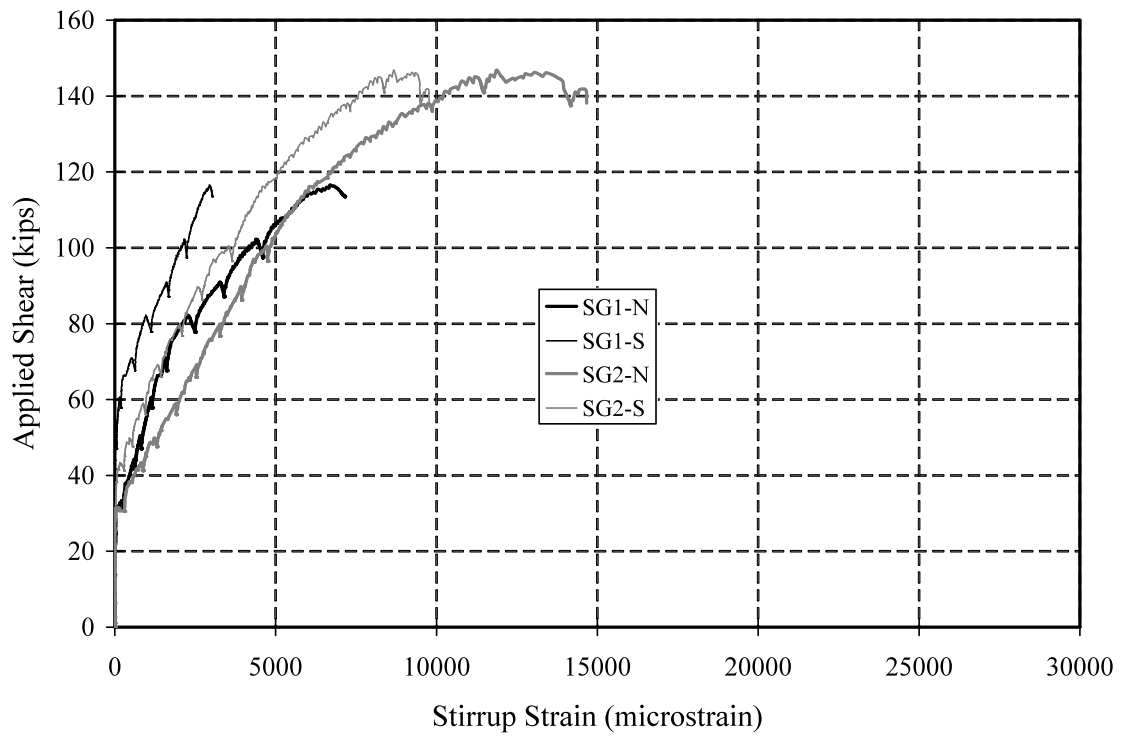
(e) Load vs. Concrete Strain
Figure F57 (cont.) Strain Gage Data for SR3



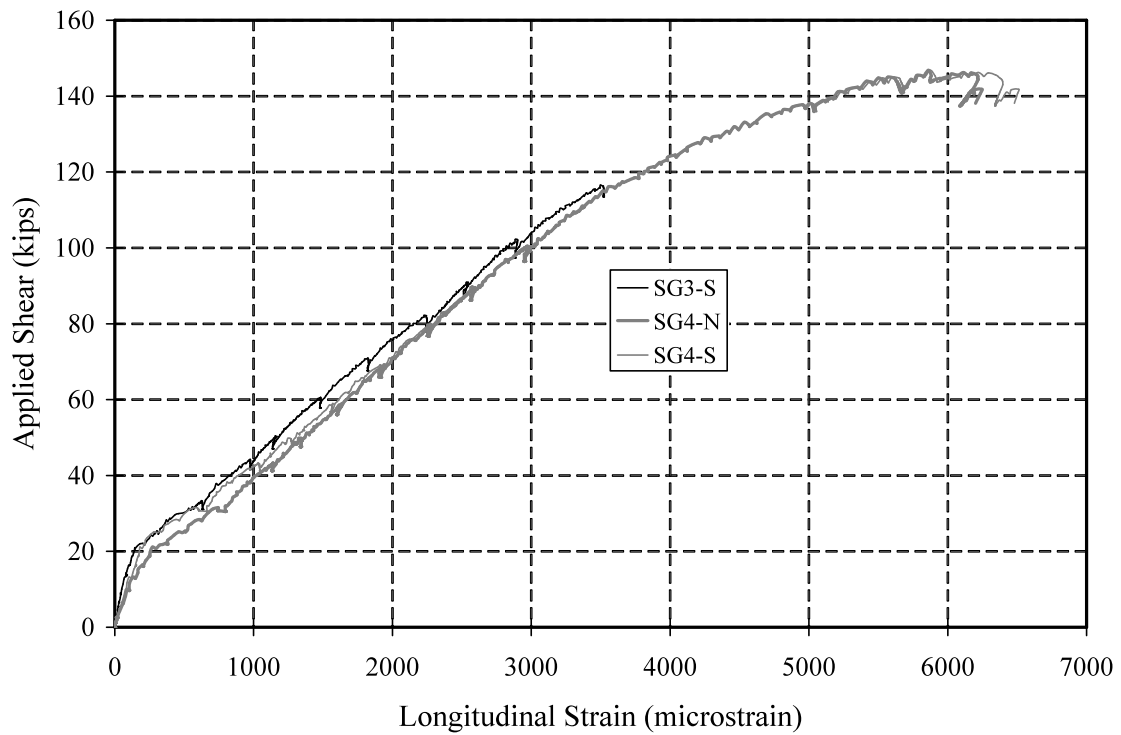
(a) Load vs. Average Stirrup Strain



(b) Load vs. Average Longitudinal Strain
Figure F58 Strain Gage Data for SR4

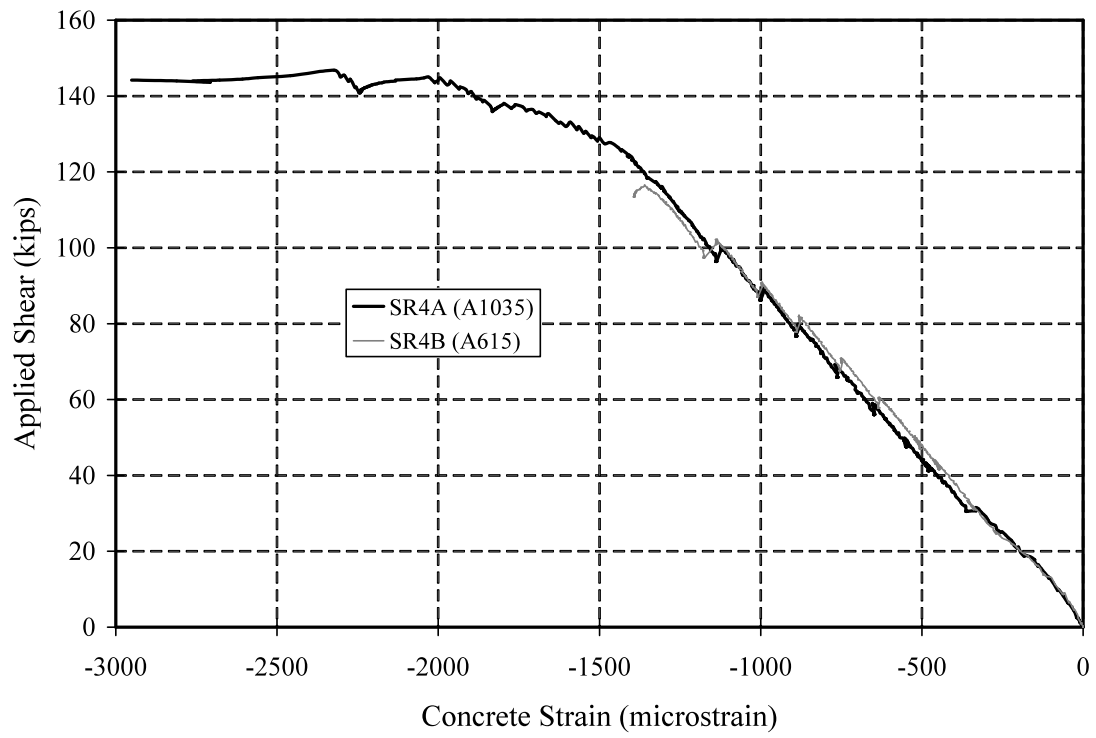


(c) Load vs. Stirrup Strain

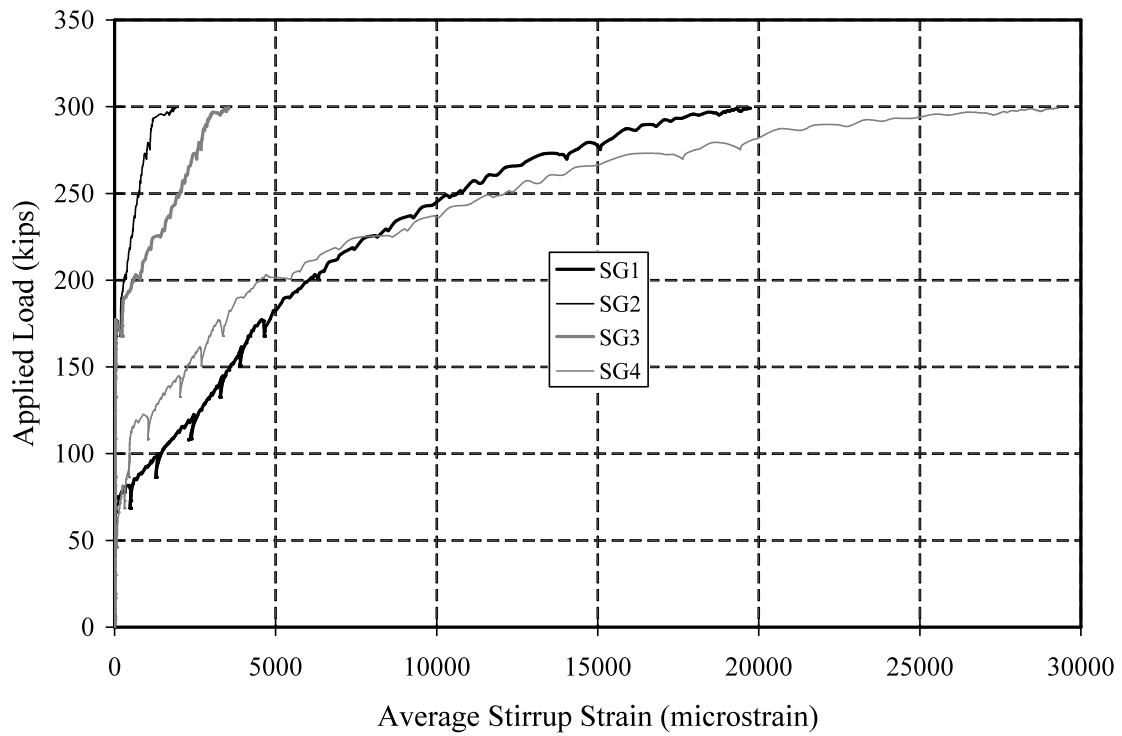


(d) Load vs. Longitudinal Strain

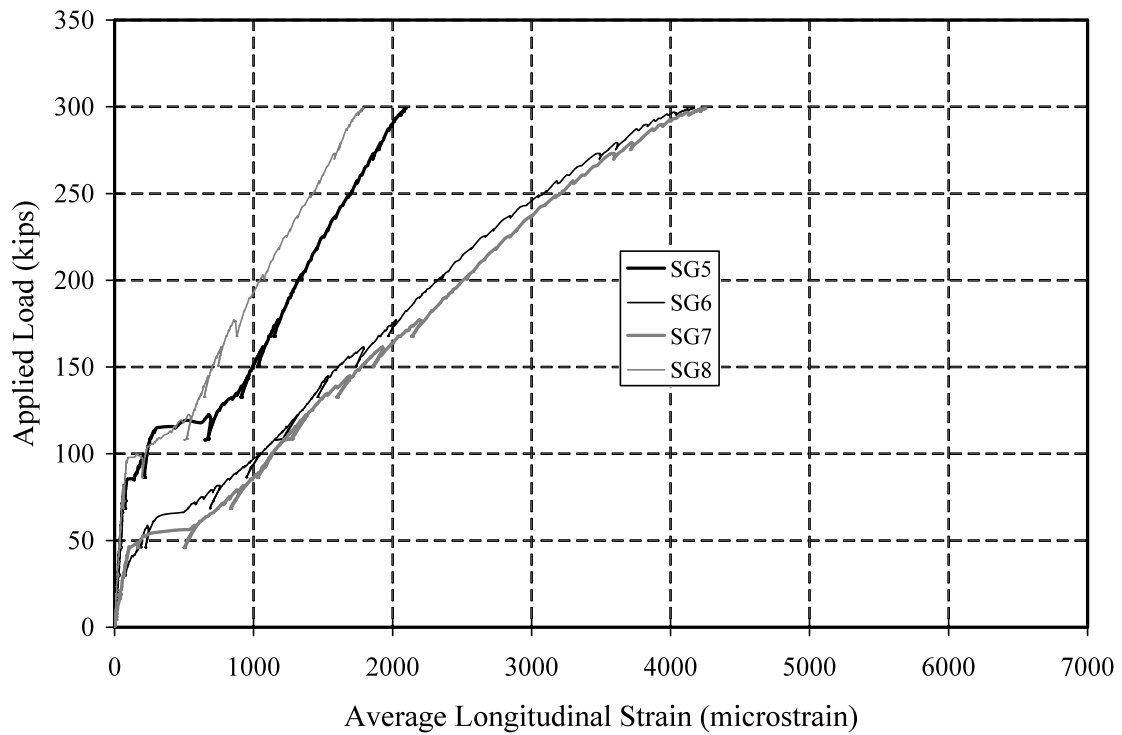
Figure F58 (cont.) Strain Gage Data for SR4



(e) Load vs. Concrete Strain
Figure F58 (cont.) Strain Gage Data for SR4

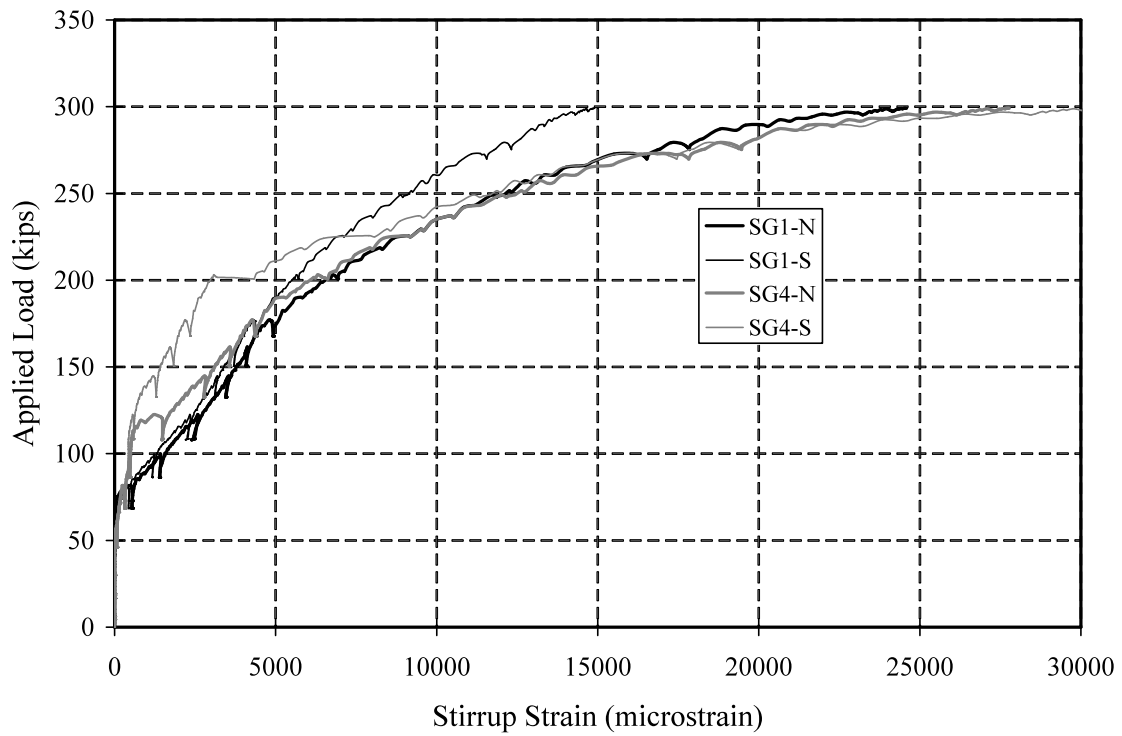


(a) Load vs. Average Stirrup Strain (All Locations)

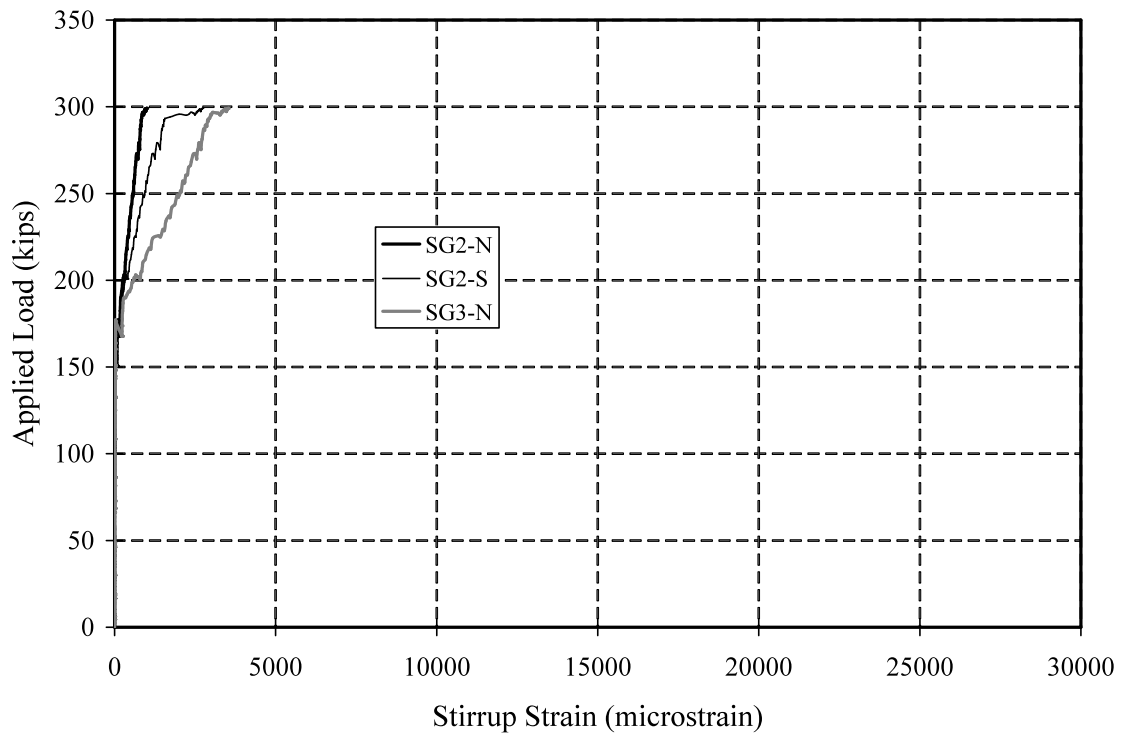


(b) Load vs. Average Longitudinal Strain (All Locations)

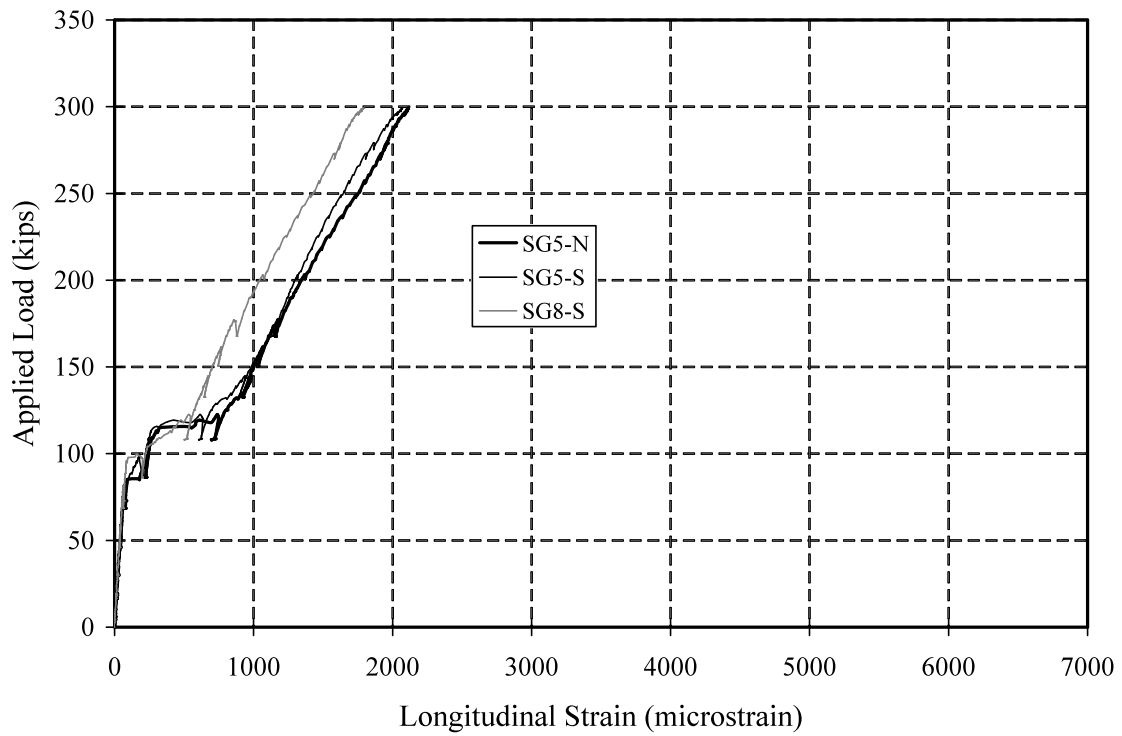
Figure F59 Strain Gage Data for SR5



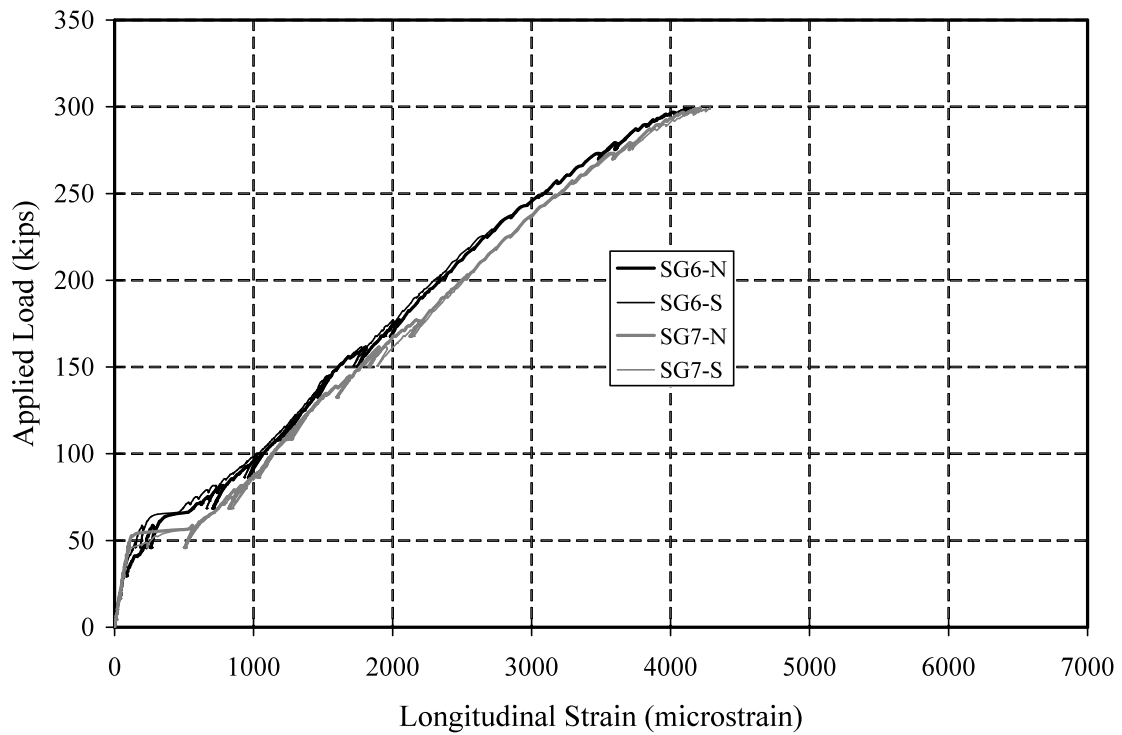
(c) Load vs. Stirrup Strain (Near Supports)



(d) Load vs. Stirrup Strain (Near Load Point)
Figure F59 (cont.) Strain Gage Data for SR5

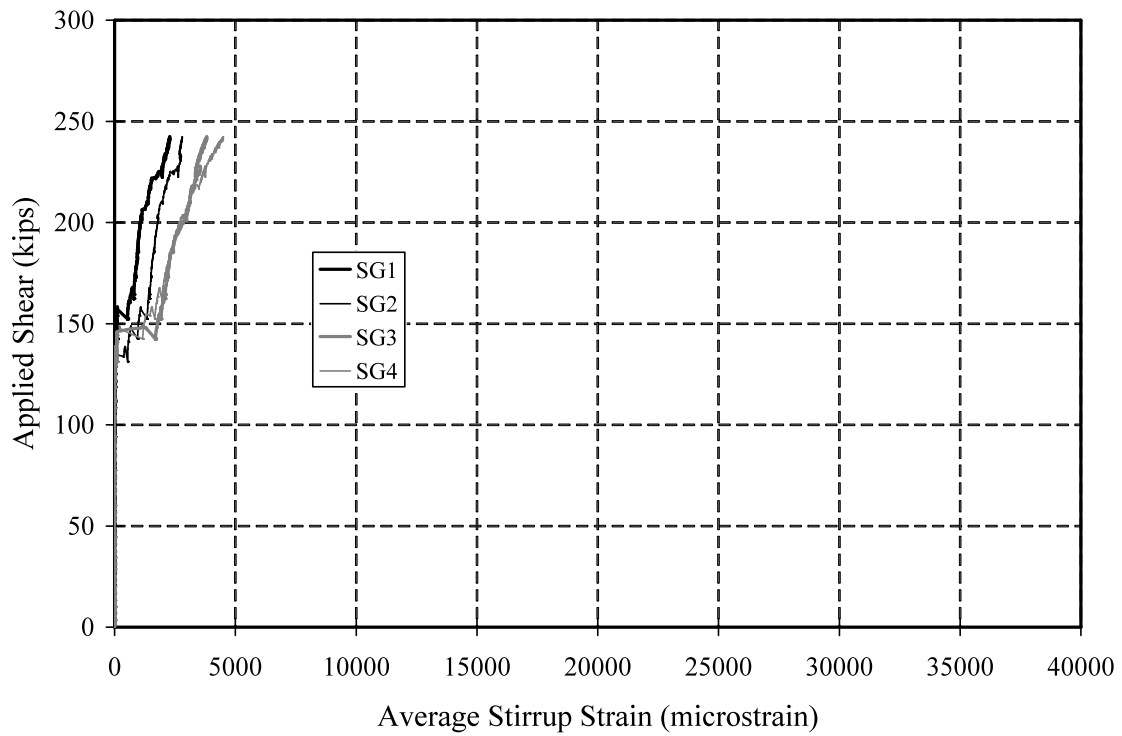


(e) Load vs. Longitudinal Strain (Near Supports)

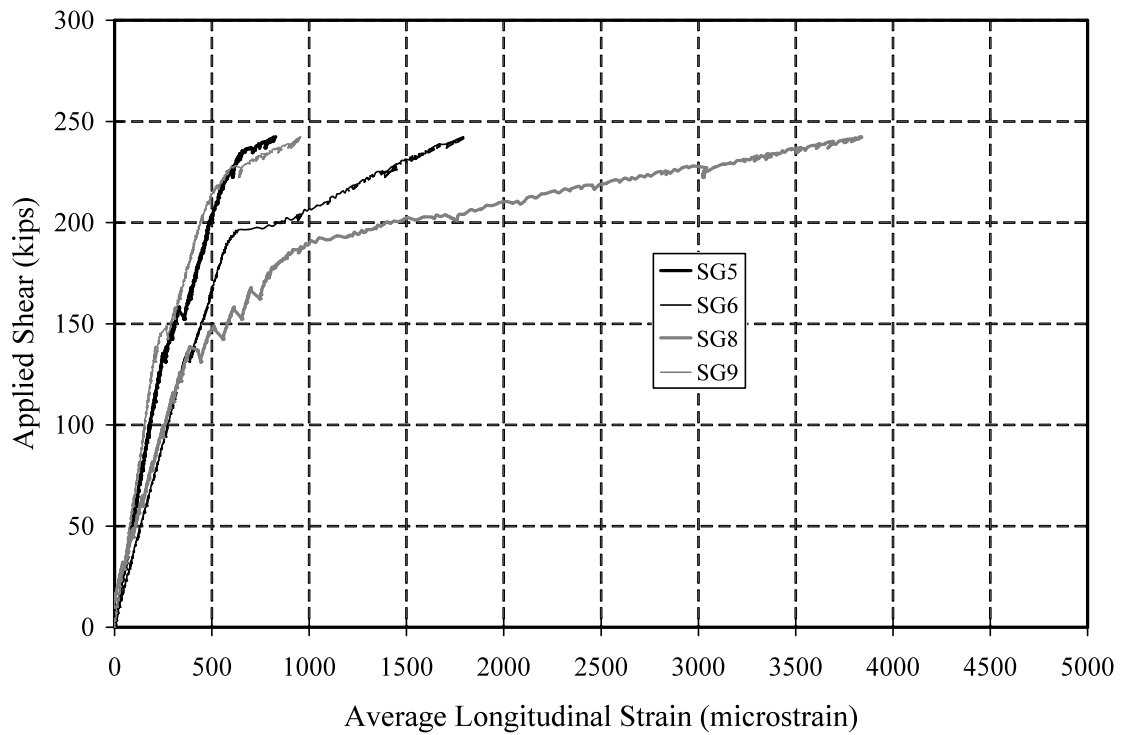


(f) Load vs. Longitudinal Strain (Near Load Point)

Figure F59 (cont.) Strain Gage Data for SR5

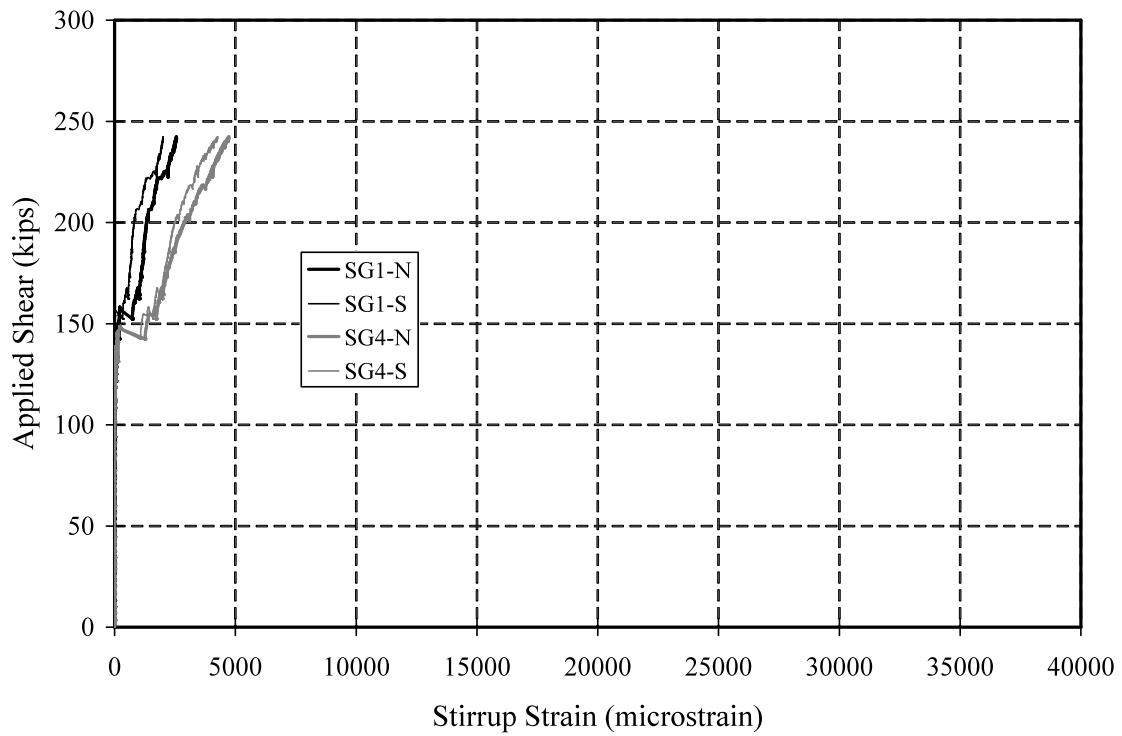


(a) Load vs. Average Stirrup Strain (All Locations)

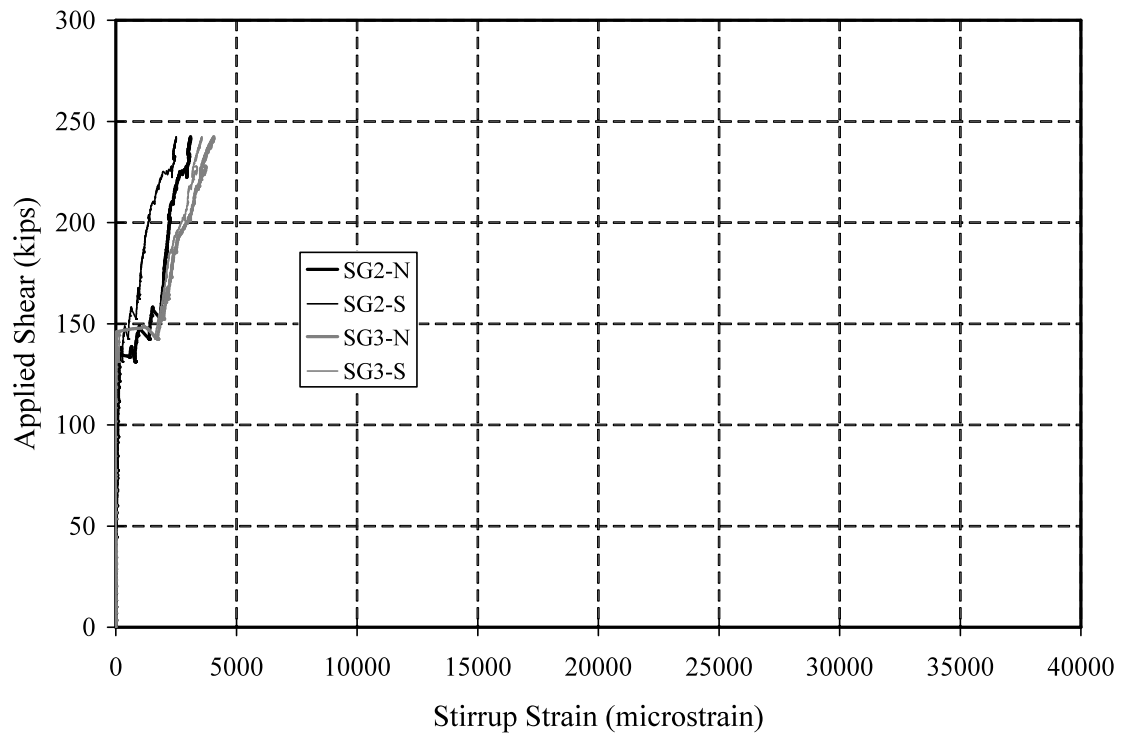


(b) Load vs. Average Longitudinal Strain (All Locations)

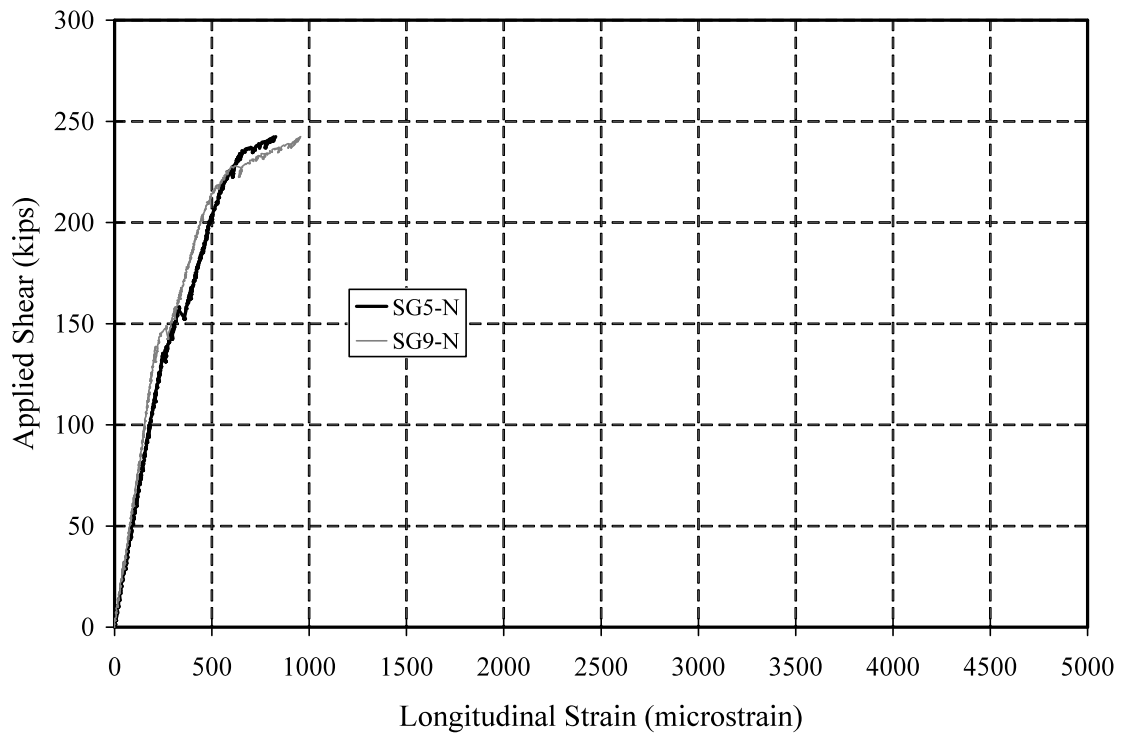
Figure F60 Strain Gage Data for SP1



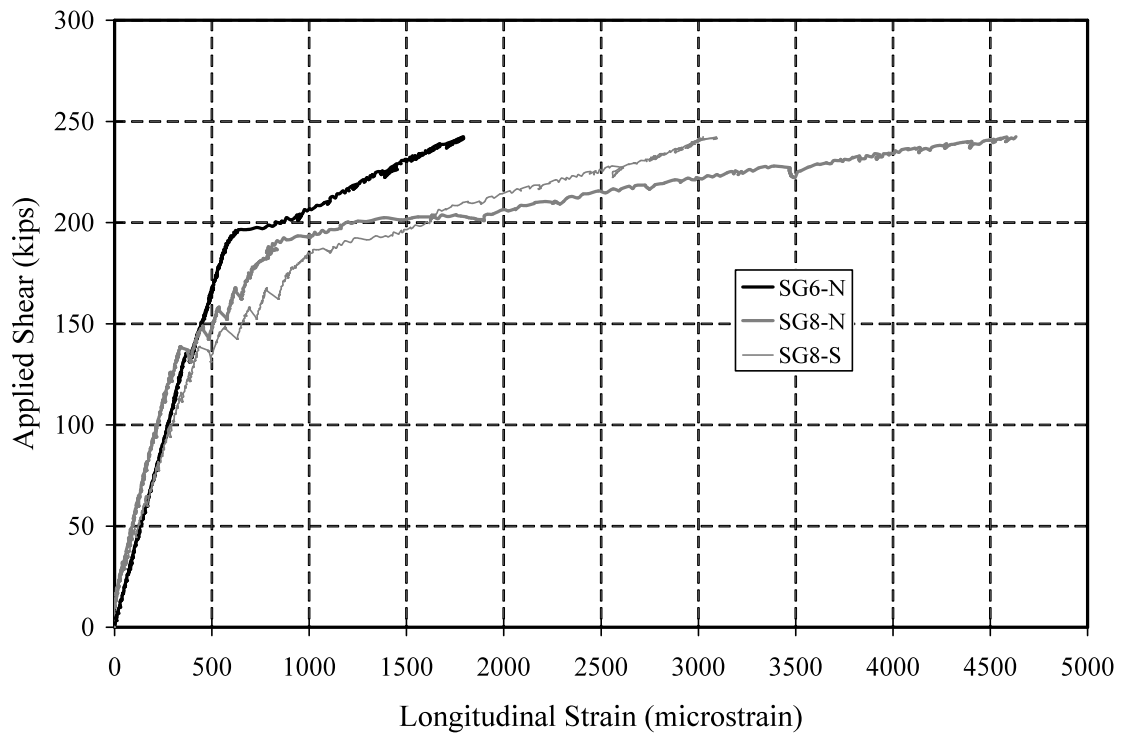
(c) Load vs. Stirrup Strain (Near Supports)



(d) Load vs. Stirrup Strain (Near Load Points)
Figure F60 (cont.) Strain Gage Data for SP1

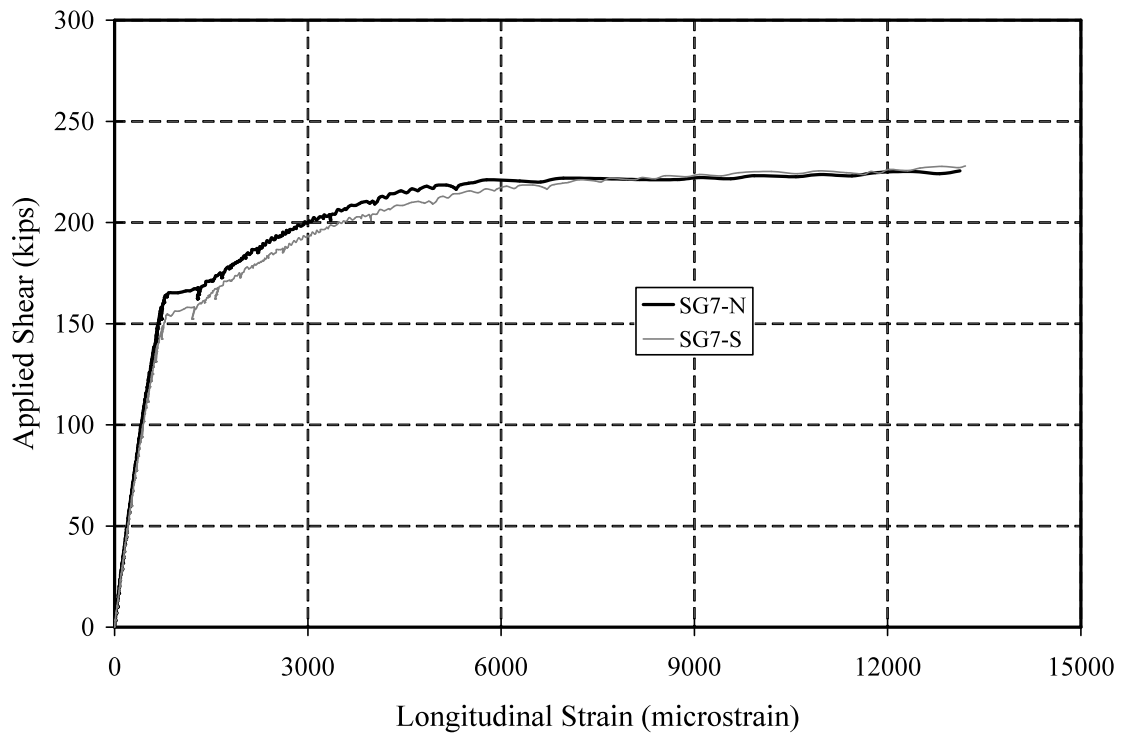


(e) Load vs. Longitudinal Strain (Near Supports)

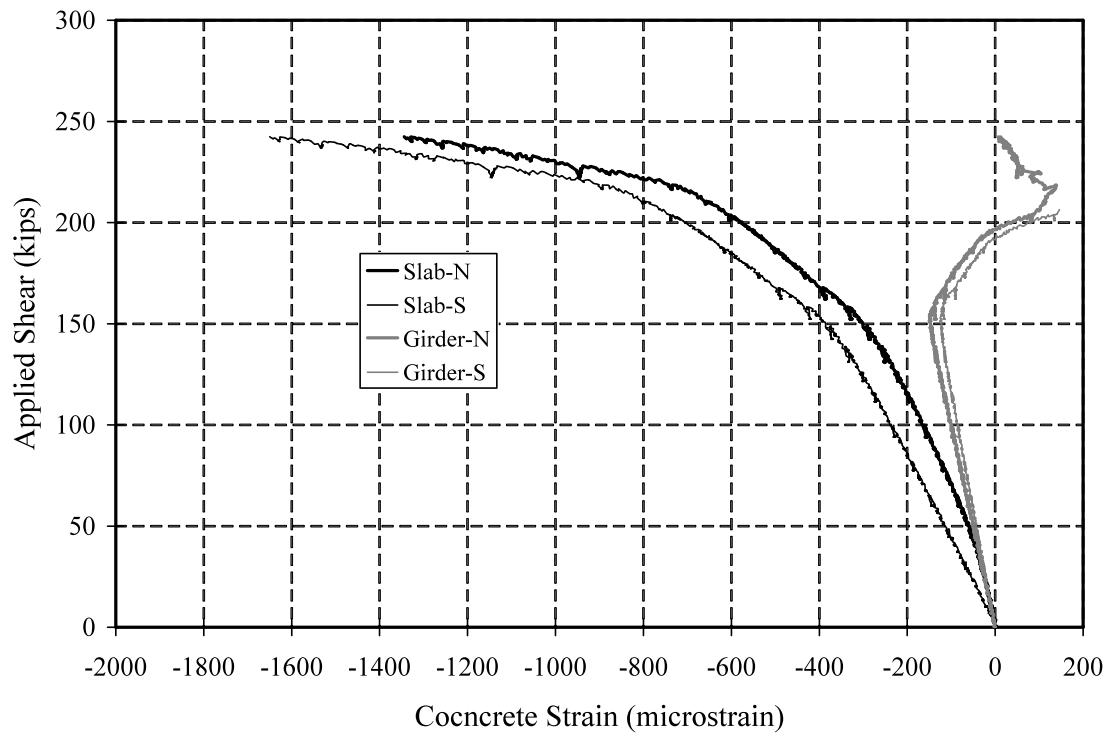


(f) Load vs. Longitudinal Strain (Near Load Points)

Figure F60 (cont.) Strain Gage Data for SP1

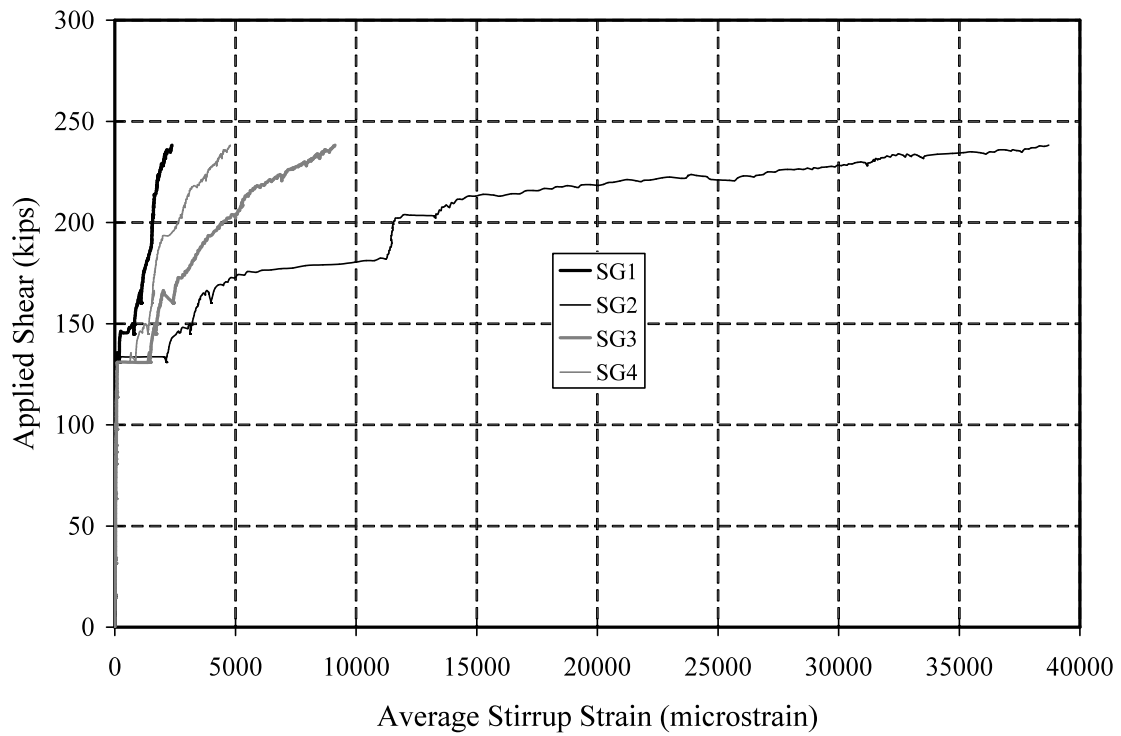


(g) Load vs. Longitudinal Strain (Mid-Span)

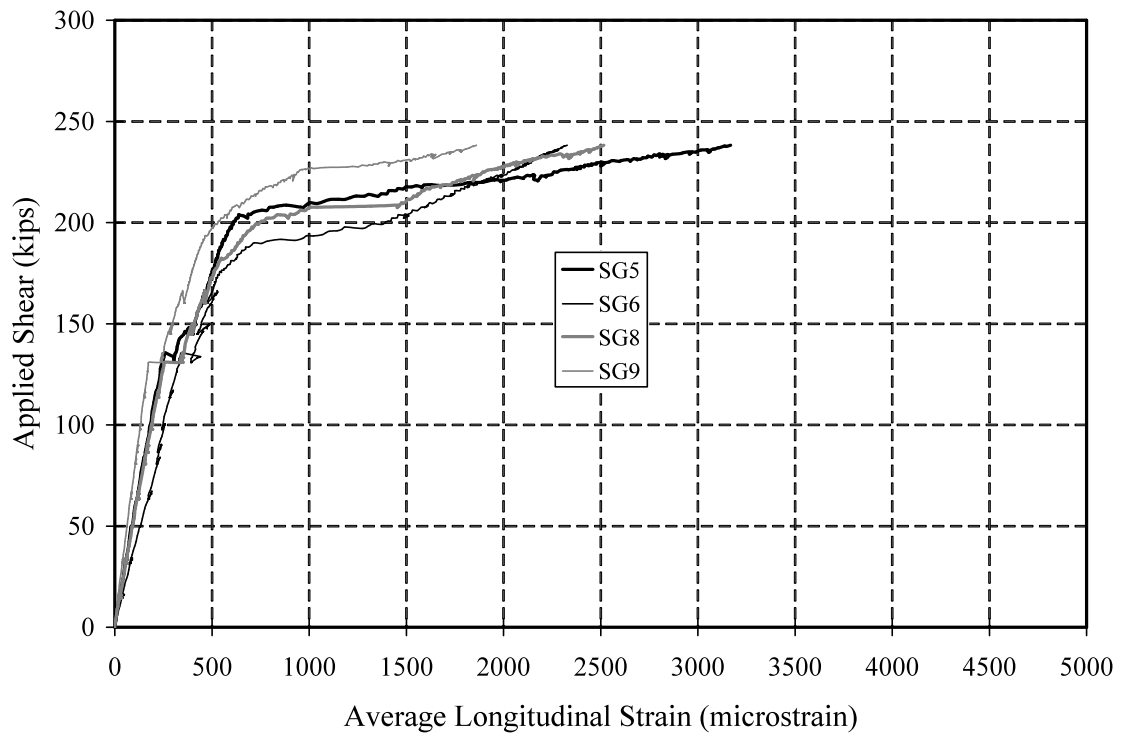


(h) Load vs. Concrete Strain

Figure F60 (cont.) Strain Gage Data for SP1

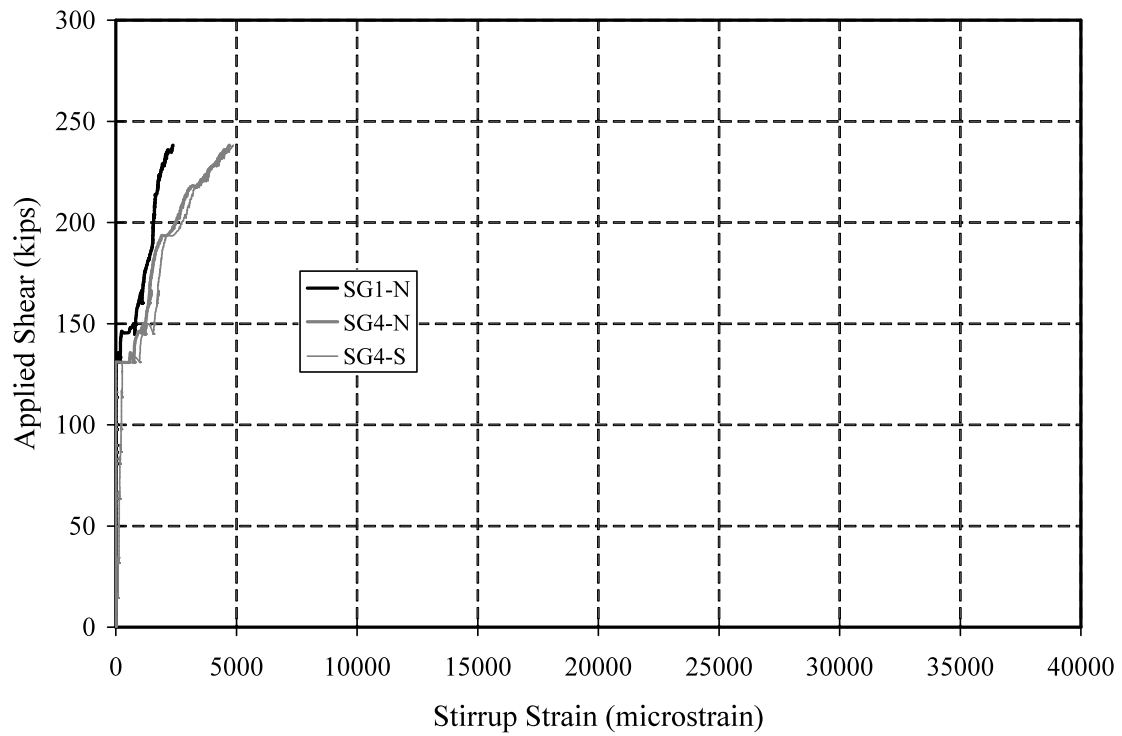


(a) Load vs. Average Stirrup Strain (All Locations)

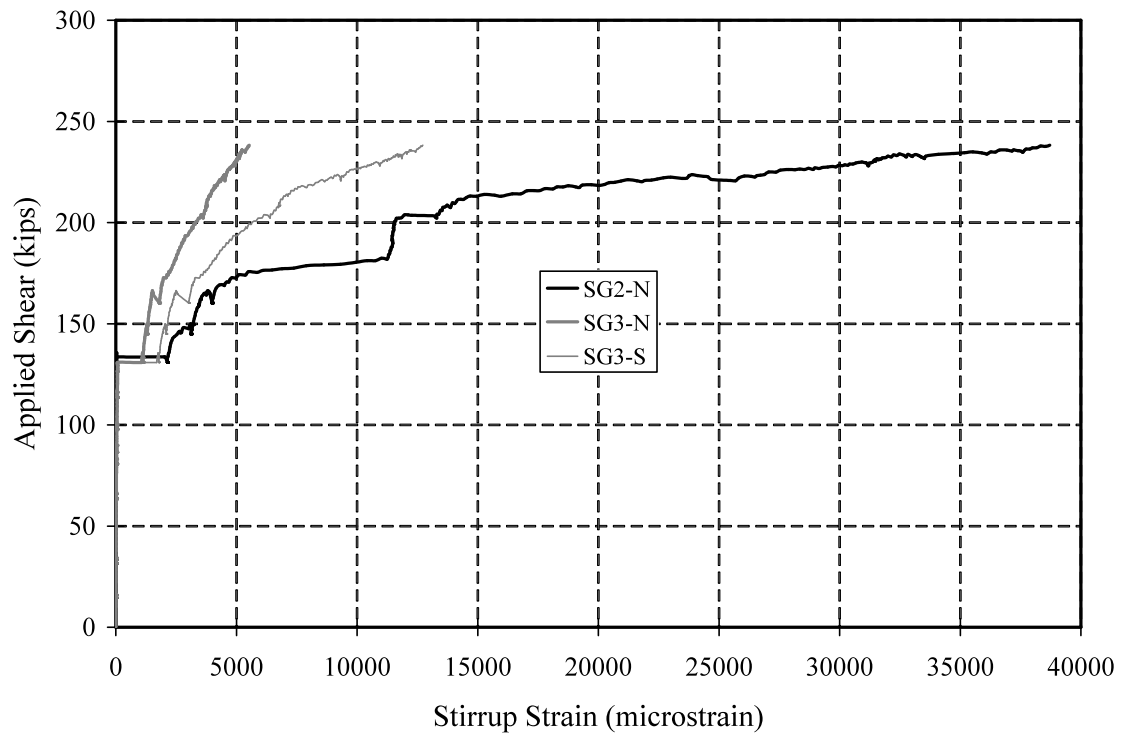


(b) Load vs. Average Longitudinal Strain (All Locations)

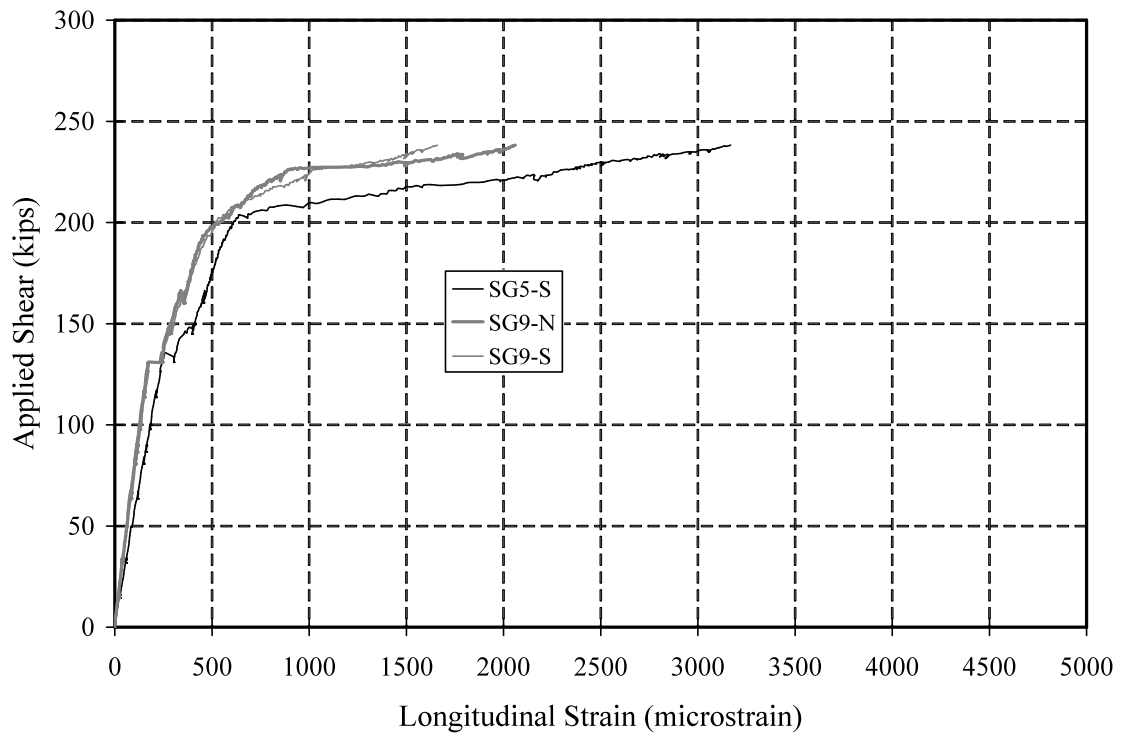
Figure F61 Strain Gage Data for SP2



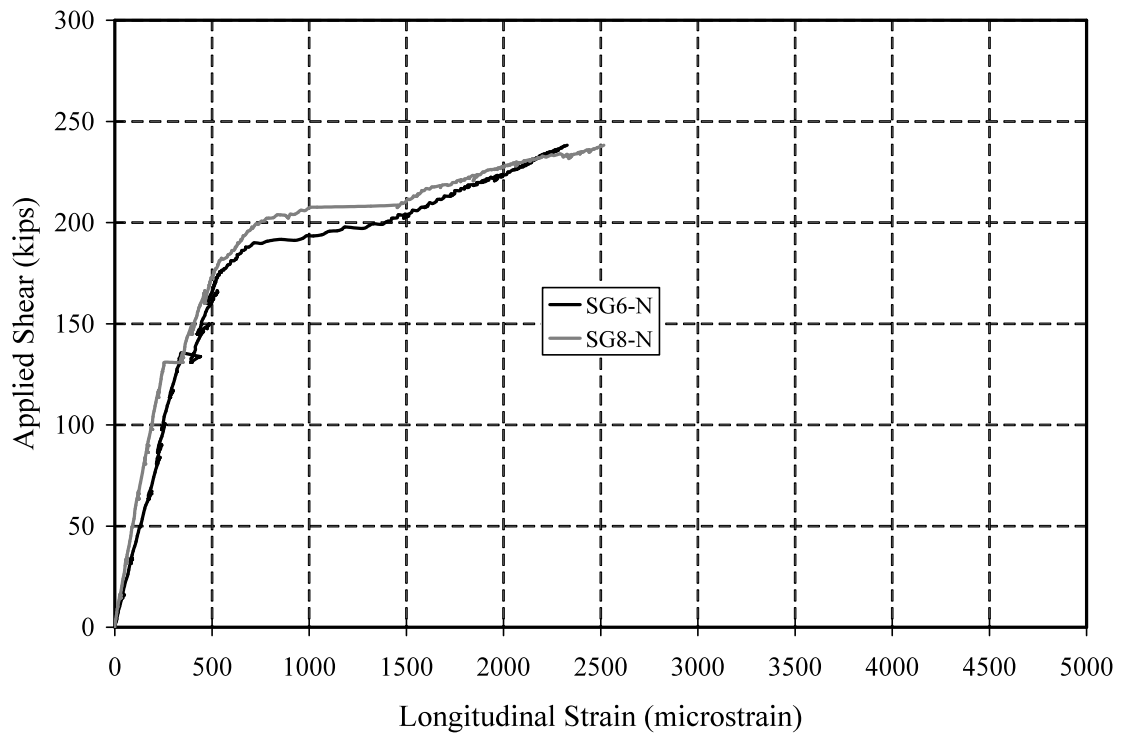
(c) Load vs. Stirrup Strain (Near Supports)



(d) Load vs. Stirrup Strain (Near Load Points)
Figure F61 (cont.) Strain Gage Data for SP2

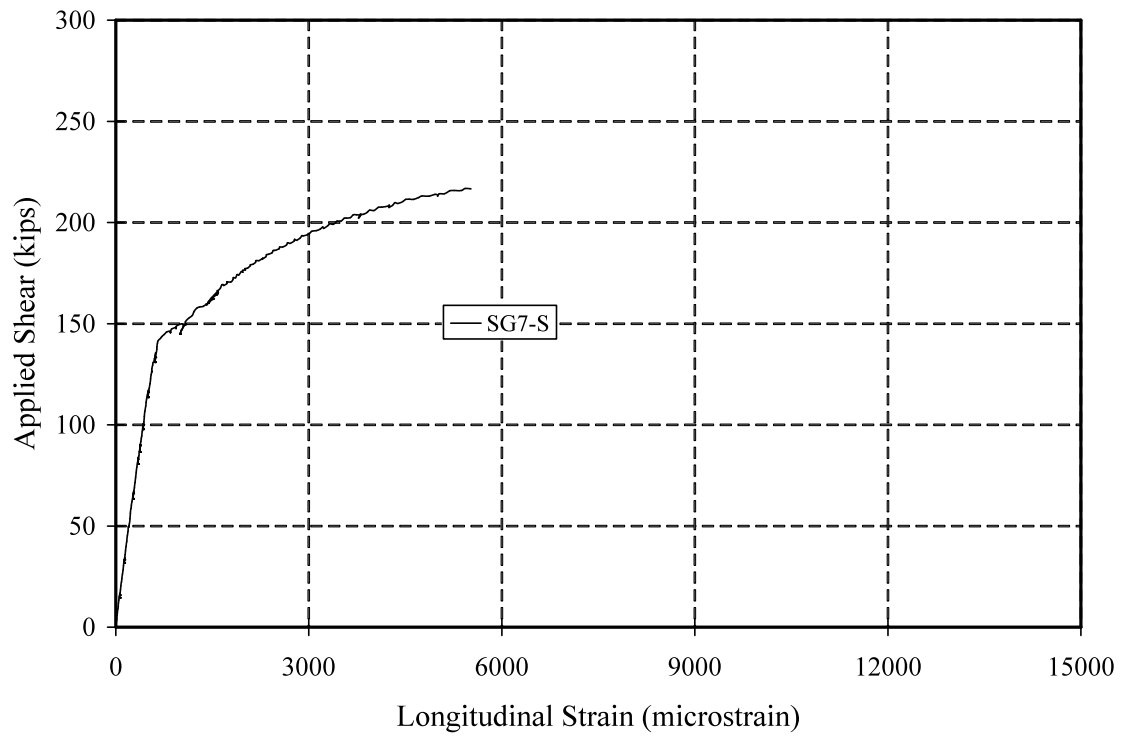


(e) Load vs. Longitudinal Strain (Near Supports)

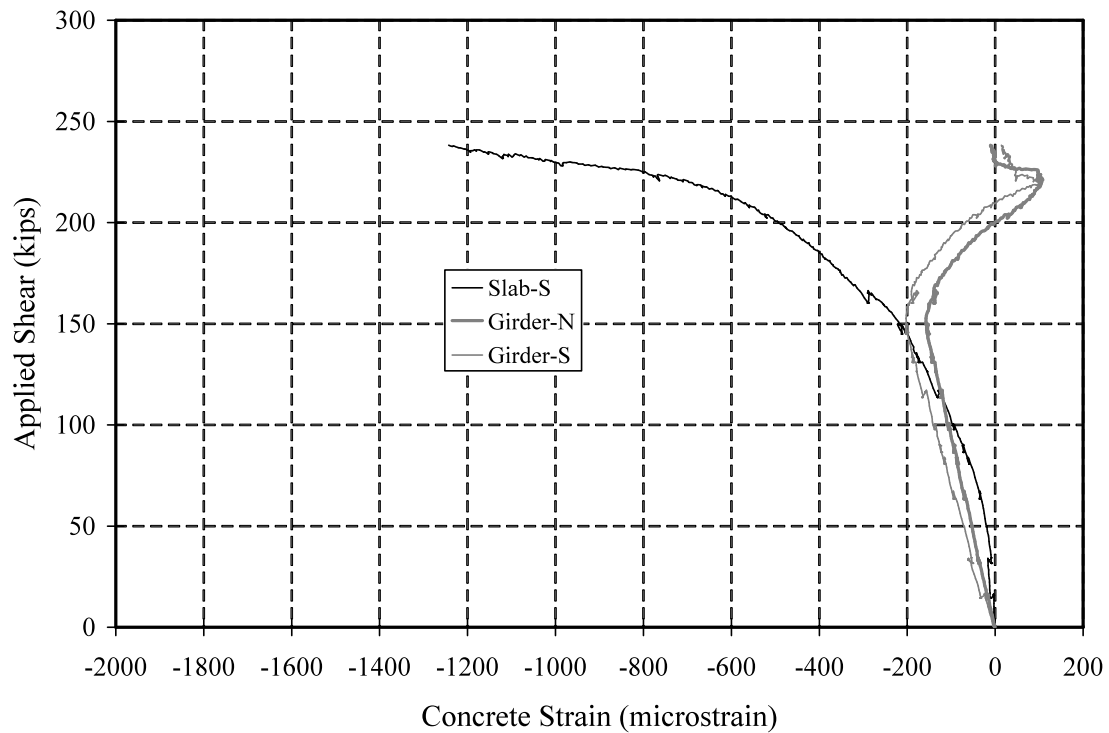


(f) Load vs. Longitudinal Strain (Near Load Points)

Figure F61 (cont.) Strain Gage Data for SP2

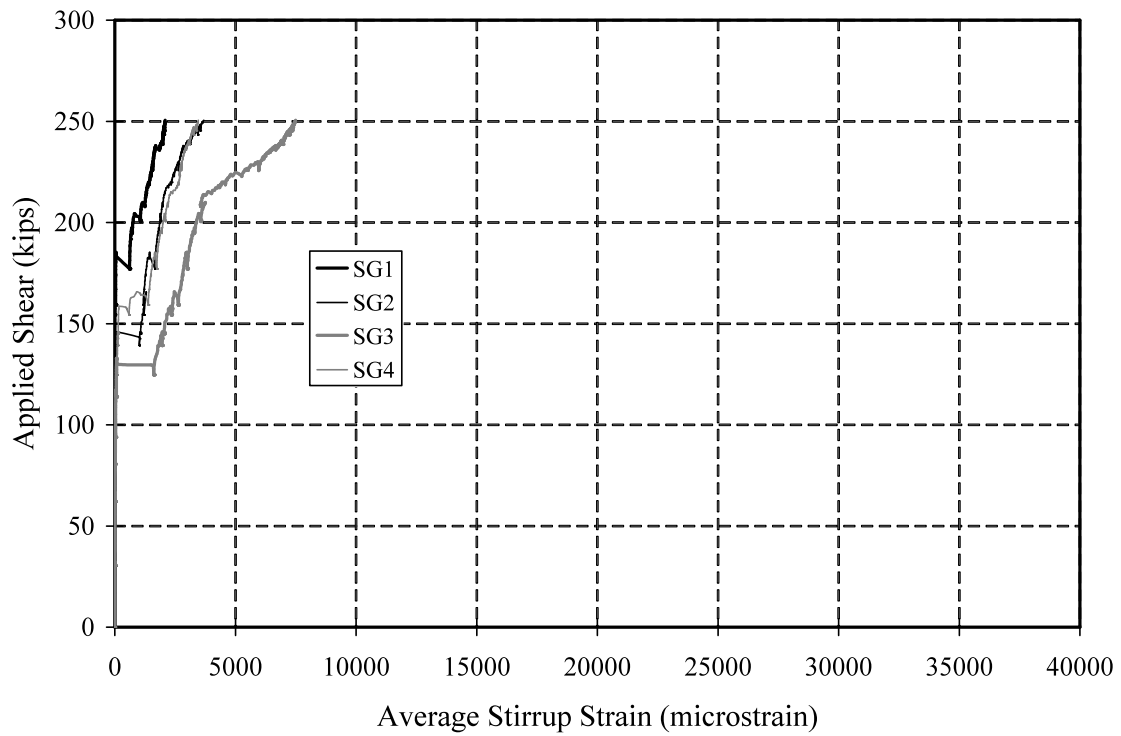


(g) Load vs. Longitudinal Strain (Mid-Span)

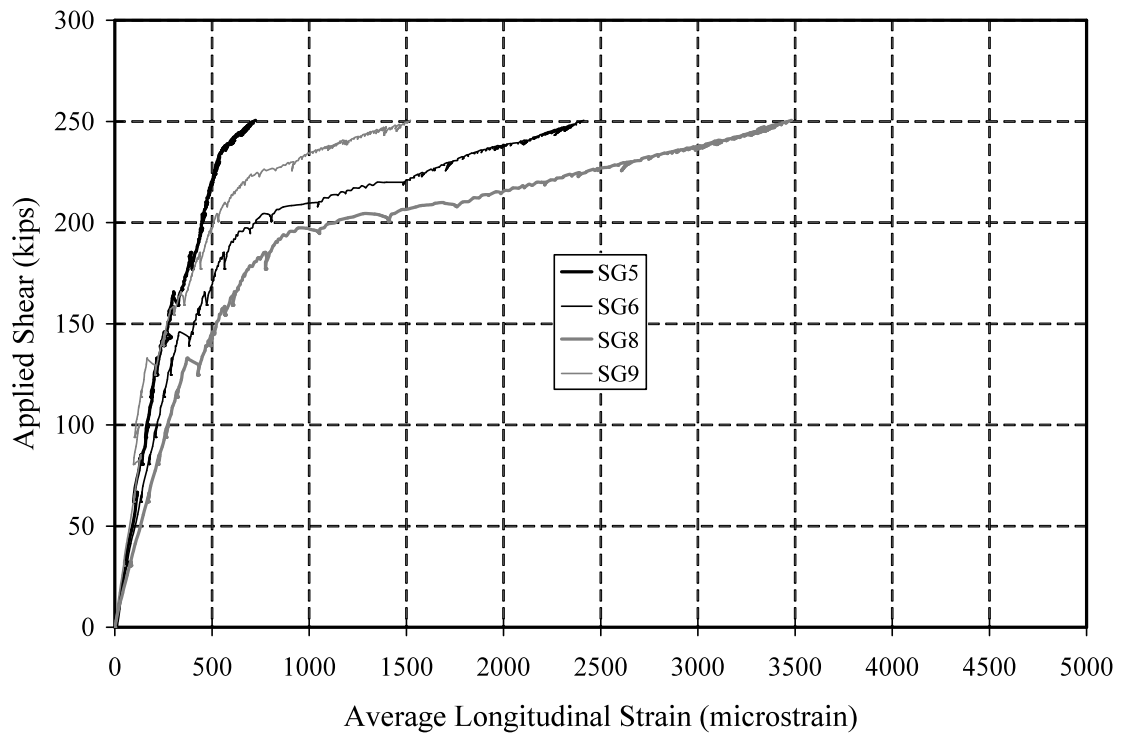


(h) Load vs. Concrete Strain

Figure F61 (cont.) Strain Gage Data for SP2

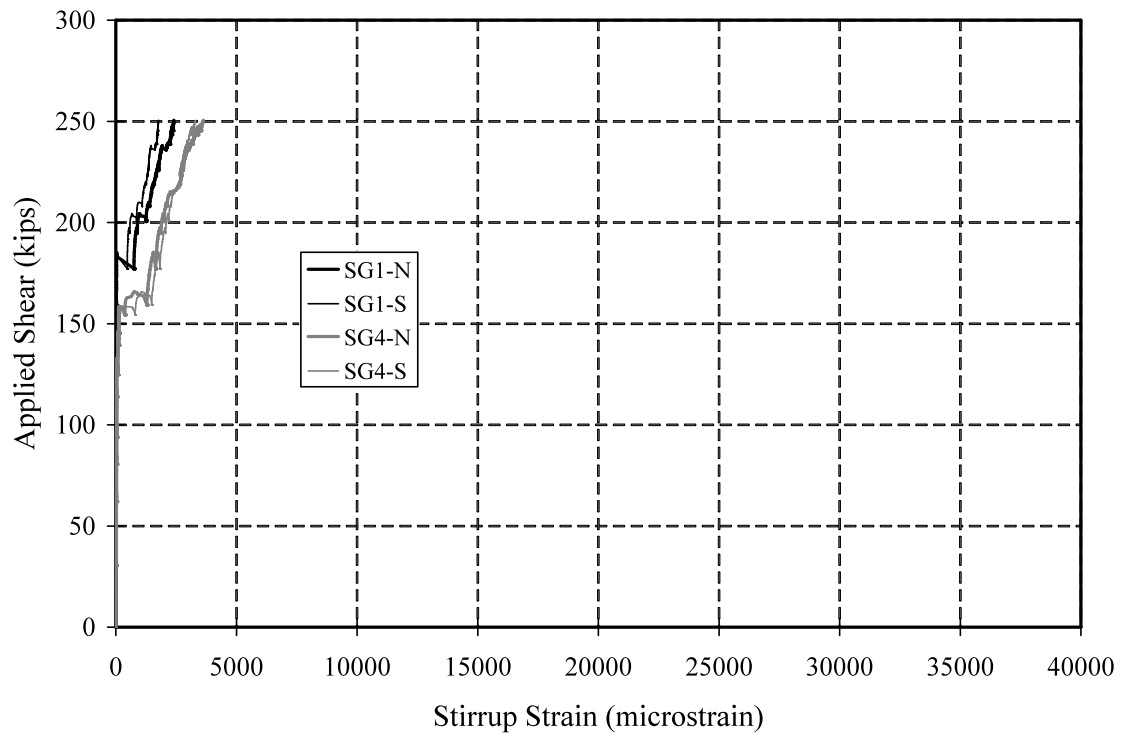


(a) Load vs. Average Stirrup Strain (All Locations)

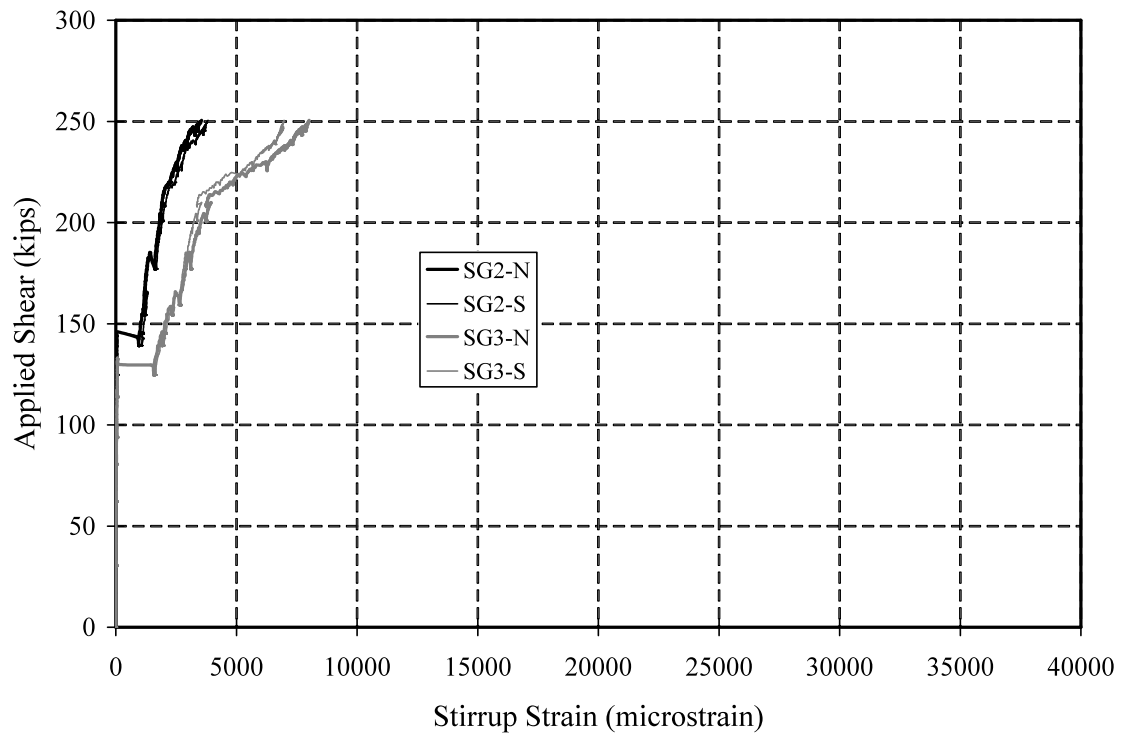


(b) Load vs. Average Longitudinal Strain (All Locations)

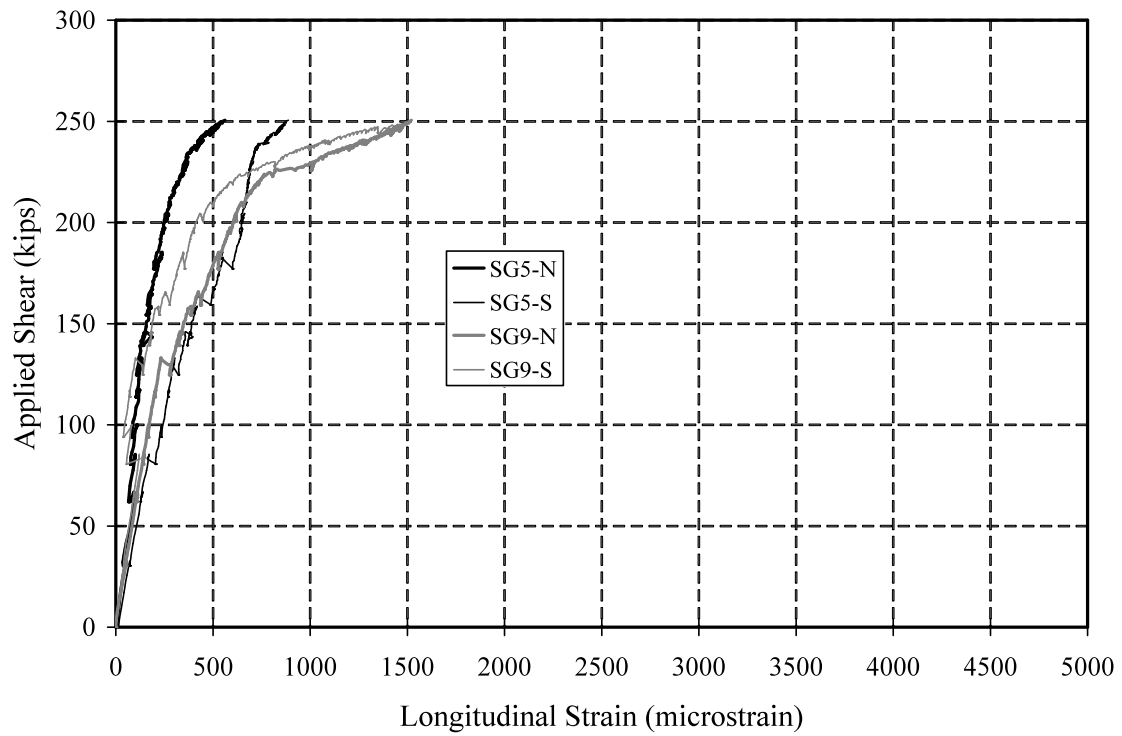
Figure F62 Strain Gage Data for SP3



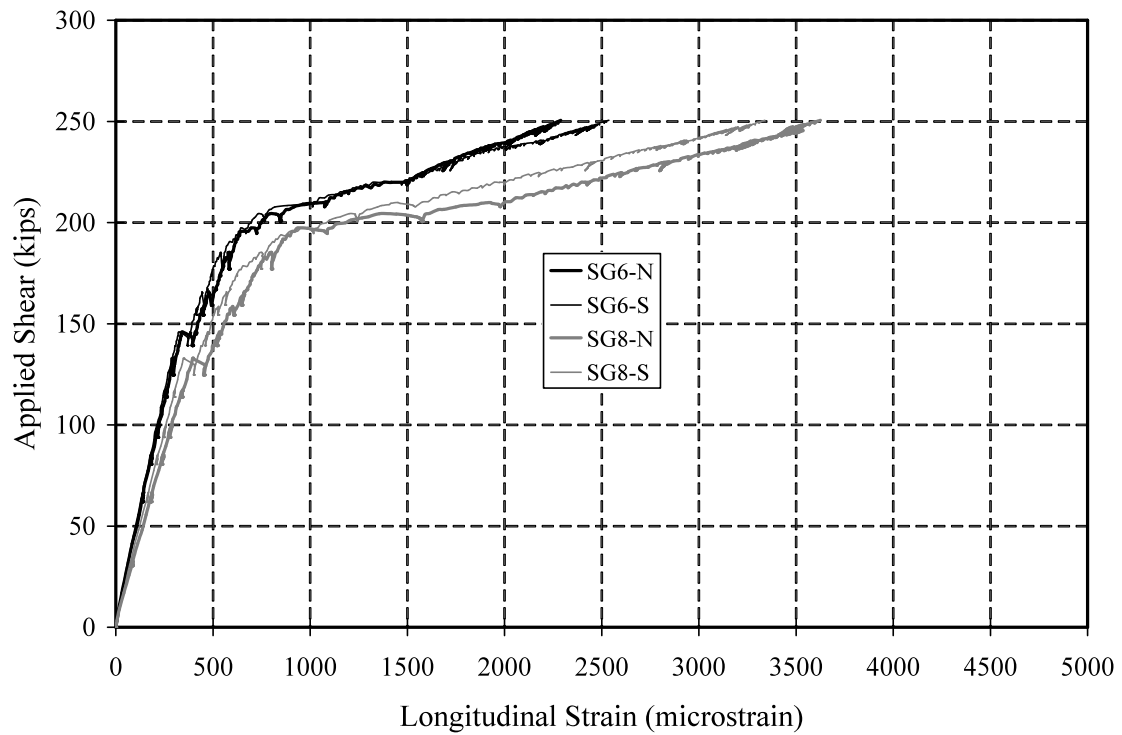
(c) Load vs. Stirrup Strain (Near Supports)



(d) Load vs. Stirrup Strain (Near Load Points)
Figure F62 (cont.) Strain Gage Data for SP3

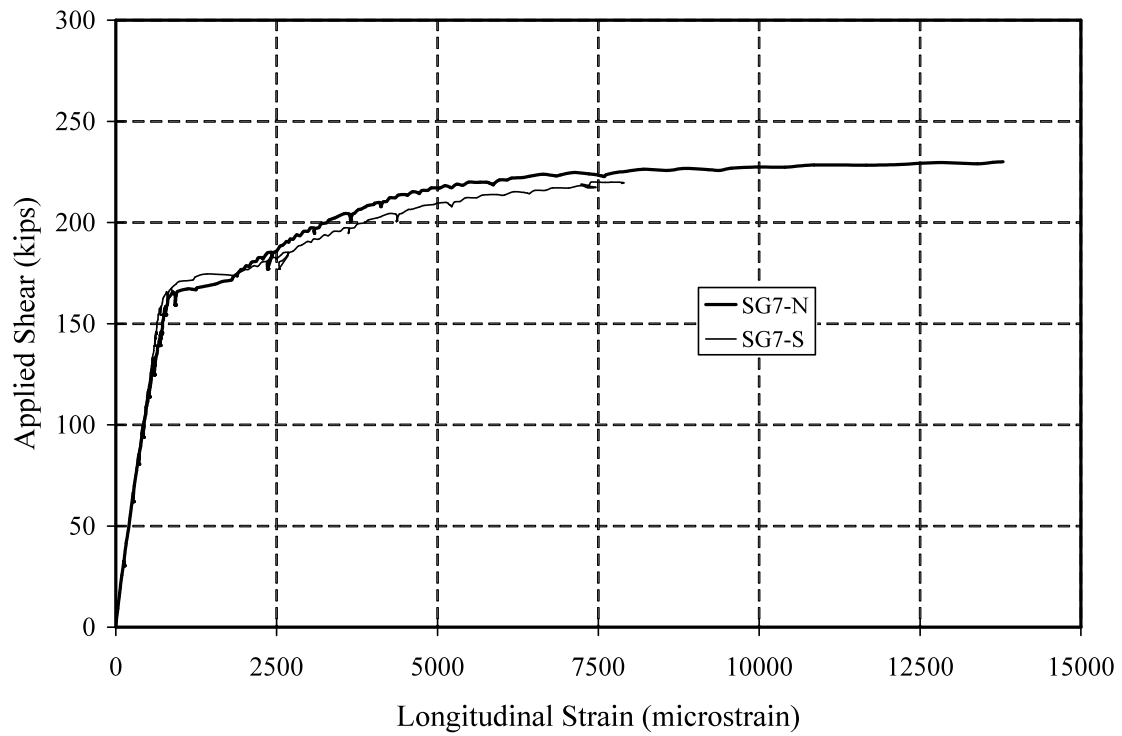


(e) Load vs. Longitudinal Strain (Near Supports)

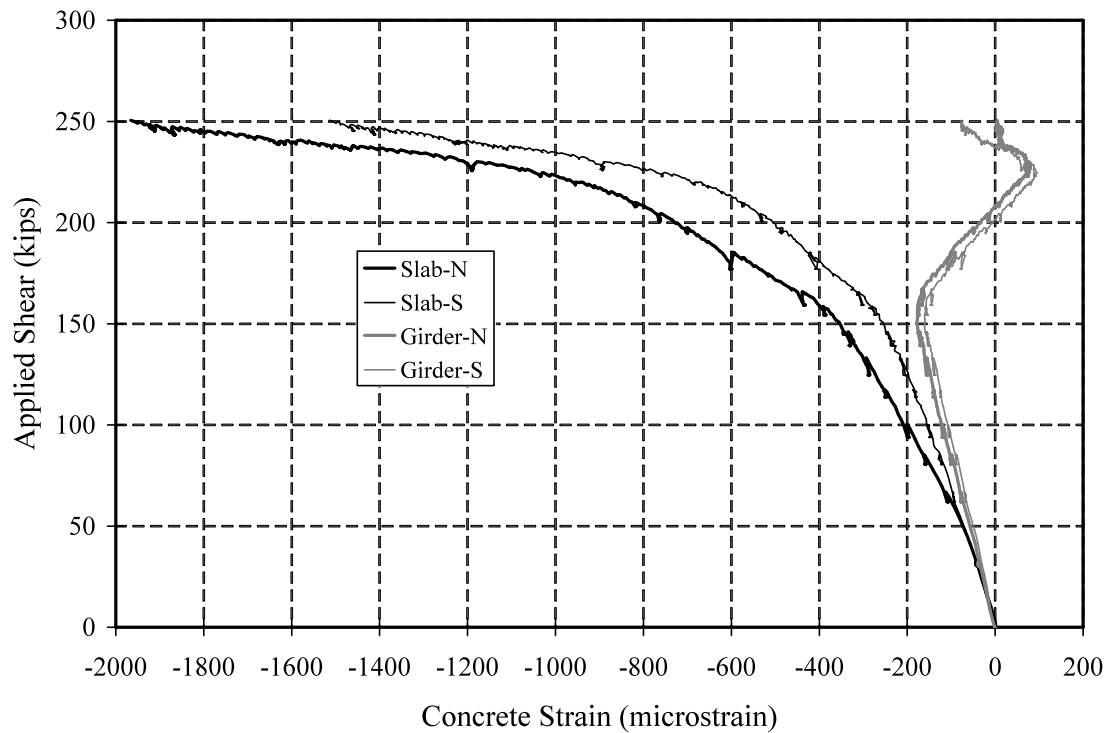


(f) Load vs. Longitudinal Strain (Near Load Points)

Figure F62 (cont.) Strain Gage Data for SP3

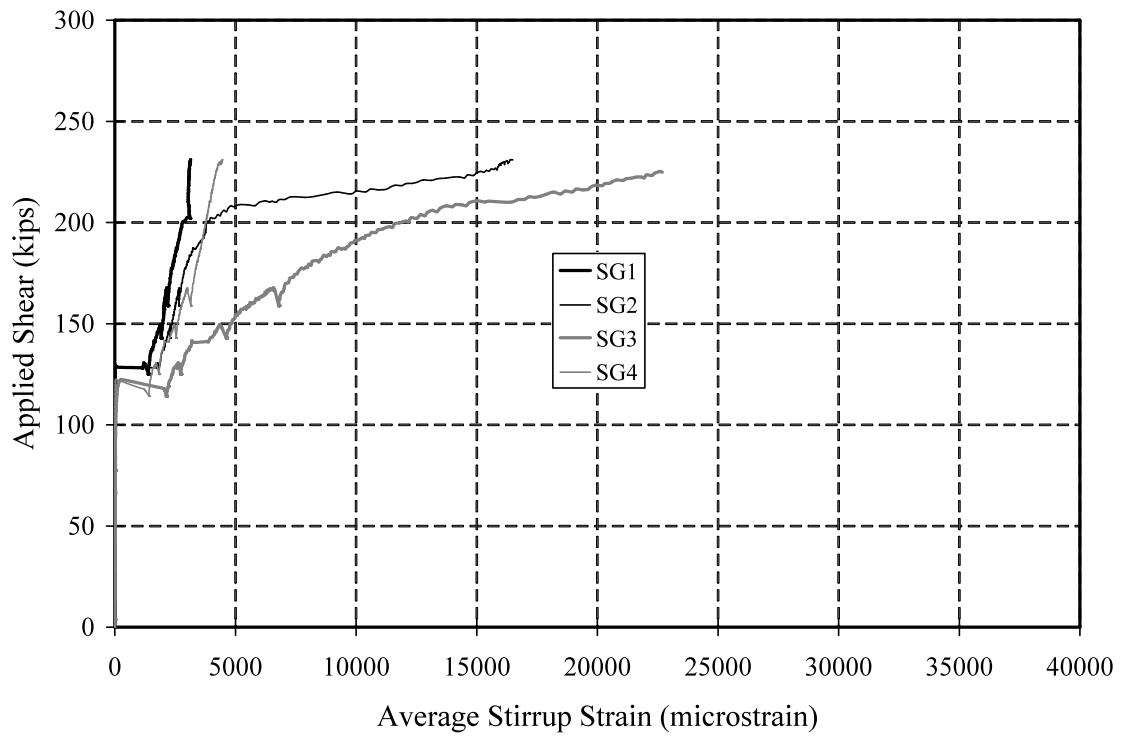


(g) Load vs. Longitudinal Strain (Mid-Span)

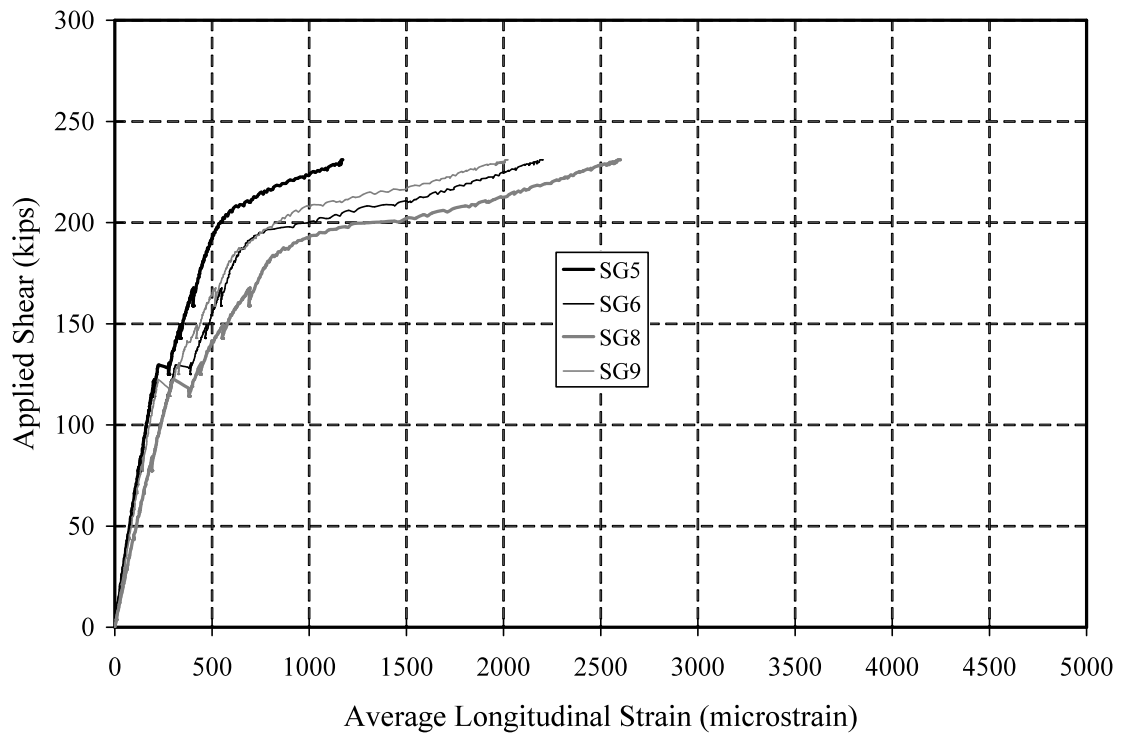


(h) Load vs. Concrete Strain

Figure F62 (cont.) Strain Gage Data for SP3

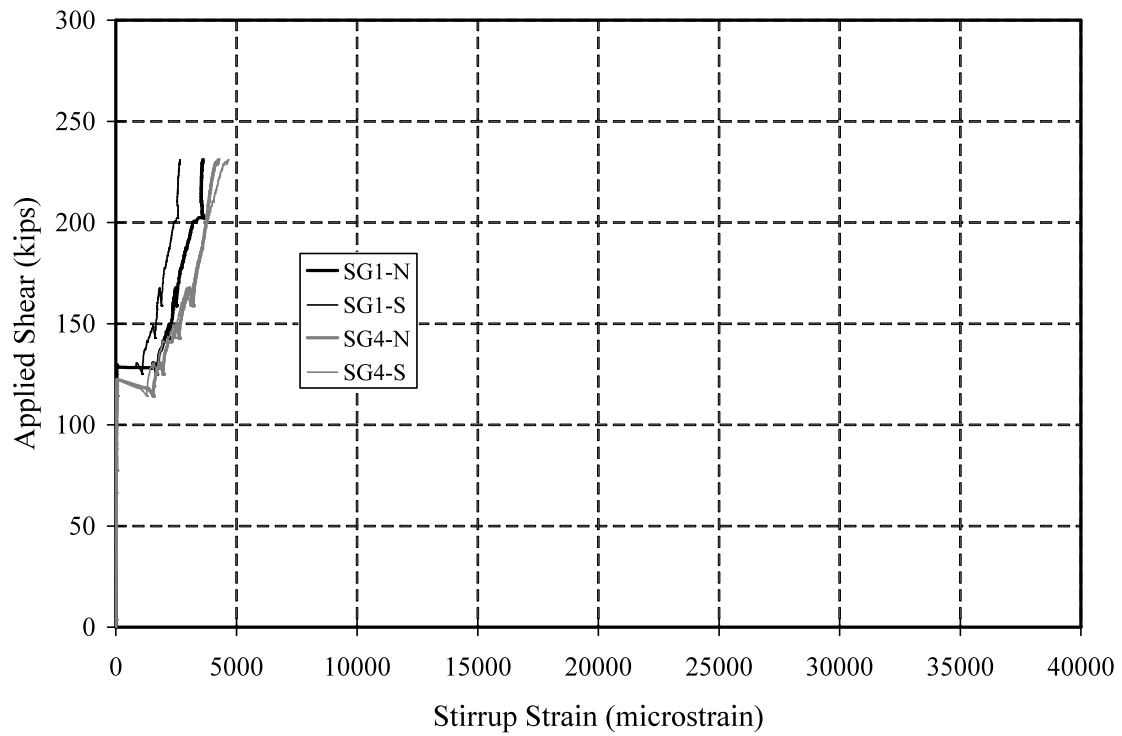


(a) Load vs. Average Stirrup Strain (All Locations)

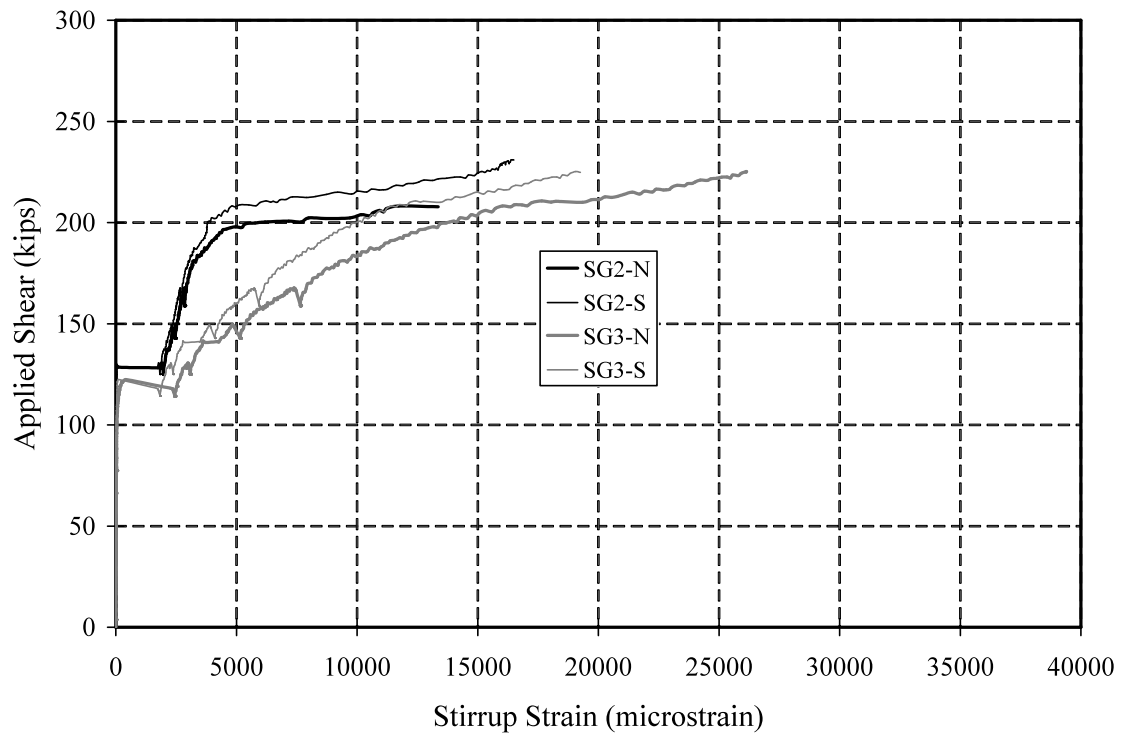


(b) Load vs. Average Longitudinal Strain (All Locations)

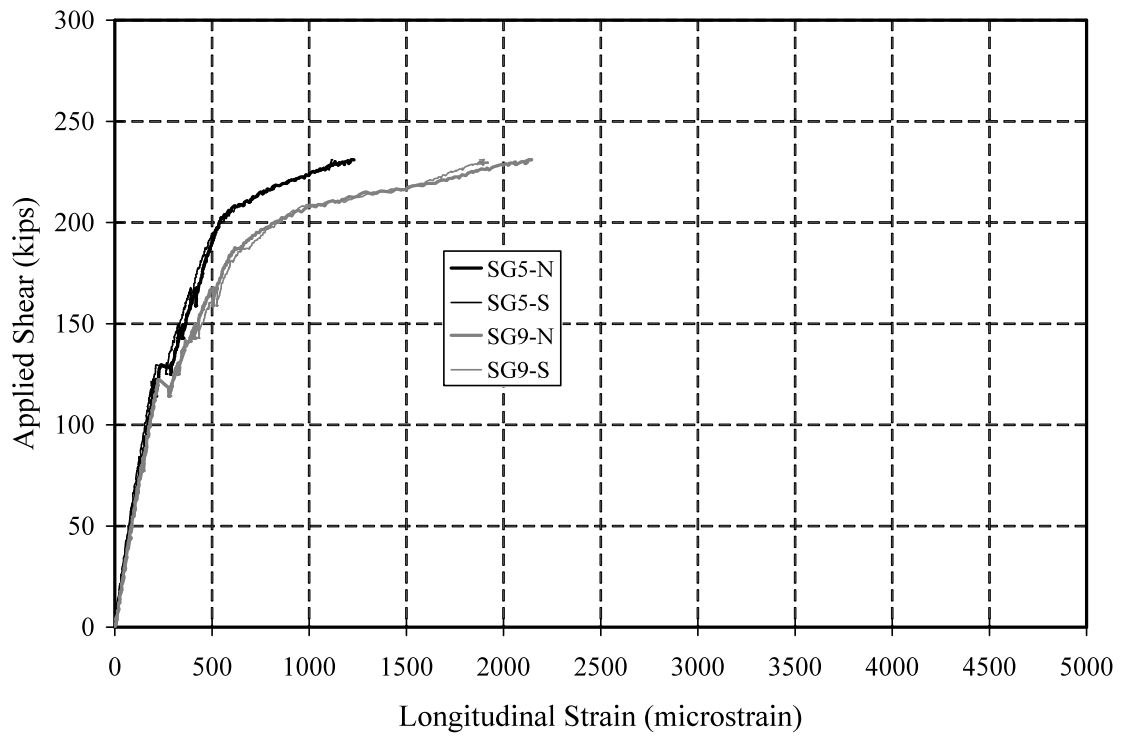
Figure F63 Strain Gage Data for SP4



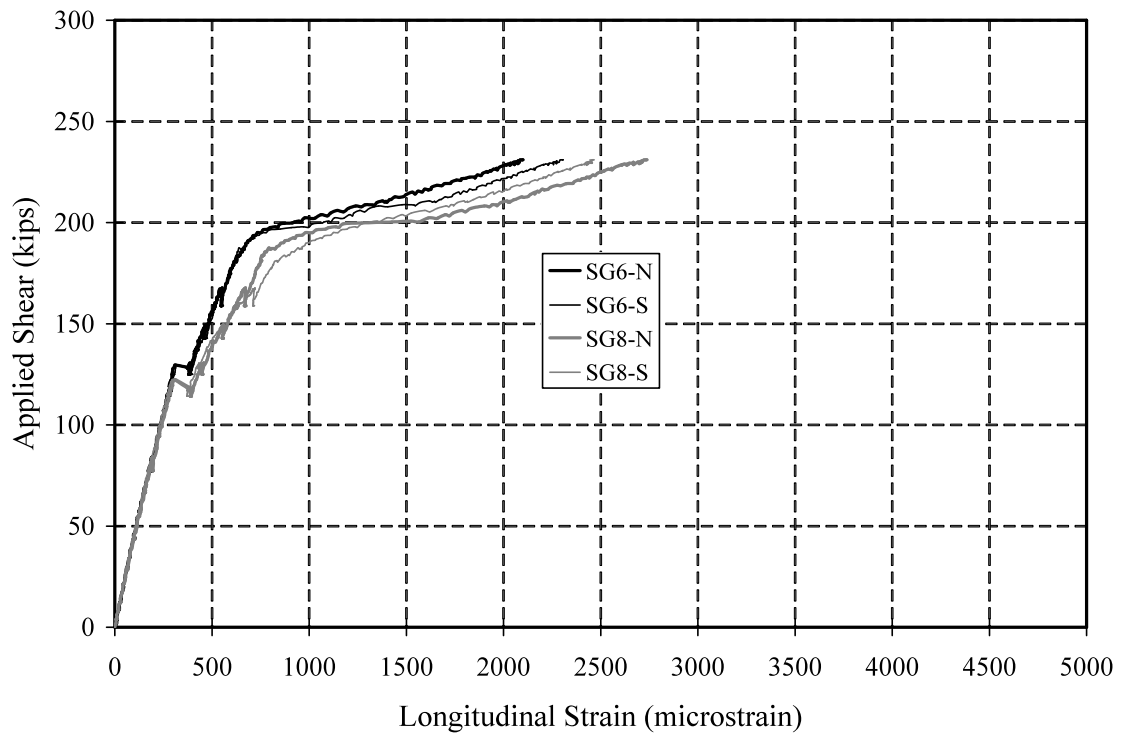
(c) Load vs. Stirrup Strain (Near Supports)



(d) Load vs. Stirrup Strain (Near Load Points)
Figure F63 (cont.) Strain Gage Data for SP4

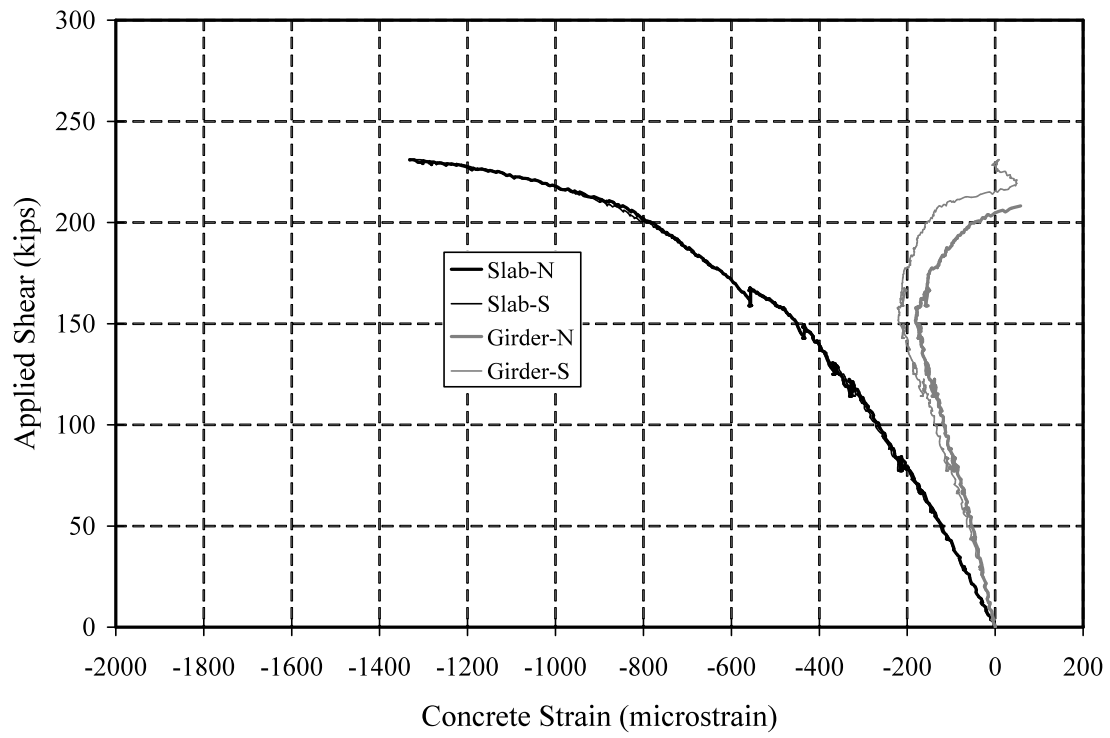


(e) Load vs. Longitudinal Strain (Near Supports)



(f) Load vs. Longitudinal Strain (Near Load Points)

Figure F63 (cont.) Strain Gage Data for SP4

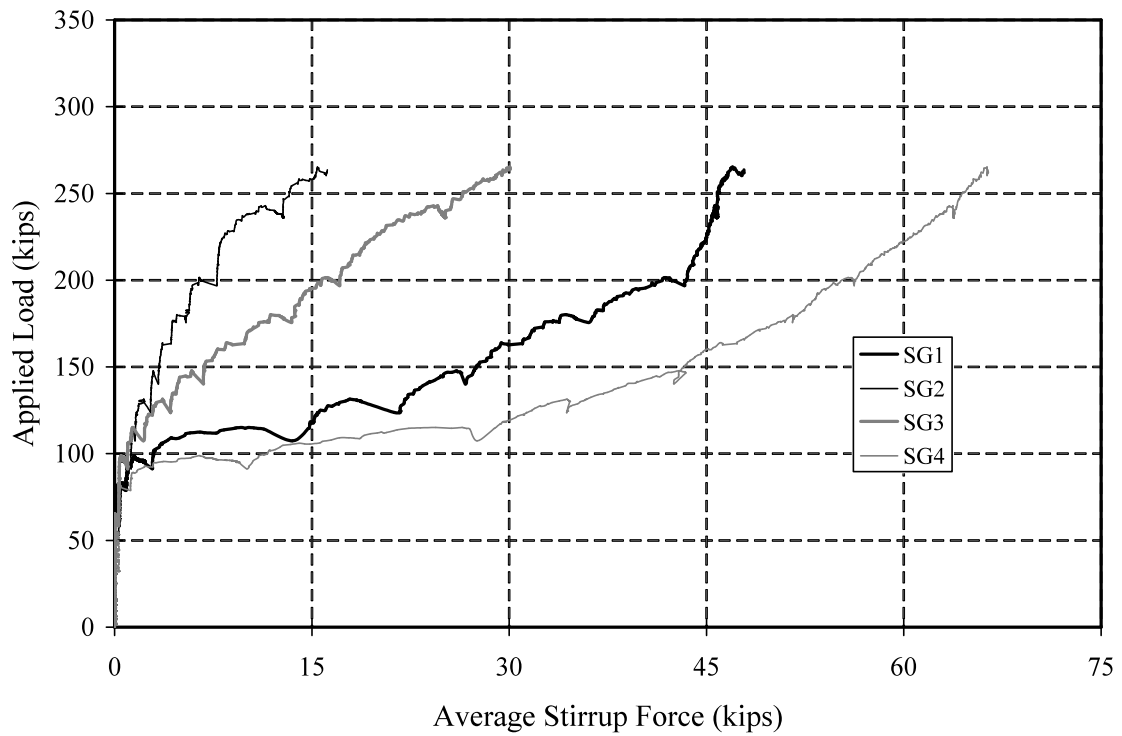


(g) Load vs. Concrete Strain
Figure F63 (cont.) Strain Gage Data for SP4

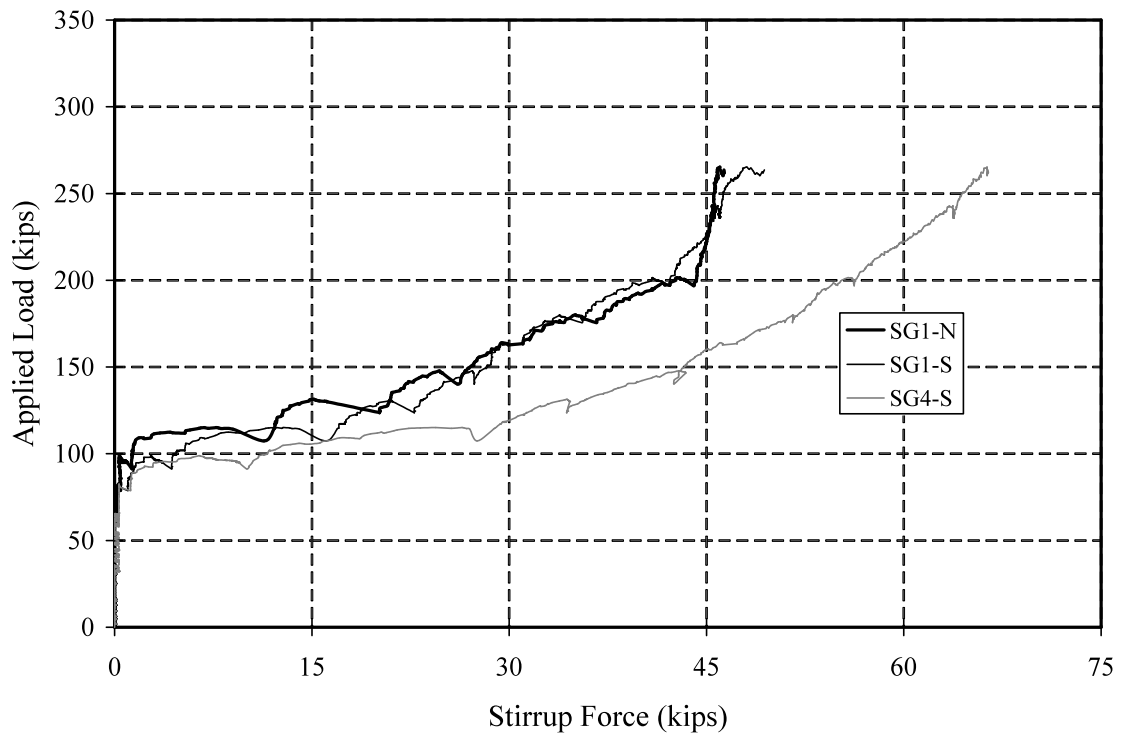
F.7.5 Load-Stirrup Force Behavior

Comparing the strain values of the A615 and A1035 stirrups is misleading since the two stirrups have different spacing and different cross-sectional areas throughout the specimens. In order to accurately compare the performance of both stirrup types, their strain values need to be converted into stirrup forces. In the design phase, it was the stirrup forces that were held equal by using the equation $V_s = \frac{A_v f_s d_v}{s}$. Accordingly, the stirrup strain data were converted into stress by interpolating the measured stress-strain relationships of the stirrups (#4 A615 and #3 A1035) – refer to Appendix A. Once the stirrup stress (f_s) was found through interpolation, the resulting stress was multiplied by the appropriate stirrup cross sectional area and shear depth (A_v, d_v) and divided by the stirrup spacing (s) to compute the stirrup force (V_s). This conversion process was replicated for each stirrup strain datum in each of the specimens. The resulting theoretical stirrup forces could then be compared directly. The results are presented in Figures F64 through F72.

Upon review of the stirrup force data, two specimens were distinguished for unusual behavior: specimens SR1 and SR3. Specimen SR1 showed higher A1035 stirrup forces in both of the locations (near the supports and near the load point) while specimen SR3 showed higher A615 stirrup forces. This ambiguity was later reconciled after crack patterns were examined in reference to the locations of the stirrup strain gages. In each case, the locations of the strain gages attributing to excessive stirrup forces appeared to have coincided with crack propagation, which result in localized increases in steel strain. This phenomenon was checked for all of the specimens; however, none of them showed any signs of crack interference other than the two specimens mentioned. Figure 64 (d) and Figure 66 (c) show the crack patterns of specimens SR1 and SR3 along with the locations of their strain gages (exact strain gage locations are designated by 'X'). For specimen SR1, strain gages SG3 and SG4 (both on A1035 stirrups) experienced localized cracking effects, refer to Figure F64 (d). For specimen SR3, Figure F66 (c) shows a substantial crack through SG1 which was installed on an A615 stirrup.

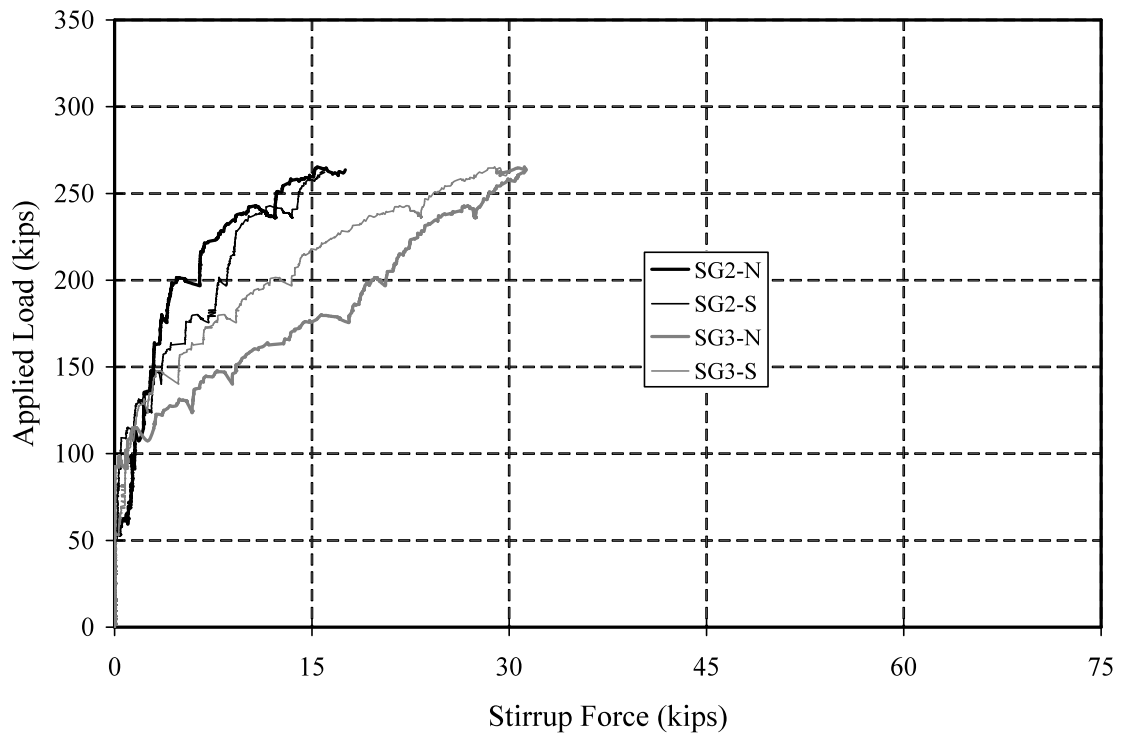


(a) Load vs. Average Stirrup Force (All Locations)

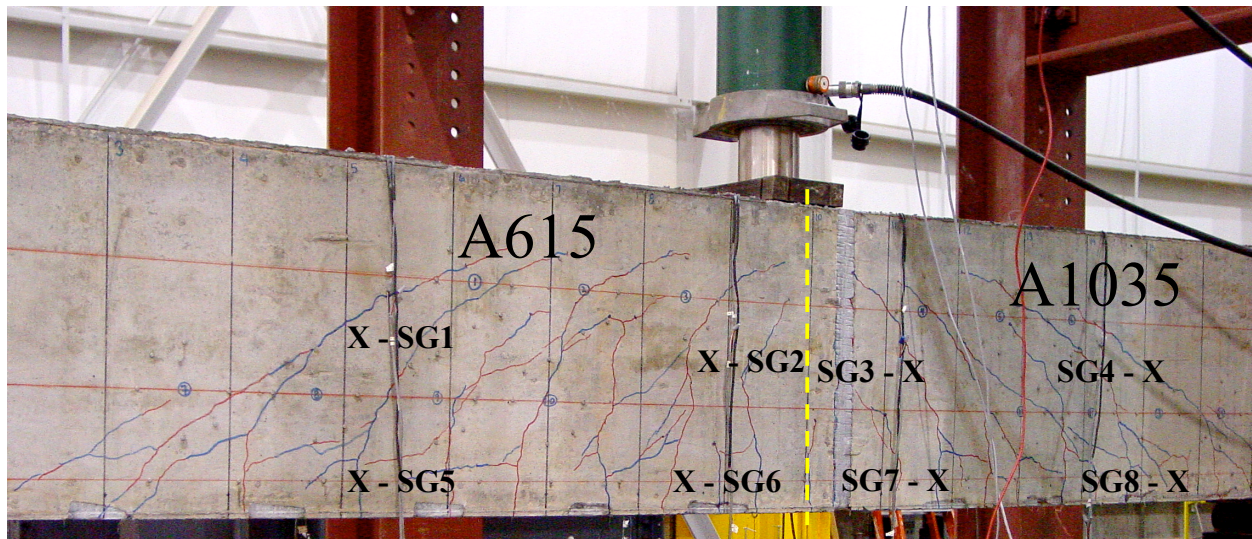


(b) Load vs. Stirrup Force (Near Supports)

Figure F64 Stirrup Force Data for SR1

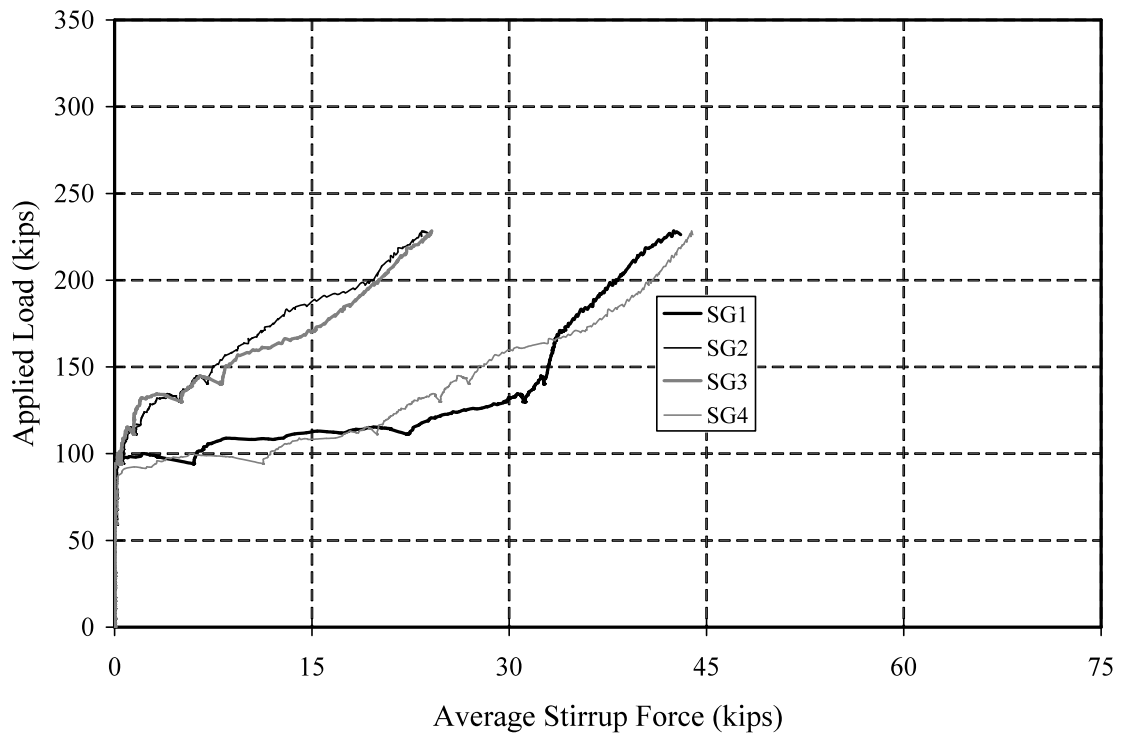


(c) Load vs. Stirrup Force (Near Load Point)

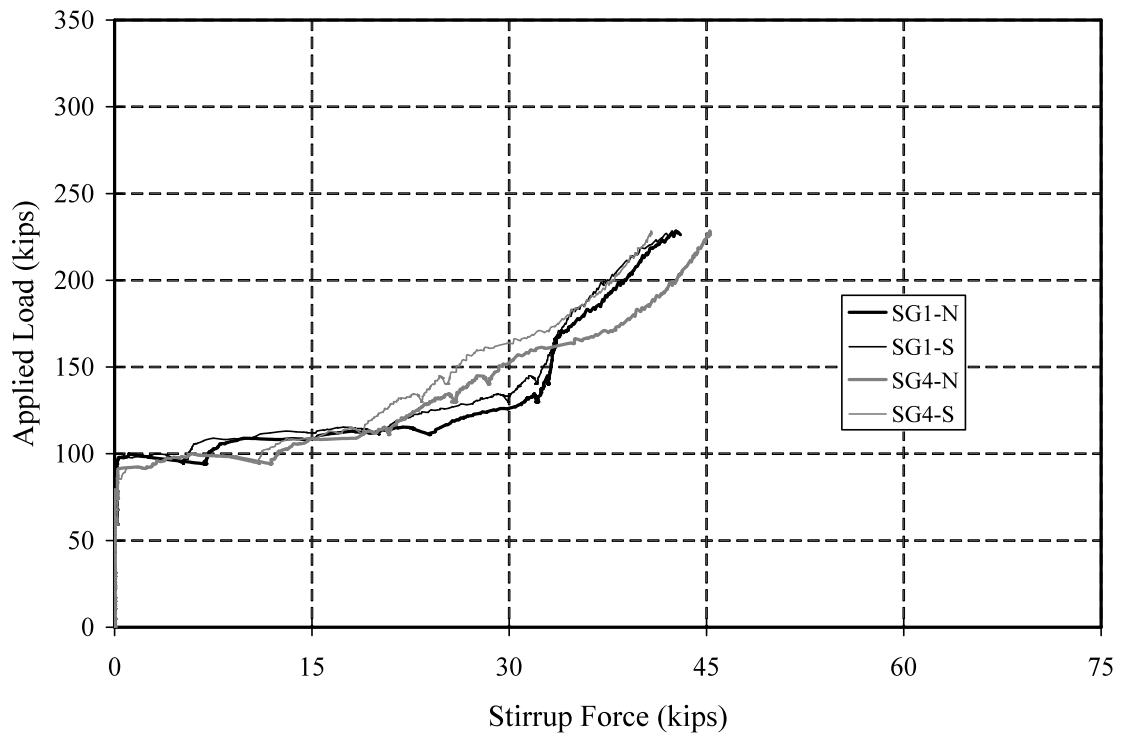


(d) Crack Interference

Figure F64 (cont.) Stirrup Force Data for SR1

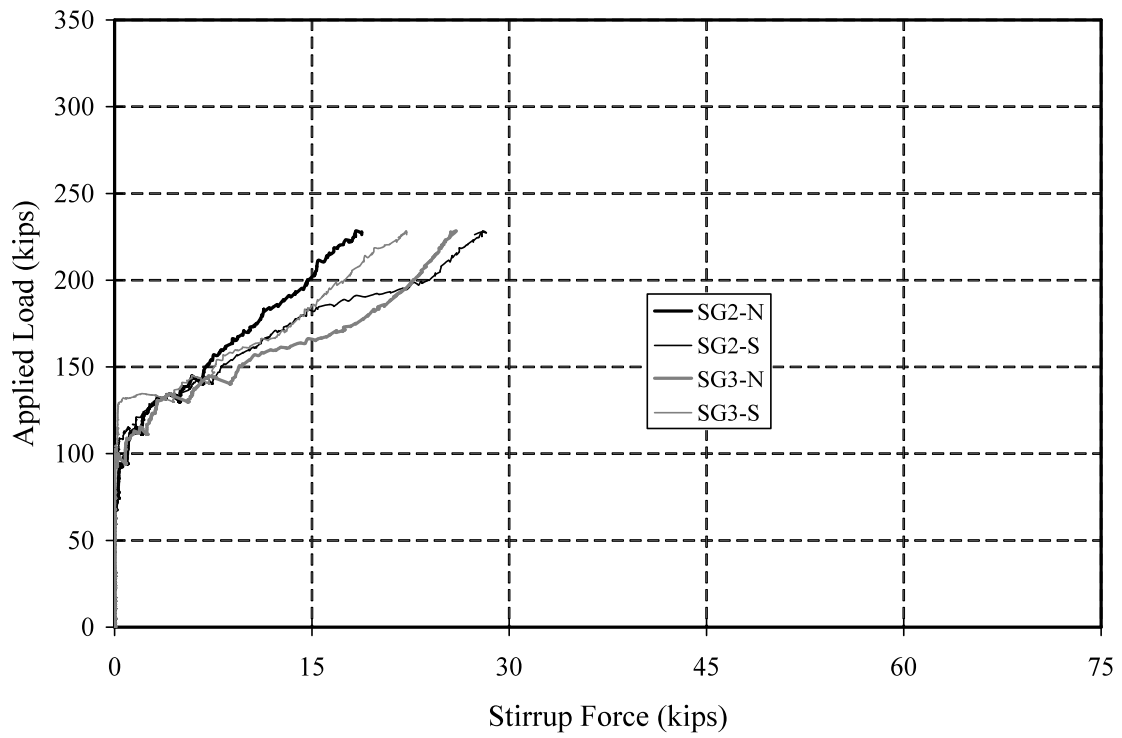


(a) Load vs. Average Stirrup Force (All Locations)

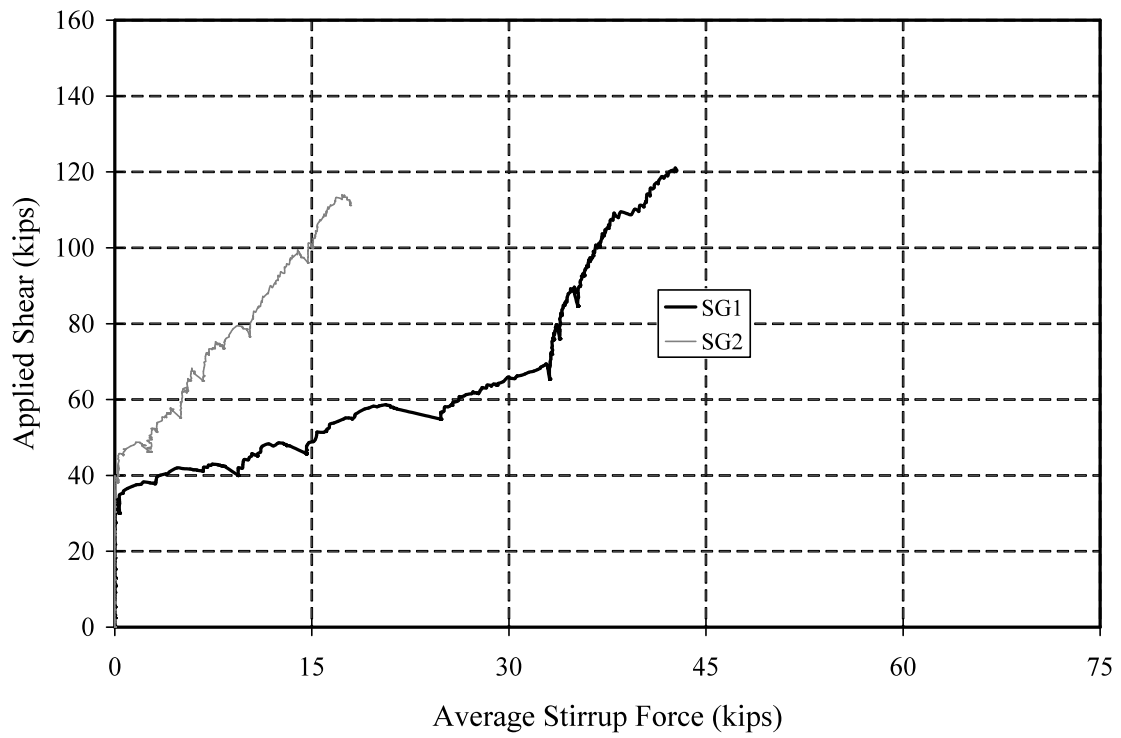


(b) Load vs. Stirrup Force (Near Supports)

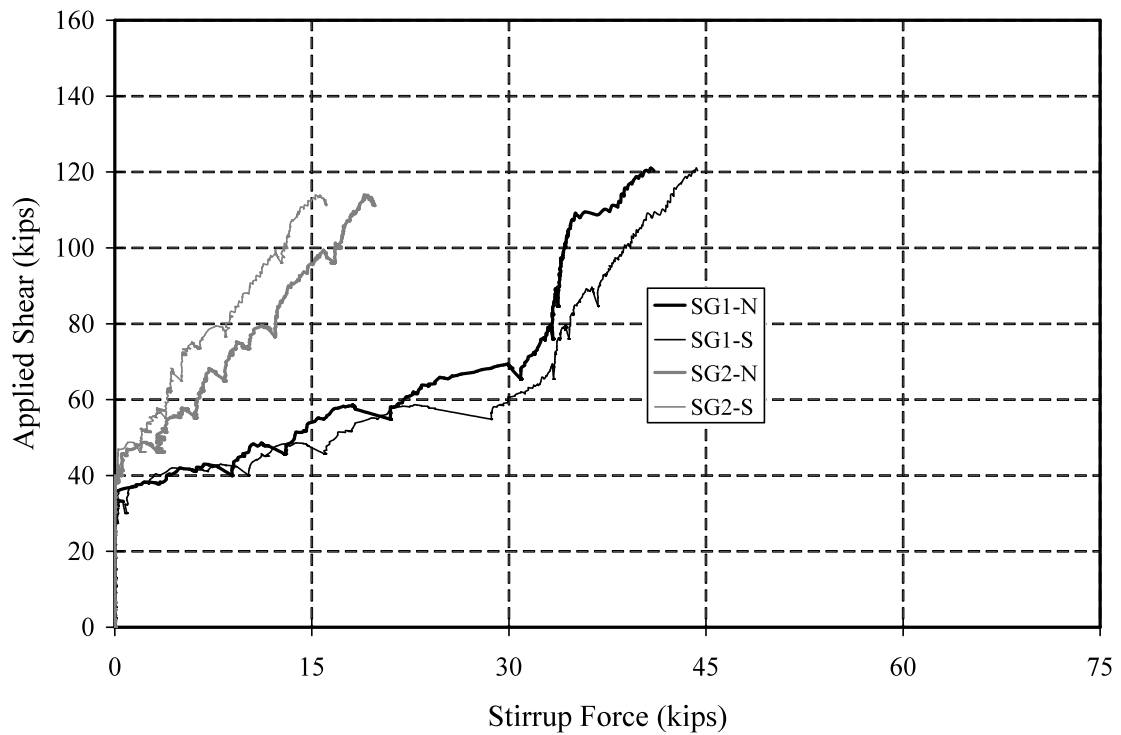
Figure F65 Stirrup Force Data for SR2



(c) Load vs. Stirrup Force (Near Load Point)
Figure F65 (cont.) Stirrup Force Data for SR2



(a) Load vs. Average Stirrup Force

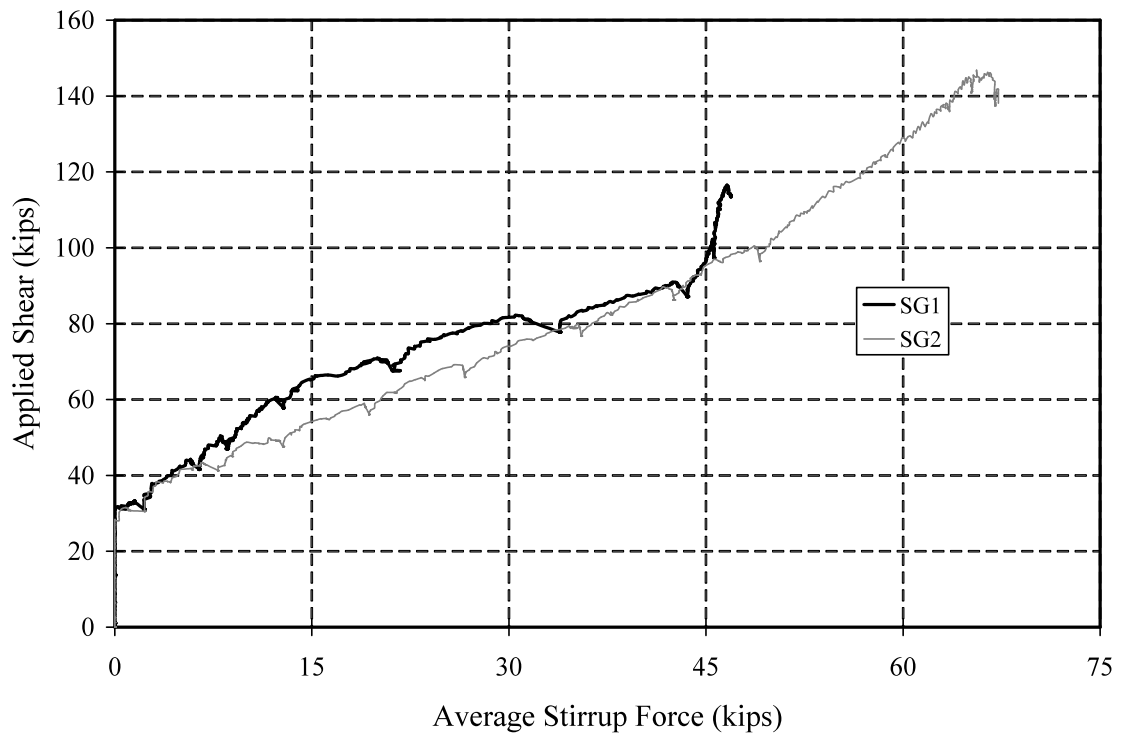


(b) Load vs. Stirrup Force

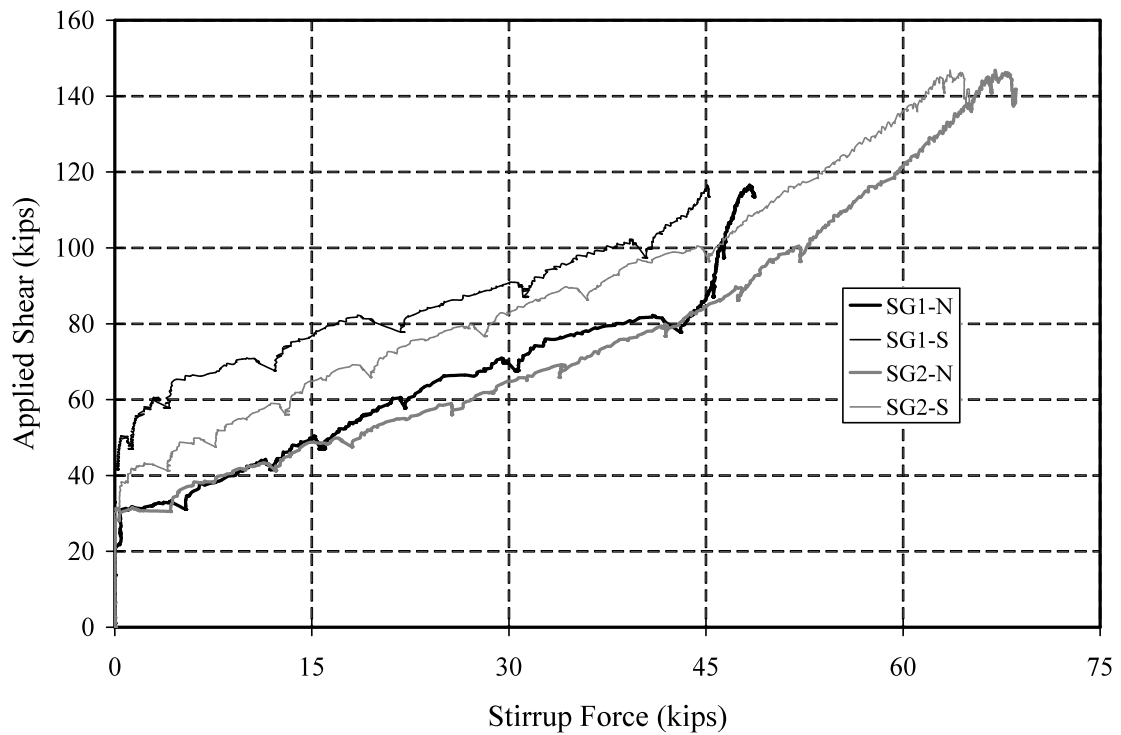
Figure F66 Stirrup Force Data for SR3



(c) Crack Interference
Figure F66 (cont.) Stirrup Force Data for SR3

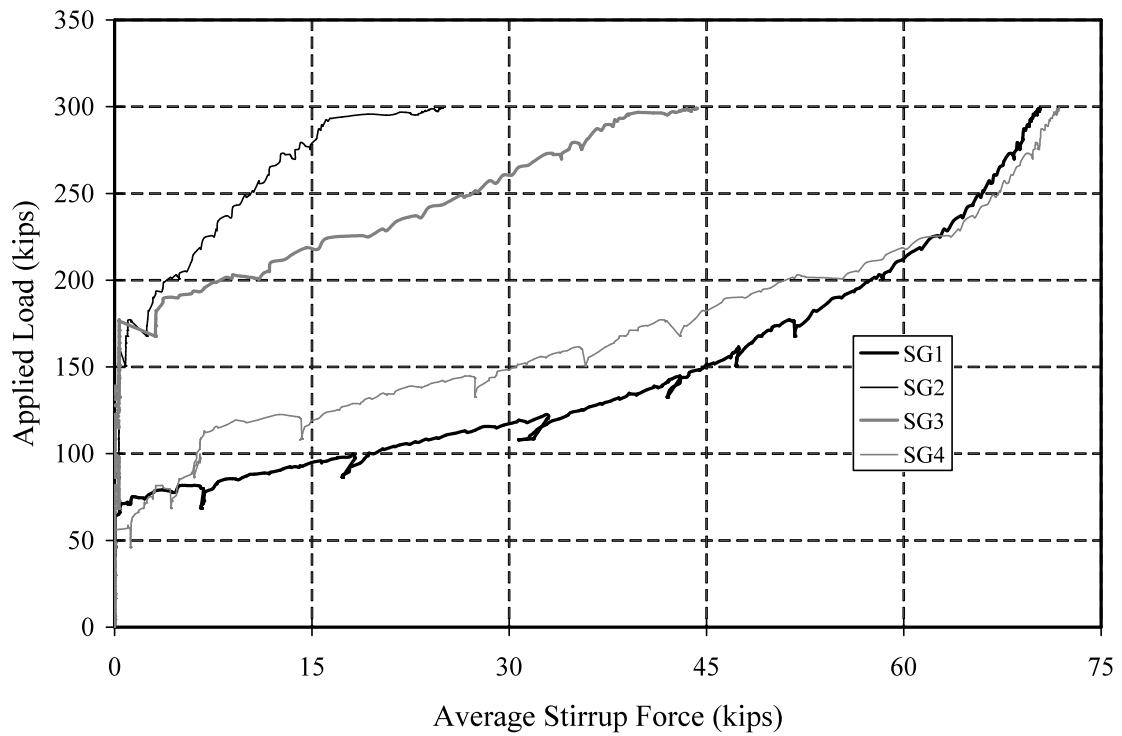


(a) Load vs. Average Stirrup Force

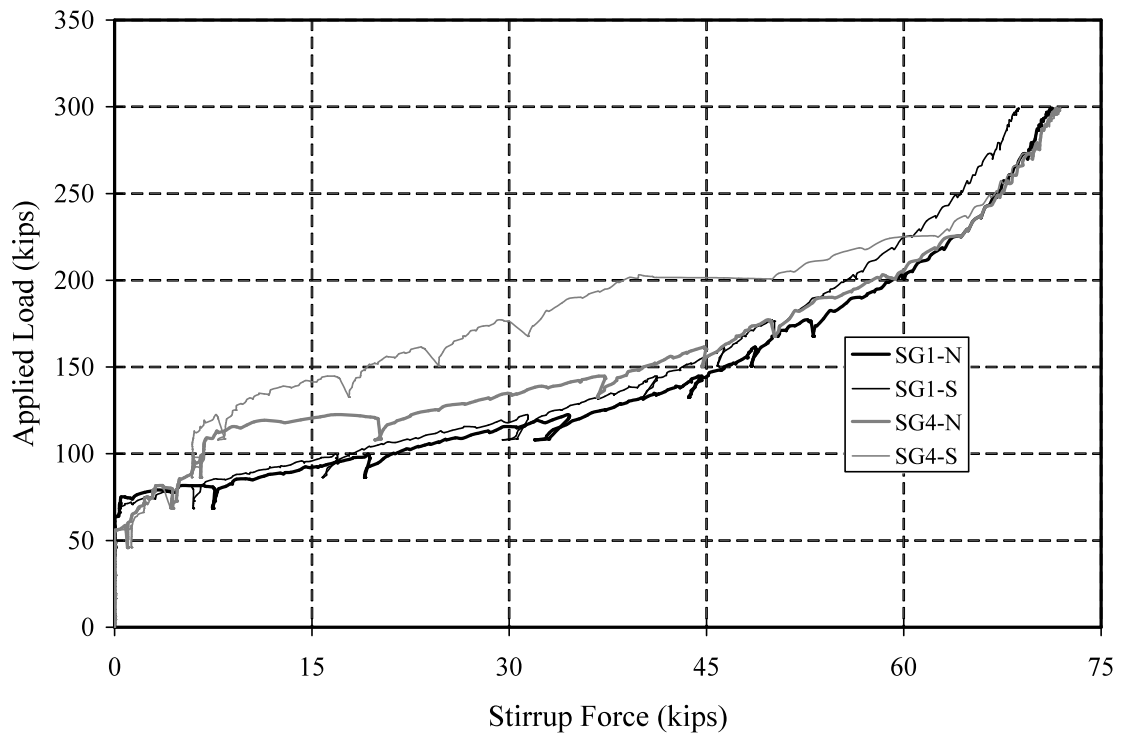


(b) Load vs. Stirrup Force

Figure F67 Stirrup Force Data for SR4

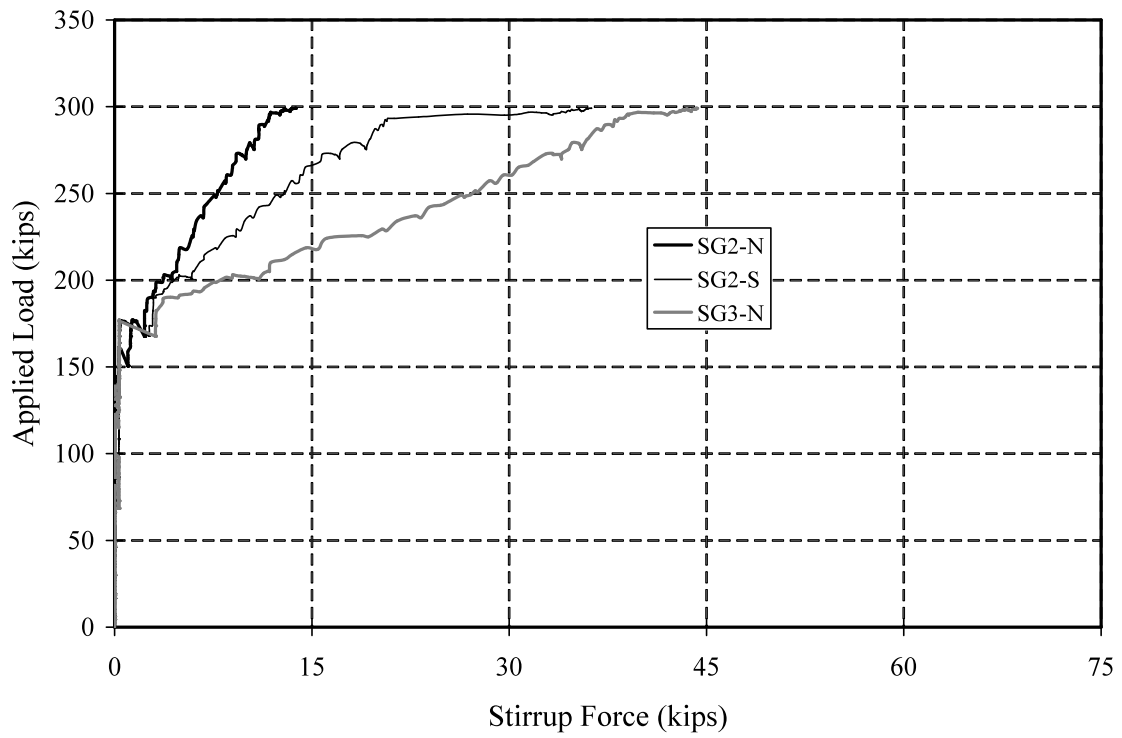


(a) Load vs. Average Stirrup Force (All Locations)

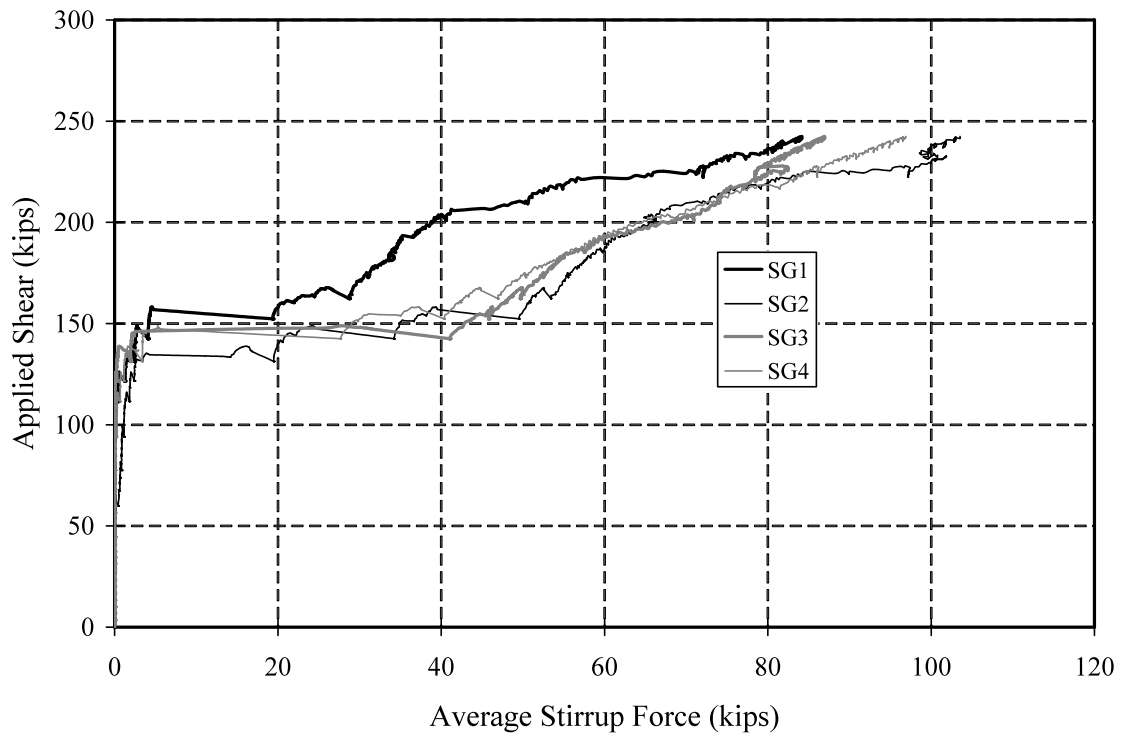


(b) Load vs. Stirrup Force (Near Supports)

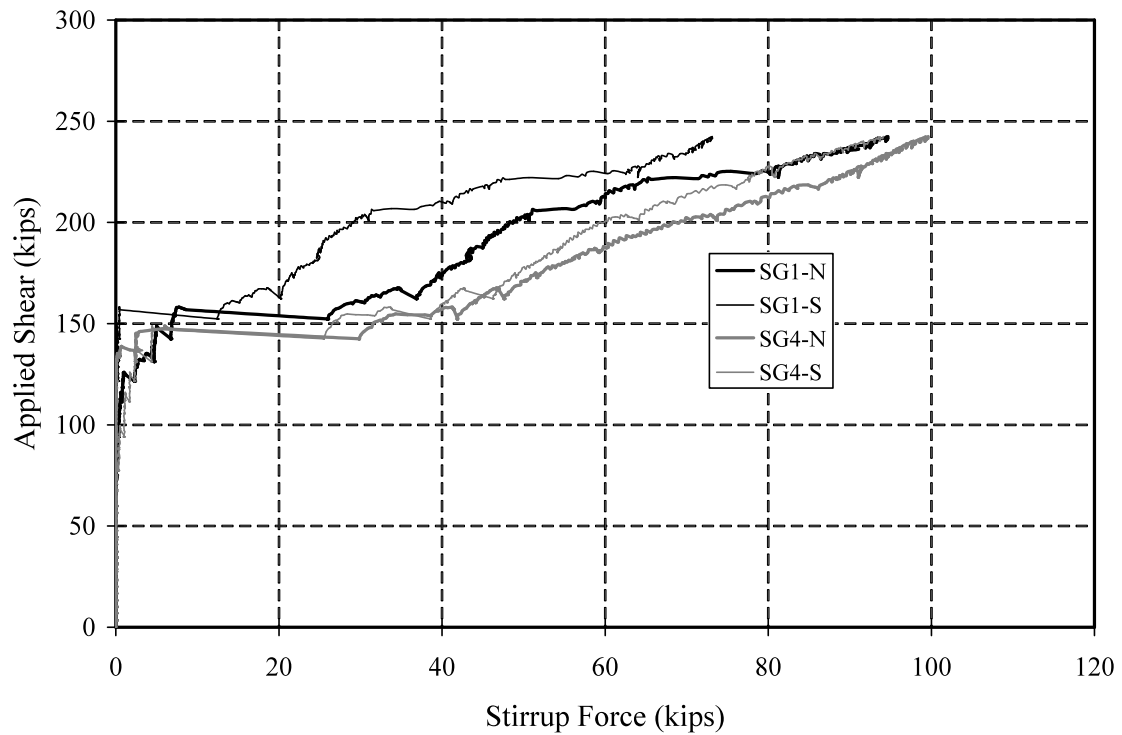
Figure F68 Stirrup Force Data for SR5



(c) Load vs. Stirrup Force (Near Load Point)
Figure F68 (cont.) Stirrup Force Data for SR5

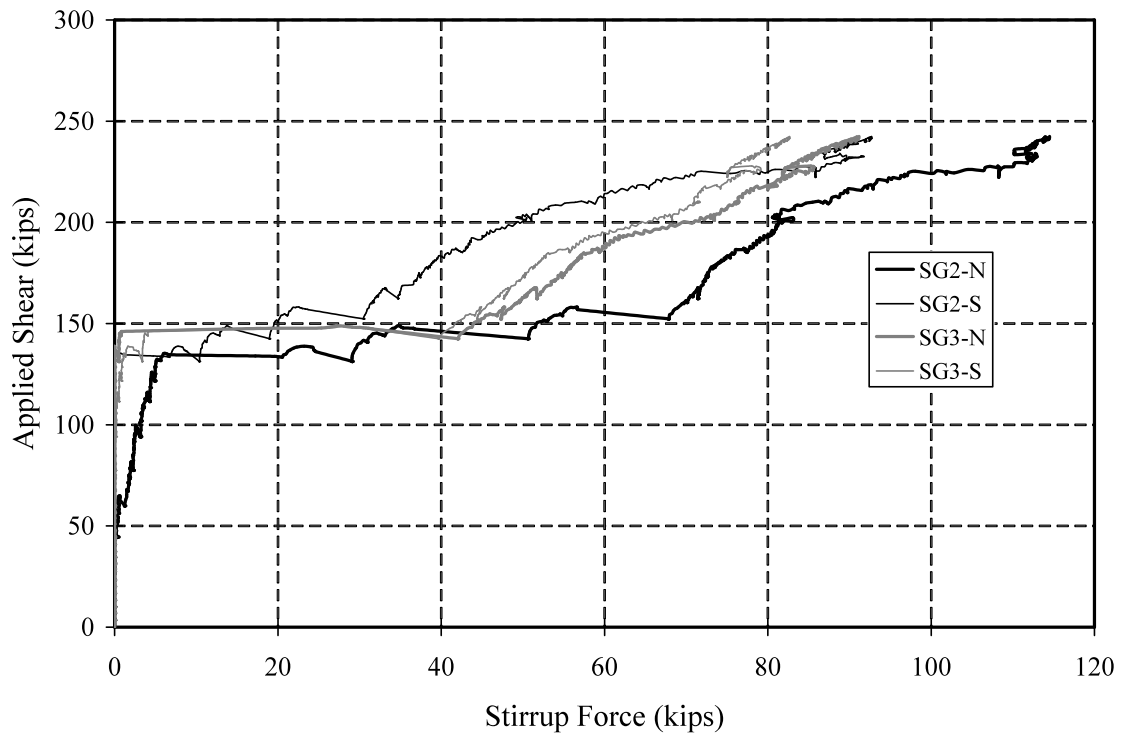


(a) Load vs. Average Stirrup Force (All Locations)

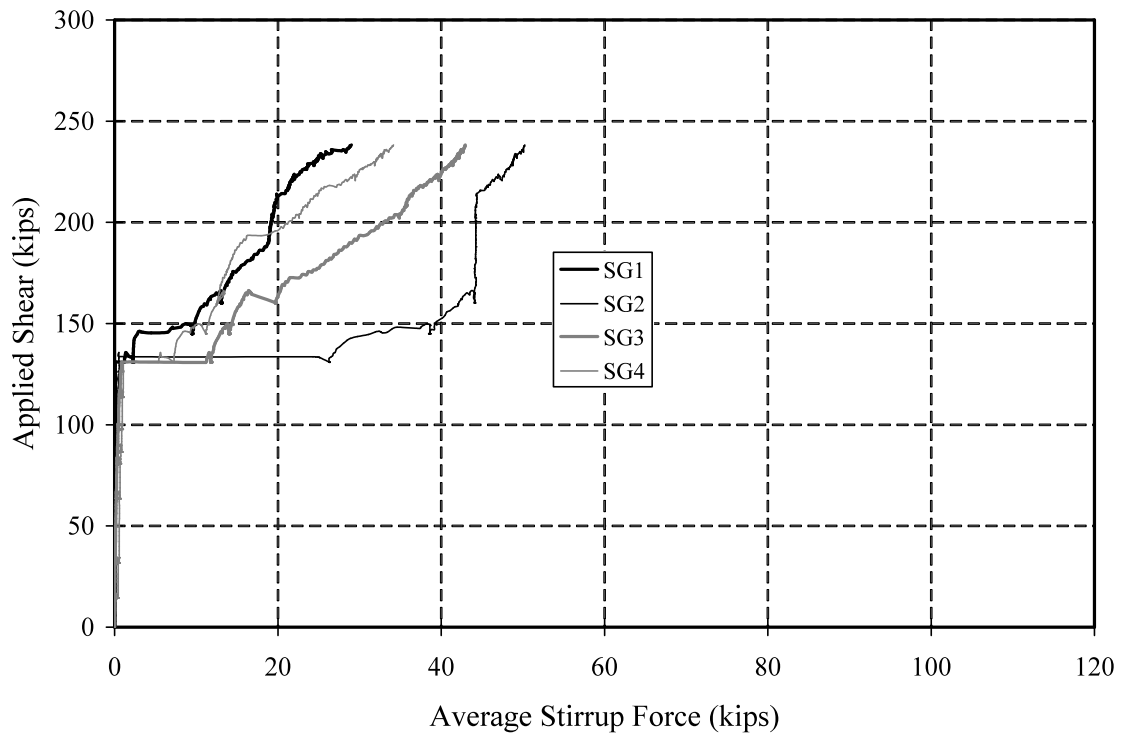


(b) Load vs. Stirrup Force (Near Supports)

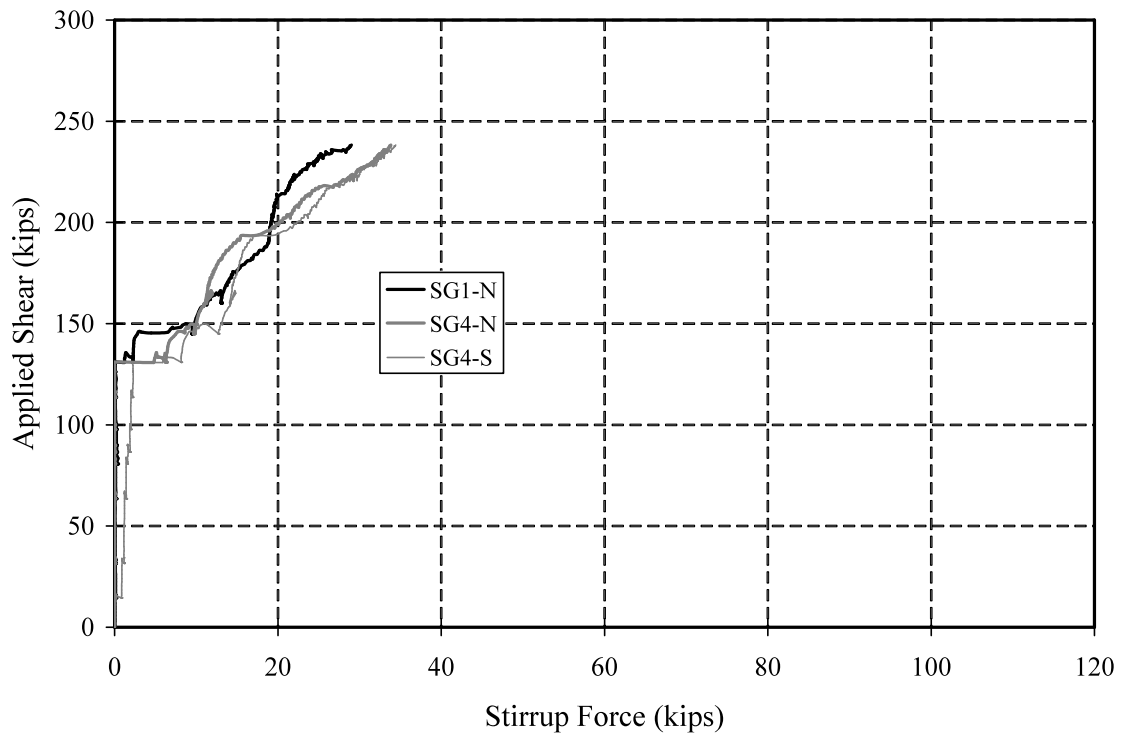
Figure F69 Stirrup Force Data for SP1



(c) Load vs. Stirrup Force (Near Load Points)
Figure F69 (cont.) Stirrup Force Data for SP1

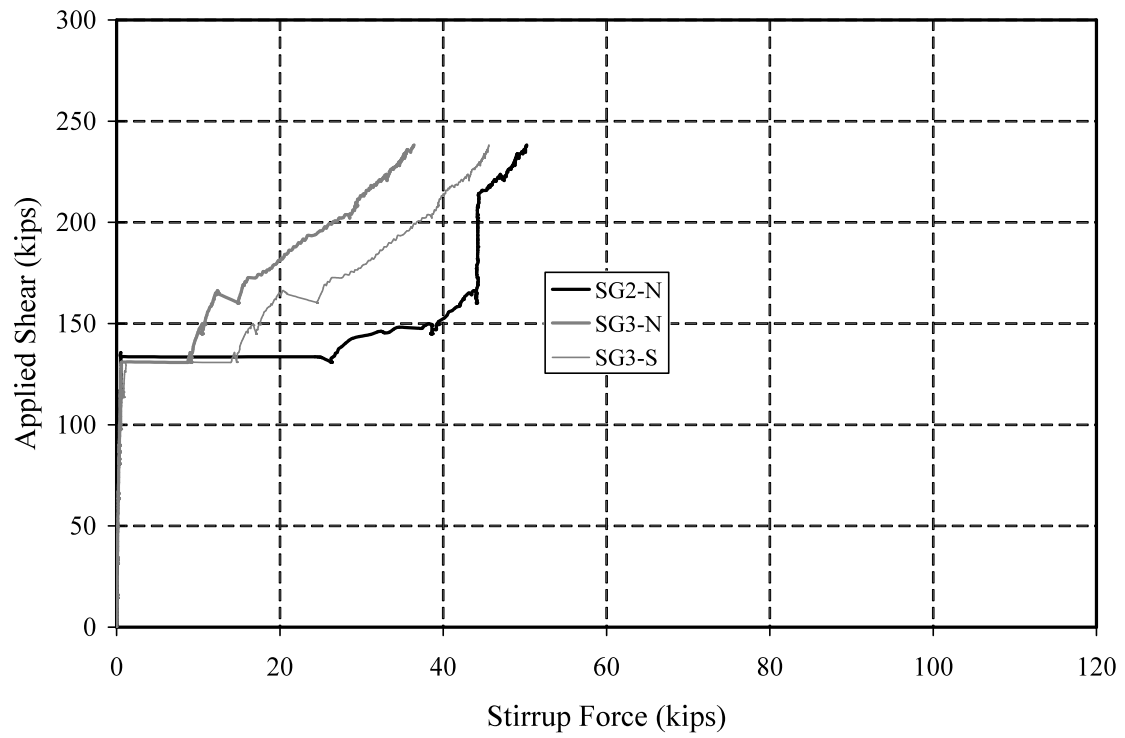


(a) Load vs. Average Stirrup Force (All Locations)

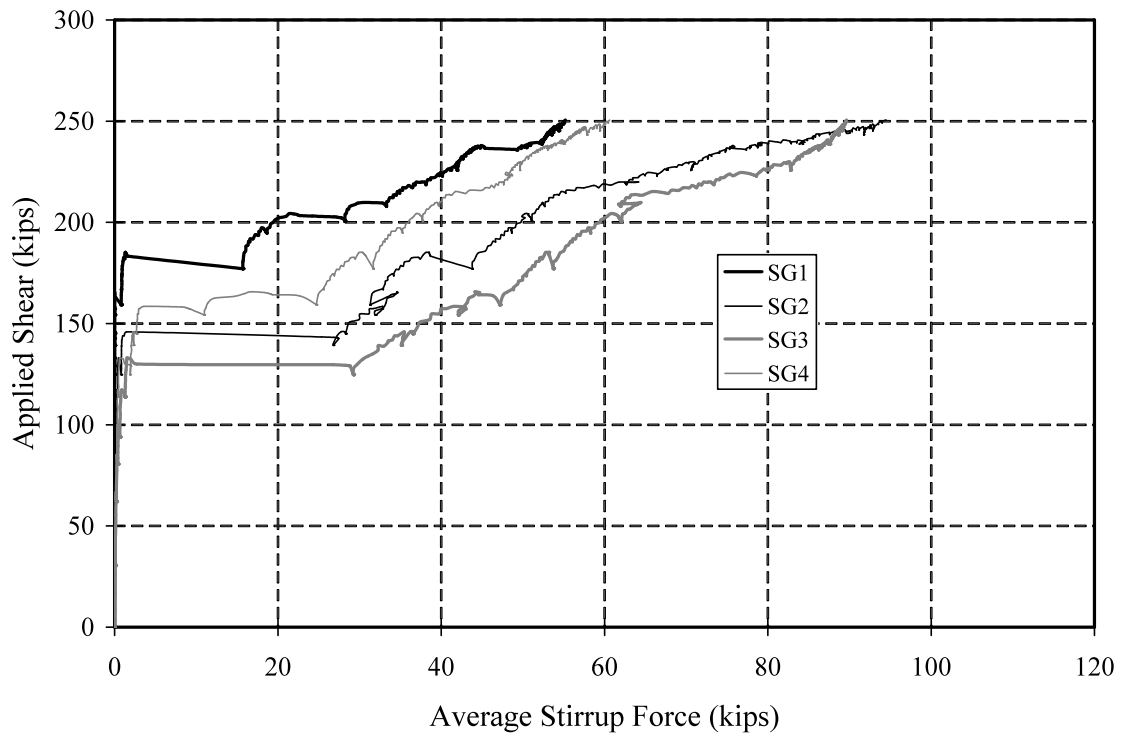


(b) Load vs. Stirrup Force (Near Supports)

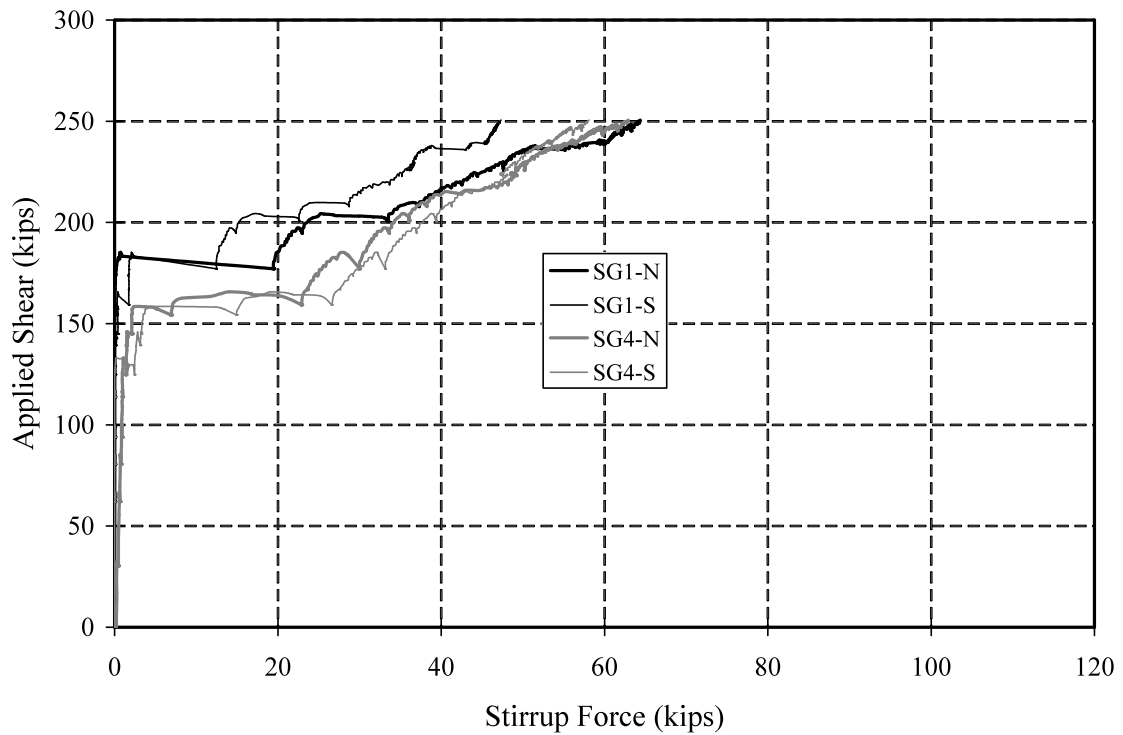
Figure F70 Stirrup Force Data for SP2



(c) Load vs. Stirrup Force (Near Load Points)
Figure F70 (cont.) Stirrup Force Data for SP2

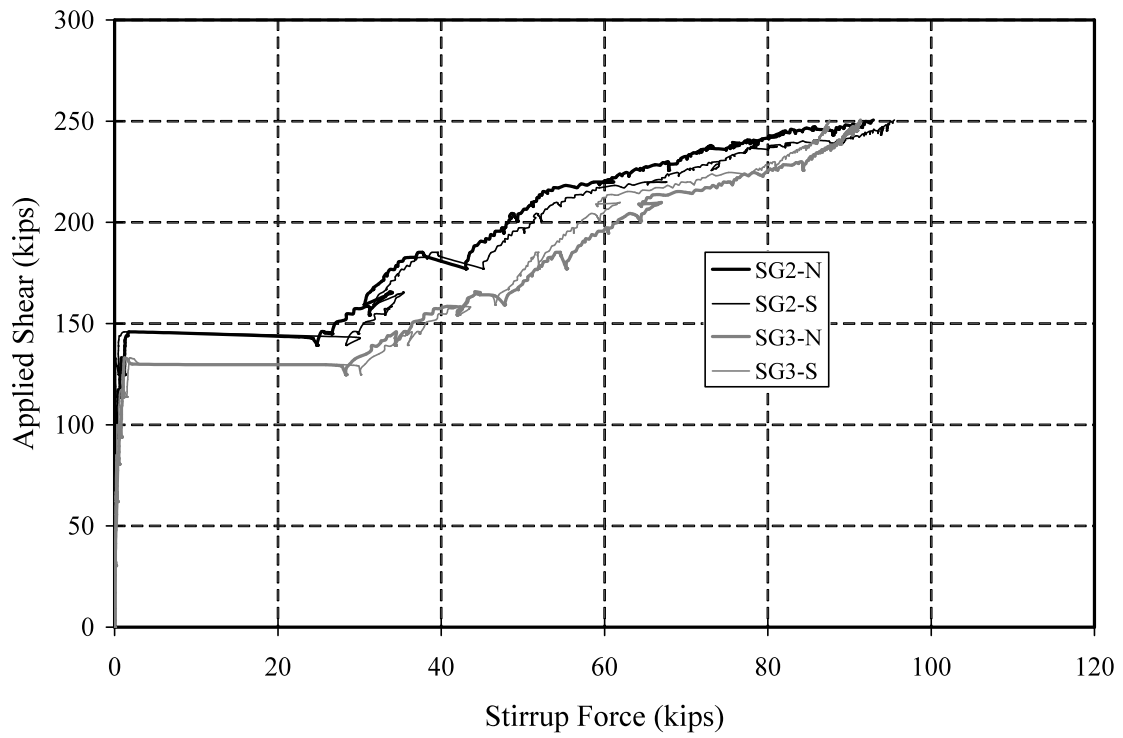


(a) Load vs. Average Stirrup Force (All Locations)

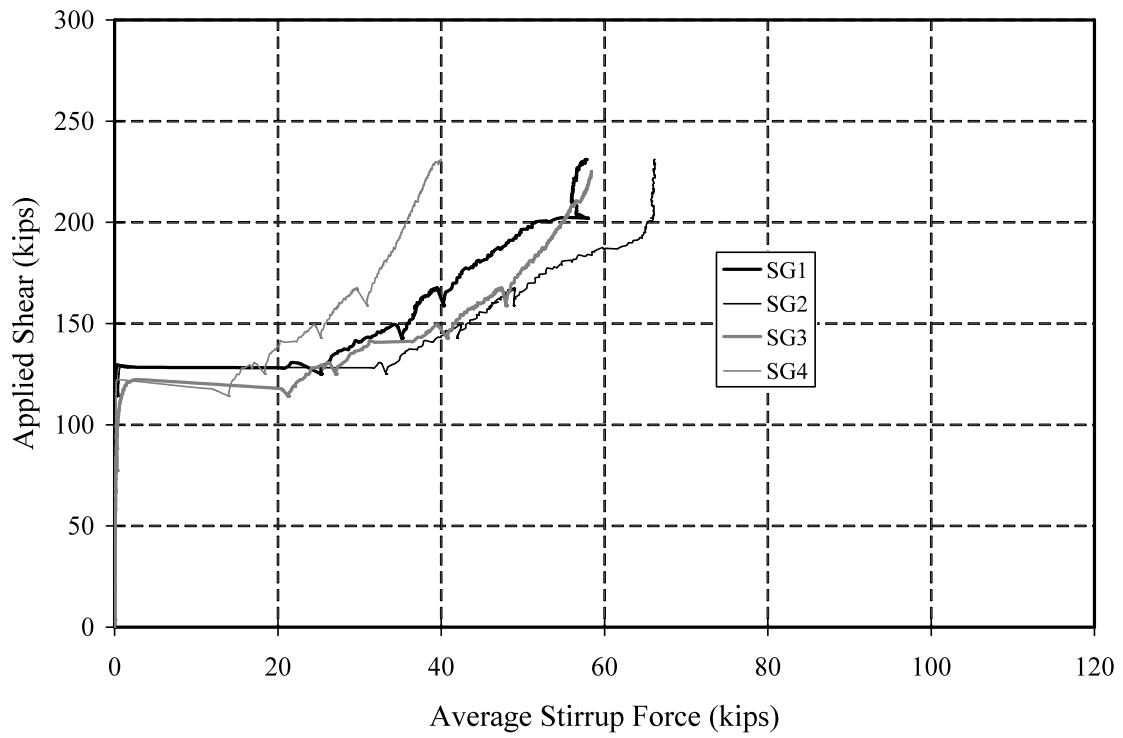


(b) Load vs. Stirrup Force (Near Supports)

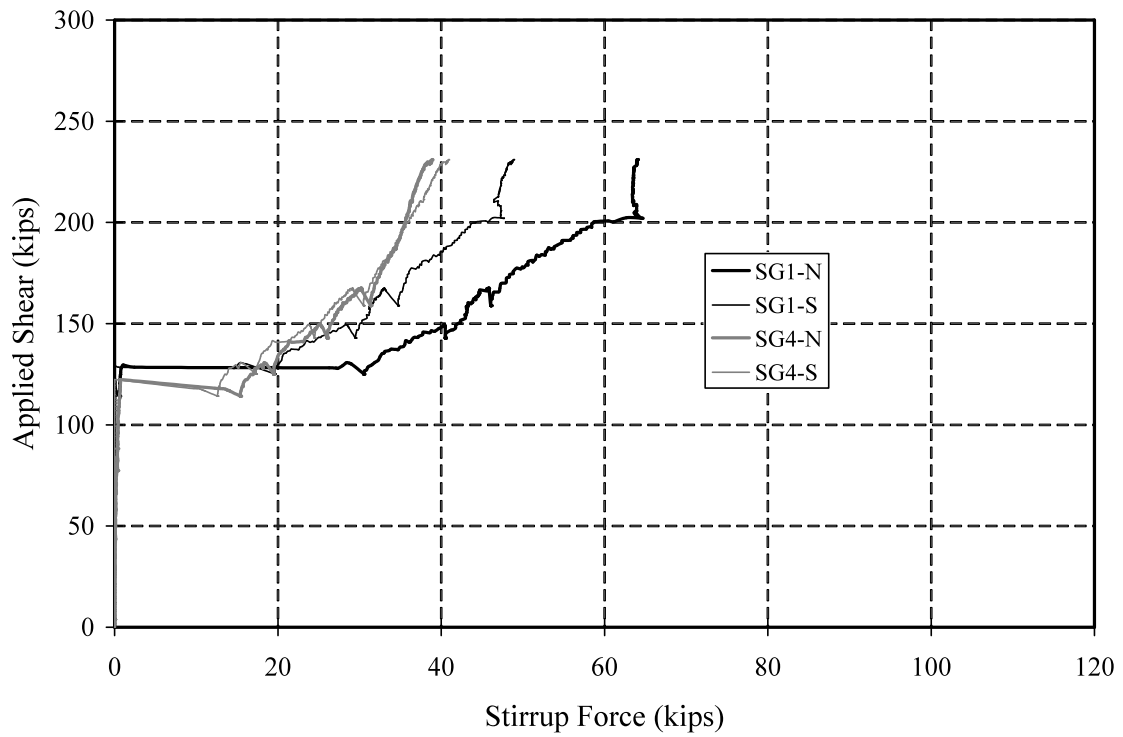
Figure F71 Stirrup Force Data for SP3



(c) Load vs. Stirrup Force (Near Load Points)
Figure F71 (cont.) Stirrup Force Data for SP3

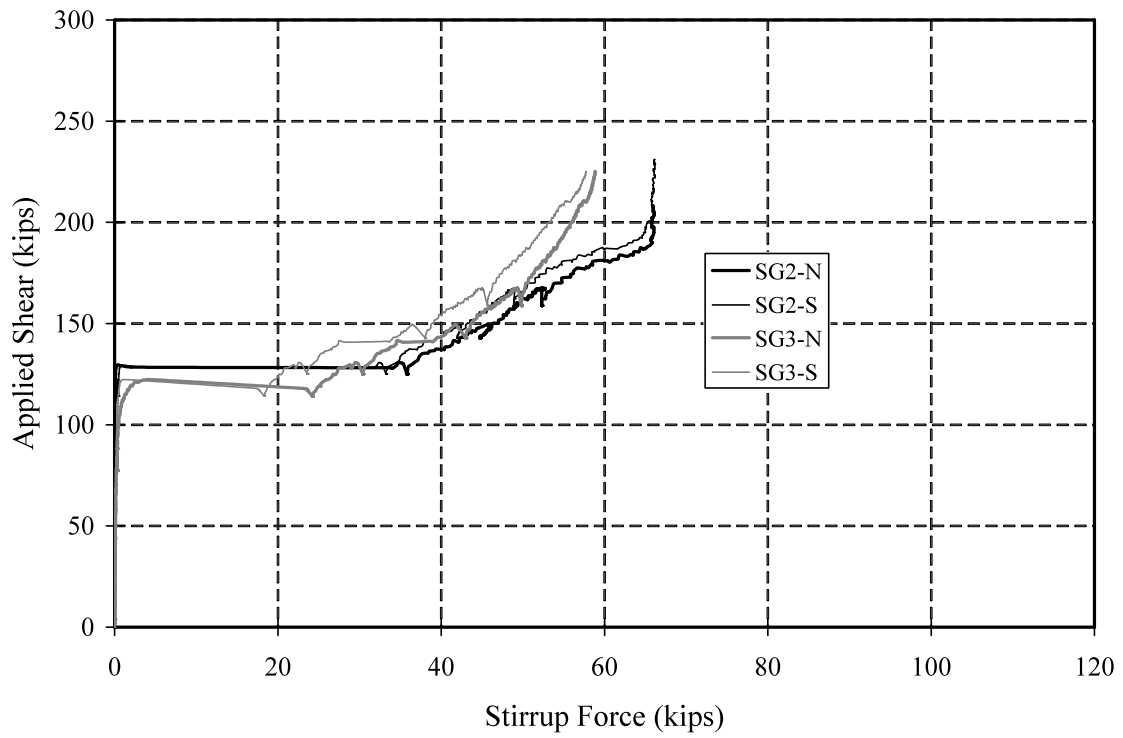


(a) Load vs. Average Stirrup Force (All Locations)



(b) Load vs. Stirrup Force (Near Supports)

Figure F72 Stirrup Force Data for SP4



(c) Load vs. Stirrup Force (Near Load Points)
Figure F72 (cont.) Stirrup Force Data for SP4