Appendix H
Beam Splice Specimens

H.1 Introduction

Specimen design, details, instrumentation, testing procedure, and material properties of eight beam splice specimens with #5 and #8 A1035 reinforcement are presented. A summary of all measured and visual data are also provided in this appendix.

H.2 Specimen Design

The splice lengths were computed based on the following equation, which was developed as part of NCHRP Project 12-60 (Ramirez and Russell 2008).

$$\ell_{db} = \left(\frac{3 f_y \psi_c \psi_t \psi_e \lambda}{40\sqrt{f'_c}\left(\dfrac{c_b + K_{tr}}{d_b}\right)} \right) d_b \qquad \text{(psi units)}$$

in which,

ℓ_{db} = development length (in.)

f_y = yield strength (psi)

ψ_c = Concrete strength factor

ψ_t = Bar location factor

ψ_e = Coating factor

ψ_s = Bar size factor

λ = Lightweight aggregate factor

f'_c = Concrete compressive strength (psi)

$$c_b = \text{Smaller of } \begin{cases} \text{Distance from center of bar to nearest concrete edge} \\ \text{one-half the center-center spacing of bars being developed} \end{cases}$$

K_{tr} = Transverse reinforcement factor, $\dfrac{A_{tr} f_{yt}}{1500 sn}$

A_{tr} = Total cross-sectional area of all transverse reinforcement having the center-to-center spacing, s, and a yield strength, f_{yt}

n = Number of bars being developed along the splitting plane

The values of various factors are as follows.

- ψ_c = Concrete strength factor
  - It is taken as 1.0 for $f'_c \leq 10{,}000$ psi and 1.2 for $f'_c > 10{,}000$ psi

- ψ_t = Reinforcement location factor
  - Horizontal reinforcement so placed that more than 12 *in* of fresh concrete is cast in the member below the development length or splice… ψ_t=1.3
  - Other reinforcement… ψ_t=1.0
- ψ_e=Coating factor
  - Epoxy-coated bars or wires with cover less than 3d_b, or clear spacing less than 6d_b… ψ_e=1.5
  - All other epoxy-coated bars or wires… ψ_e=1.2
  - Uncoated and galvanized reinforcement … ψ_e=1.0
    - However, the product, $\psi_t\psi_e$, need not be taken greater than 1.7
- ψ_s=Reinforcement size factor
  - No.6 and smaller bars and deformed wires… ψ_s=0.8
  - No.7 and larger bars… ψ_s=1.0
- λ=Lightweight aggregate concrete factor
  - For normal weight concrete, λ = 1
  - Where lightweight concrete is used, λ is limited to 0.75 unless f_{ct} is specified, for such cases, λ is permitted to be taken as $\dfrac{f_{ct}}{\left(6.7\sqrt{f'_c}\right)} \leq 1.0$
- The value of $\dfrac{c+K_{tr}}{d_b}$ cannot be taken greater than 2.5.

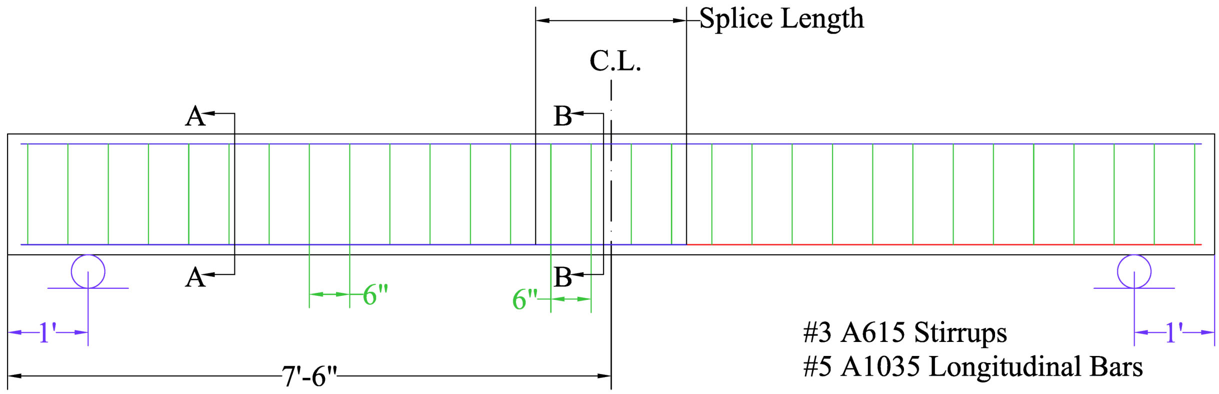
Using the aforementioned equation, the required splice lengths for eight beam splice specimens were calculated. The test specimens involved #5 and #8 spliced bars cast in 10-ksi and 15-ksi concrete. For all the specimens, #3 Grade 60 A615 transverse reinforcement was provided over the splice length. The parameters used in the calculations are summarized in Table H1.

H.3 Specimen Details

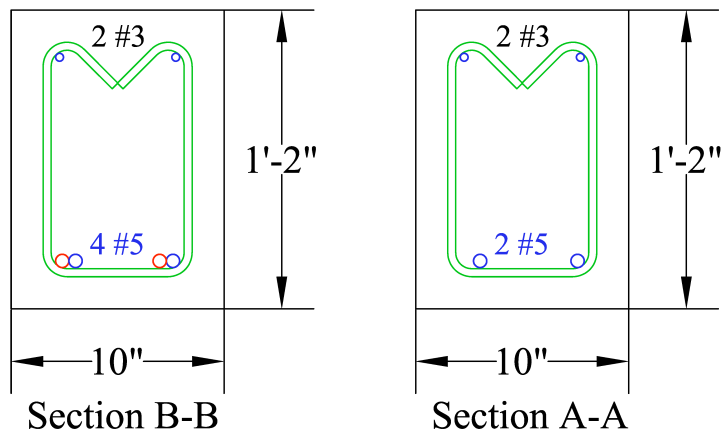
The specimen details are illustrated in Figure H1. Over the length of the splice, #3 Grade 60 A615 stirrups were spaced at 6" and 8" for #5 and #8 spliced bars, respectively. The measured concrete compressive strengths are summarized in Table H2. The concrete mix designs are summarized in Appendix A. The tabulated values are the strengths corresponding to when the specimens were tested. As indicated in Table A1, the 10-ksi specimens (i.e., D5-1, D5-2, D8-1, and D8-2) used batch 1 of #5 and #8 A1035 bars; batch 2 of #5 and #8 A1035 bars were used in D5-3, D5-4, D8-3, and D8-4 (i.e., the specimens cast in 15-ksi concrete). Refer to Figure A1 (a, b, e, and f) for the stress-strain relationships of these bars.

Table H1 Calculation of Splice Lengths for Various Specimens

Variable	Specimen							
	D5-1	**D5-2**	**D5-3**	**D5-4**	**D8-1**	**D8-2**	**D8-3**	**D8-4**
b (in.) - beam width	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
d_b (in.) - bar diameter	5/8	5/8	5/8	5/8	1.00	1.00	1.00	1.00
Target f_y (ksi)	100	125	100	125	100	125	100	125
f_{yt} (ksi) - yield strength of stirrups over the lap length	60	60	60	60	60	60	60	60
s (in.) - spacing of stirrups over the lap length	7	7	7	7	7	7	7	7
$A_{stirrups}$ (in.^{2}) - area of one leg of stirrups over the lap length	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
d_t (in.) - diameter of stirrups over the lap length	3/8	3/8	3/8	3/8	3/8	3/8	3/8	3/8
f'_c (ksi) - concrete strength	10	10	15	15	10	10	15	15
ψ_c - concrete strength factor	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
ψ_t - bar location factor	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ψ_e - coating factor	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
λ - lightweight aggregate factor	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Side cover to stirrups (in.)	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Bottom cover to stirrups (in.)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Center-to-center of bars being developed (in.)	5.00	5.00	5.00	5.00	4.25	4.25	4.25	4.25
Clear space between splices (in.)	3.75	3.75	3.75	3.75	2.25	2.25	2.25	2.25
c_b (in.)	1.69	1.69	1.69	1.69	1.88	1.88	1.88	1.88
A_{tr} (in.^{2}) - vertical splitting failure	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
n - vertical splitting failure	1	1	1	1	1	1	1	1
K_{tr} - vertical splitting failure	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
A_{tr} (in.^{2}) - Horizontal splitting failure	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
n - horizontal splitting failure	2	2	2	2	2	2	2	2
K_{tr} - horizontal splitting failure	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Controlling value of K_{tr}	0.63	0.63	0.63	0.63	0.63	0.63	0.63	0.63
$(c_b+K_{tr})/d_b$	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
ℓ_d (in.)	22.5	28.1	18.4	23.0	36.0	45.0	29.4	36.7
ℓ_d (d_b)	36	45	29	37	36	45	29	37



(a) Elevation



(b) Cross Section

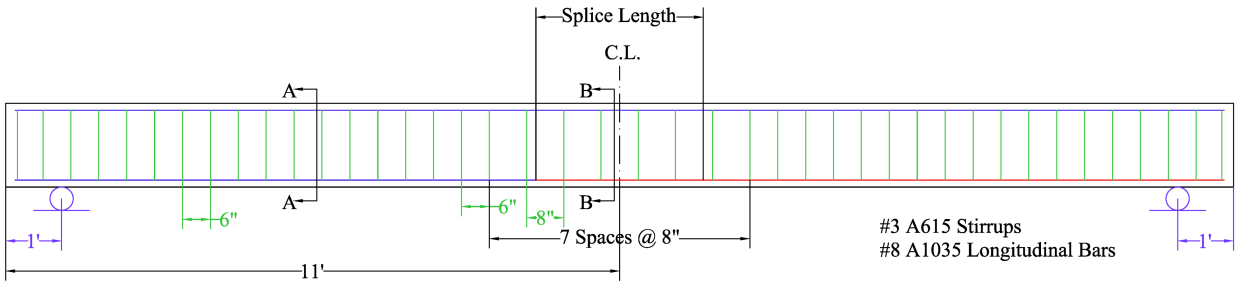
Splice Length	**Specimen**			
	D5-1	**D5-2**	**D5-3**	**D5-4**
Target f_y (ksi)	100	125	100	125
Design f'_c (ksi)	10	10	15	15
ℓ_d (in.)	22 1/2	28 1/8	18 3/8	23
ℓ_d (d_b)	36	45	29	37

(c) Provided Splice Lengths

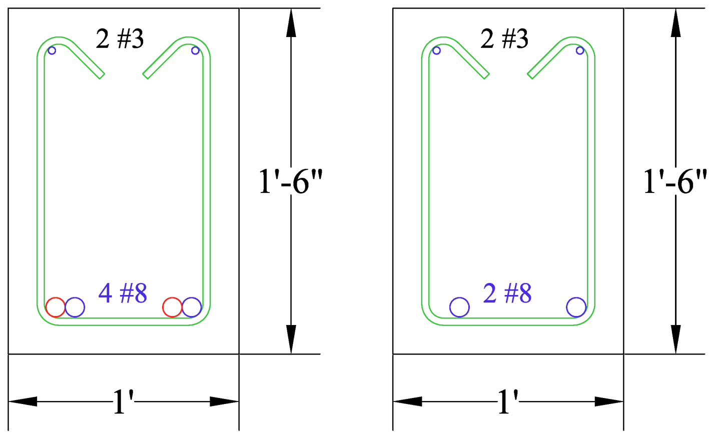
Specimen	**Length**	**Width (in)**	**Depth (in)**	**Effective Depth (in)**
D5-1	15'-0"	10.20	14.06	11.92
D5-2	15'-0"	10.15	14.04	11.97
D5-3	15'-0"	10.14	14.48	12.29
D5-4	15'-0"	10.05	14.18	11.99

(d) As-built Dimensions

Figure H1 Details of Splice Specimens - #5 bars



(a) Elevation



Section B-B   Section A-A

(b) Cross Section

Splice Length	Specimen			
	D8-1	**D8-2**	**D8-3**	**D8-4**
Target f_y (ksi)	100	125	100	125
Design f'_c (ksi)	10	10	15	15
ℓ_d (in.)	36	45	29 3/8	36 3/4
ℓ_d (d_b)	36	45	29	37

(c) Provided Splice Lengths

Specimen	Length	Width (in)	Depth (in)	Effective Depth (in)
D8-1	22'-0"	12.23	18.05	15.80
D8-2	22'-0"	12.25	18.19	15.82
D8-3	22'-0"	12.09	17.99	15.62
D8-4	22'-0"	12.03	18.13	15.76

(d) As-built Dimensions

Figure H1 (cont.) Details of Splice Specimens - #8 bars

Table H2 Measured Concrete Compressive Strength*

Specimen	f'_c (ksi)
D5-1	12.72
D5-2	12.72
D5-3+	15.50
D5-4+	15.50
D8-1	13.30
D8-2	13.30
D8-3+	14.42
D8-4+	14.42

* Strengths corresponding to when the specimens were tested.
+ The compressive strength was established based on cores taken from the ends of the specimens[*]. The core strengths were corrected to obtain equivalent in-place strength (Wight and MacGregor, 2009). The other strengths are based on 4”×8” cylinders that were “field cured”, i.e., these cylinders were kept near the specimens at the lab.

The value of concrete strength affects the splice length required to develop the target stress. Using the same variables shown in Table H1, the splice lengths were recalculated based on the measured concrete strengths (Table H2). Table H3 summarizes the difference between the splice length based on the design concrete strengths and the required splice length if the measured concrete strengths are used in the calculations. For specimens D5-1, D5-2, D8-1, and D8-2 in which the actual concrete strengths were higher than the design value of 10 ksi, the provided splice lengths were 11 to 13% longer than what would be used to develop the target stresses of 100 or 125 ksi. To a lesser degree (1.6%), the provided splice lengths for D5-3 and D5-4 were also longer than what is needed to develop 100 and 125 ksi. On other hand, the provided splice lengths for D8-3 and D8-4 are less than what is need because the measured concrete strength was slightly less than the concrete strength used in the design calculations. These differences are within normal construction variations.

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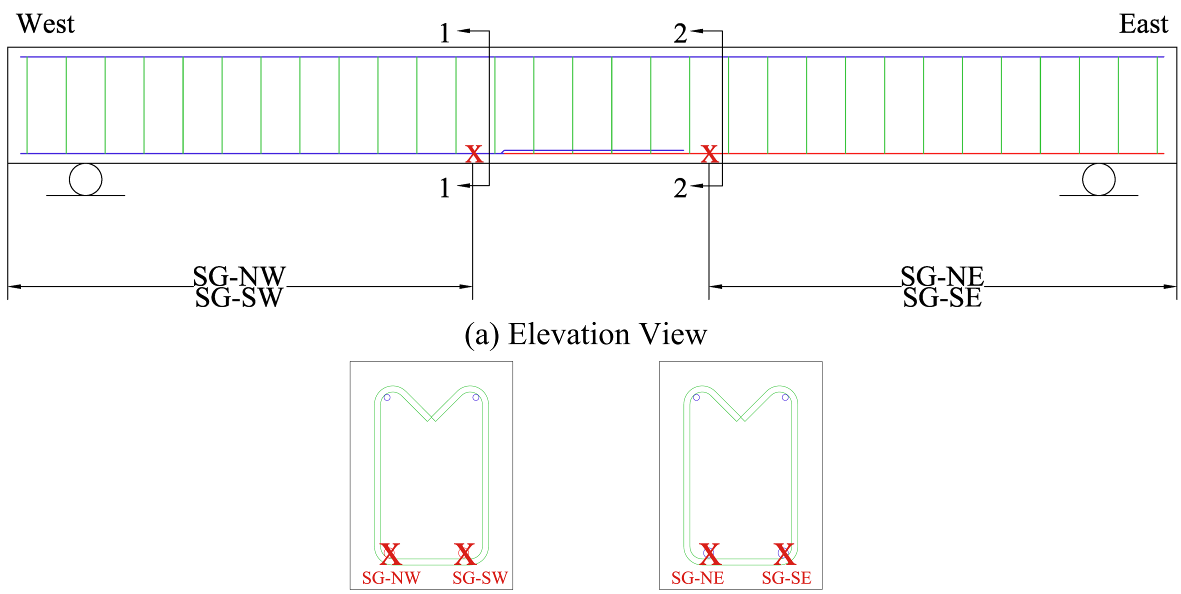
Core Locations

Table H3 Difference in Splice Length

Difference	Specimen							
	D5-1	**D5-2**	**D5-3**	**D5-4**	**D8-1**	**D8-2**	**D8-3**	**D8-4**
Length (in.)	4.08	5.10	0.48	0.60	4.78	5.98	-0.59	-0.74
Percentage	11.3%	11.3%	1.6%	1.6%	13.3%	13.3%	-2.0%	-2.0%

H.4 Instrumentation

Four strain gages were bonded to the ends of the spliced bars to measure the strains and hence assess whether the target stresses could be developed. The strain gage locations are shown in Figure H2. At the midspan, two strain gages were bonded to the sides of the beam near the top surface in order to measure the concrete compressive strain, refer to Figure H3. As shown in Figure H4, a wire potentiometer was attached to the soffit of the beam to measure the midspan deflection.



Section 1-1 Section 2-2

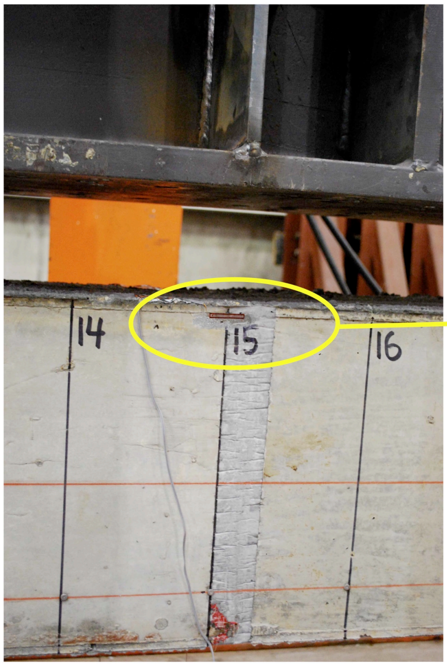
(b) Cross Section View

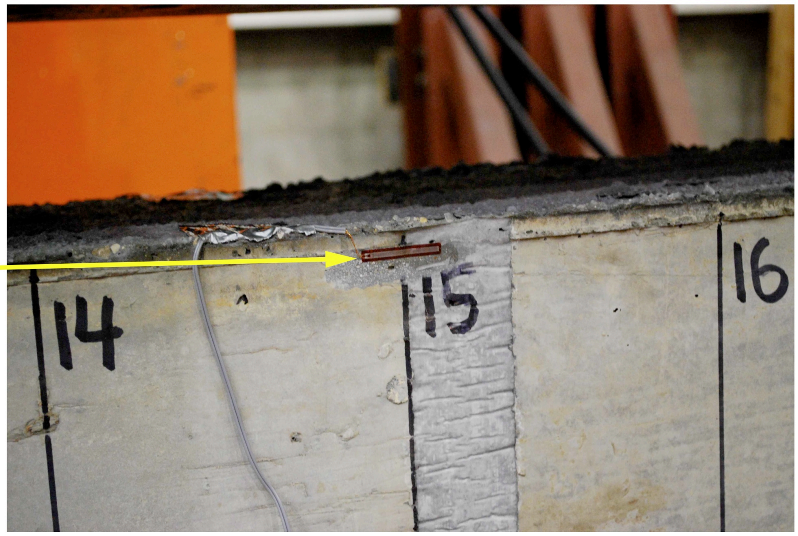
Strain Gage Label	**Specimen**							
	D5-1	**D5-2**	**D5-3**	**D5-4**	**D8-1**	**D8-2**	**D8-3**	**D8-4**
SG-NW	71.75	71.63	78.50	76.50	100.38	100.75	114.13	110.50
SG-SW	71.63	71.50	78.38	76.63	100.13	100.25	114.13	110.88
SG-NE	72.13	71.63	78.63	77.50	100.63	99.88	115.50	111.75
SG-SE	72.75	72.13	78.25	77.50	101.00	100.75	115.38	112.25

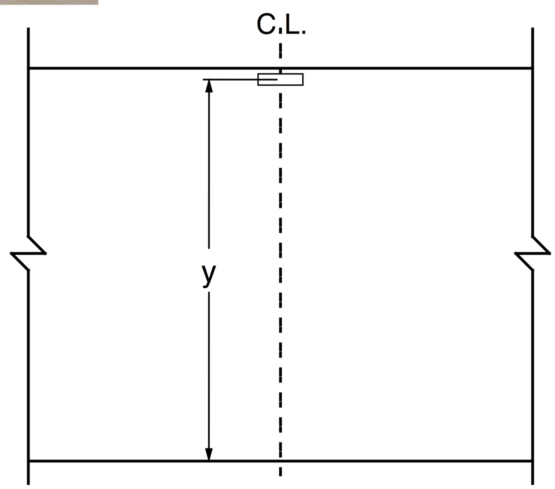
SG=Strain Gage; N, S=North, South; W, E=West, East

(c) Distances (in inches) from the West and East Ends

Figure H2 Strain Gage Locations







Dimension y (inches)

Specimen	South Face	North Face
D5-1	13 9/16	13 12/16
D5-2	13 11/16	13 1/16
D5-3	14 6/16	14 6/16
D5-4	13 14/16	13 14/16
D8-1	17 5/16	17 9/16
D8-2	17 8/16	17 9/16
D8-3	17 14/16	17 14/16
D8-4	17 3/16	17 11/16

Figure H3 Locations of Surface Strain Gages

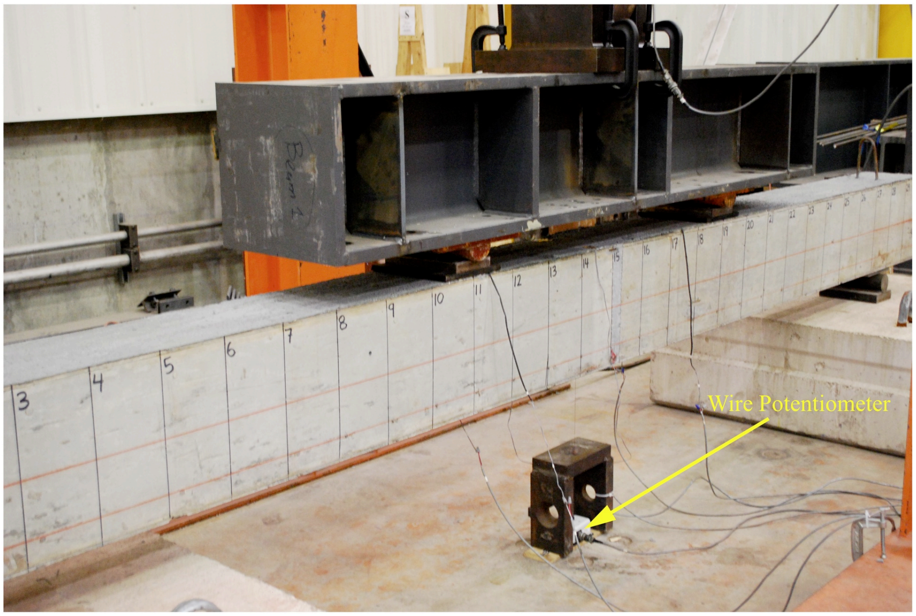


Figure H4 Instrumentation for Measuring the Midspan Deflection

H.5 Loading and Test Setup

The specimens were tested in a four-point loading arrangement, with the constant moment region of 4' and 6' for D5 and D8 specimens, respectively; refer to Figure H5. These lengths ensured that the splices would be subjected only to moment. The test setup is shown in Figure H6.

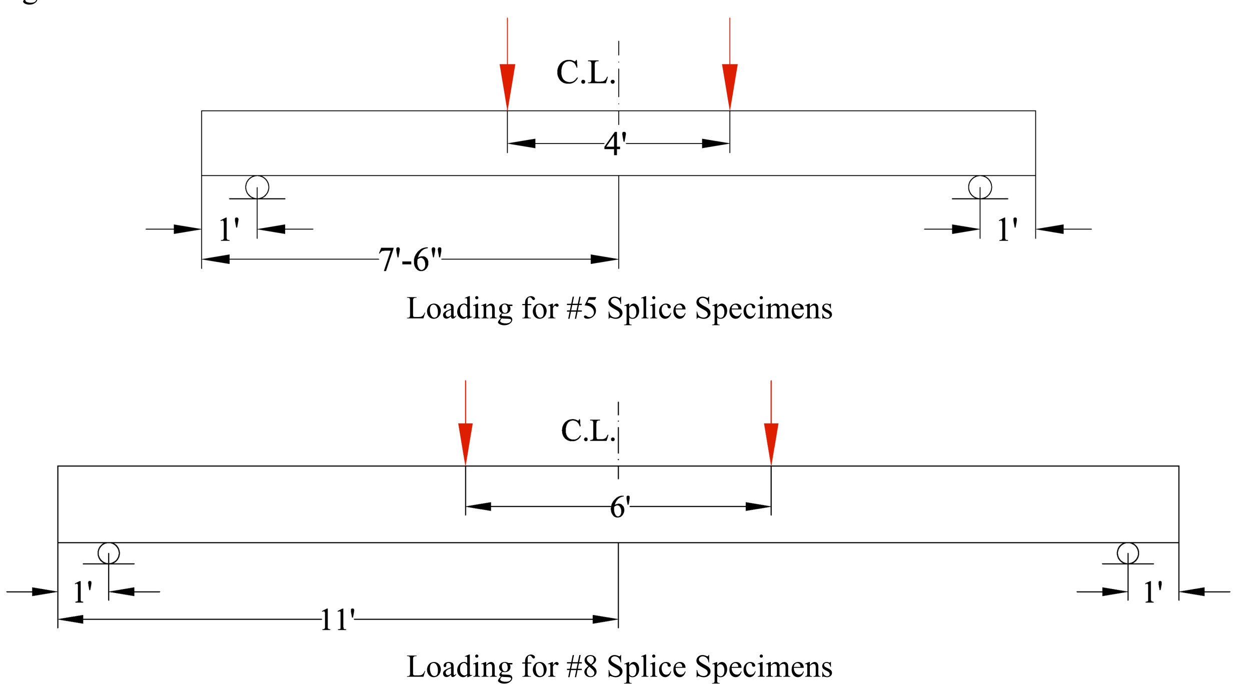
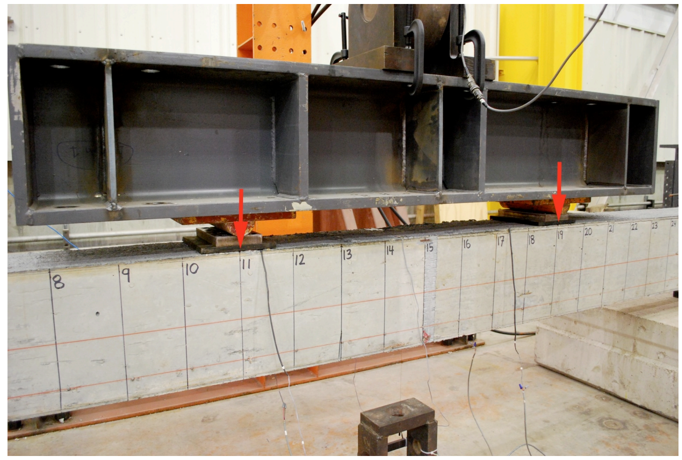


Figure H5 Loading Arrangement

Overall View



Loading Points

Figure H6 Test Setup

H.6 Test Results

A pictorial representation of the failure mode of the specimens is provided in Figure H7. With the exception of specimens D5-4 and D8-2, all the specimens exhibited splitting and slip at the splice ends after reaching and exceeding the target stress levels. In case of specimen D5-4, both of the spliced bars fractured. Specimen D8-2 did not exhibit characteristics of splice failure. The behavior of this specimen was similar to a beam with continuous bars, i.e., the failure was initiated by concrete crushing after developing large strains in the longitudinal bars.

The load-midspan deflection results are summarized in Figure H8. In addition to the measured load-deflection relationships, the analytical load-deflection responses are also shown. The analytical load-deflections were obtained by using a computer program called Response 2000 (Bentz 2000), which is abbreviated as R2K in Figure H8. The parameters needed to characterize the material properties of A1035 longitudinal bars and concrete are summarized in Table H4. In order to be able to use the Ramberg-Osgood function to define the stress-strain relationships of A1035 bars, the longitudinal bars were modeled as prestressing tendons with zero prestrain. The program's default values were used to define the Grade 60 transverse reinforcement. It should be noted that Response 2000 assumes that the longitudinal bars are continuous, and bond transfer along the splice length is not simulated. By comparing the computed load-deflection responses against their experimental counterparts, it will be possible to indirectly assess the effectiveness of splices. That is, if the measured load-deflections are close (within expected range of differences between experimental and analytical load-deflection responses of beams with continuous longitudinal bars) to the computed responses, the splices are effective to transfer the stresses in the longitudinal bars. The measured load-deflections for the #5 and #8 spliced beams are provided collectively in Figures E9a and E9b, respectively.

The load-longitudinal bar strains are plotted in Figure H10 separately for each specimen. On each plot, the strain corresponding to the target stress of 100 or 125 ksi is also shown. These strains were obtained from the measured stress-strain relationships reported in Appendix A. The average strain was obtained from the strains measured by the four strain gages. In case of specimen D8-3, strain gages SG-SW and SG-SE malfunctioned; hence, the average strain for this specimen is based on the data from SG-NW and SG-NE. Figure H11 depicts the relationship between the applied load and average longitudinal strain for #5 and #8 splices. The strains corresponding to 100 or 125 ksi are also shown in Figure H11. Due to slight differences between the stress-strain relationships of the bars, the target strains are different between the 10-ksi specimens (D5-1, D5-2, D8-1, and D8-2) and 15-ksi specimens (D5-3, D5-4, D8-3, and D8-4). All the specimens reached and exceeded their respective target stress. The load-concrete compressive strains measured on the south and north faces (see Figure H3 for the location of the strain gages) are plotted in Figure H12. Figure H13 shows the load-average concrete strain for the #5 and #8 spliced beams.

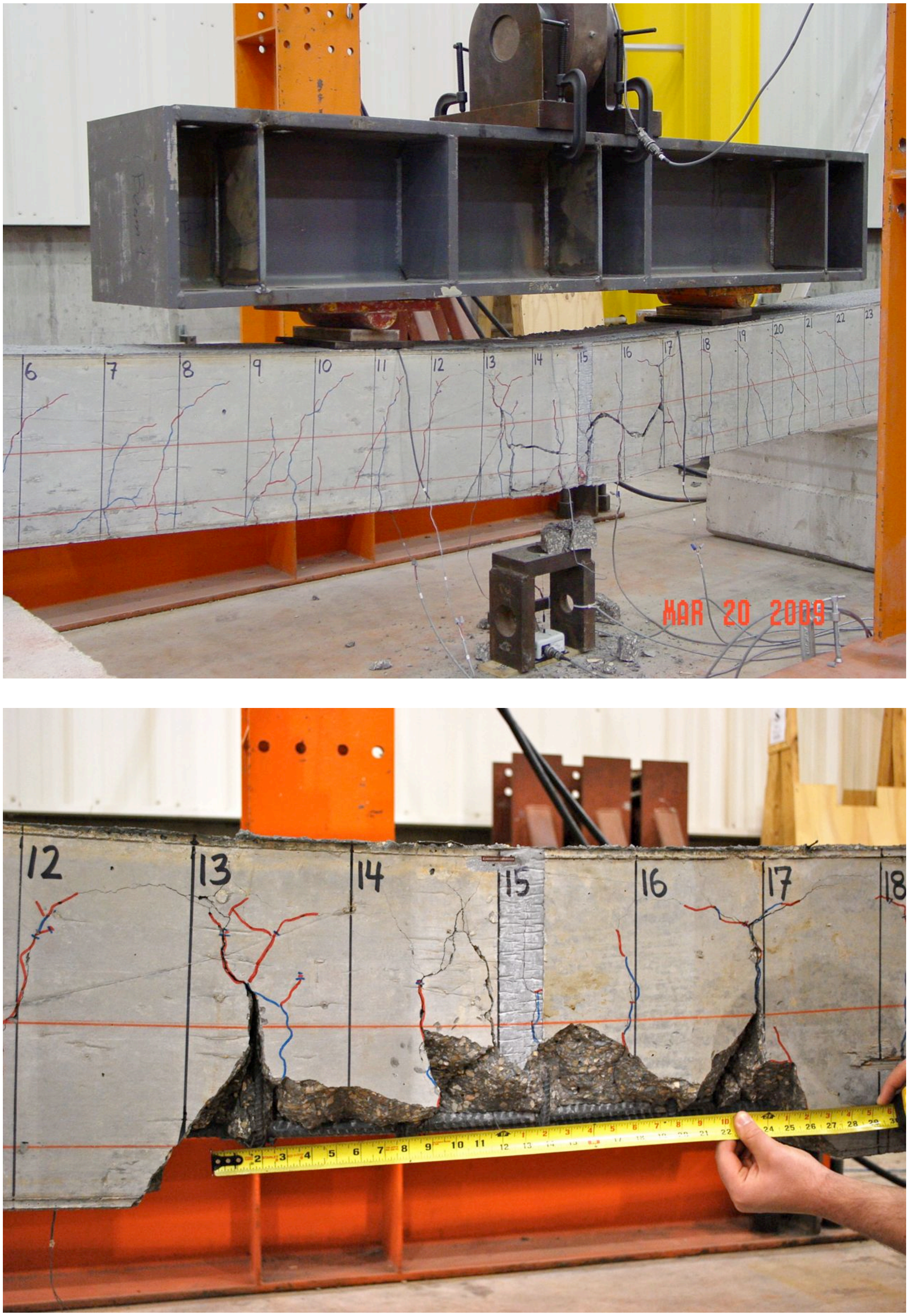
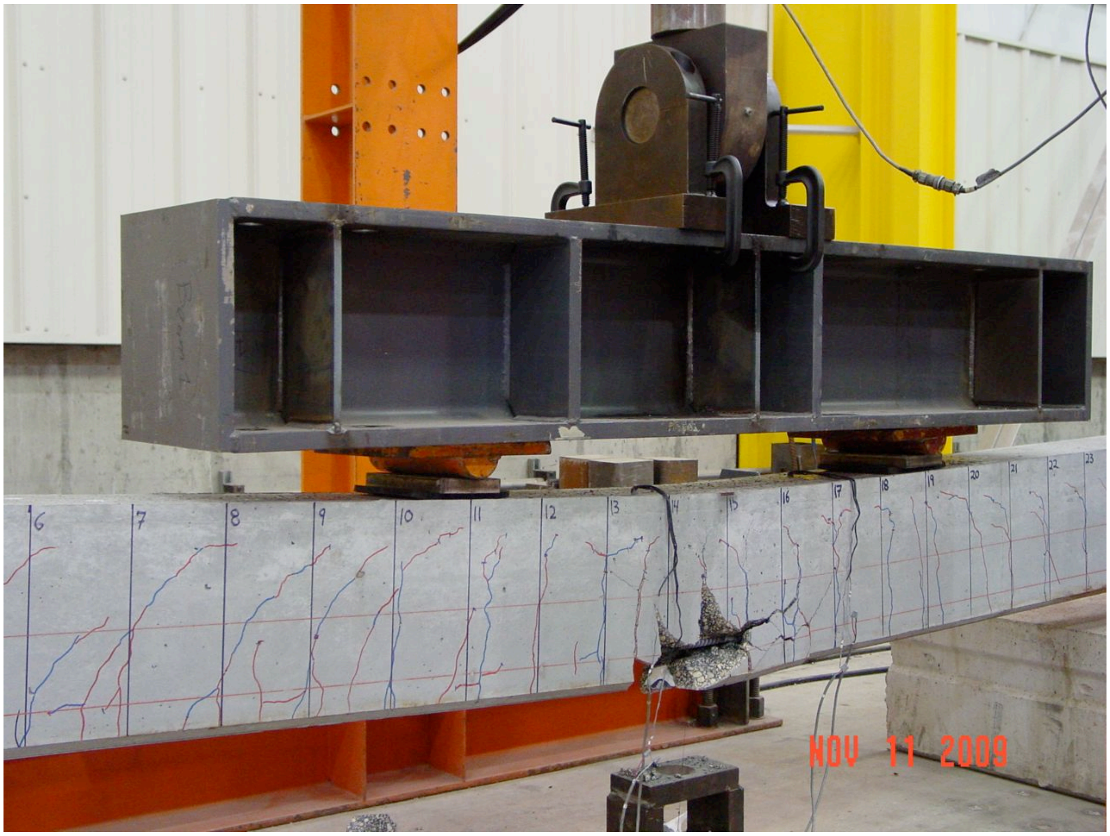


Figure H7 Failure Mode – Specimen D5-1

Figure H7 (cont.) Failure Mode – Specimen D5-2



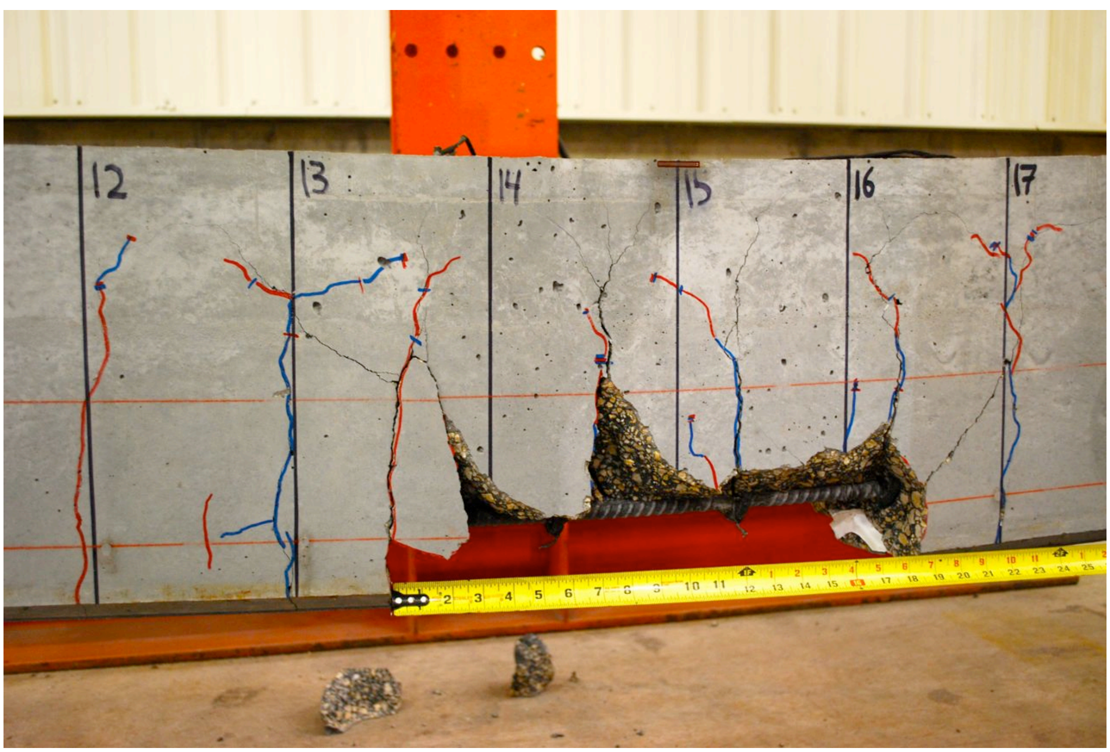
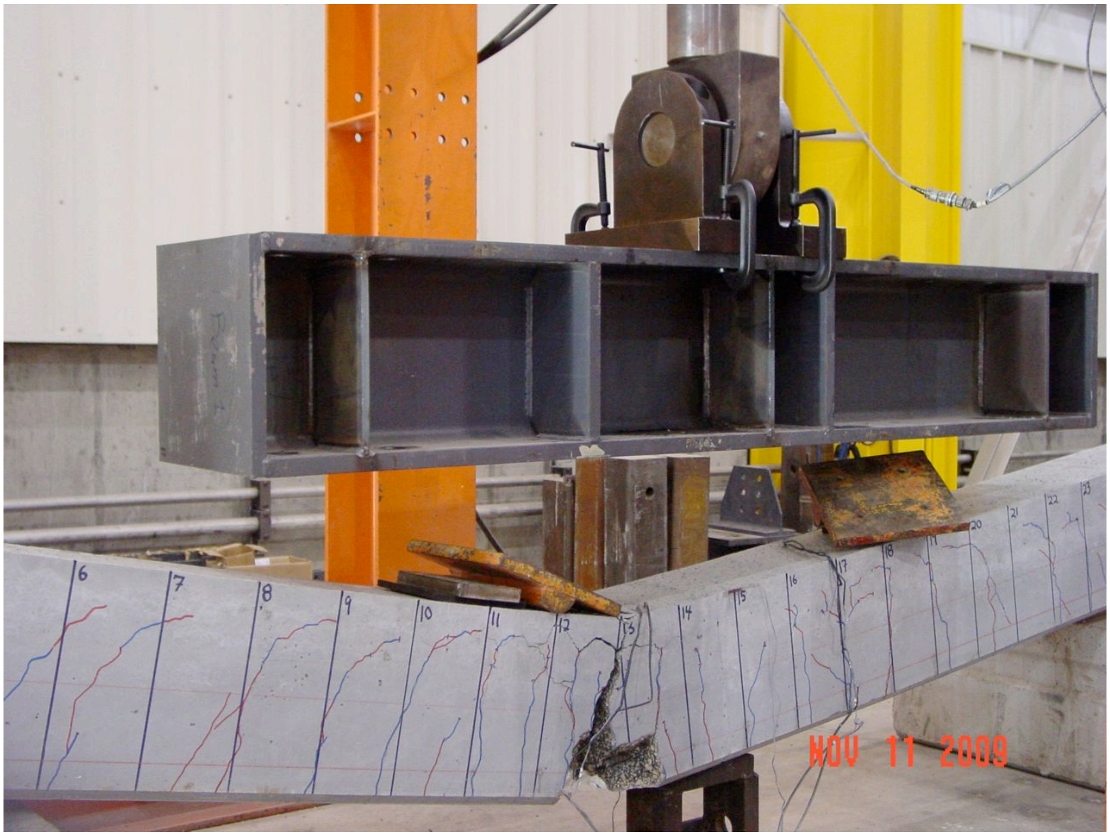


Figure H7 (cont.) Failure Mode – Specimen D5-3



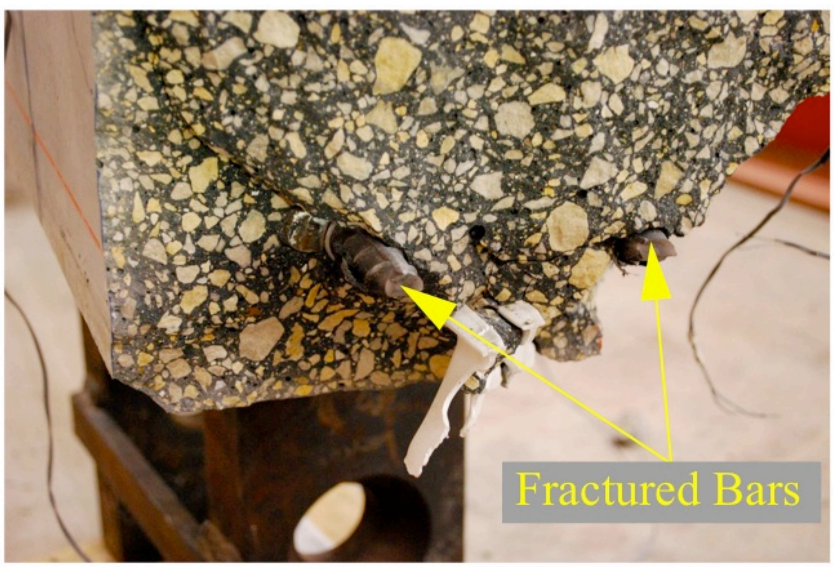


Figure H7 (cont.) Failure Mode – Specimen D5-4

Figure H7 (cont.) Failure Mode – Specimen D8-1

Figure H7 (cont.) Failure Mode – Specimen D8-2

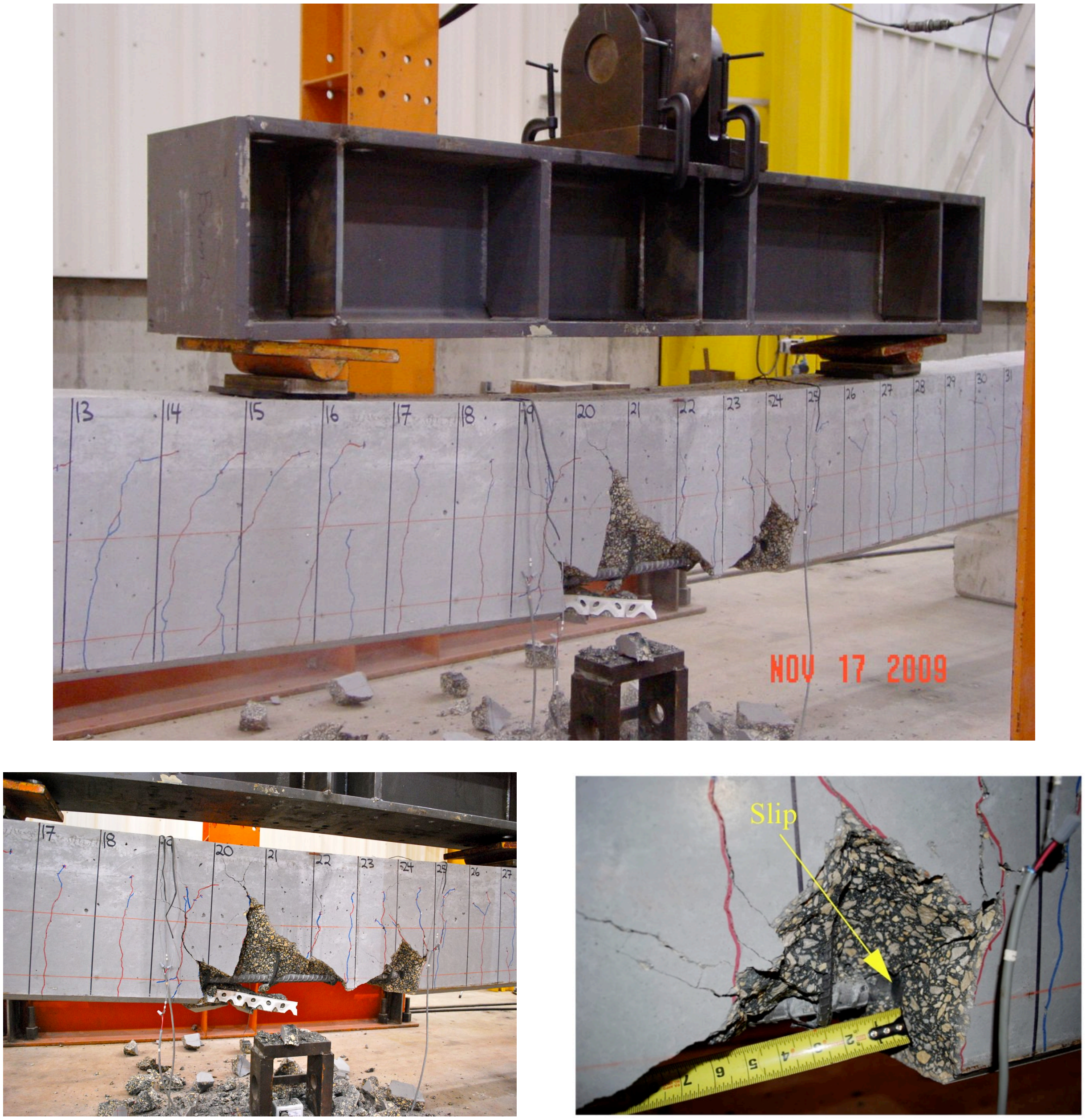


Figure H7 (cont.) Failure Mode – Specimen D8-3

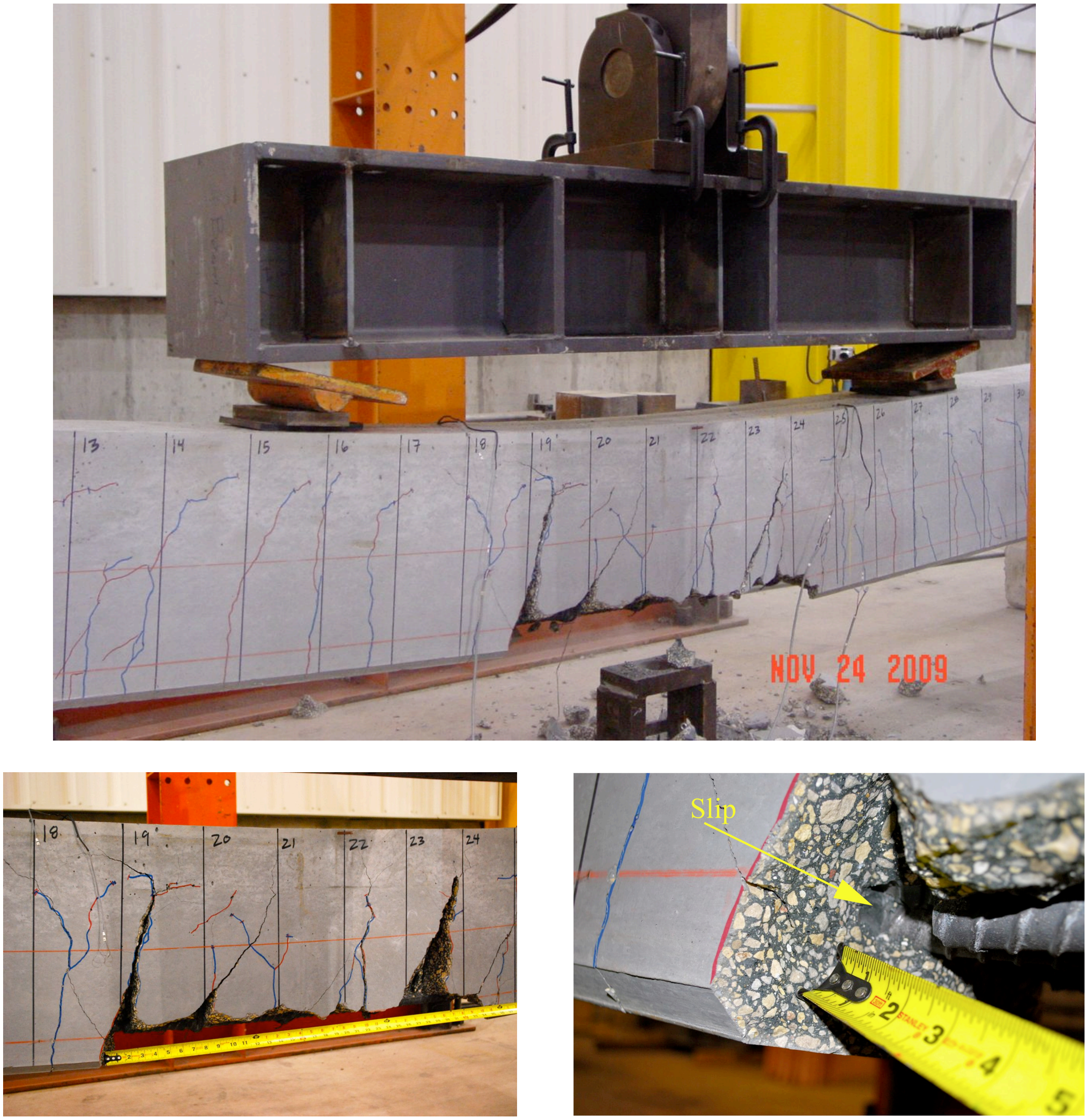


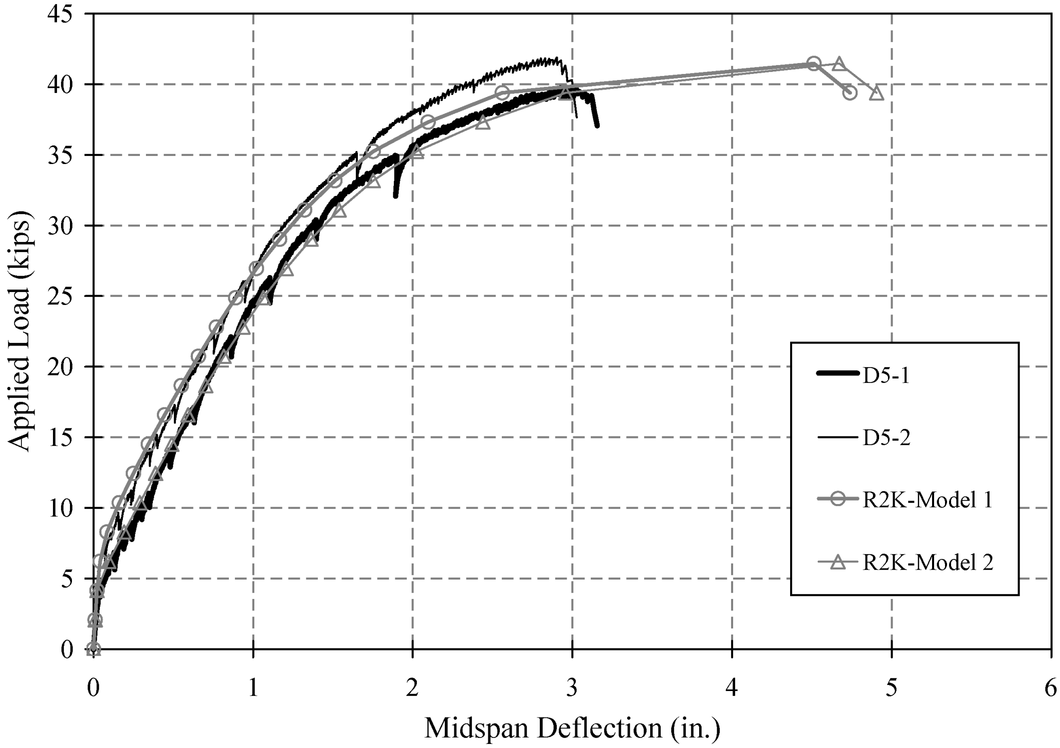
Figure H7 (cont.) Failure Mode – Specimen D8-4

Table H4 Response 2000 Modeling Parameters

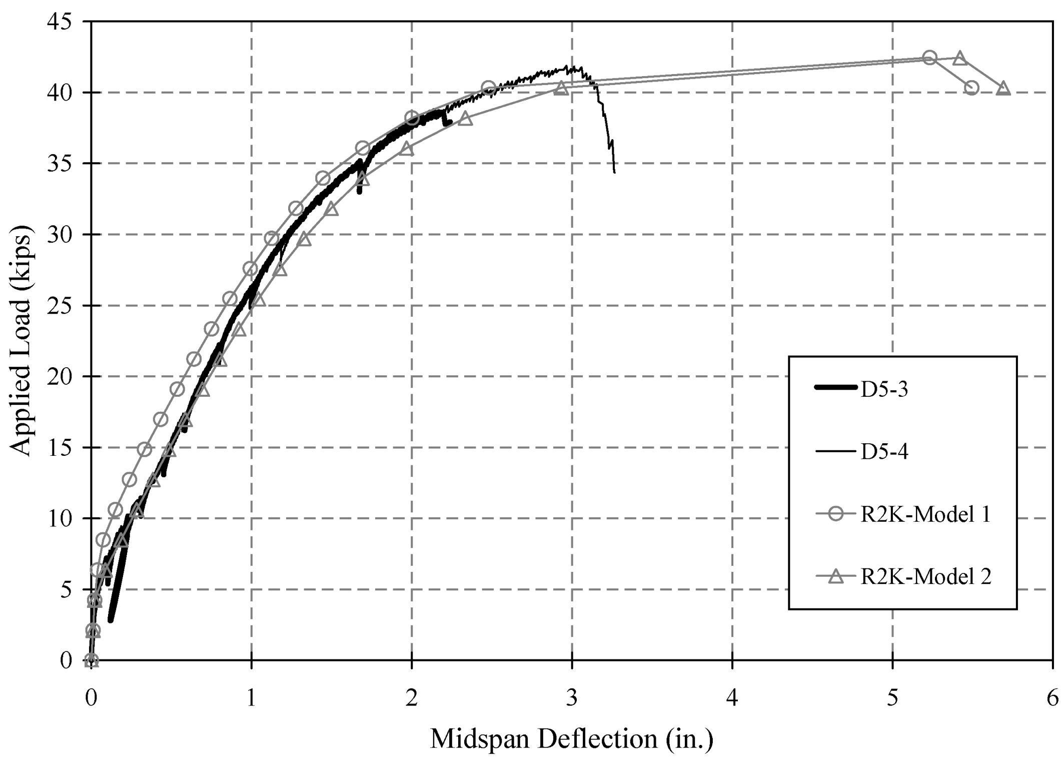
	Parameter	Specimen D5-1 or D5-2		Specimen D5-3 or D5-4	
		R2K-Model 1	R2K-Model 2	R2K-Model 1	R2K-Model 2
Ramberg-Osgood Parameters	A	0.01	0.01	0.01	0.01
	B	182	182	182	182
	C	2.2	2.2	2.5	2.5
	E_s (ksi)	29000	29000	29000	29000
	Ultimate stress (ksi)	162	162	165	165
	Fracture strain (milistrain)	60	60	60	60
Concrete Model Parameters	f'_c (psi)	12720	12720	15498	15498
	Tensile strength (psi) - Auto	391	391	423	423
	Peak strain (mili strain) - Auto	2.77	2.77	3.02	3.02
	Aggregate size (in.)	0.4	0.4	0.4	0.4
	Tension stiffening factor	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

	Parameter	Specimen D8-1 or D8-2		Specimen D8-3 or D8-4	
		R2K-Model 1	R2K-Model 2	R2K-Model 1	R2K-Model 2
Ramberg-Osgood Parameters	A	0.055	0.055	0.015	0.015
	B	225	225	200	200
	C	2.9	2.9	2.4	2.4
	E_s (ksi)	29000	29000	29000	29000
	Ultimate stress (ksi)	155	155	157	157
	Fracture strain (milistrain)	60	60	60	60
Concrete Model Parameters	f'_c (psi)	13300	13300	14415	14415
	Tensile strength (psi) - Auto	398	398	230	230
	Peak strain (mili strain) - Auto	2.83	2.83	2.92	2.92
	Aggregate size (in.)	0.4	0.4	0.4	0.4
	Tension stiffening factor	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

* PTC: Popovics/Thorenfeldt/Collins

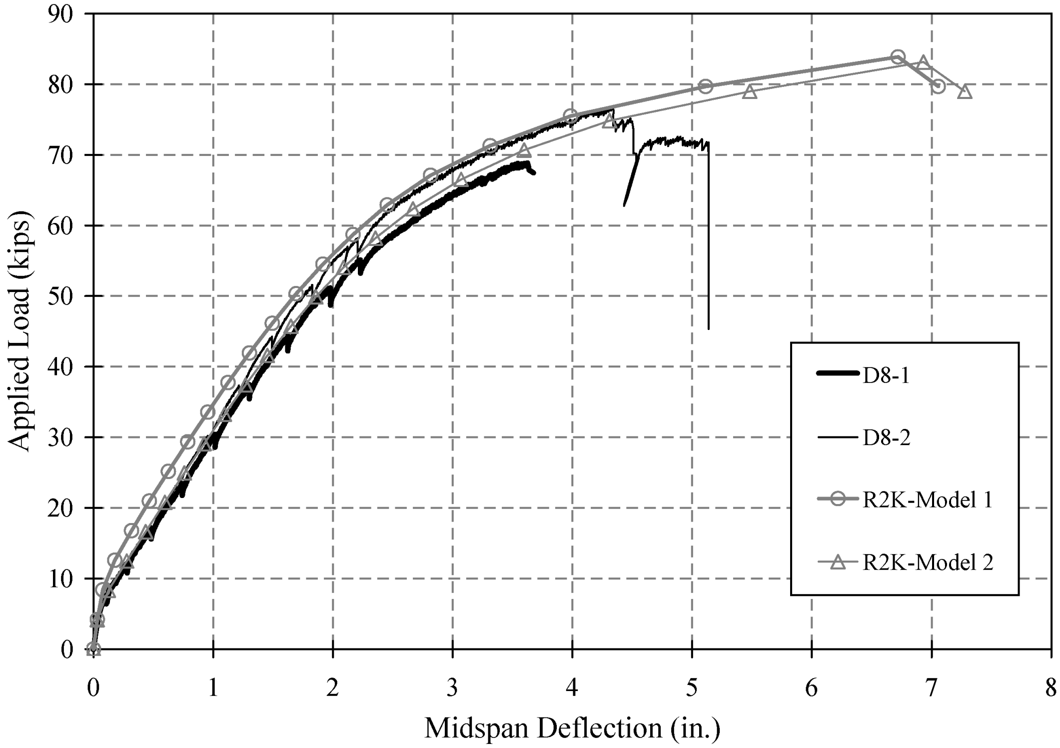


(a) Specimens D5-1 and D5-2

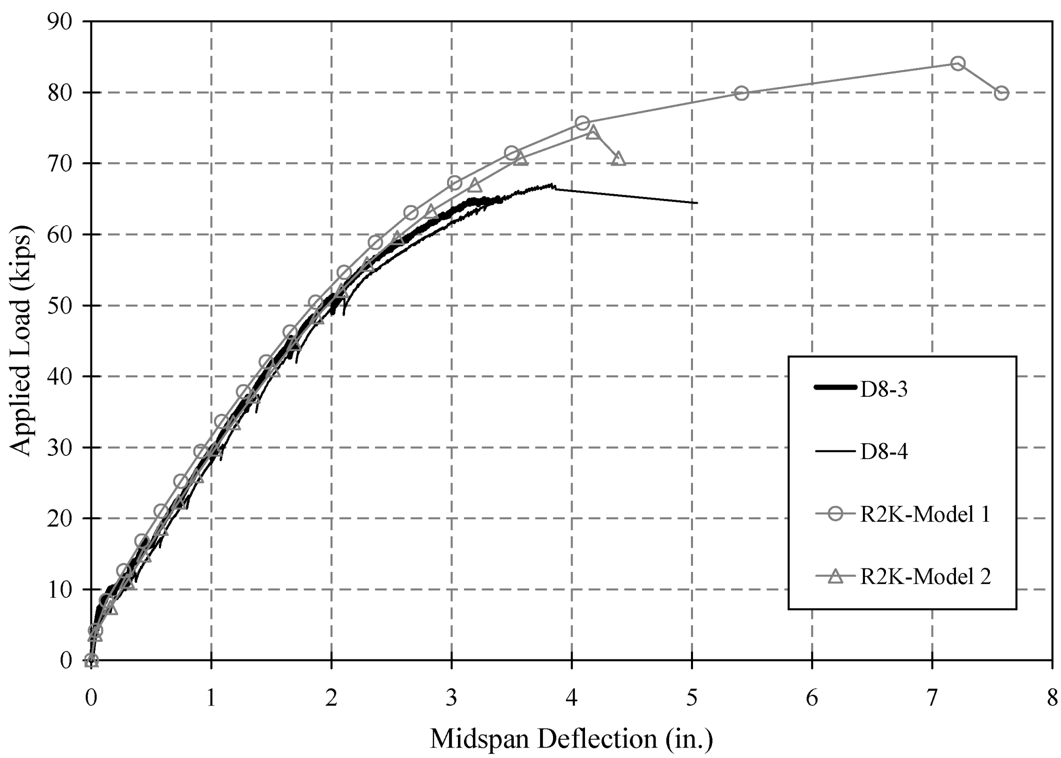


(b) Specimens D5-3 and D5-4

Figure H8 Load-Deflection Relationships

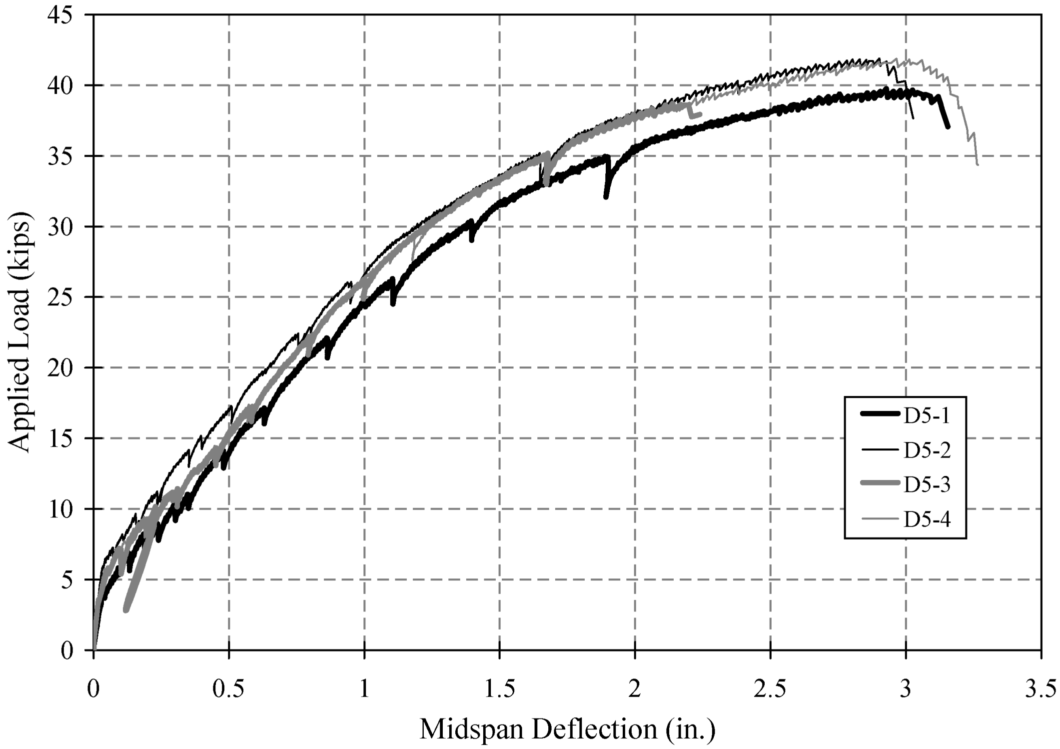


(c) Specimens D8-1 and D8-2

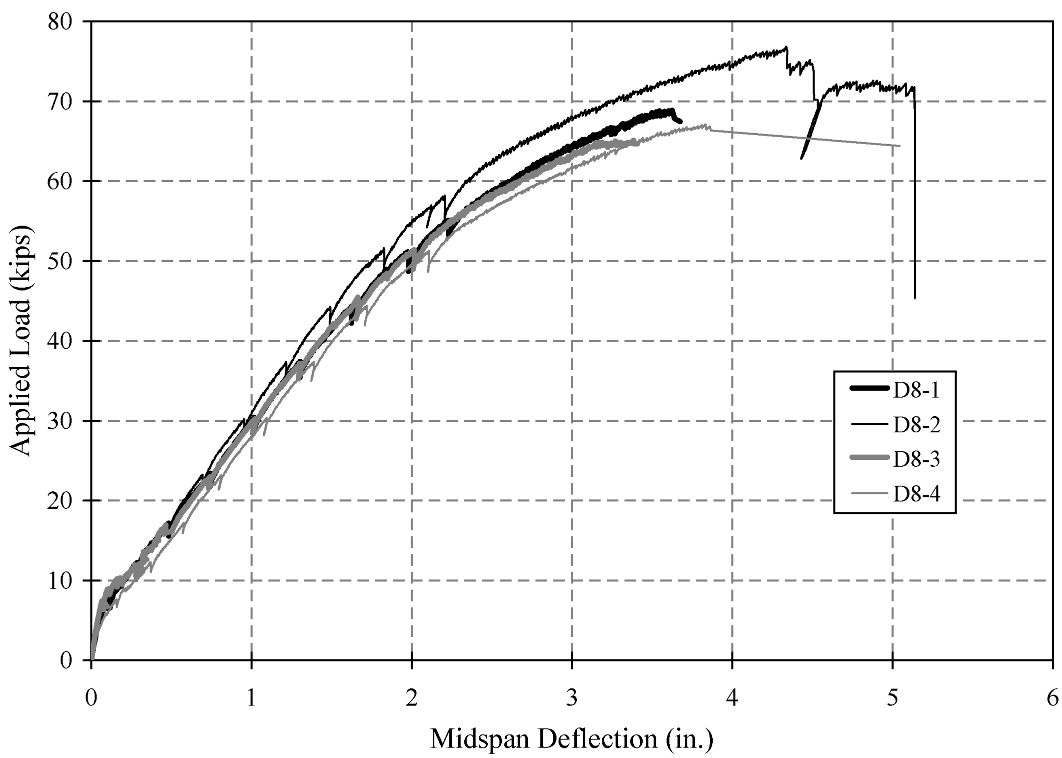


(d) Specimens D8-3 and D8-4

Figure H8 Load-Deflection Relationships (cont.)

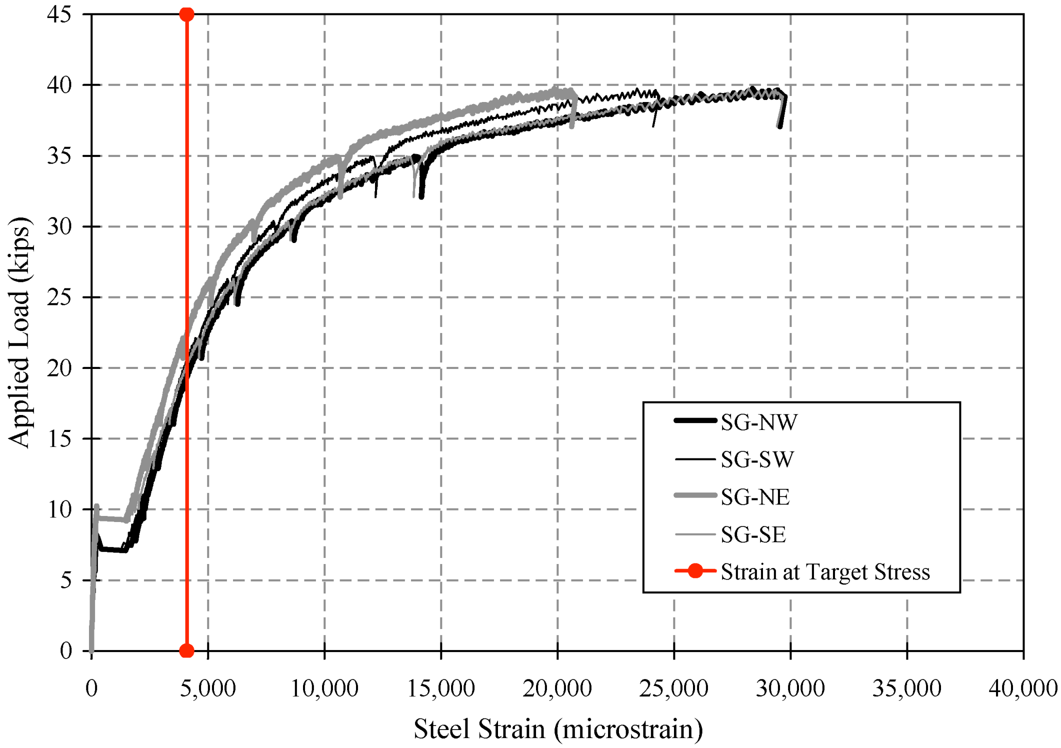


(a) Specimens D5-1, D5-2, D5-3, and D5-4

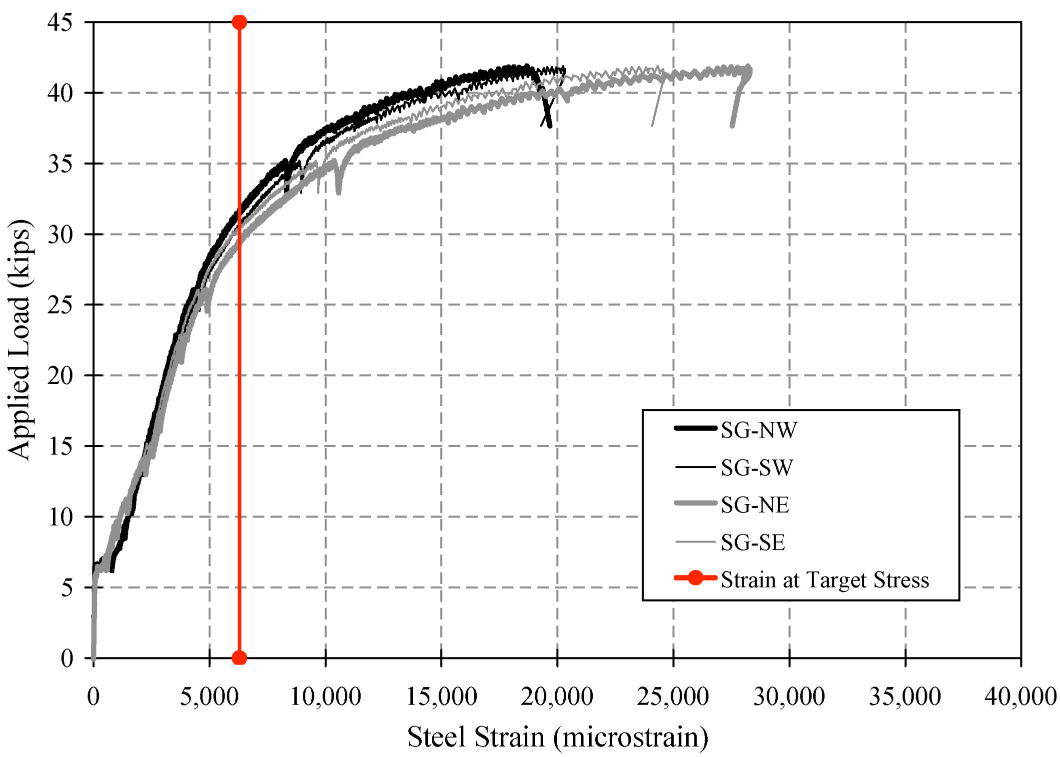


(b) Specimens D8-1, D8-2, D8-3, and D8-4

Figure H9 Combined Load-Deflection Relationships

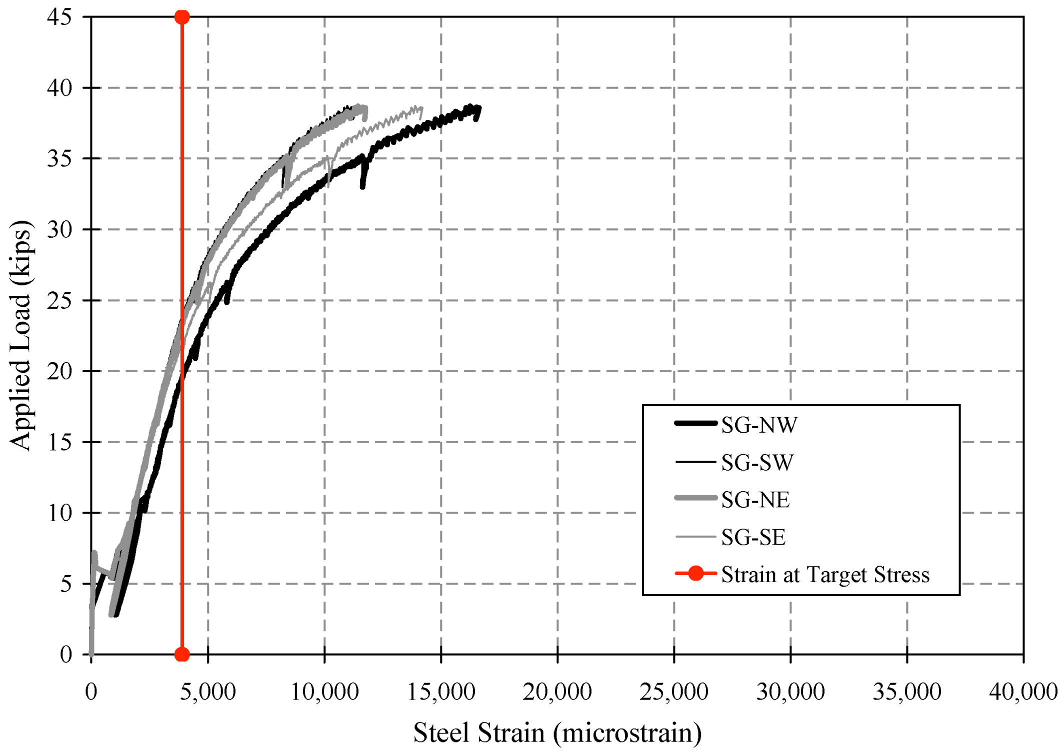


(a) Specimen D5-1

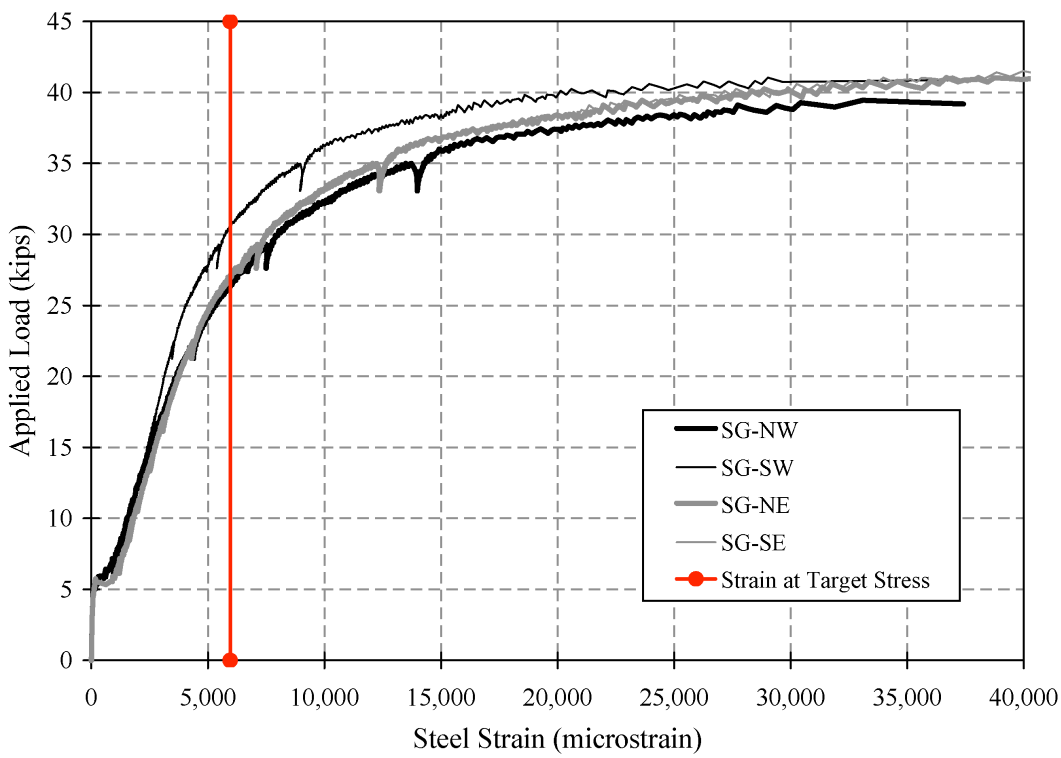


(b) Specimen D5-2

Figure H10 Load-Longitudinal Steel Strain Relationships

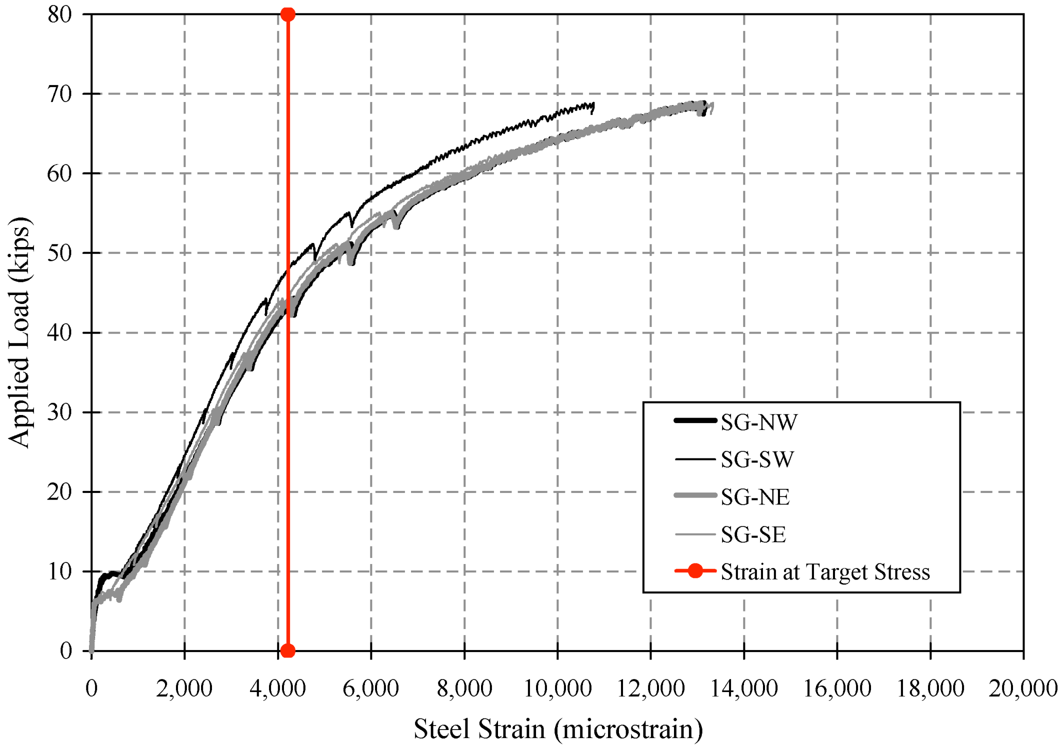


(c) Specimen D5-3

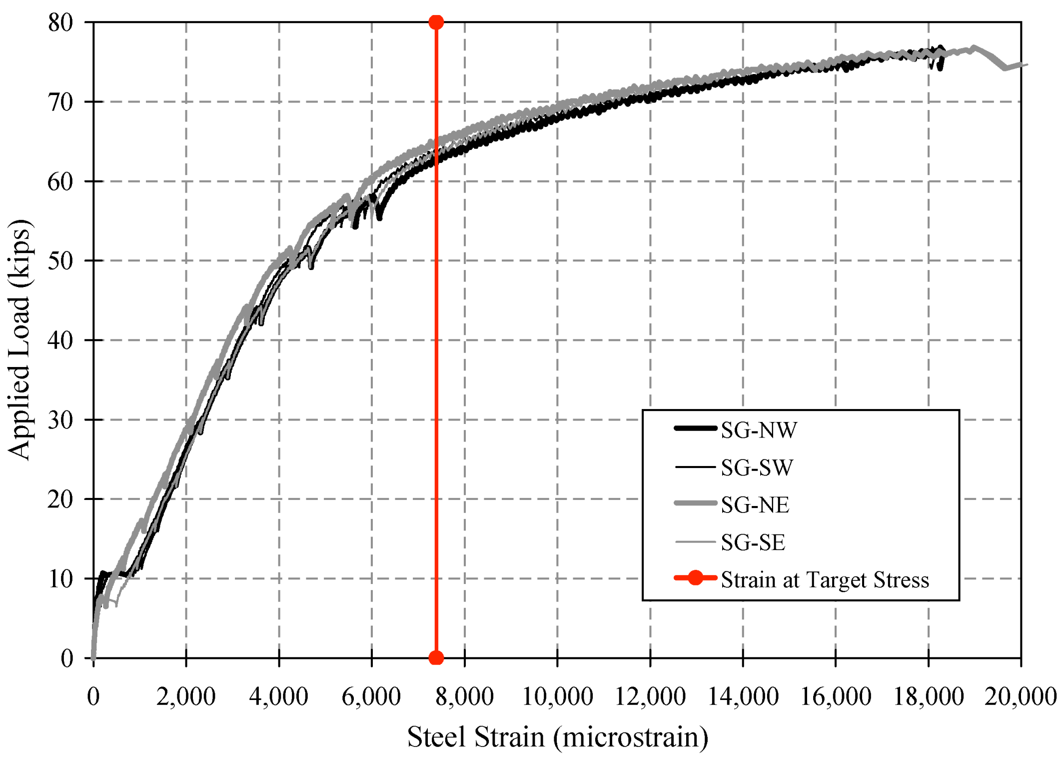


(d) Specimen D8-4

Figure H10 Load-Longitudinal Steel Strain Relationships (cont.)

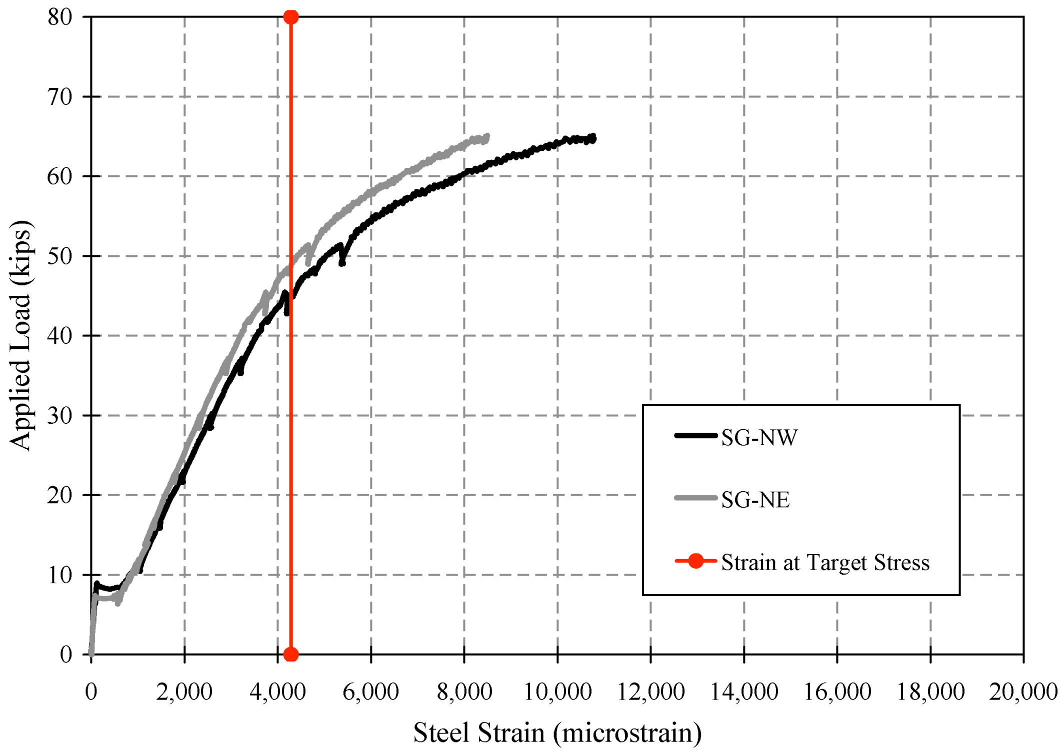


(e) Specimen D8-1

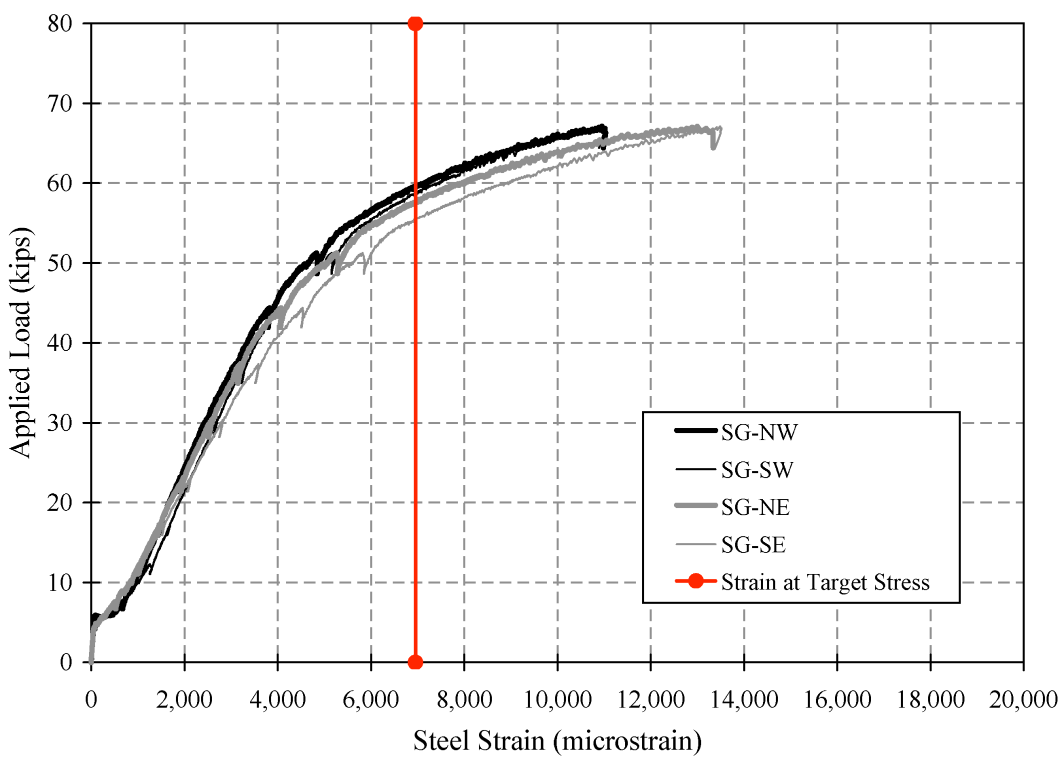


(f) Specimen D8-2

Figure H10 Load-Longitudinal Steel Strain Relationships (cont.)

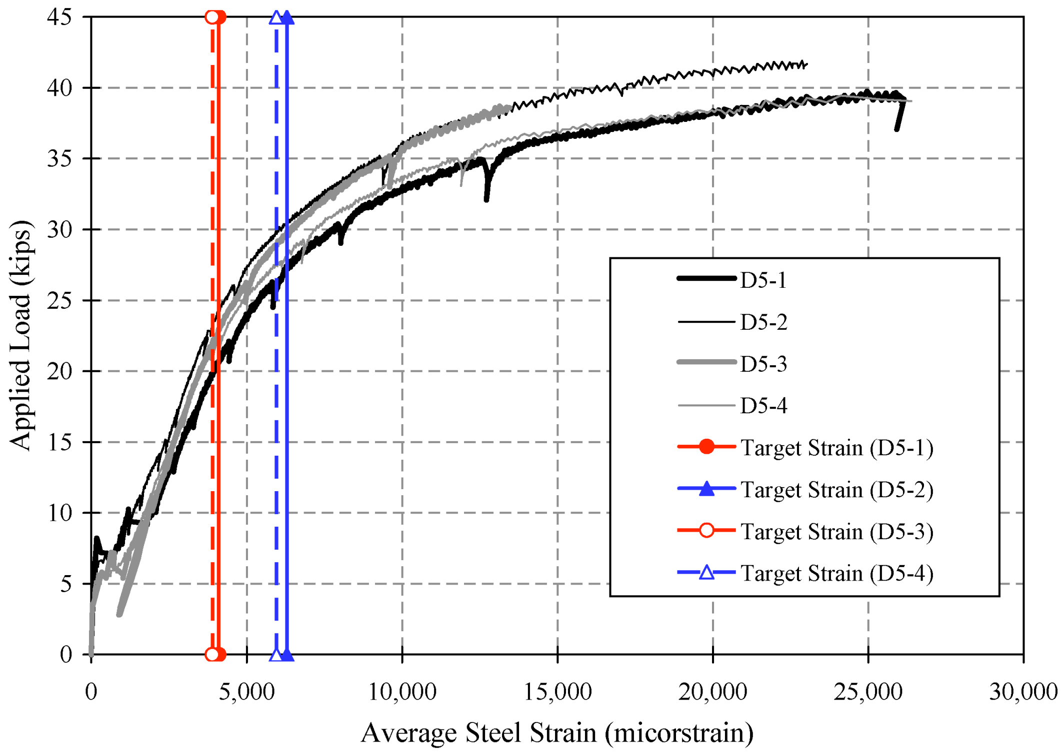


(g) Specimen D8-3

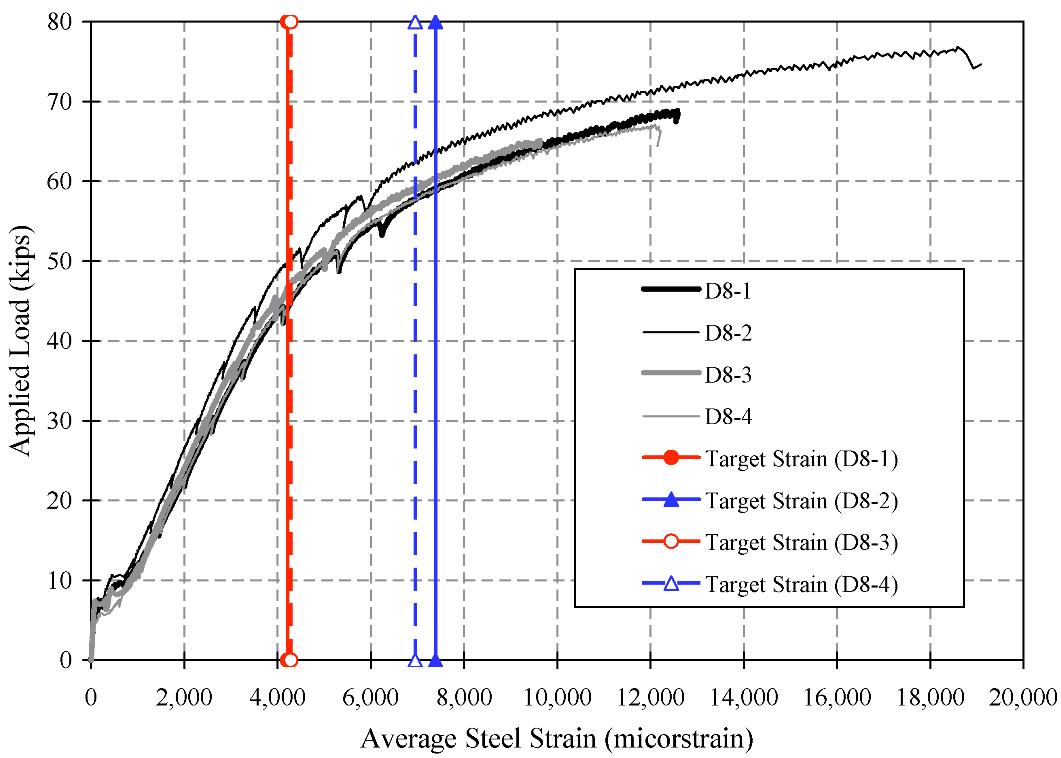


(h) Specimen D8-4

Figure H10 Load-Longitudinal Steel Strain Relationships (cont.)

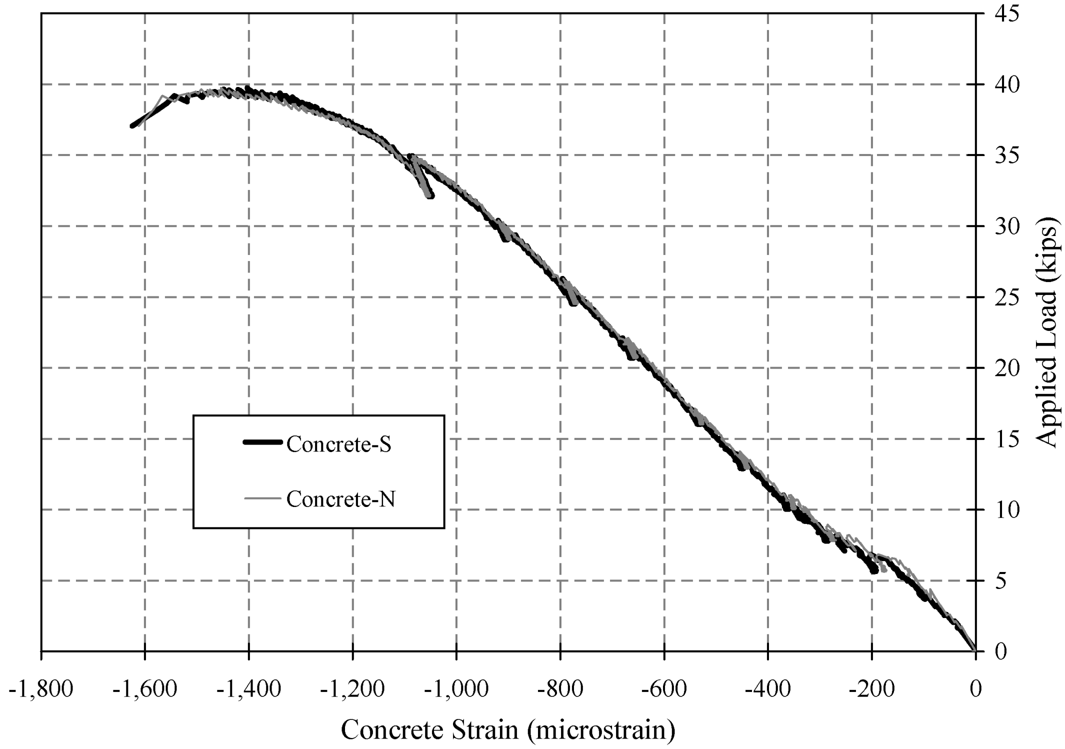


(a) Specimens D5-1, D5-2, D5-3, and D5-4

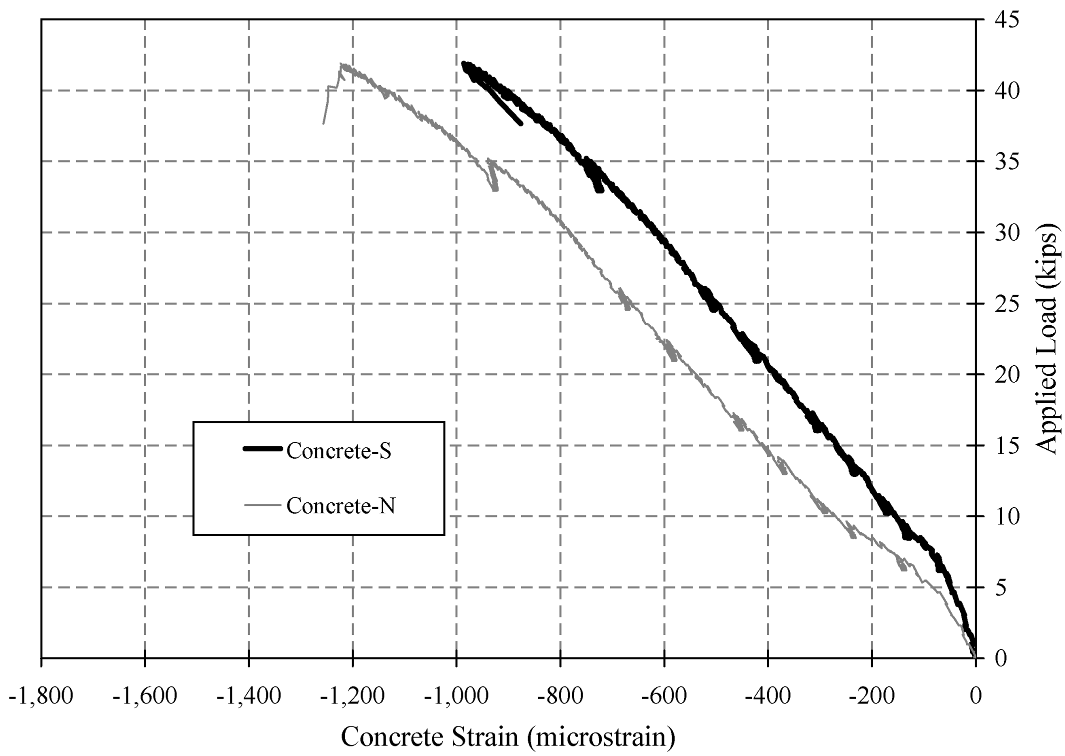


(b) Specimens D8-1, D8-2, D8-3, and D8-4

Figure H11 Load-Average Longitudinal Steel Strain Relationships

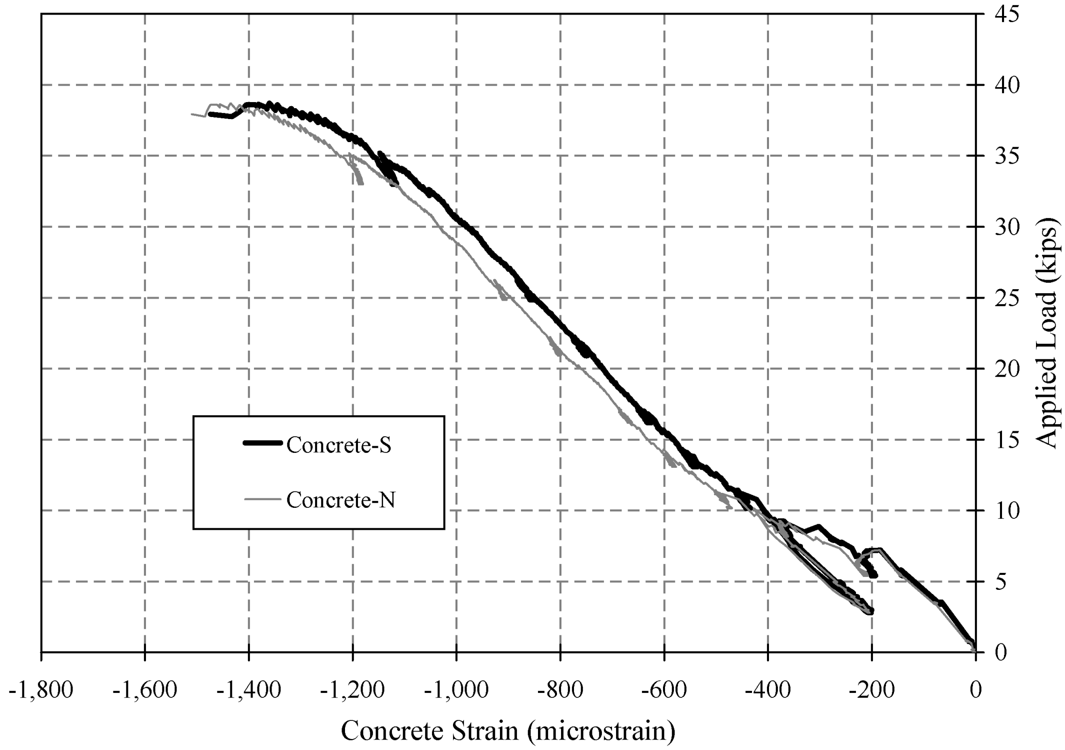


(a) Specimen D5-1

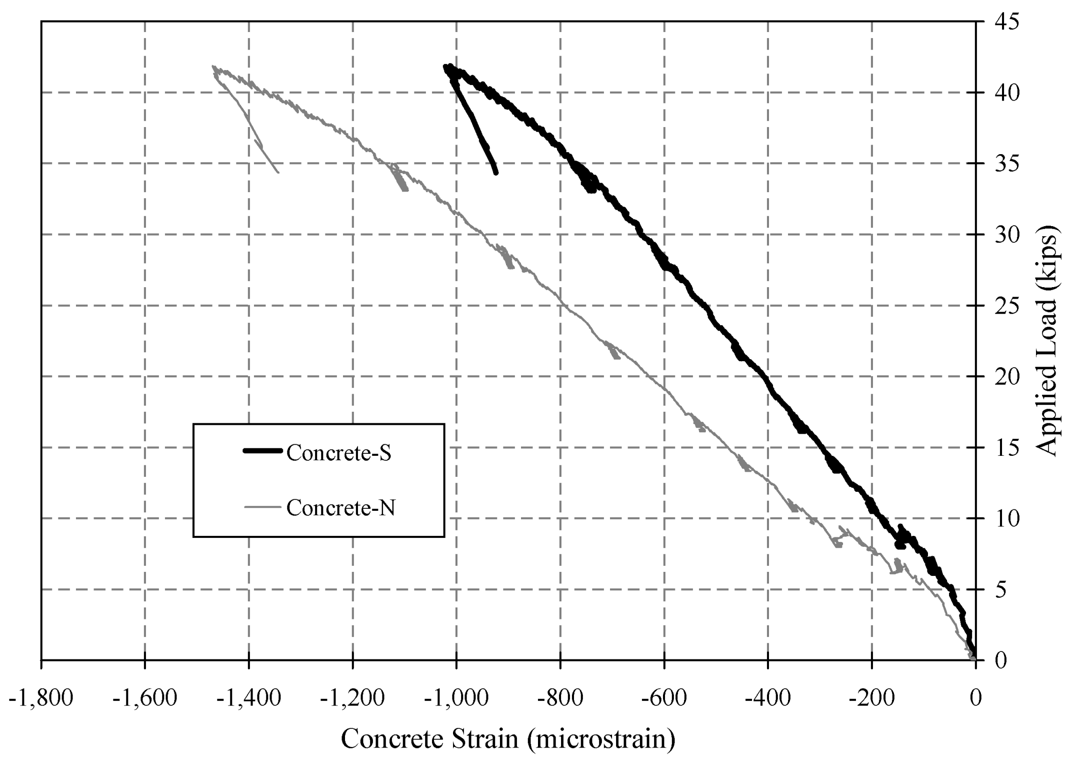


(b) Specimen D5-2

Figure H12 Load-Concrete Compressive Strain Relationships

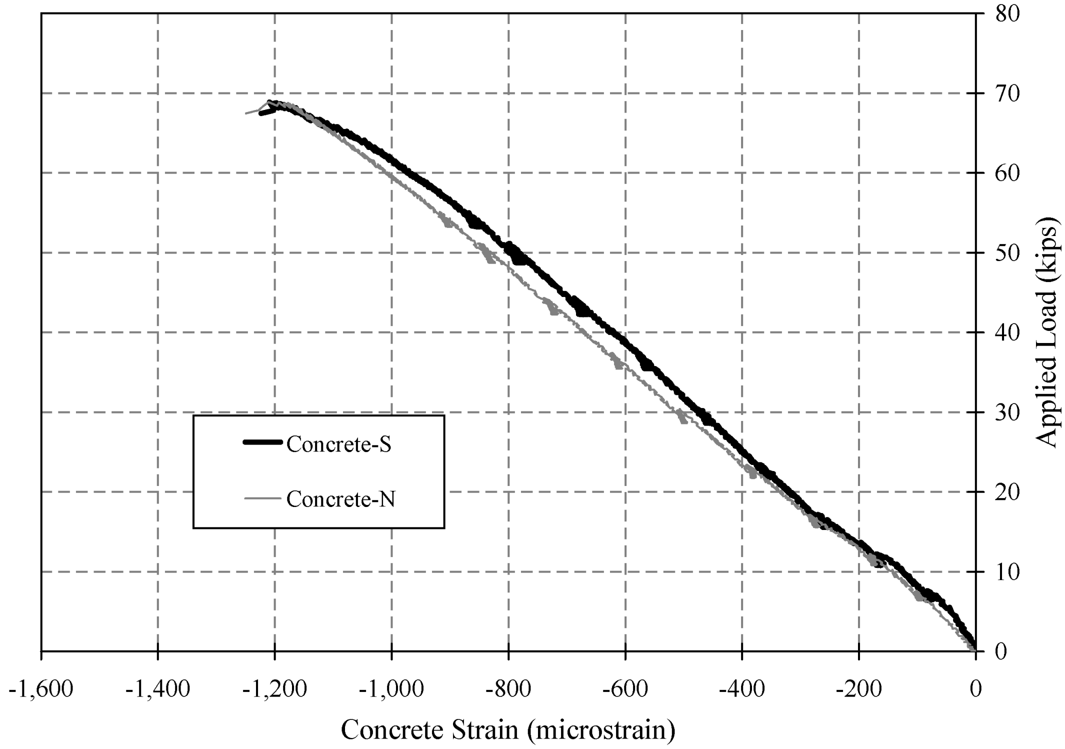


(c) Specimen D5-3

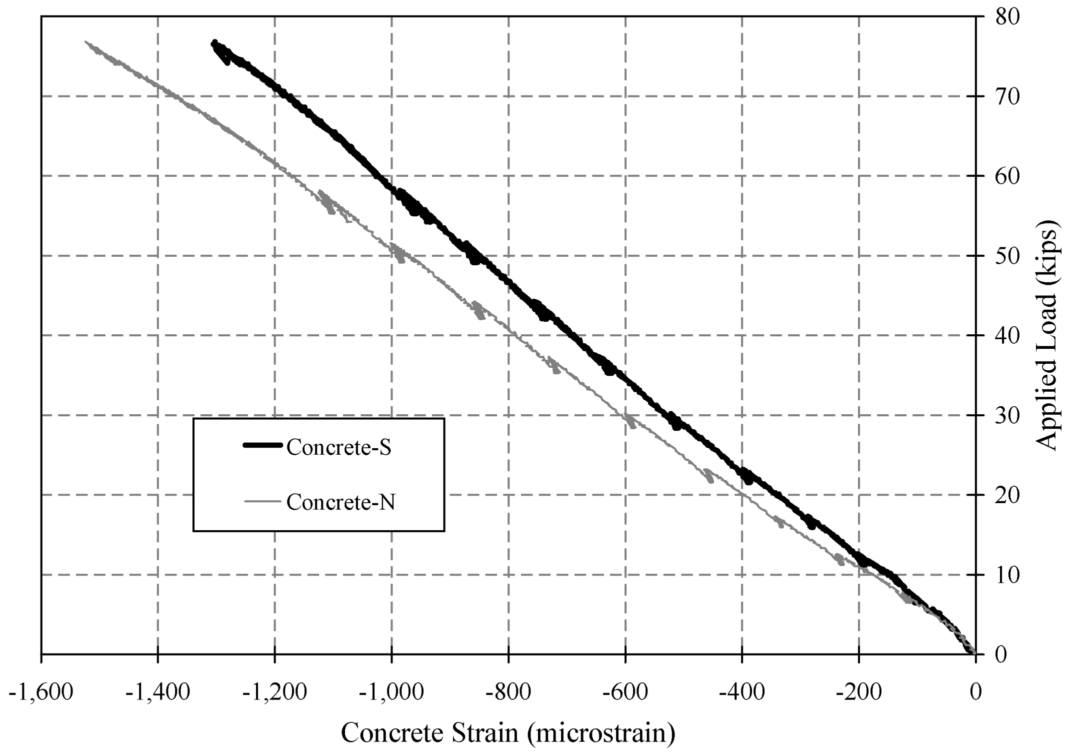


(d) Specimen D5-4

Figure H12 Load-Concrete Compressive Strain Relationships (cont.)

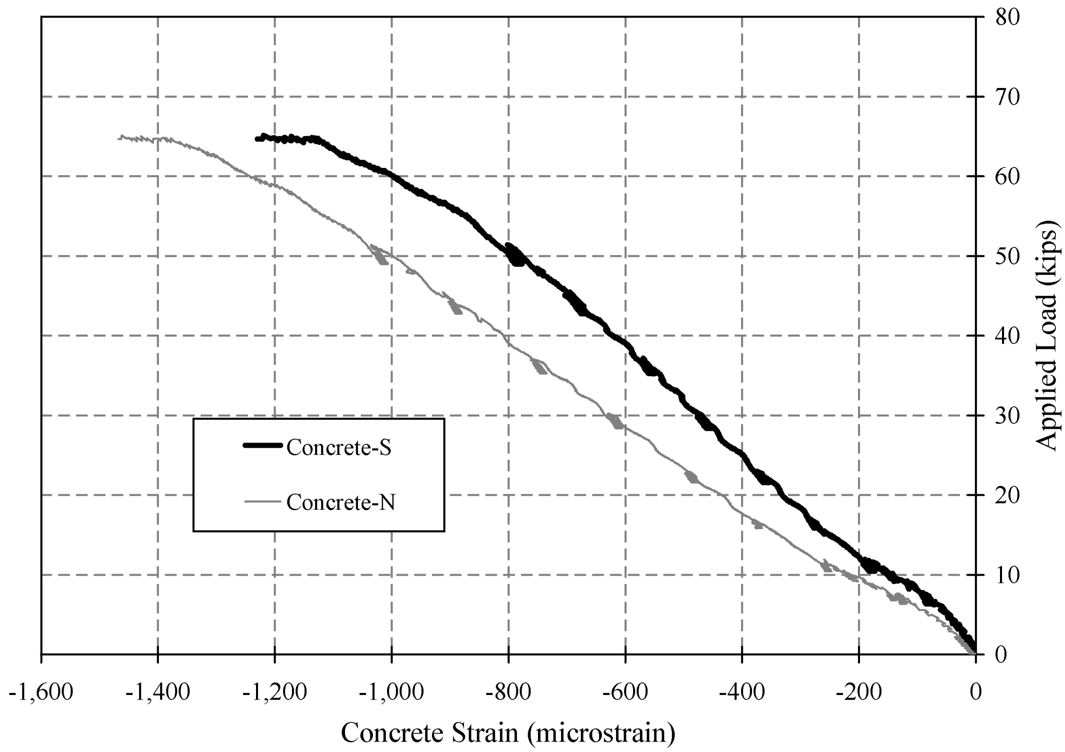


(e) Specimen D8-1

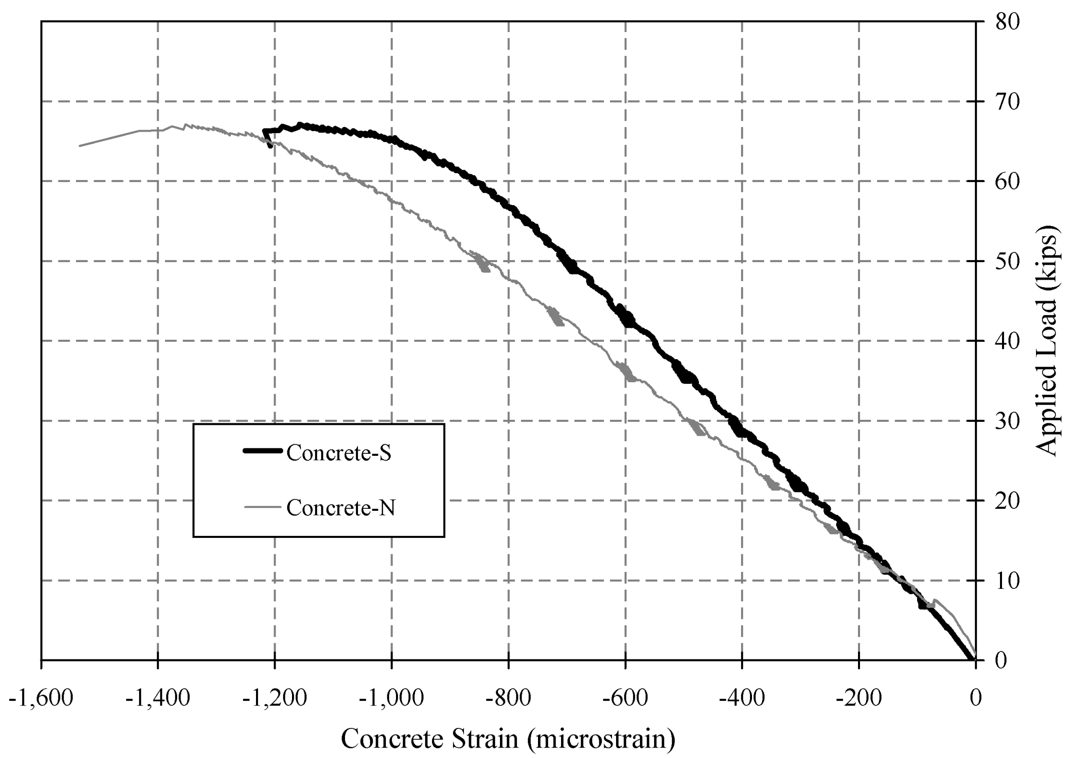


(f) Specimen D8-1

Figure H12 Load-Concrete Compressive Strain Relationships (cont.)

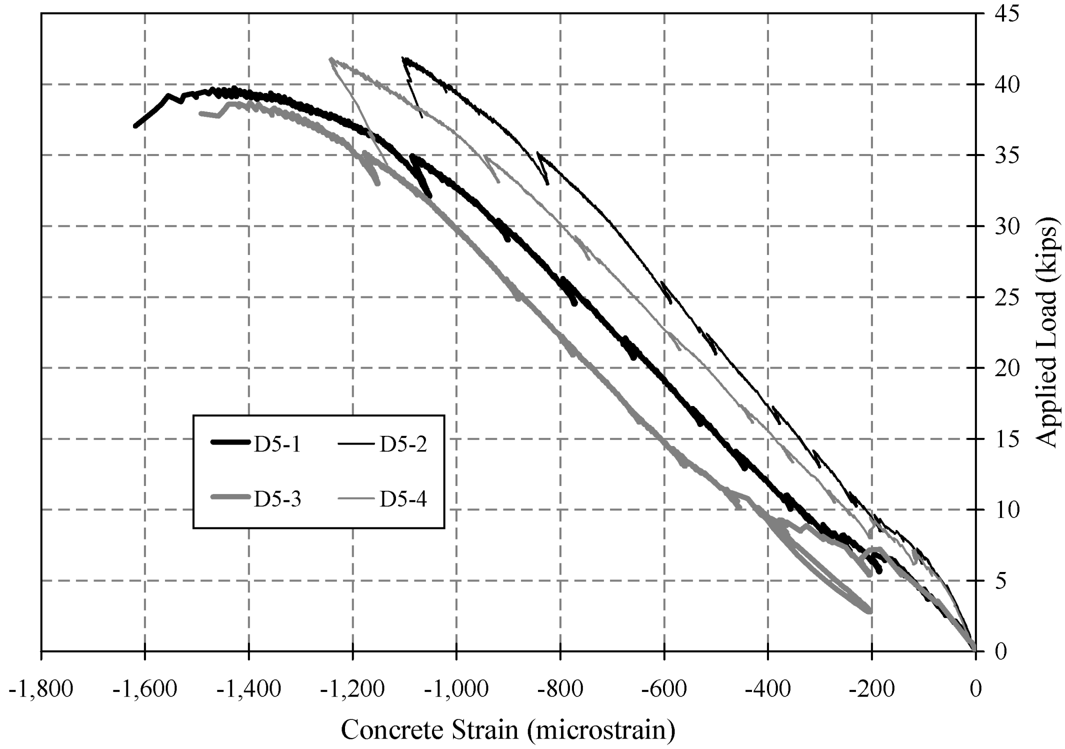


(g) Specimen D8-3

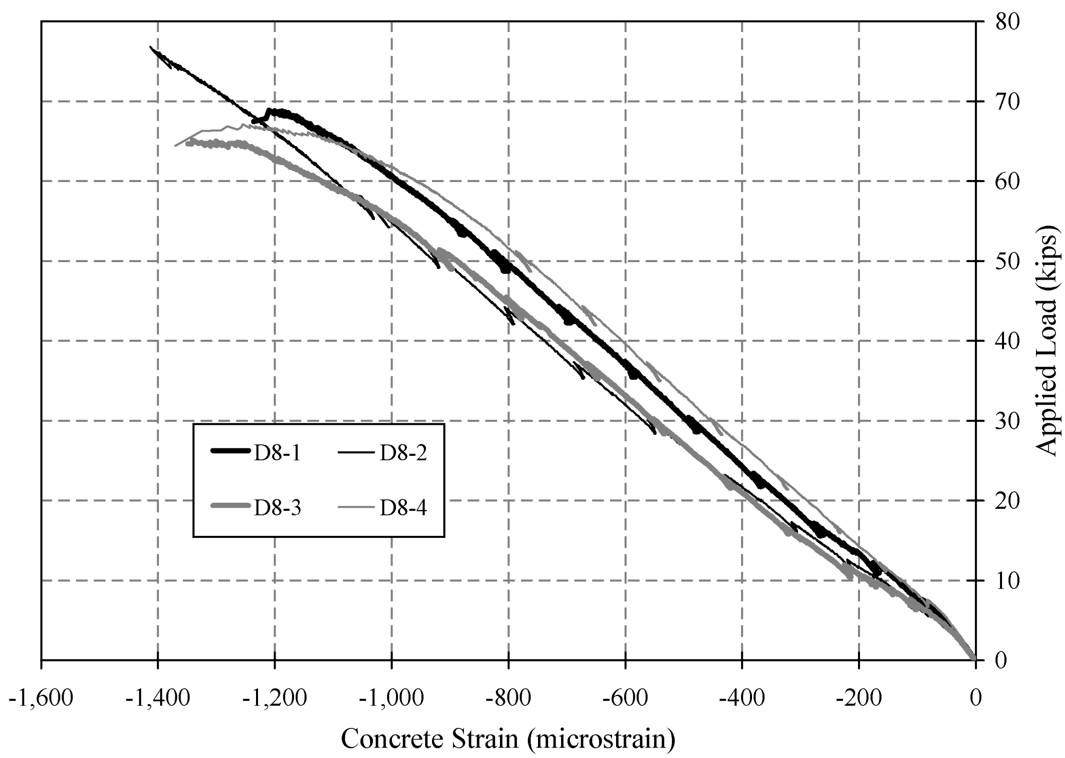


(h) Specimen D8-4

Figure H12 Load-Concrete Compressive Strain Relationships (cont.)



(a) Specimens D5-1, D5-2, D5-3, and D5-4



(b) Specimens D8-1, D8-2, D8-3, and D8-4

Figure H13 Load-Average Concrete Compressive Strain Relationships