Experiments on Lipped Channel Flexural Members

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ABSTRACT

A series of tests were conducted on lipped channel flexural members to study the behavior of edge stiffened elements. The details and the results of these tests as well as tests by others are discussed in this paper. All the test results are compared with those predicted by the AISI Specification.

1 INTRODUCTION

Test results [Willis and Wallace (1990a and b)] on lipped channel flexural members have shown some disagreement with the values predicted by the AISI Specification. The main reason for the discrepancies is thought to be the provisions for edge stiffened compression elements. This paper is the first in a series of three papers describing the research sponsored by the American Iron and Steel Institute at Cornell University to develop improved design procedures for edge stiffened elements.

This paper discusses a series of tests conducted at Cornell University on lipped channel flexural members. Tests were conducted on identical specimens except for the length of the lip stiffener and the lateral bracing mechanisms to obtain pure flexure. The details and the results of these tests are discussed in this paper. The results of tests by others are also briefly described. All the test results are compared with those predicted by the provisions of the AISI Specification (1991).

The results of these tests were used to provide confirmation for the parametric finite element studies conducted. The finite element studies are described in the second paper of this series. Based on the test results and the finite element studies, provisions for the design of edge stiffened compression elements are developed in a third paper.

2 TEST SPECIMENS

The parameter of interest is the compression lip length, therefore all specimen dimensions were nearly identical except for the lip length. Three types of specimens with lip lengths of 1 1/8" (28.58 mm), 1" (25.4 mm), and 7/8" (22.23 mm) were tested. These specimens are designated as specimens A, B, and C, respectively. The sections used were commercially available cold-rolled sections. The compression lip of specimen C was cold-rolled with a 1 1/8" lip. This lip was narrowed down to 7/8" using a portable electric shear fitted with a guide.

Dimensions of the specimens are listed in Table 1. The specimen designation scheme is as follows: The first letter represents the lip size. The letters following the hyphen represent the bracing conditions. "W" tests were braced at the web, "T" tests had steel decks fastened to the top flange only, "TB" tests had steel decks fastened to the top and bottom flanges. The tabulated dimensions are averages of measurements taken at three foot intervals. An average of several tensile coupon results is listed as the yield strength of each specimen.

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3 TEST SET-UP

All tests are carried out in a vacuum box. The vacuum chamber allows a uniform load to be placed on two beams at once. The beams are eighteen feet long and simply supported as shown in Figure 2. Details of the test set up for the three bracing conditions used are described in the next section.

3.1 Specimens Braced at the Web

For the specimens braced at the webs, lateral braces were placed every two feet as shown in Figure 3. Figure 4 gives a cross-section view of the set up. A computer analysis indicates that this interval of bracing produces a torsional effect of less than one percent of the total stress. The braces, composed of the same C-sections, resist lateral and torsional bending. Plywood strips cross both specimens and produce a uniform load. Teflon sheets are placed at the wood/lipped channel interface to prevent friction.

Two types of connections to the web were tried: a two-bolt connection (see Figure 5) and a three-bolt connection (see Figure 6). Table 2 compares the results of both tests. Rotations for the 2-bolt and 3-bolt case were about 3° and 1°, respectively. In the three-bolt case, severe lipped channel deformation was observed at the location of the top bolt. The authors believe that three holes in the web may interfere with the beam reaching its ultimate strength. Therefore, this study will deal with only the two-bolt connection tests.

3.2 Specimens Braced on Top Flange Only

Another set of tests used steel decks fastened to the top flange of each lipped channel. Figure 7 shows the cross section view of the set up. The deck was fastened at one foot intervals on the flange centerline. Self-tapping screws with rubber washers were used. Due to the lipped channel's thickness, the holes in the flanges had to be pre-drilled. The dimensions of the steel decks are shown in Figure 8.

3.3 Braced on the Top and Bottom Flanges

The test set up for these tests was nearly identical to the one previously discussed except steel decks were fastened (at one foot intervals) to the bottom flange as well. Figure 9 describes the set up.

It was very difficult and awkward to place the steel decks on the bottom flanges. Placement of these decks in the center region of the beam was nearly impossible. Therefore, small steel channel sections were attached to the bottom flange in the middle third section of the beam in replacement of the steel decks. This is drawn in Figure 10.

4 TEST PROCEDURE

During the tests, stable vacuum pressures were recorded at 5 to 10 psf increments. Vertical deflection, horizontal deflection, and rotation were measured and recorded as well.

The vertical deflections were measured at the top flange-web intersection from a stationary point outside the vacuum box. Horizontal deflections were measured at the bottom web-flange intersection. Rotations were measured at the web mid-height. Figure 11 describes the measured deflections.

5 TEST RESULTS

5.1 Ultimate Moments

The maximum moments reached by the sections are listed in Table 3. These moments are calculated for the beam mid-span at the ultimate load. M_n is the nominal moment strength predicted by the 1986 AISI Specification. Figure 12 graphically describes the effect of lip size on the section's moment capacity.

The following observations are made:
- M_t decreases 7 to 15% (an average of 10.7%) as the lip size increases from 7/8" to 1".
- M_t increases 3 to 6% (an average of 3.3%) as the lip size increases from 1" to 1 1/8"
- The strongest section has the smallest lip size (7/8"), followed by the 1 1/8" lipped section, followed by the 1" lipped section.
- The lipped channels tested with steel decks attached to the top flange only ("T" series) yield significantly lower results than the "W" and "TB" test series.
- The AISI Specification (1991) predicts the largest lipped section to be the strongest. The predictions are contrary to the experiment results and unconservative in all cases except one.

5.2 Maximum Deflections

The maximum lipped channel deflections are listed in Table 4. Measurements are made as described in Section 1.3 of this report. Positive deflection directions and variable definitions are shown in Figure 11. The table shows the following:
- The lipped channels braced on the top flange only rotated an average of 84% more than the other two types of tests. The large rotations caused large lateral deflections.
- Maximum vertical deflections decreased with increasing lip size.
- "T" test series produced the greatest deflections.
- "TB" test series produced the least deflections.

5.3 Stiffnesses

The following was observed regarding the stiffnesses of the specimens:
- Specimens with braces attached to the web are the stiffest, and the ones braced on the top flange are the least stiff of all.
- Lip size does not greatly affect the stiffness. The 1 1/8" lip size tends to be the stiffest followed by the 1" and 7/8" lip sizes which have nearly identical stiffness. This is true for all brace conditions.

5.4 Failure Modes

Failure is defined as collapse of one lipped channel in the vacuum box. In most cases this collapse is sudden, therefore no conclusions on the mechanism leading to this collapse can be made. All failures were due to lipped channel buckling. The screws used to fasten the deck did not fail or pull out in any of the experiments.

The tests that were braced on the top flange only ("T" series) failed in a manner different from the "W" and "TB" tests. An instant before failure, the lipped channel quickly rotated about its shear center until the web was almost parallel to the floor and then collapsed. This test series remained twisted even after the load was removed.

Waves in the flange and lip were sometimes observed in the lipped channel adjacent to the failed beam. This was seen only for lipped channels braced on the top and bottom flanges. This indicates that the mechanism leading to sudden failure may be lip buckling leading to flange buckling which leads to overall buckling.

Sketches of the buckled lipped channel cross-sections are shown in Figure 13. The figure indicates the span location of beam failure. If failure was at a brace location, it occurred at the brace nearest to mid-span. Otherwise, the lipped channel buckled at or very near mid-span.

6 EXPERIMENTS BY OTHER RESEARCHERS

This section briefly describes the conditions of other researcher's experiments who have tested edge stiffened C-sections as beams.

6.1 Willis and Wallace (1990a and b)

Willis and Wallace (Ref. 1, 2) performed an experimental study on various C-section edge stiffened lipped channels supporting through fastened metal building roof panels. The main parameters of this experiment were lip width and the location of the fastener relative to the web. The test set up consisted of two C-section lipped channels that were twenty feet long and spaced five feet apart. The lipped channels supported a conventional roof deck comprised of 7 foot long sheets. The deck was fastened to each of the two lipped channels with self-drilling fasteners spaced at one foot intervals. No other bracing was provided. The lipped channels were uniformly loaded with concrete blocks.

Specimens 1C2, 1C3, and 1C4 had identical material properties and nearly identical dimensions except for the lip width. The compression lip of the second and third specimen was narrowed using a portable electric shear fitted with a guide. The element sizes and test results can be interpreted from Table 5 (in Section 2.2 of this report) which summarizes all the other researcher's specimens and results as well.

6.2 Ellifrit and Sputo (1992)

Ellifrit and Sputo(1992) used eighteen foot lipped channels that were simply supported. They were loaded by two point loads. The location of the loads and lateral braces are implied in the test name (listed in Table 5): the load was applied at *(M)*id-point or *(*T)hird point. Braces were located at the *(T)*op flange only or *(B)*oth top and bottom flanges. All of the beams were loaded at the points they were braced. Test C14F is the exception. This test was fully braced and load points were 2.5 feet off center.

6.3 Schuster (1992)

Specimens of Schuster (1992) were 14 feet long with a constant moment region span of 6 feet. All beams were simply supported. Lateral bracing was provided approximately every 20 inches by the use of wooden blocks against the web. Aluminum angles were attached to the top and bottom flange of each specimen at one foot intervals.

6.4 Results

Table 5 lists design ratios and test results for each experimenter. The nominal moment capacity (M_n) was calculated according to the 1986 AISI Specification. This table shows the unconservative nature of the specification. It does not show, however, any trend or hint as to the location of this unconservatism.

7. EFFECTS OF SHEARING THE LIP STIFFENER

Both the authors and Willis and Wallace shaved the edge of the compression lip stiffener with an electric shear to obtain smaller lip lengths for some test specimens. These researchers observed that the sections with the smallest lip size (the ones that were sheared) had the greatest strength. This result was not expected, nor was it predicted by the AISI Specification. Consequently, the authors performed a simple experiment to observe the residual stress effects produced by shearing the lip of a section.

7.1 Test Set-up and Procedure

A two foot portion of already tested specimen A-W (see Table 1) was cut off and strain gaged in the longitudinal direction as shown in Figure 14. This section was cut from the beam's end where the section's geometry and material properties were not affected by the previous testing. Two strain gages, "Trans1" and "Trans2", measured strains in the transverse direction.

One-eighth of the lip was sheared with an electric portable shear. Afterwards, the residual strains were measured. For maximum accuracy, the strains before and after shearing were measured without moving or disturbing the specimen.

Another simple experiment was done on another piece of the same section (A-W). With a band saw, about a two foot long, inch wide strip was cut longitudinally along the lip near the corner radius. This strip curled into an arc. Measuring the length of the arc and the arc height, the stresses through the thickness of that portion of the cross section were estimated. Results are discussed in the next section.

7.2 Results

The measured residual stresses are listed in Table 6 for the locations shown in Figure 14. It shows that the residuals reach up to about half the yield stress on some lip locations. For the most part, the residual stresses in the flange (for all gage directions) are small.

The height of the arc produced after cutting the lip with a band saw indicates that an approximate stress of 25 ksi is present through the thickness of the lip near the radius. The compression is on the inside (facing the web) and the tension is on the outside. The assumption that this residual is superimposed on the shearing residual implies that the material on the inside lip is at or near yield before any load is placed on the section.

8 CONCLUSIONS

The experiments of the authors show the same trend as those of Willis and Wallace tests: the section with the smallest lip size is the strongest of all three tested. This is true for all brace conditions. It is quite probable that this trend may be due to the shearing effects of the lip. In all cases where the lip material was sheared, an increase in strength was observed. The strain gage experiment performed by the authors shows that residual stresses caused by shearing may reach up to about half the yield strength. In addition, a high residual stress is already present near the corner with the stiffening lip. The combination of these residual stresses is sufficient to affect the behavior and strength characteristics of the section.

The brace details affect the ultimate capacity of the lipped channels. It is the opinion of the authors that the "T" test series (steel decks fastened to the top flange only) were not adequately braced and lower failure loads were caused by increased stresses due to torsion. The "W" test series rotated slightly more than the "TB" test series and therefore had slightly lower maximum moments. The difference in the results is insignificant and may be due to other factors such as material properties. The authors believe that both the "W" and "TB" test series were adequately braced which allowed for the section's moment strength to be reached.

The present AISI Specification is unconservative in predicting the bending capacity of edge stiffened C-sections. This is true for the experiments done by all researchers mentioned in this paper. The analytical studies presented in the two accompanying papers by Moreyra and Peköz (1994a and b) are aimed at improving the AISI Specification provisions.

9 ACKNOWLEDGEMENTS

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APPENDIX - NOTATION

D1, D2, H, W1, W2, $\theta1$, $\theta2$, $\theta3$, $\theta4$	Cross-sectional dimensions defined in Fig. 1
V, H	Displacements defined in Fig. 11
"Transl" and "Trans2"	measured strains in the transverse direction (Fig. 13)
M_t	Maximum moment observed in test
M_n	Nominal moment capacity calculated according to the AISI Specification (1991)

Table 1 Measured Dimensions of Authors' Specimens.

Dimensions are in inches or degrees. Yield stress units are ksi. All radii are 0.1875". See Figure 1 for dimension definitions, 1" = 25.4 mm.

	1 1/8" Lipped Sections			1" Lipped Sections			7/8" Lipped Sections		
	A-W	A-T	A-TB	B-W	B-T	B-TB	C-W	C-T	C-TB
T	0.071	0.071	0.071	0.071	0.071	0.071	0.069	0.073	0.071
H	8.547	8.550	8.633	8.538	8.549	8.641	8.558	8.554	8.613
B1	2.415	2.450	2.462	2.473	2.479	2.488	2.450	2.445	2.472
B2	2.479	2.472	2.496	2.447	2.443	2.466	2.480	2.485	2.500
C1	1.122	1.124	1.130	0.981	0.982	0.950	0.879	0.867	0.878
C2	0.980	0.974	0.979	1.119	1.122	1.138	0.956	0.962	0.984
$\theta 1$	87.8	88.5	89.0	90.3	90.0	90.6	90.3	90.8	90.1
$\theta 2$	92.0	91.8	90.4	90.0	90.3	90.8	91.3	91.8	91.4
$\theta 3$	91.0	90.7	89.5	90.8	91.3	90.9	91.0	91.0	90.4
$\theta 4$	90.0	90.7	89.9	89.5	87.8	88.6	90.8	91.0	90.5
F_y	57.6	56.9	63.5	57.5	58.7	61.6	59.9	57.8	62.7

Table 2 Comparison of two and three-bolt connection test results

Lip Size	Connection Type	M_t	M_t/M_n
1 1/8"	2 bolts	123.76	.91
	3 bolts	**	**
1"	2 bolts	117.13	.81
	3 bolts	126.36	.86
7/8"	2 bolts	138.02	1.02
	3 bolts	126.26	.92

** No experiments were done for this case.
1" = 25.4 mm.

Table 3 Experimental and predicted section strength.

TEST	M_t*	M_n**	M_t / M_n
A-W	123.76	143.52	0.86
A-T	105.75	142.64	0.74
A-TB	127.38	159.34	0.80
B-W	117.13	143.91	0.81
B-T	103.77	145.81	0.71
B-TB	123.94	150.13	0.83
C-W	138.02	135.83	1.02
C-T	116.00	142.42	0.81
C-TB	132.64	146.63	0.90

* Test maximum moment (k-in)
** Nominal moment capacity (k-in) predicted by the 1986 AISI Specification
1 k-in = 113 N-m

Table 4 Maximum Test Deflections.
See Figure 11 for variable definitions and positive directions.

TEST	V_{max} (in)	H_{max} (in)	θ_{max} (deg)
A-W	2.50	0.17	2.3
A-T	2.66	1.27 **	16.7
A-TB	2.46	NM	*
B-W	2.36	0.23	3.1
B-T	2.88	1.33 **	17.5
B-TB	2.69	NM	*
C-W	3.09	0.22	3.0
C-T	3.34	1.33 **	17.5
C-TB	3.17	NM	*

NM = Not measured
* = Negligible. Less than 1/2 degree
** = Calculated from rotations
1" = 25.4 mm

Table 5 Tests by other researchers and the Authors.
D = lip full width; w = flange flat width; h = web flat width; T = thickness (in.), F_y = yield stress in ksi units, M_n = ultimate moment predicted by AISI

Source	TEST	T	D/w	w/T	h/T	D/T	Mt/Mn	Fy
Willis and Wallace (1990)	1C2	0.061	0.672	25.92	119.15	17.42	0.857	53.9
	1C3		0.612	25.92	119.15	15.88	0.919	53.9
	1C4		0.533	25.92	119.15	13.83	0.993	53.9
Ellifrit, Sputo and Haynes (1992)	C14F	0.0723	0.31	37.83	103.85	11.74	0.95	63.6
	C14TT	0.0728	0.328	34.77	102.88	14.31	0.77	62
	C14TB		0.422	34.59	102.74	14.6	1.04	62
	C14MT		0.413	35.1	102.67	14.49	1.05	62
	C14MB		0.404	35.02	102.88	14.16	1.03	62
Schuster (1992)	CS1	0.048	0.398	26.79	160.39	10.65	0.83	52
	CS2		0.398	26.79	160.39	10.65	0.83	52
	CS3		0.386	27.6	160.39	10.65	0.86	52
Authors' Tests	A-W	See Table 1	0.591	26.73	113.1	15.8	0.86	57.6
	A-T		0.581	27.22	113.14	15.82	0.74	56.9
	A-TB		0.581	27.395	114.31	15.91	0.8	63.5
	B-W		0.502	27.55	112.97	13.82	0.81	57.5
	B-T		0.5	27.63	113.76	13.83	0.71	58.7
	B-TB		0.482	27.76	114.42	13.38	0.83	61.6
	C-W		0.454	28.07	116.59	12.74	1.02	59.9
	C-T		0.451	26.36	110.04	11.88	0.81	57.8
	C-TB		0.449	27.54	114.03	12.37	0.9	62.7

Table 6 Measured residual stresses produced by shearing the lip.

Location	**Residual Stress (ksi)**	**Compression / Tension**
A1	2.06	Compression
A2	2.42	Compression
A3	1.92	Compression
B1	4.6	Compression
B2	4.8	Compression
B3	36.6	Tension
C1	18.5	Compression
C2	32.4	Compression
Trans1	2.3	Compression
Trans2	2.2	Compression

1 ksi. = 6.895 N/mm^2

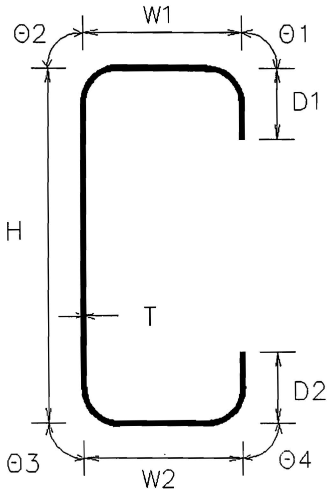


Figure 1 Measured dimensions of test specimens.

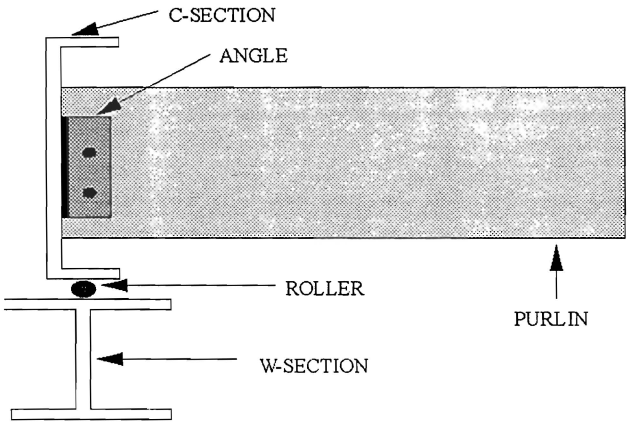


Figure 2 Simple supports used in experiments.

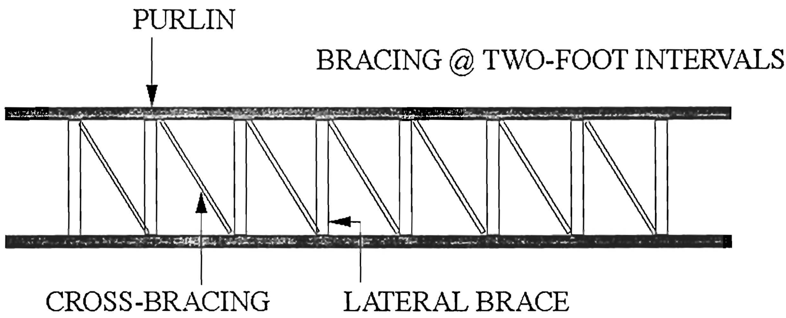


Figure 3 Plan view of bracing system for purlins braced at the web.

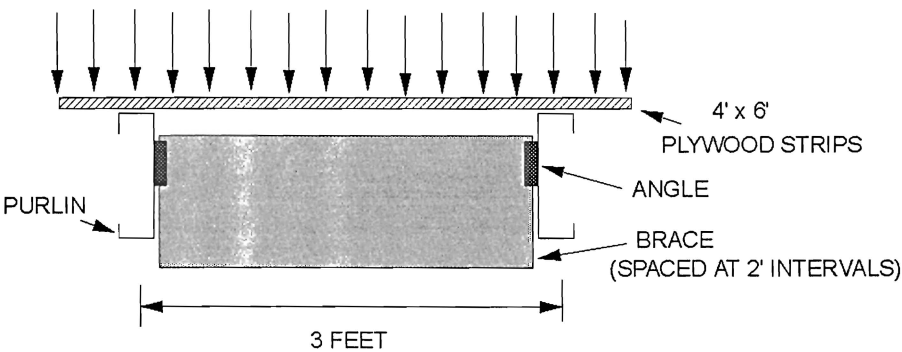


Figure 4 Cross section view of purlins braced at the web.

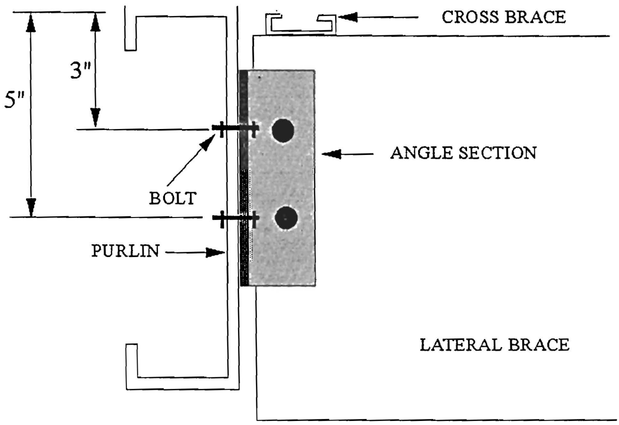


Figure 5   Cross section view of 2-bolt connection to web.

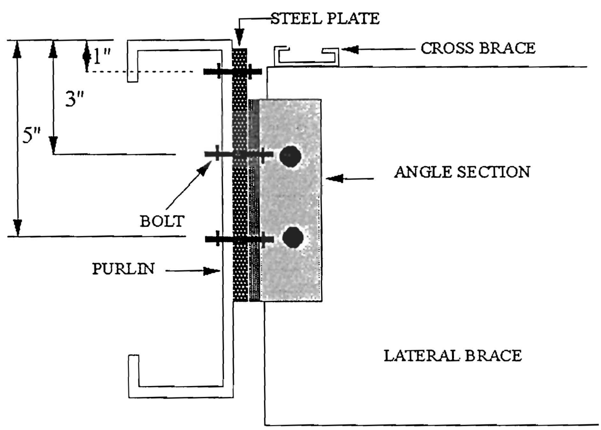


Figure 6   Cross section view of 3-bolt connection to web.

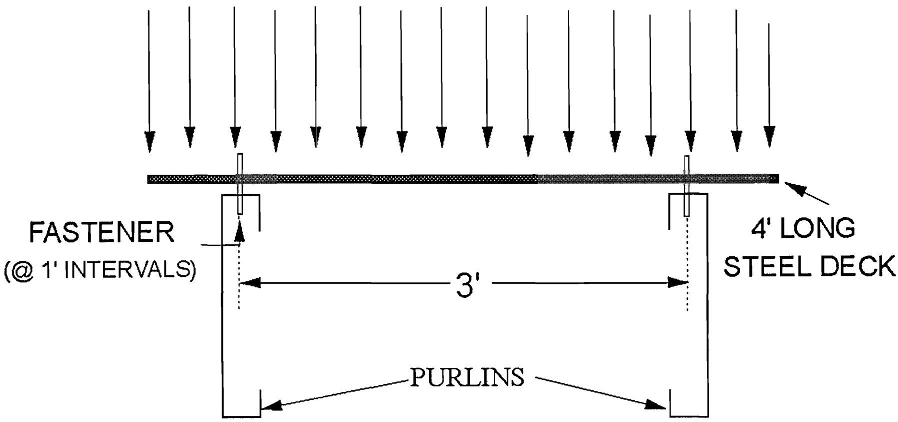


Figure 7 Cross-section view of purlins braced on the top flange only.

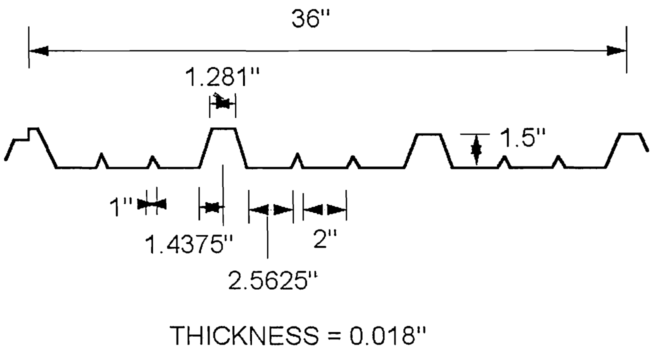


Figure 8 Steel decks used in experiments.

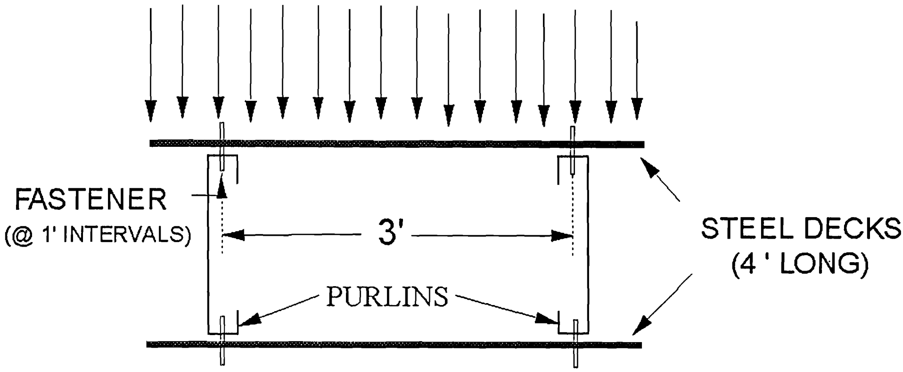


Figure 9 Cross section view of bracing system for experiments braced on the top and bottom flanges.

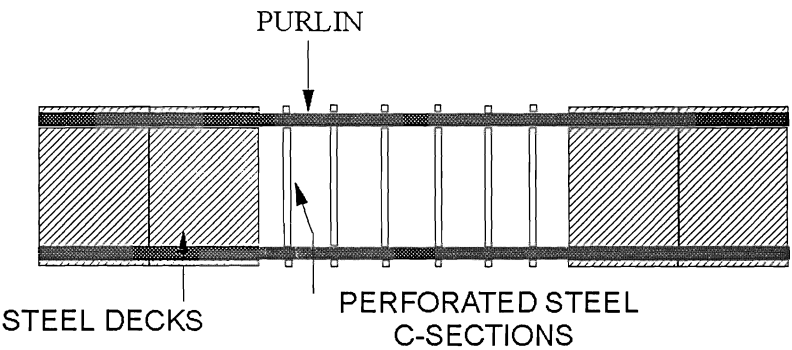


Figure 10 Plan view of bottom flange bracing for experiments braced on top and bottom flanges.

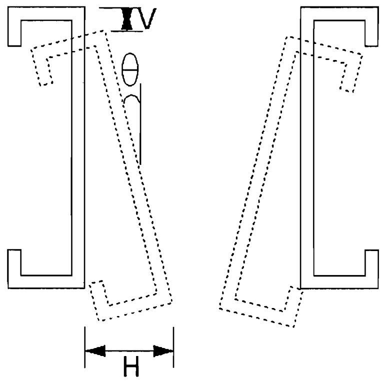


Figure 11 Positive direction of deflections and variable definitions

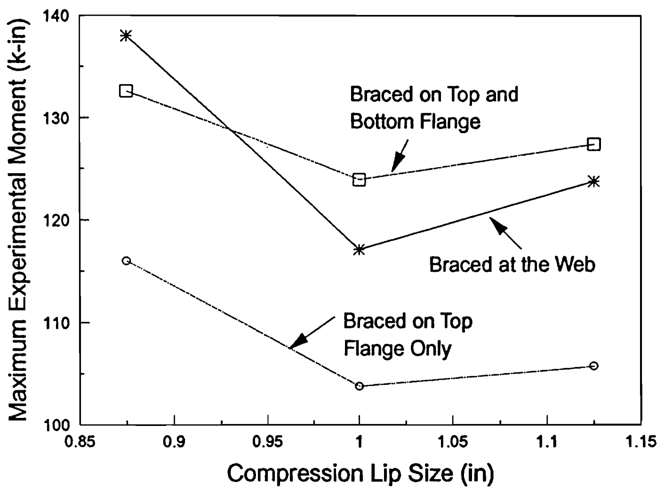
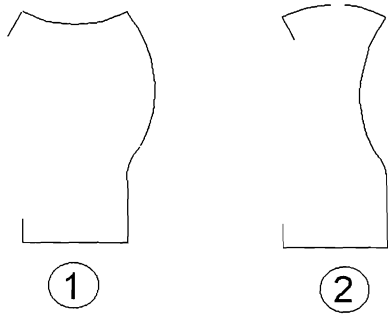


Figure 12 Experiment maximum moment versus lip size.



TEST	Deformed X-Sect.	Location of buckle is at brace location
A-W	1	yes
A-T	2	yes
A-TB	1	no
B-W	1 & 2	no
B-T	2	yes
B-TB	1 & 2	yes
C-W	2	no
C-T	2	yes
C-TB	1	yes

Figure 13 Deformed shape of failed specimens.

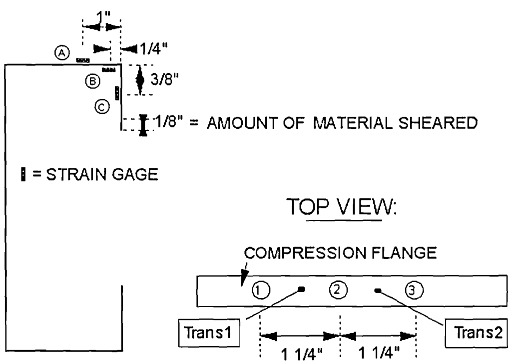


Figure 14 Strain gage locations for experiment to measure residual stresses due to lip shearing.